

Tracking the athlete's eye: Comparing oculomotor metrics with non-athletes

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ABSTRACT

Oculomotor measures provide objective, quantifiable markers of brain health that support the assessment and longitudinal monitoring of concussion outcomes. Athletes may perform differently than non-athletes on these tasks due to sport-specific training, yet existing protocols use normative ranges based on general populations. This study established baseline oculomotor metrics in college athletes using a virtual reality protocol and compared performance to general population normative data. A total of 163 university student-athletes (ages 17-30) completed an eight-subtest protocol assessing smooth pursuit, saccades, vestibular ocular reflex, optokinetic nystagmus, anti-saccades, and spontaneous nystagmus. Results revealed significant differences between athletes and the general population on 28 of 44 metrics, indicating distinct performance levels in head and eye movements. These findings emphasize the need for athlete-specific normative standards to ensure accurate concussion assessment. The normative ranges established provide a foundation for future concussion evaluation and management in athletes, underscoring the critical need to compare athletes to sport-specific rather than general population standards for improved diagnostic accuracy and clinical utility.

Keywords: Sport medicine, Assessment, Oculomotor, Vestibular, Virtual reality, Concussion.

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INTRODUCTION

Oculomotor measures provide objective brain health metrics that can be valuable for assessing and monitoring concussion progression (Hunfalvay et al., 2019). Advances in virtual reality technology now make it possible to administer these measures in non-medical environments, such as on the sports field, offering a practical tool for evaluating athletes in real time. However, previous research suggests that athletes may perform differently from non-athletes on oculomotor tasks, likely reflecting sport-specific training effects and performance demands (Kubitz et al., 2020; Garner et al., 2023; Laby & Appelbaum, 2021; Zwierko et al., 2019). Despite this, existing protocols and normative ranges are based primarily on non-athlete populations (Lunkova et al., 2024). Comparing athletes to these reference values is therefore essential to determine whether their performance diverges significantly from typical norms. If so, the development of athlete-specific normative ranges will be critical to improving the accuracy and clinical relevance of concussion diagnosis and management in this unique population.

An estimated 1.6 to 3.8 million sport-related concussions occur every year in the United States (Centers for Disease Control and Prevention, 2019; Choe, 2016), not including the large number of sub-concussive events that often go unreported (Nauman, Talavage, & Auerbach, 2020). Despite this high prevalence, there are still no universally accepted diagnostic criteria to reliably detect concussions or to characterize the severity of their pathophysiological and functional sequelae, nor are there rehabilitation protocols endorsed by most sport clinicians (Broglia, Sosnoff, & Ferrara, 2009). Traumatic brain injury is not a single event but rather a sequence in which the initial concussion acts as a catalyst for a cascade of physiological and functional changes in the brain and body, expressed with varying paces, severities, and durations of symptoms (Choe, 2016). Assessing concussions remains particularly challenging because current approaches rely heavily on self-report and subjective clinical evaluation, which are limited in accuracy and sensitivity (Dams-O'Connor et al., 2014; Dorman et al., 2015; Finnoff et al., 2009; Kontos et al., 2014; Kroshus et al., 2015; McLeod & Leach, 2012). Moreover, these methods are often not sensitive enough to detect subtle impairments that persist beyond the acute stage, with their effectiveness diminishing after four weeks to three months post-injury (Cavanaugh et al., 2005; Slobounov et al., 2011).

Concussion assessment in athletes presents unique challenges that add complexity to an already difficult task. In many cases, evaluations must be performed by clinicians in distracting and high-pressure environments, where grading and capturing all possible impairments is particularly challenging (Dams-O'Connor et al., 2014; Kroshus et al., 2015). Furthermore, while portable testing technologies hold promise, they are not equally inclusive or effective for all populations. For instance, functional near-infrared spectroscopy (fNIRS), a widely studied tool, often fails to collect valid data from individuals with darker complexions or coarse/thick hair, disproportionately affecting athletes from the African Diaspora and Latinx backgrounds (Tucker & Rivera, 2021), highlighting broader systemic disparities and biases in neuroscience (Webb, Etter, & Kwasa, 2022). Another concern is that although the percentage of reported concussions in sports is lower compared to other daily activities, athletes are uniquely pressured to return to play quickly, often without a clear understanding of the injury's severity or potential long-term consequences. Given the highly variable nature of concussion signs and symptoms, some injuries are mislabelled as "*mild*" or dismissed altogether as "*not real*," contributing to premature return-to-play decisions. Critically, prior research indicates that even athletes who appear asymptomatic may still show structural and functional brain changes (Broglia, Sosnoff, & Ferrara, 2009), underscoring the limitations of current assessment approaches and the risks faced by this population.

