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ORIGINAL RESEARCH

Assessment of an eye-tracking tool to discriminate between concussed and not concussed professional male rugby players: a cohort study

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ABSTRACT

Objectives: Concussion is a common injury in rugby union ('rugby') and yet its diagnosis is reliant on clinical judgment. Oculomotor testing could provide an objective measure to assist with concussion diagnosis. NeuroFlex® evaluates oculomotor function using a virtual-reality headset. This study examined differences in NeuroFlex® performance in clinician-diagnosed concussed and not concussed elite male rugby players over three seasons.

Methods: NeuroFlex® testing was completed alongside 140 head injury assessments (HIAs) in 122 players. The HIA is used for suspected concussion events. Of these 140 HIAs, 100 were eventually diagnosed as concussed, 38 were not concussed (2 were unclear) Eight of the 61 NeuroFlex® metrics were analysed as they were comparable at all time points. These eight metrics, from three oculomotor domains (vestibulo-ocular reflex, smooth pursuit and saccades), were tested for their ability to distinguish between concussed and not concussed players using mean difference / odds ratios and corresponding 95% confidence intervals (CI's). General and generalised linear mixed models, accounting for baseline test performance, were used to determine any meaningful differences in concussed and not concussed players. The diagnostic accuracy of these differences was provided by the area under the receiver operating curve (AUC).

Results: Only one of the eight metrics (number of saccades, smooth pursuit domain) had clear differences in performance between concussed and not concussed players at the HIA during the match (odds ratio: 0.76, 95%CI: 0.54–0.98) and after 48 hours (0.74, 95%CI: 0.52–0.96). However, the direction of this difference was contrary to clinical expectations (concussed performed better than not concussed) and the AUC for this outcome was also poor (0.52).

Conclusion: NeuroFlex® was unable to distinguish between concussed and not concussed players in this elite male cohort. Future research could study other cohorts, later time points before return to play, and the tool's role in rehabilitation.

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Head injuries; closed; eye movements; rugby; brain concussion

Background

Sports-related concussion (SRC) is a common injury in collision sports, such as rugby union ('rugby') [1]. Owing to the difficulties in diagnosing SRC's during matches, rugby union, through its international governing body World Rugby, implemented the head injury assessment (HIA) protocol in 2014 for patients sustaining meaningful head impact events [2]. Under this protocol, players who display clear and obvious signs of a concussion, such as loss of consciousness or ataxia, are diagnosed with a SRC, are immediately removed from the field of play, and referred to as 'Criteria 1' cases. All the other head impact events without these clear signs of concussion are known as 'Criteria 2' cases. Criteria 2 cases must undergo an off-field assessment – known as an HIA1 – by an experienced medical practitioner to ascertain if they could be concussed or are fit to continue participating in the match. Regardless of whether a 'Criteria 2' player is removed or returned to play after their HIA1, they are required to complete two further medical assessments as part of the HIA protocol: one after the match ('HIA2') and one after two night's sleep ('HIA3'). Criteria 2 players can receive a SRC diagnosis after either the HIA2 or HIA3

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assessments, or both. Even though Criteria 1 cases are, by definition, diagnosed as concussed from the outset, they also need to complete the HIA2 and HIA3 assessments to monitor clinical progress [2]. HIA assessments are based on the Sports Concussion Assessment Tool developed from the Consensus Statement on Concussion in Sport [3].

The HIA1 assessment for Criteria 2 players is high pressure for both the player and medical practitioner. Mostly, the player wants to pass the assessment as quickly as possible to return to the match. In contrast, the clinician's priority is to avoid missing a concussion diagnosis, despite the HIA1 time limit of 12 min to complete the assessment. As a result of this pressure, the ability of HIA1 assessment to identify a player who is eventually diagnosed as concussed is of particular importance to World Rugby [4]. A 2020 diagnostic accuracy study of the HIA1 found that the sensitivity and specificity were 77% and 87%, respectively [4]. While this is good overall, this sensitivity indicates that just over 2 out of every 10 Criteria 2 players who eventually end up with an SRC diagnosis manage to pass their HIA1 and return to the match. And the reported specificity indicates that just over 1 in every 10 players who undergo an HIA1 fail the screen and are removed from play but are not later diagnosed with a concussion by a clinician. Therefore, any test or tool that could assist in improving the HIA1 accuracy has the potential to reduce the number of false negative concussed players that are returned to a match, and help prevent false positives, where non-concussed players are needlessly removed from play.