Post-concussion impairments in athletes vary by factors such as sport, gender, and type of head impact, and may not always present with obvious symptoms (Chen et al., 2019; Choe, 2016; Kontos et al., 2019; Lumba-Brown et al., 2020). Although many are believed to "fully recover" within one to two weeks, this definition is problematic, as subtle physiological, cognitive, and motor changes may persist undetected (Pearce, Tommerdahl, & King, 2019; Quintana et al., 2020). In fact, 15%–20% of individuals report lingering symptoms beyond three weeks, and up to 38% meet criteria for post-concussion syndrome, with measurable oculomotor deficits such as impaired antisaccades observed months after injury (Johnson, Zhang, Hallett, & Slobounov, 2015). These findings show how athletes may return to play while still experiencing subtle, unresolved impairments that escape current testing protocols. Thus, protocols including a combination of the prevalence history, self-report symptoms, clinical evaluation, and objective measures evaluating vestibular, cognitive, visual, and somatosensory integration, would have greater sensitivity to identify deficits at all stages after a concussion (Capó-Aponte et al., 2012).

In this context, oculomotor metrics offer a promising avenue, as they provide objective, quantifiable measures of brain function that may overcome many of the limitations of traditional concussion assessment methods (Hunfalvay et al., 2019). Visuomotor pathways assessment provide an objective and reliable perspective on brain functioning related to concussions (Hunfalvay et al., 2019; Johnson, Zhang, Hallett, & Slobounov, 2015; Kelly et al., 2019; Kontos et al., 2017). Neural pathways supporting oculomotor functions such as saccades, antisaccades, and optokinetic nystagmus span wide areas of the brain that are particularly vulnerable to concussive injury. Lesions in these circuits can be detected through measurable eye and gaze responses (Hunfalvay et al., 2019; Johnson, Zhang, Hallett, & Slobounov, 2015). For example, dysfunction in optokinetic nystagmus has been linked to patients with chronic concussion or post-concussive syndrome (Cochrane et al., 2019). Importantly, oculomotor testing can capture brain dysfunction even after symptoms are no longer reported and the injury is presumed resolved (Kelly et al., 2019). Thus, technologies assessing visuomotor pathways may support clinicians in building individualized concussion profiles and in tracking recovery across different stages of healing (Kontos et al., 2017; Lumba-Brown et al., 2020).

Oculomotor measures using virtual reality have been explored as tools to generate brain health-related metrics, with normative ranges calculated from general population samples. For example, the NeuroFlex protocol has normative ranges derived from a sample population of healthy individuals (Lunkova et al., 2024). The normative ranges were calculated as the 95% confidence interval for metrics with a distribution resembling normal. For non-normal metrics, the upper range was defined as $Q3+1.5IQR$ and the lower range was defined as $Q1-1.5IQR$ (Soave et al., 2023). However, athlete-specific normative values are essential, as athletes often perform differently from non-athletes. Research demonstrates that visual-perceptual and visual-cognitive abilities vary depending on the visual demands of each sport, the training of specific visual skills, vestibulo-ocular reflex (VOR) adaptations, and the athlete's level of expertise (Kubitz et al., 2020; Laby & Appelbaum, 2021; Millard et al., 2021; Slobounov et al., 2011). Evidence suggests that athletes frequently show superior performance on several vestibulo-oculomotor measures compared to non-athletes (Kubitz et al., 2020; Laby & Appelbaum, 2021; Lange et al., 2018; Millard et al., 2021; Quintana et al., 2020; Vera et al., 2020). For instance, Laby and Appelbaum (2021) reported that high-achieving athletes displayed better perceptual cue detection, more efficient eye movements, and faster processing than less-skilled athletes or non-athletes. Similarly, Kubitz et al. (2020) found that sport-specific training correlated with enhanced visual-oculomotor skills, noting that elite baseball players outperformed amateurs and non-athletes in measures such as cardinal gaze speed. This "*sport-specific training effect*" highlights how different sports impose unique visual and visuomotor demands that shape performance (Vera et al., 2020).

Although athletes often demonstrate superior visuomotor abilities, research shows they do not always outperform the general population. Performance differences depend on several factors, including the specific oculomotor skill being tested, whether that skill is routinely practiced in a given sport, and the timing of assessment. For example, some oculomotor functions may decline immediately following strenuous exercise (Garner et al., 2023; Zwierko et al., 2019). Importantly, a lack of differences between athletes and non-athletes should not automatically be interpreted as "typical performance." Instead, it may reflect underlying issues such as prior trauma, concussion history, or the stage of recovery after an injury. More broadly, variables such as age, handedness, fatigue, central nervous system function, exercise load, and level of expertise should be considered when interpreting oculomotor metrics.

Baseline measures, such as those provided by the NeuroFlex protocol (Lunkova et al., 2024; Soave et al., 2023), offer valuable insight but capture performance only at a single point in time and are shaped by an individual's training history. For athletes, these baselines already reflect sport-specific adaptations and enhancements, which may differ markedly from those of non-athletes. Without comparisons to non-athletes, it becomes difficult to determine whether performance reflects training-related advantages, typical population-level functioning, or deficits associated with injury. Establishing these comparisons is a critical first step toward identifying meaningful differences between populations and developing normative data that are specific to athletes. The subsequent ability to then have the capacity to properly compare athletes to athletes can complete a meaningful comparison with full consideration of contributing factors to results encountered. In concussion management—particularly when eye-tracking assessments are used for return-to-play decisions—athlete-specific benchmarks are essential. They ensure that the unique influences of training, trauma history, and sport demands are accounted for, thereby improving the accuracy, reliability, and clinical utility of oculomotor assessments.

The primary goal of this project is to compare oculomotor health-related metrics between college athletes and the typical adult population. By analysing differences across groups, this study will clarify whether athletic participation influences visuomotor performance and identify the extent to which athletes may demonstrate distinct patterns. A secondary goal is to establish baseline measures specific to athletes, which may serve as a valuable reference point for clinicians and researchers using eye-tracking technologies in the evaluation and monitoring of concussions. Such population-specific normative data are critical for developing accurate, non-invasive, and objective tools for return-to-play decision-making and broader concussion management protocols.

MATERIAL AND METHODS

Participants

A total of 163 university student-athletes between 17 and 30 years of age, 95 female and 68 male, were tested using objective oculomotor and related vestibular metrics protocol. Participants self-disclosed their racial/ethnicities: 54 (33%) Latinx, 27 (16.7%) from the African diaspora, 16 (9.87%) mixed heritage, 40 (24.7%) Caucasian, 9 (5.5%) Asian, 3 (1.9%) Pacific Islander, 1 (0.6%) "other", and 12 (7.4%) did not disclose this information.

The student-athlete status was determined per the National Collegiate Athletic Association (NCAA) and California State University, Los Angeles (CSULA) guidelines and included all student-athletes participating in either Fall or Spring sports. Data from two athletes were not included in the study due to data collection difficulties. All student-athletes, regardless of concussion history were recruited as participants. Written

informed consent was obtained prior to the study, and procedures were approved by the CSULA Institutional Review Board.

Measures

The NeuroFlex® software, introduced in 2016, employs virtual reality (VR) technology to capture head and eye responses generating crucial metrics of brain health (Soave et al., 2023). This tool was developed on the premise of overlap between eye movement circuitry and concussion pathophysiology effects on the brain, thus aiming to detect oculomotor impairments post-concussion. Previous research found consistency in concussion identification between NeuroFlex® metrics and functional magnetic resonance imaging (fMRI) (Lunkova et al., 2024). The protocol consists of eight subtests with accompanying software for data analysis on a dashboard with reports within 8-10 minutes. The dashboard normative ranges were generated from a sample of 700 male and female healthy adult participants with no reported history of head injuries (Lunkova et al., 2024). The technology built into the VR headset is non-invasive, including 2D cameras to record each eye position and 3D accelerometers to track the head.

Oculomotor measures protocol

1. *Smooth pursuit in 2D (Head-free)*: In this test, head movement is required to keep the target within visual range ($H \pm 30$ deg, $V \pm 30$ deg). The participant is instructed to keep a 2D moving target centred in the screen by coordinating responses from both the eyes and head.

2. *Smooth pursuit in 2D (Head-fixed)*: In this test, the target remains within ± 20 degrees. The head-free test is a functional representation of real-life movement while the head-fixed test isolates the oculomotor functions to a greater degree.

3. *2D Saccades*: This test evaluates the saccadic system which creates rapid jumps in the eye position to new targets (saccades) with the head fixed. The targets appear randomly within the field of vision (± 25 degrees). The test detects deficits particularly related to a specific target location (e.g., only on the left or right side).