Various eye tracking assessments and tools have been developed in recent years in response to this call for objective indicators of concussion [5,6]. In particular, saccade, anti-saccade, and smooth pursuit assessments have been highlighted for their potential usefulness in the acute phase of concussion assessments [5–9]. A 2020 review of eye tracking technologies referred to a conference proceeding that described promising value of the I-PAS® tool, which counts saccades [9]. In the referenced pilot study, the I-PAS ®, had a sensitivity of 75% and specificity of 81%, with an area under the receiver operating curve of 0.81. A 2022 systematic review of sideline tests of vestibular and oculomotor function found limited, but positive sensitivity and specificity of the King–Devick test [6], which includes functional assessment of saccades. However, an original study in elite male adult rugby players found the King Devick test to have poor sensitivity and specificity [10], but this original study was not included in the 2022 systematic review [6].

Neuroflex ® (Saccade Analytics, Montreal, Canada) is a commercially available eye tracking tool that aims to diagnose concussion by rapidly testing six components of oculomotor function using a virtual reality headset. Specifically, Neuroflex® tests saccades, anti-saccades, smooth pursuits, optokinetic nystagmus, spontaneous/gaze-evoked nystagmus, and the vestibular-ocular reflex (through active visual gain). The most recent Concussion in Sport consensus statement [3] has suggested that multi-modal and ocular testing are objective testing domains that could offer additional diagnostic value. The NeuroFlex® platform's rapidity, simplicity, and portable nature all offer the potential for its use during the off-field HIA1 concussion screening assessment. The only completed study to date on NeuroFlex® compared eleven metrics in three groups of youth: a healthy group without a history of SRC and two SRC groups within 90 days of injury [11]. One SRC group had recovered from the injury, while the remainder had persisting symptoms. This study found that seven NeuroFlex® metrics were worse in the SRC group with persisting symptoms than in those with a resolved SRC or without any history of SRC [11]. However, to our knowledge, NeuroFlex® is yet to be assessed in the acute phases of SRC.

The aim of this study was to investigate if there were differences in how concussed/non-concussed players performed in Neuroflex® assessments following a suspected head injury. It was of particular interest to see if there were any differences during the HIA1 (off-field screen) time-point.

Methods

This study is reported according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [12]. Ethical approval for this study was sought from World Rugby's Institutional Ethics committee, which is comprised of scientific and nonscientific members from both sexes and included a player representative, and received approval number G-2102-02564.

Study design

This was a prospective cohort study with a nested case–control design. The nested case–control part of the study were the players who were diagnosed as either concussed (cases) or not concussed (controls).

Study setting

All players of the 12 teams involved in the Super Rugby Pacific elite male rugby competition (https://super.rugby/superrugby/) between the years of 2021 and 2023. This competition is comprised of professional rugby teams from Oceania (Australia, New Zealand, and Pacific Islands including Fiji). Data were collected on players by medical staff within each team.

Participants

All players representing a team in the Super Rugby competition between 2021 and 2023 were eligible to participate (Figure 1). Before the start of the 2021 season, all team medical staff were invited to a large online meeting to discuss the study and raise any concerns or discuss any issues. A study information leaflet was created for all teams and players. These team medical staff then discussed the study with each of their respective teams, using the information leaflets. All professional rugby players are required to have a valid and relevant baseline for the head injury assessment, which is usually checked in the pre-season period. This period was used as an opportunity to discuss the study with the players and invite them to be a part of the study. This process was repeated for any new players who entered the squad at the start of each year. If the player consented to be a part of the study – through written informed consent – they were

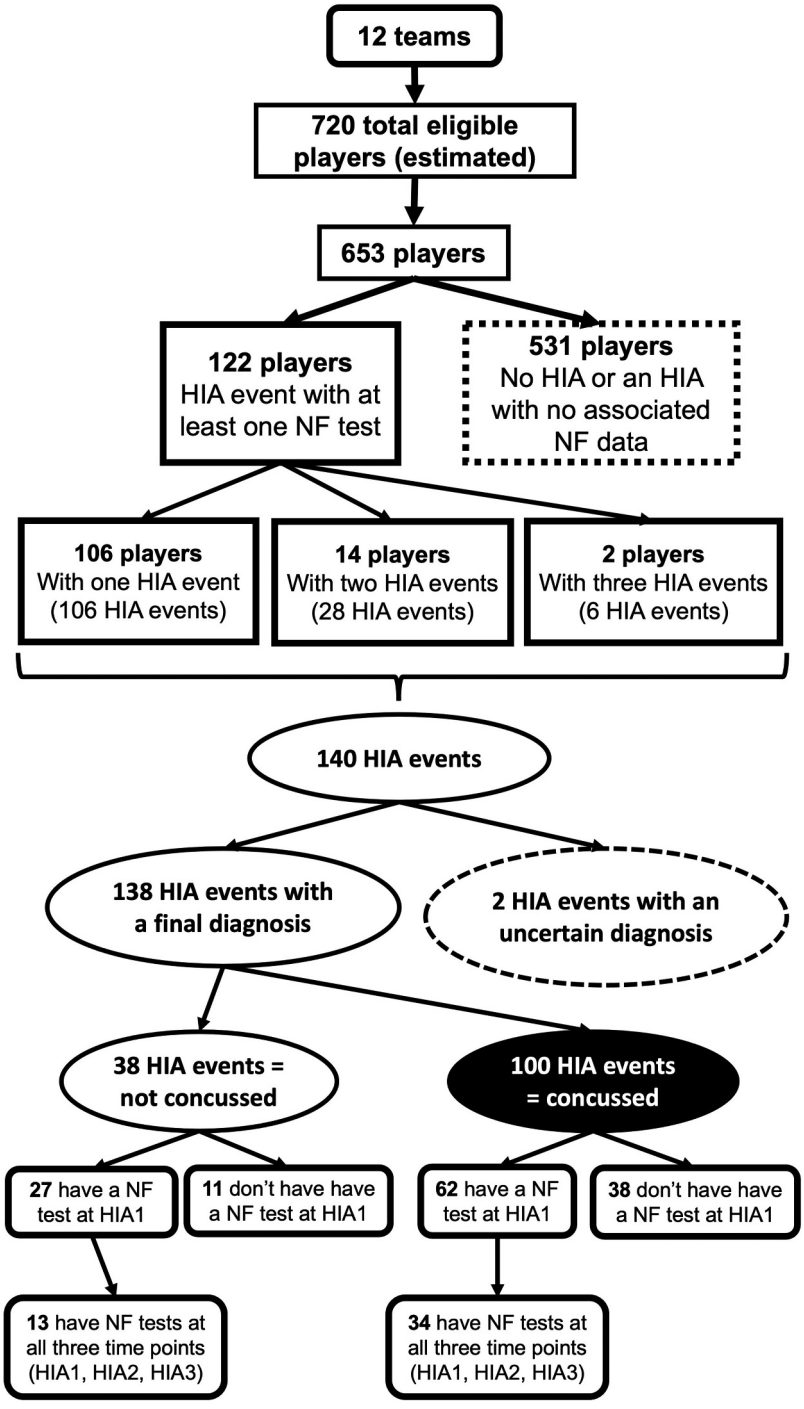

Figure 1. Flow diagram depicting the study participants at each stage. HIA – head injury assessment, NF – NeuroFlex®.