4. *Active Visual Vestibular Ocular Reflex (AVVOR) Horizontal*

5. *Active Visual Vestibular Ocular Reflex (AVVOR) Vertical*

The AVVOR horizontal and vertical assesses the coordination of the eyes with head movement during brief and rapid head motion as the semicircular canals of the inner ear elicit compensatory eye movements to maintain the image on the fovea. This requires coordination of vestibular, visual, and neck proprioception. The presented target will jump left to right (for AVVOR-H protocol), or up and down (for AVVOR-V protocol). The subject will need to move their head rapidly to allow fixation of gaze over large target jumps.

6. *Optokinetic Nystagmus*: This is evaluated by asking the participant to fixate on a target while a visual field of dots provides visual slip stimuli in horizontal or vertical directions at variable velocities. The result is a nystagmus in the direction of the induced visual slip (field velocity) where the individual makes pursuits in the direction of the target movement, and corrective saccades in the opposite direction. The participant must keep the head fixed throughout this test.

7. *Anti-saccades*: Evaluates inhibition (cognitive aspect), or the ability to resist reflexively a stimulus and the ability to re-map peripheral vision. Participants are provided with a distracting target and instructed to look in

the opposite direction. An error is recorded if the saccade is performed in the direction of the target instead of the opposite direction. The target position is randomized between trials to avoid a training effect.

8. Spontaneous Nystagmus: To assess the involuntary movement of the eyes in absence of visual, vestibular, or cognitive stimuli, the participant looks at a flashed target that quickly disappears. Then, the participant is asked to try and preserve the orientation of the eyes in the dark for several seconds. The test identifies any imbalance in the gaze orientation system and whether it is related to a particular sector of the visual field.

Procedure

Athletes were assessed individually (Figure 1). They completed the informed consent approved by the California State University, Los Angeles IRB, and the virtual reality oculomotor protocol (8 subtests). The total time for the completion of the protocols was approximately 10 minutes.



Figure 1. Virtual reality set-up and recording.

Analysis

To quantify the differences between the athletes' baselines and the NeuroFlex normative dataset, two different analysis methods were selected: 1) an unpaired comparison via unpaired t-test or Mann-Whitney U (MWU) test depending on the normality of the metric, and 2) Kolmogorov-Smirnov two-sample test to compare the distribution between the two groups to determine the likelihood of the groups coming from the same distribution. The median sample size used for computing the NeuroFlex® norms across all protocol metrics was 216, whereas 163 for the athletes' metric norms.

Normality for each metric was assessed using the Kolmogorov-Smirnov test and Shapiro-Wilks test for the NeuroFlex athletes' normative groups comparison. Due to our data set containing negative values, the data was used as is without any transformations. Metrics that were not normally distributed used the MWU test for significance testing. Metrics that were normally distributed used the unpaired t-test for significance testing. A p -value less than .05 was associated with statistical significance. All statistical tests were performed with Python 3.11.5.

The Kallmann Method was used to compute the normative ranges for the VOMS test, where there are a limited number of possible outcomes for each measured metric. The method follows two main steps: 1) Outlier Removal: The Chauvenet criteria remove data points with a probability of occurrence less than $1/(2 \times \text{sample-size})$. 2) Quantile Selection was used to select 2.5% and 97.5% quantiles as the lower and upper norms to capture 95% of the dataset range.

The Hoffmann method was used to determine normative ranges that achieve higher accuracy and reproducibility than the ones that only depend on quantiles, especially where the outcome measurables are continuous or have many possibilities. The Hoffmann method obtains the 2.5% and 97.5% quantiles from an extrapolation of a linear regression approach and are referred to as the lower and upper thresholds of the normative range.

RESULTS

The virtual reality oculomotor software normative sample data was compared with 163 student-athletes from diverse backgrounds to determine the likelihood of the two groups coming from the same distribution. The unpaired t-tests MWU and the Kolmogorov-Smirnov revealed the metrics that were and were not significantly different between the athletes and the virtual reality oculomotor software normative sample. Overall, 28 out of 44 metrics were significantly different between the two samples (Table 1), indicating that a large proportion of athlete metrics differ from those of the non-athlete population. The result for most of the measures matched, except for two metrics, AVVOR-H gain right 75deg/s and smooth pursuit (head free) number of saccades, in which the unpaired test and Kolmogorov-Smirnov tests did not match. However, for these two metrics, although only one of the two tests was significant, the other was marginally significant.

Table 1. Comparison between NeuroFlex® normative sample distribution with the athletes' sample.