required to have a NeuroFlex® (Saccade Analytics, Montreal, Canada) assessment at baseline and at every stage of the HIA protocol, should they be suspected of a head injury while participating in a Super Rugby match. A total of 653 players from the 12 participating teams had a NeuroFlex® baseline test performed representing 91% of all possible Super Rugby professional male rugby players. The mean age (± standard deviation) was 26.0 ± 3.8 years of the 568 players who supplied a valid date of birth. Of these 653 players, 122 had an HIA event that had a NeuroFlex® test from at least one time point of the HIA protocol (HIA1, HIA2, or HIA3). These 122 players produced 140 unique HIA events (Figure 1).

At the conclusion of the HIA protocol, a player is either diagnosed as 'concussed' or not ('not concussed') [2], unless the HIA protocol is incomplete in which case the diagnosis is unsure/uncertain ($n = 2$). For this study, **cases** were those players who entered the HIA protocol during a match and were diagnosed as concussed (100 out of 138, 72%) and **controls** were those that were not concussed (38 out of 138, 28%). As this clinical diagnosis was outside of the researchers' control, the

Table 1. Neuroflex® test count by Head Injury Assessment time point (HIA1, HIA2, HIA3) and final diagnosis.

	Diagnosis from HIA protocol				
	Not concussed (n = 38)	Concussed (n = 100)	Unsure (n = 2)	Total (n = 140)	Total with diagnosis (n = 138)
Includes HIA1	*27*	*62*	*1*	***90***	***89***
HIA1 only	4	3	0	**7**	**7**
HIA1 and HIA2	7	18	1	**26**	**25**
HIA1 and HIA3	3	7	0	**10**	**10**
HIA1, HIA2 and HIA3	13	34	0	**47**	**47**
Does not include HIA1	*11*	*38*	*1*	***50***	***49***
HIA2 only	4	7	1	**12**	**11**
HIA2 and HIA3	5	14	0	**19**	**19**
HIA3 only	2	17	0	**19**	**19**

HIA – head injury assessment.

number of cases and controls were determined naturally. Figure 1 provides a flowchart of the teams, players, and HIA assessments involved in this study.

Because the HIA1 process was a specific focus of this study, Figure 1 and Table 1 are split into those HIA events that did and did not include a NeuroFlex ® test at the HIA1 stage. In total, there were 89 NeuroFlex tests from the HIA1 stage (Figure 1 and Table 1): 62 of these 89 tests had an eventual diagnosis of concussed (70%, 62/89). Within the HIA events that had a NeuroFlex® test at HIA1, most (47 out of 89, 53%) had tests at all three stages of the HIA process. There are multiple reasons that contribute to a missing NeuroFlex® test at an HIA time-point. These include a player having a concomitant head laceration or facial injury that prevented NeuroFlex® testing; a technical reason that resulted in an invalid NeuroFlex® test (goggles fogging up, for example); the medical team not having access to the NeuroFlex® device at the time of testing (common issue at HIA3 stage as this is performed at various venues) or the player not having an actual HIA medical assessment (a player can only have a NeuroFlex® test if they have an HIA assessment). Common reasons for missing an HIA assessment include the player being transferred to hospital for imaging or other assessments or exiting the team environment for leave while unfit to play.

Further 49 hIA events with a diagnosis had NeuroFlex® tests that did *not* include the HIA1 (Figure 1 and Table 1), the majority of which (78%) also had a final diagnosis of concussed. These remaining NeuroFlex® tests that did not have an HIA1 test were evenly split between an HIA2 only, HIA2 + hIA3 and HIA3 only (Table 1). In addition to the reasons listed above for missing a NeuroFlex® test at various time-points, a common reason for not having a NeuroFlex® test at HIA1 was that many players felt too unwell to perform the test. This was not unexpected, especially for Criteria 1 players.