Measures	Unpaired test p-value	KS test p-value
Active Visual VOR (Horizontal) Mean Vergence	0.00 *	0.00 ^
Active Visual VOR (Horizontal) Vergence Standard Deviation	0.45 *	10.09 ^
Active Visual VOR (Horizontal) Gain Right 75deg/s	14.76 *	55.40
Active Visual VOR (Vertical) Mean Vergence	11.36 *	1.56 ^
Active Visual VOR (Vertical) Vergence Standard Deviation	4.34 *	0.10 ^
Active Visual VOR (Vertical) Gain Down Mean	0.00 *	0.02 ^
Active Visual VOR (Vertical) Gain Down 50 deg/s	0.52 *	1.70 ^
Active Visual VOR (Vertical) Gain Down 75 deg/s	0.00 *	0.00 ^
Active Visual VOR (Vertical) Gain Up Mean	0.00 *	0.00 ^
Active Visual VOR (Vertical) Gain Up 25 deg/s	1.33 *	7.90 ^
Active Visual VOR (Vertical) Gain Up 50 deg/s	0.10 *	6.18 ^
Active Visual VOR (Vertical) Gain Up 75 deg/s	0.00 *	0.00 ^
Smooth Pursuit (Head Free) Head Contribution Mean	26.18 *	0.54 ^
Smooth Pursuit (Head Free) Head Contribution Horizontal	7.43 *	5.35 ^
Smooth Pursuit (Head Free) Head Contribution Vertical	35.27 *	0.57 ^
Smooth Pursuit (Head Free) Number of Saccades	58.08	2.22 ^
Optokinetic Nystagmus Gain Left 25 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Left 50 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Right 25 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Right 50 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Down 25 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Down 50 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Up 25 deg/s	0.00 *	0.00 ^
Optokinetic Nystagmus Gain Up 50 deg/s	0.00 *	0.00 ^
Antisaccades Mean Latency	4.75 *	0.47 ^
Antisaccades Acquisition Error	6.24 *	22.71 ^
Antisaccades Mean Vergence	0.00 *	0.00 ^
Saccades Mean Latency	0.00 *	0.00 ^

Note. * = significant differences found with the MWU test. ^ = significant differences found with the KS test.

Table 2 .Descriptive statistics and normative ranges for protocol metrics for all student-athletes using NeuroFlex®.