Variables

Outcome variables

A shortened NeuroFlex® test was developed to suit the time constraints of the HIA1 (off-field screen) assessment. This shortened version of the test assessed three of the six oculomotor domains (Table 2): (1) vestibular-ocular reflex, (2) smooth pursuit, and (3) saccades. The assessment of these three domains produces 18 metrics (Table 1). Any metric that implied that the variable was a composite or calculated metric (such as 'mean' or 'standard deviation') were excluded from the analyses *a priori*. This decision was made to ensure that if differences were identified, they could be analyzed causally in the future [13].

This left eight metrics for analysis as outcome variables (marked with a ^ in Table 2). There were six metrics from the vestibulo-ocular reflex domain: horizontal gain at 25, 50 and 75 degrees/second in both left and right eyes (three metrics for each eye). There was one metric from the smooth pursuit domain (measured in the fixed head position): number of saccades. And a final metric from the saccades domain: acquisition error.

Model covariates

The main predictor variable of interest was the players' final diagnosis as a result of entering the HIA protocol: this could either be concussed (cases) or not concussed (controls) and thus binary. A diagnosis of concussion is given immediately if a player is a Criteria 1 case (clear and obvious sign of concussion, such as ataxia, recognized by a clinician). In all HIA events, Criteria 2 cases are later given a diagnosis of concussion if a player fails either his HIA2 or HIA3 test, or both. It is possible for a player to not receive a diagnosis in the HIA. This occurs when a Criteria 2 player does not have all required medical assessments

Table 2. The 18 NeuroFlex® metrics produced by three tests of oculomotor domains (listed as table headers in bold) during the Head Injury Assessment 1 (performed during a match).

Vestibulo-ocular reflex	Smooth pursuit	Saccades
Horizontal Gain Left 25deg/s^	Head Fixed – Mean Vergence^	Saccades – Acquisition Error^
Horizontal Gain Left 50deg/s^	Head Fixed – Number of Saccades^	Saccades – Mean Latency
Horizontal Gain Left 75deg/s^	Head Fixed – Vergence Standard Deviation	Saccades – Mean Vergence
Horizontal Gain Left Mean^	Head Fixed – Mean Error	Saccades – Vergence Standard Deviation
Horizontal Gain Right 25deg/s^		
Horizontal Gain Right 50deg/s^		
Horizontal Gain Right 75deg/s^		
Horizontal Gain Right Mean^		
Horizontal Mean Vergence		
Horizontal Vergence Standard Deviation		

^ eight metrics chosen for analysis as their name did not imply composite/calculated valueDeg/s – degrees per second.

Table 3. NeuroFlex® metrics and domains tested at the various Head Injury Assessment time points (HIA1, HIA2, HIA3) for 138 HIA events with a diagnosis of concussed or not concussed.

Oculomotor domain	NeuroFlex® Metric	HIA time point	Mean Difference or *Odds Ratio*: Concussed vs Not Concussed	95% Lower CI	95% Upper CI
Vestibulo-ocular reflex	Horizontal Gain Left 25deg/s	HIA 1	−1.85	−6.88	3.18
		HIA 2	0.05	−4.82	4.93
		HIA 3	2.71	−2.56	7.98
Vestibulo-ocular reflex	Horizontal Gain Left 50deg/s	HIA 1	0.20	−4.64	5.05
		HIA 2	−1.81	−6.53	2.90
		HIA 3	3.03	−2.04	8.10
Vestibulo-ocular reflex	Horizontal Gain Left 75deg/s	HIA 1	3.26	−1.83	8.35
		HIA 2	−2.28	−7.16	2.61
		HIA 3	2.68	−2.61	7.97
Vestibulo-ocular reflex	Horizontal Gain Right 25deg/s	HIA 1	−2.76	−7.61	2.08
		HIA 2	1.39	−3.29	6.06
		HIA 3	1.22	−3.90	6.33
Vestibulo-ocular reflex	Horizontal Gain Right 50deg/s	HIA 1	−0.56	−5.27	4.14
		HIA 2	−1.39	−5.95	3.16
		HIA 3	0.57	−4.41	5.55
Vestibulo-ocular reflex	Horizontal Gain Right 75deg/s	HIA 1	3.90	−0.96	8.77
		HIA 2	−2.23	−6.87	2.41
		HIA 3	1.94	−3.17	7.05
Saccades	Saccades – Acquisition Error	HIA 1	0.14	−21.4	21.68
		HIA 2	16.29	−7.18	39.76
		HIA 3	−2.02	−23.9	19.86
Smooth pursuit	Head Fixed – Number of Saccades	HIA 1*	*0.76*	*0.54*	*0.98*
		HIA 2	*0.92*	*0.65*	*1.18*
		HIA 3*	*0.74*	*0.52*	*0.96*

*Clear difference between concussed and not concussed performance.
deg/s – degrees per second, HIA – head injury assessment, CI – confidence interval
Italics font indicates that the difference, and associated 95% CI, is an odds ratio rather than a mean difference.

completed and thus their final diagnosis is unclear: for this study, these two cases were excluded from analyses (Table 3).

The other predictor variables were the baseline score of the player who has had an HIA test and the three time points of the HIA protocol (HIA1, HIA2, or HIA3).

Data sources/measurement

The eight NeuroFlex® metrics of interest for cases and controls who entered the HIA protocol were downloaded from the NeuroFlex® cloud repository for analysis. This data was merged with data from HIA assessments that is stored on a custom-developed HIA Application (SCRM App, XXXXX [removed for confidentiality]) to obtain the diagnosis (concussed or not concussed). In addition, these eight metrics were downloaded for all players who completed a baseline test.

Bias

For the duration of the study period, the players' performance in the NeuroFlex® test was blinded to prevent this influencing the medical staff or the player in terms of their clinical diagnosis of concussion. In addition, the NeuroFlex® test was only performed after the HIA protocol was completed at each time point. The selection of the eight NeuroFlex® metrics (out of a possible 61) for analysis was done so without input from the company. With any observational study, there is the risk of selection bias. To our knowledge (as reported by the medical team) only two HIA events had players refuse to do any NeuroFlex® testing at all. All remaining 'missing' NeuroFlex tests are due to medical reasons explained and detailed previously in the 'participants' section and Figure 1 and Table 1.

Study size

The number of baselines is determined by 653 players who volunteered and consented to take part in the study out of the 12 eligible teams from the Super Rugby competition in the three seasons from 2021 to 2023. The study size for cases and controls was determined by players who had volunteered for the study and that entered the HIA process during a Super Rugby match due to suspicion of a head injury.

Statistical methods

One model was produced for each NeuroFlex® metric (eight models in total). Three predictor variables were added to each of these eight models as fixed effects: (i) corresponding NeuroFlex® baseline, (ii) HIA time point (HIA1, HIA2, and HIA3), and (iii) concussion status at the end of the HIA protocol ('concussed' = case, or 'not concussed' = control). In addition, the unique ID of each HIA was added to each model as a random effect to account for correlation within the same player and HIA event.

The type of model fitted depended on the distribution of each Neuroflex® metric at the various HIA time points. All six vestibulo-ocular metrics were normally distributed, Smooth Pursuit (Fixed Head) was Poisson distributed and Saccades *Acquisition Error* (Saccades) was lognormally distributed.

To establish differences between concussed and not concussed players, general linear mixed models were used for normally and lognormally distributed outcomes, while generalized linear mixed models were used outcomes that were not normally distributed. 'Clear differences' would be indicated by the difference between concussed and not concussed players

having both the upper and lower 95% confidence interval (95% CI) on the same side of zero (for general linear models) or one (for the odds ratios from generalized linear mixed models).