Protocol name	Sample size	Mean	SD	Min	25%	Median	75%	Max
Active Visual VOR (Horizontal)_Gain Left 25deg/s	163	91.11	9.65	65.03	85.96	92.03	96.69	117.79
Active Visual VOR (Horizontal)_Gain Left 50deg/s	162	89.08	10.57	55.94	82.35	90.13	96.84	114.74
Active Visual VOR (Horizontal)_Gain Left 75deg/s	162	87.08	12.84	45.74	78.85	87.03	96.68	113.93
Active Visual VOR (Horizontal)_Gain Left Mean	163	88.07	10.04	54.8	81.24	88.62	95.72	113.62
Active Visual VOR (Horizontal)_Gain Right 25deg/s	163	92.23	8.84	64.9	87.51	92.47	98.9	118.11
Active Visual VOR (Horizontal)_Gain Right 50deg/s	163	90.2	9.61	52.55	85.24	90.01	96.94	118.02
Active Visual VOR (Horizontal)_Gain Right 75deg/s	161	86.86	11.5	41.45	80.85	87.52	94.21	115.75
Active Visual VOR (Horizontal)_Gain Right Mean	163	87.43	9.25	56	82.27	87.65	93.67	113.72
Active Visual VOR (Horizontal)_Mean Vergence	163	0.34	1.27	-6.92	-0.16	0.37	0.96	3.72
Active Visual VOR (Horizontal)_Vergence Standard Deviation	163	2.31	3.01	0.63	1.09	1.46	2.33	25.2
Active Visual VOR (Vertical)_Gain Down 25 deg/s	163	85.35	9.15	54.84	79.89	86.44	91.26	103.66
Active Visual VOR (Vertical)_Gain Down 50 deg/s	161	85	10.7	45.82	79.68	86.24	91.98	103.55
Active Visual VOR (Vertical)_Gain Down 75 deg/s	147	85.59	11.92	43.26	80.27	87.08	93.17	108.12
Active Visual VOR (Vertical)_Gain Down Mean	163	85.72	9.58	58.83	81.16	86.5	92.22	106.54
Active Visual VOR (Vertical)_Gain Up 25 deg/s	163	82.17	8.76	56.37	77.44	82.63	88.35	102.4
Active Visual VOR (Vertical)_Gain Up 50 deg/s	159	82.87	9.87	49.71	77.3	83.05	89.39	103.12
Active Visual VOR (Vertical)_Gain Up 75 deg/s	137	82.8	12.47	42.91	74.63	84.15	90.25	120.56
Active Visual VOR (Vertical)_Gain Up Mean	163	82.58	9.61	54	76.48	83.63	89.11	102.43
Active Visual VOR (Vertical)_Mean Vergence	163	0.31	1.19	-5.52	-0.27	0.28	0.71	5.9
Active Visual VOR (Vertical)_Vergence Standard Deviation	163	1.16	0.86	0.41	0.78	0.94	1.29	7.72
Antisaccades_Acquisition Error	163	6.29	2.24	2.2	4.74	5.65	7.67	13.21
Antisaccades_Directional Accuracy	163	71.11	22.53	8.33	58.33	75	83.33	100
Antisaccades_Mean Latency	163	451.02	93.02	299.48	389.06	435.67	486.28	772.11
Antisaccades_Mean Vergence	163	0.59	2.09	-6.55	-0.16	0.37	0.99	17.78
Antisaccades_Vergence Standard Deviation	163	2.25	3.01	0.53	1.09	1.43	2.04	22.95
Optokinetic Nystagmus_Gain Down 25 deg/s	163	76.32	13.24	36.47	69.96	79.18	83.84	124
Optokinetic Nystagmus_Gain Down 50 deg/s	143	58.41	16.31	20.14	48.49	58.14	68.04	132.81
Optokinetic Nystagmus_Gain Down Mean	163	70.52	13.21	31.05	63.85	71.49	78.46	119.01
Optokinetic Nystagmus_Gain Left 25 deg/s	162	86.77	9.32	38.71	82.36	87.68	93.01	111.41
Optokinetic Nystagmus_Gain Left 50 deg/s	128	67.09	12.72	19.78	59.14	65.72	76.62	99.56
Optokinetic Nystagmus_Gain Left Mean	162	79.13	10.85	33.69	73.76	80.3	86.89	102.42
Optokinetic Nystagmus_Gain Right 25 deg/s	163	87.47	8.39	43.72	85.07	88.74	92.35	105.31
Optokinetic Nystagmus_Gain Right 50 deg/s	124	70.16	16.89	25.22	61.57	70.2	77.47	180.24
Optokinetic Nystagmus_Gain Right Mean	163	80.72	10.38	41.15	74.33	82.53	87.51	107.2
Optokinetic Nystagmus_Gain Up 25 deg/s	163	76.37	12.21	31.36	70.23	78.48	84.9	101.64
Optokinetic Nystagmus_Gain Up 50 deg/s	134	60.19	14.76	18.14	51.16	61.47	71.88	87.86
Optokinetic Nystagmus_Gain Up Mean	163	70.36	12.57	30.82	63.66	71.85	78.68	103.53
Optokinetic Nystagmus_Mean Vergence	163	-0.88	2.8	-10.03	-2.21	-1.15	-0.07	15.82
Optokinetic Nystagmus_Vergence Standard Deviation	163	3.36	3.62	0.63	1.56	2.06	3.68	27.2
Saccades_Acquisition Error	163	2.37	1.89	1.23	1.68	2.08	2.5	23.98
Saccades_Mean Latency	163	253.03	27.07	201.7	235.8	249.59	265.65	365.03
Saccades_Mean Vergence	163	0.23	1.12	-3.14	-0.34	0.13	0.61	7.56
Saccades_Vergence Standard Deviation	163	1.62	1.67	0.54	0.87	1.2	1.64	13.83
Smooth Pursuit (Head Fixed)_Mean Error	163	2.4	1.54	1.3	1.77	2.06	2.44	18.02
Smooth Pursuit (Head Fixed)_Mean Vergence	163	0.72	1.51	-7.94	0.08	0.78	1.37	6.74
Smooth Pursuit (Head Fixed)_Number of Saccades	163	11.53	9.4	1	5	10	15	57
Smooth Pursuit (Head Fixed)_Vergence Standard Deviation	163	2.24	2.4	0.64	1.22	1.55	2.14	17.36
Smooth Pursuit (Head Free)_Head Contribution Horizontal	163	93.41	9.19	48.07	89.69	94.7	99.36	111.32
Smooth Pursuit (Head Free)_Head Contribution Mean	163	92.89	10.69	37.5	89.01	93.44	99.55	113.27
Smooth Pursuit (Head Free)_Head Contribution Vertical	163	91.47	14.9	21.6	83.8	92.85	99.72	123.21
Smooth Pursuit (Head Free)_Mean Error	163	2.55	0.59	1.71	2.22	2.45	2.74	7.04
Smooth Pursuit (Head Free)_Mean Vergence	163	0.19	1.35	-3.47	-0.45	0.09	0.56	10.47
Smooth Pursuit (Head Free)_Number of Saccades	163	11.86	8.32	1	5	9	18	37
Smooth Pursuit (Head Free)_Vergence Standard Deviation	163	1.24	1.53	0.33	0.62	0.88	1.32	12.13
Spontaneous Nystagmus_Average Drift Horizontal	163	0	0.01	-0.04	0	0	0	0.05
Spontaneous Nystagmus_Average Drift Mean	163	0.01	0.01	0	0	0.01	0.01	0.05
Spontaneous Nystagmus_Average Drift Vertical	163	0	0	-0.01	0	0	0	0.02
Spontaneous Nystagmus_Mean Tremor Frequency	163	0.26	0.19	0	0.12	0.21	0.37	1.01
Spontaneous Nystagmus_Mean Tremor Velocity Horizontal	163	44.11	27.9	0	26.3	40.11	57.23	133.63
Spontaneous Nystagmus_Mean Tremor Velocity Mean	163	51.8	31.9	0	31.13	46.26	64.92	176.6
Spontaneous Nystagmus_Mean Tremor Velocity Vertical	163	22.58	21.66	0	8.06	16.13	30.57	175.13

For the calculation of normative ranges, some students did not perform on all subtests; consequently, each metric was based on data from a minimum of 124 students. Relevant descriptive statistics for all participants (irrespective of gender or team) and the cohort normative ranges are reported in Table 2. These resulting

normative ranges can serve as more precise comparison values for athletes, offering an alternative to the normative dashboard values from the NeuroFlex system. Unlike the dashboard data, which is based on measurements from the general population, these ranges resulting from athletes' performance, are better suited to account for the unique performance characteristics and physiological adaptations of this group.

DISCUSSION

Oculomotor measures offer robust, objective indicators of brain function and are particularly valuable for assessing concussions in athletes. Because visual information integrates with attention, cognitive control, memory, and motor systems to generate the three-dimensional representations that guide perception and action, disruptions in oculomotor performance can provide insight into neurological function (Laby & Appelbaum, 2021). Eye-tracking thus reflects more than how an athlete "sees and reacts"; it reveals how the brain is processing and coordinating information. Prior research demonstrates the clinical utility of these measures: oculomotor assessments have shown up to 90% accuracy in differentiating healthy from concussed athletes and in monitoring recovery (Cheever et al., 2018). Virtual reality-based oculomotor tools further enhance this approach by capturing head and eye responses to generate brain health metrics, facilitating concussion identification even when subjective reports are limited. Importantly, establishing individual athlete baselines allows clinicians to detect changes quickly, guide rehabilitation, and support safe return-to-play decisions (Capó-Aponte et al., 2012). Collectively, these findings reinforce the convenience and clinical importance of oculomotor assessments in concussion management for athletes.

Athletes, however, represent a unique population whose sport-specific training can shape oculomotor performance. This raises an important clinical question: can their performance be fairly compared to that of non-athletes when determining thresholds for potential brain injury? In our study, we found significant differences in the average scores of 28 oculomotor measures between athletes and the normative non-athlete sample. These results suggest that athletes do not perform at the same level as the general adult population in head and eye movement tasks, reinforcing the need for athlete-specific normative standards. Notably, significant group differences emerged in AVVOR, smooth pursuit, optokinetic nystagmus, and antisaccades—findings consistent with prior research. For example, Vera et al. (2020) reported superior visual discrimination in basketball players compared to non-athletes, while Kubitz et al. (2020) showed that baseball players demonstrated significantly faster gaze speed than amateurs or non-athletes. Similarly, Zwierko et al. (2019) found enhanced visuomotor performance, as measured by saccadic tasks, in soccer players. Together, these findings suggest that athletes outperform non-athletes in visuomotor skills such as saccades, accommodation speed, and convergence—likely as a result of repetitive practice and sport-specific demands. Consequently, comparing athletes against non-athlete norms risks misinterpretation of clinical outcomes. Ideally, normative data should not only be athlete-specific but further refined by sport type, given the distinct training regimens, visual demands, and cognitive processing requirements inherent in different sports (Laby & Appelbaum, 2021).