Only those outcomes with a clear difference between concussed and not concussed players at any HIA timepoint were tested for diagnostic accuracy. It was agreed *a priori* that diagnostic accuracy, tested via a receiver operating curve (ROC), would be the critical evaluation in this study. Where a ROC was used, the least square means for both concussed and non-concussed players were used as thresholds, with the highest area under the curve (AUC) value taken as the diagnostic accuracy of the test. An AUC of 0.5 indicates that the probability of a correctly predicted diagnosis is no better than chance, while increasing values of AUC above 0.5 indicates increasingly reliability in the prediction, and an AUC of 1.0 indicates perfect prediction accuracy.

Results

The differences in performance between concussed ($n = 100$) and not concussed HIA events ($n = 38$) in eight NeuroFlex® metrics at all three HIA time points are shown in Table 3 and Supplementary Figures S1–5. Of the eight metrics, only number of saccades (from the Smooth Pursuit -head fixed domain) was clearly different between concussed and not concussed players (Table 3, Supplementary Figure 5. For number of saccades, concussed players had, on average, a 24% and 26% lower score than not concussed players, after adjusting for all predictor variables at HIA1 (odds ratio: 0.76, 95% CI: 0.54–0.98, and HIA3 (odds ratio: 0.74, 95% CI: 0.52–0.96), respectively. However, the diagnostic accuracy of this difference for number of saccades was very poor at HIA1 and HIA3 (AUC = 0.52).

The remaining seven other metrics were not clearly different between concussed and not concussed players at any of the three HIA time points (Table 3, Supplementary Figures S1–5).

Discussion

The main finding of this study was that, in general, the performance of eight Neuroflex® metrics was not sufficiently different between concussed and not concussed professional male rugby players at all stages of the HIA process. These eight metrics measured three oculomotor components: active visual vestibulo-ocular reflex, saccades, and smooth pursuit. One of the metrics – the number of saccades from a fixed head smooth pursuit test – was clearly different between concussed and not concussed players at the HIA1 stage. However, concussed players performed, on average, better (with a lower score) than not concussed players, which is contrary to the manufacturer's expectations. Moreover, the subsequent area under the receiver operating curve for concussed players was small (0.52), demonstrating very weak predictive utility.

Overall, the lack of notable differences were unexpected, especially for the smooth pursuit and saccadic measurements of the present study, which have been indicated as reliable, valid, and clinically plausible for the acute assessment of concussion in adult populations previously [5–7,9,14]. Indeed, the area under the curve for another commercially available tool (I-NeuroFlex®) was reported to be 0.81 in a young male cohort [9] – not in an original article, but in a review that refers to a conference proceeding; this result should, therefore, be interpreted with caution [9]. Similarly, a 2022 systematic review and meta-analysis reported that the King–Devick test reported a sensitivity and specificity of 0.77 and 0.82, respectively, in adult cohorts [6]. However, these authors do warn that these sensitivity and specificity outcomes were only meta-analyzed from four studies using the King–Devick test and should thus be interpreted as 'low evidence.' Only two of the four studies defined a diagnostic threshold: a post-injury score worse than baseline or if any errors were made [6]. Moreover, a study of the King–Devick test in a directly comparable cohort to that of the present study reported equally poor sensitivity (0.60) and specificity (0.39) as this study [10]. This original study in elite male rugby players also found an area under the receiver operating curve for worse King–Devick test performance in concussed players of 0.51 [10], which is similar to what we found in the present study for the best performing PAS® metric, number of saccades. Unfortunately, the present study is thus the second study that has failed to find diagnostic utility in the immediate setting of a commercially available ocular test, which is concerning for the field in general.

Besides the explanation that NeuroFlex® is unable to accurately distinguish between concussed and not concussed rugby players at the HIA1–3 timepoints, there could be alternative explanations that we cannot exclude.