While previous research has demonstrated that oculomotor functions can be enhanced through training (Millard et al., 2021), the specific source of athletes' superior performance remains uncertain. It is not yet clear whether their advantages over non-athletes arise from enhanced visual search strategies, faster information processing, improved acuity, or advanced oculomotor control. Further work is needed to disentangle whether these benefits reflect general physiological factors, such as increased blood flow and central nervous system efficiency (Lange et al., 2018), or whether they are primarily shaped by the unique demands of different sports. Importantly, athletes do not always outperform non-athletes. For instance, oculomotor performance has been shown to decline immediately after strenuous activity, with decrements in

saccade duration and velocity (Zwierko et al., 2019), demonstrating that not all metrics measured between athletes and non-athletes were found to be significantly different. This suggests that fatigue can negatively impact visuomotor skills, potentially increasing injury risk and complicating assessment outcomes. Because these conditions are specific to the athletic population, normative data tailored to athletes are essential for more accurate clinical interpretation. Our study contributes to this effort by generating preliminary athlete-specific normative ranges, which—although not yet sport-specific—provide a more reliable framework for clinical use than comparisons to non-athlete norms, which risk introducing bias.

Concussions are complex injuries that affect individuals differently, requiring careful monitoring from the acute phase through recovery (Cavanaugh et al., 2005). Virtual reality–based oculomotor protocols provide an effective means of capturing objective measures, tracking change over time, and offering meaningful baseline comparisons for athletes. However, to fully support clinical decision-making, it is essential to move beyond the assumption that athletes will outperform non-athletes. Therefore, having non-athletes as the minimum and only threshold to surpass places athletes at a disadvantage because their performance and results should be evaluated based on their sport, experience level, and their own personal baseline. This further substantiates the need for visual and oculomotor abilities to be assessed with population-specific benchmarks (Soave et al., 2023). Athletes' training often enhances sport-specific visuospatial and oculomotor skills, yet their performance can also be influenced by fatigue, concussion history, and the unique demands of their sport. Understanding these distinctions is critical for interpreting test results accurately. By identifying systematic differences between athletes and non-athletes and generating normative ranges specific to the athletic population, our study provides an important step toward improving concussion assessment. Athlete-specific norms offer clinicians a more reliable and contextually appropriate framework for evaluating neurological function, guiding return-to-play decisions, and ultimately enhancing both the care and recovery of athletes.

CONCLUSIONS

This study suggests that athletes differ significantly from non-athletes in multiple oculomotor metrics, underscoring the need for population-specific normative ranges in clinical concussion assessment. While oculomotor measures offer robust and objective indicators of brain function, interpreting them against general population data risks overlooking enhancements linked to sport-specific training as well as potential deficits arising from injury, fatigue, or other sport-related conditions. Our findings contribute preliminary normative values for athletes, providing clinicians with a more reliable framework for evaluating concussion-related changes in this population. Establishing athlete-specific benchmarks is essential for accurate diagnosis, monitoring recovery, and guiding return-to-play decisions, as well as for advancing our understanding of how sport training and neurological health interact. Further research, including larger and sport-specific samples, is warranted to refine these norms and to explore the mechanisms underlying both enhanced and diminished oculomotor performance in athletes.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualization: [Clea Tucker] — Developed the overall concept and design of the study. Methodology: [Clea Tucker] — Designed the methodology and conducted the experiments. Software: [Arianna Soave, Nafiseh Ghoroghchian, William Pei] — Developed or used software tools for data analysis. Validation: [Clea

Tucker] — Verified the results and the overall accuracy of the study. Formal Analysis: [Clea Tucker, Beatriz Barragan] — Analysed the data and interpreted results. Investigation: [Clea Tucker] — Conducted the research and collected data. Resources: [Clea Tucker] — Provided the resources or facilities needed for the study. Data Curation: [Clea Tucker] — Managed and curated the data for analysis. Writing – Original Draft: [Clea Tucker, Beatriz Barragan] — Wrote the initial draft of the manuscript. Writing – Review & Editing: [Clea Tucker, Beatriz Barragan] — Critically reviewed and edited the manuscript. Visualization: [Arianna Soave, Nafiseh Ghoroghchian, William Pei] — Created visual representations of the data. Supervision: [Clea Tucker] — Oversaw the research and provided guidance. Project Administration: [Clea Tucker] — Managed the project and organized the workflow. Funding Acquisition: [Clea Tucker] — Secured funding and financial support for the project. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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