This study focused on 8 of 18 metrics that were tested at HIA1 that potentially had underpinning causal mechanisms behind their utility in predicting concussion, but there are additional 10 metrics that were apparently composite in nature to the study team (for e.g. 'mean saccades') and the underpinning causal mechanisms would, therefore, be harder to unravel. These additional metrics may nevertheless prove to be better predictors of concussion than the eight metrics we focussed on in the present study. In addition to these 18 metrics tested at HIA1, there were additional 43 metrics in total at the two other HIA time points (HIA2 and HIA3) from the complete testing battery. Further exploration could consider examining more of these metrics, but this moves from focussing on well-understood neurological mechanisms related to concussion and explores more arbitrary combinations of metrics that may prove challenging to explain mechanistically, if they do in fact prove to have predictive utility. In addition, we were interested in the tool's ability at the HIA1 stage, which required a shortened protocol (and thus fewer metrics tested in total) to fit in with the reality of the time pressures at this testing time point.

There is also the possibility that the construct validity of these NeuroFlex® tests is imperfect [15]. For example, we assumed in the present study that the saccades acquisition error test did indeed quantify that specific oculomotor component, or at least was a proxy of the saccades oculomotor domain. A construct validity assessment was beyond the scope of the present study, but inconsistencies between

nomenclature and methods of measurement have been highlighted as a challenge within eye tracking technologies and can, therefore, not be excluded in the present study [5].

Unlike many other disease or injury states, the diagnosis of concussion relies heavily on clinical judgment [16], meaning that it is possible for misclassification or misdiagnosis of cases presented in this study. However, the present study used the current 'gold standard' for concussion diagnosis in rugby, the HIA protocol [4], using clinicians with substantial experience with SRC's at the elite level.

Finally, we chose *a priori* to focus on the acute phase of injury and it should be noted that it was beyond the scope of this study to examine the ability of NeuroFlex ® to detect differences in concussed and not concussed players beyond HIA3 (typically within 72 h) or the tool's utility in assessing readiness to return to play.

Limitations

The current study has numerous limitations. An in-match control player – who was not under suspicion of a head injury (and thus not in the HIA process) would have been a valuable addition to the both the reliability and main study. This proposal was rejected by the present study cohort and medical staff, as it was felt to be too onerous on the participants. Despite this omission, we are confident that the results presented in the current study answer a valuable clinical and academic question. A potential limitation of any study investigating a commercial product is independence or bias. To distance the study team from the commercial tool's possible bias, we deliberately requested that the analyses be performed by independent statisticians to prevent this issue (see section on statistical analyses). As shown in Figure 1, there are also 16 players who had more than one HIA event in this 3-year study period, and associated NeuroFlex® test, in this study. This potential clustering effect was not adjusted for in the analyses as including the player as a random effect in earlier versions of the model resulted in extremely small parameter estimates (i.e. including the random effect had no meaningful impact on the model in terms of the variance it explained). Also, only 47 out of 138 hIAs with a diagnosis had a NeuroFlex® test at all three HIA time points (Figure 1 and Table 1). However, as described in the Results, this is largely a reality of performing such a study in a professional sports environment and was considered in the chosen analysis plan. Selection bias is difficult to eliminate in an observational study. The study team was informed of 2 hIA events that refused to perform any NeuroFlex® testing and the remaining missing NeuroFlex® tests are considered to be due to medical reasons. Given the operational definitions in which Criteria 1 players show clear and obvious signs of a concussion, there was also a concern there could be selection bias between Criteria 1 and 2 concussed HIA events. However, an unpublished element of this analysis found no differences in NeuroFlex® performance between Criteria 1 and Criteria 2 hIA events at any time point.

Conclusion

In general, eight NeuroFlex® metrics (active visual vestibulo-ocular reflex, saccades, and smooth pursuit) were not discernibly different between concussed and not concussed professional male rugby players at any of the HIA time points (HIA1, HIA2, or HIA3). As such, these findings do not support the addition of NeuroFlex® to the current HIA protocol in elite adult male rugby. Future studies should assess the utility of this tool in assessing return to play in concussed players by performing serial assessments at later time points than the present study. Other cohorts (females and youth players) should also be considered.

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