

Article

Measuring Brain Haemodynamic Activity and Afferent Visual Function: A Preliminary Study on the Relationship Between fNIRS, the King–Devick Test and Suspected Sport-Related Concussions

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Abstract: Background/Objectives: Functional near-infrared spectroscopy (fNIRS) may help quantify changes in brain haemodynamics during sport-related concussions (SRCs). This study compared post-match prefrontal cortex (PFC) brain haemodynamics measured by fNIRS during the King–Devick test (K-DT) with players suspected of having sustained an SRC. It was hypothesized that changes in the K-DT would correspond with brain haemodynamic processes. **Methods:** Twenty-two male and female collegiate rugby players (six males and twenty-two females; age range: 18–22) completed a baseline K-DT+fNIRS assessment. Over the course of two to three matches, all participants were invited to complete at least one post-match K-DT+fNIRS assessment. If a player was suspected of having sustained an SRC, they were re-assessed with the K-DT+fNIRS. If a participant who was not suspected of having sustained an SRC performed worse on the K-DT post-match, they were included in the participant category of ‘concussion’ for the analysis. A repeated measures ANOVA was performed. Test–retest reliability was calculated using the intra-class correlation coefficient (ICC). A Pearson correlation coefficient (r) assessed the linear relationship between the changes in the K-DT and the measurements of the left and right PFC. **Results:** Differences were identified in the K-DT for the players with a suspected concussive injury post-match ($\chi^2(1) = 5.0$; $p = 0.0253$; $z = -2.0$; $p = 0.0431$; $d = 0.16$). There were also significant differences between the baseline and post-match results for all concussed players in the right PFC ($t(8) = 250$; $p = 0.0371$; $d = 0.92$) and for the concussed females in the right PFC ($t(6) = 2.78$; $p = 0.0319$; $d = 0.52$). There were no correlations between the K-DT and PFC values in the suspected concussed group. **Conclusions:** The SRC group had decreased cognitive performance and a notable change in PFC activation, while the non-concussed group showed an increase in the activation in the PFC and no change in cognitive performance scores. This represents a possible acute adjustment in brain haemodynamics and provides insight into how SRCs can negatively impact cognitive performance.

Keywords: fNIRS; brain haemodynamics; prefrontal cortex; King–Devick



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1. Introduction

The trauma that occurs within the brain from a sport-related concussion (SRC), also known as a mild traumatic brain injury (mTBI), results in a transient pathophysiological process that can lead to a short-lived neurological dysfunction [1,2]. Additionally, there may be an attenuation of brain haemodynamic responses and glucose metabolism, with the former showing alterations in research studies measuring, amongst other components, cerebral blood flow in paediatric SRC patients and collegiate-aged football players [3–6].

The nature of SRCs is often the result of a direct blow to the head, neck, and elsewhere on the body that can be transmitted to the head and brain [7]. Symptoms can vary from patient to patient, with symptom categories including physiological (headache and fatigue), vestibulo-ocular (dizziness with head movement), vestibulospinal and cervical (imbalance and lightheadedness), and mood and cognition (poor concentration, mood, and behavioural symptoms) [8,9].

The immediate post-injury concussion assessment, or one conducted within a short period, relies upon self-reported symptoms. This is followed up with an assessment of balance and cognition [2] and ideally utilizes a multifaceted assessment protocol [10]. Fortunately, there are standardized assessment tools, such as the Sideline Concussion Assessment Tool 6th Edition (SCAT6) [11], the most widely reported assessment tool, and this incorporates the Standardized Assessment of Concussion (SAC) [12,13] and the Brain Injury Screening Tool (BIST) [14,15]. It has been recommended that the SCAT6 and other assessments for concussions are not utilized as stand-alone tools [2]. Other possible addendum measures may include ImPACT (Immediate Post-Concussion Assessment and Cognitive Test), a neurocognitive test for the management of concussions [16]; the King-Devick Test (K-DT), a timed (in seconds) rapid number naming test [17,18]; eye tracking sensors [2,19,20]; a vestibulo-ocular assessment (most notably, the Vestibular Ocular Motor Screen (VOMS)) [21]; and biomarkers [22,23].

Functional near-infrared spectroscopy (fNIRS) is a non-invasive, portable, and easy-to-use device that allows for the measurement of cerebrovascular changes in brain deoxyhaemoglobin, oxyhaemoglobin (O₂Hb), and total haemoglobin concentration at the cortical surface via near-infrared absorption through the skull [24–27]. Although used primarily in research, fNIRS is also growing in the medical field as a clinical tool in paediatrics for persons with commutative disorders, those in intensive care, and patients with psychiatric problems [28–30]. Using fNIRS in concussions could be beneficial, as the primary cortical site measured during cognitive assessments is the prefrontal cortex (PFC), which contains executive processes that can affect various cognitive domains. As one might expect, it has been shown that there is an increase in PFC activation (as measured via fNIRS) during mentally demanding tasks [31]. Furthermore, the altered brain activation of those participating in sports with an SRC who are subjected to single tasks (e.g., the K-DT) could provoke additional mechanisms that allow for the stimulation of attentional resources via a means measurable by fNIRS. Objective physiological measures such as those obtained with fNIRS can be used concurrently with current guidelines that utilize neuropsychological outcomes [2].

During the application of fNIRS, neurocognitive tasks such as the Stroop test are often used, and as described above, the K-DT could be ideal for assessing brain activation with a suspected concussion [17,18,32]. The K-DT is sensitive to changes in the vestibulo-ocular system, language function, and attention caused by concussions [33,34] by detecting attentional deficits and impaired saccadic eye movements [35], as it involves attention, number recognition, language retrieval, and saccadic eye movements [36]. The slowing of K-DT times is associated with reduced neuropsychological function in the cognitive domains of processing speed, attention and working memory, and executive function [36]. Research

has shown the K-DT to have the greatest diagnostic accuracy 0–6 h post-concussion with the worsening of performance time (slower times post-concussion versus at the baseline) varying from 3.5 to 5 s, with the developer recommending that any suspected post-match concussion injury with K-DT results greater than 1 s should be further evaluated to rule out a concussion [37–40].

Crucially, there needs to be a purpose or reason to incorporate fNIRS with a neurocognitive task while evaluating an athlete with an SRC. Firstly, it should not be a stand-alone assessment and should ideally be combined with other evaluations such as the SCAT6, ImPACT, K-DT, and the VOMS—in other words, as a multifaceted approach [41,42]. Moreover, as Memmini et al. [43] noted in their exploratory study using fNIRS to assess the haemodynamic response of a concussed brain, once the concussed individual becomes asymptomatic, there is an improvement in the haemodynamic response, which they suggest gives the individual the ability to respond quickly even though they are not fully recovered. This may inadvertently place the athlete at risk for a secondary injury, or second impact syndrome, if they are returned prematurely to the sport [43]. This is further supported by studies from Plenger et al. [44] and Bryer et al. [45] that suggest that following a concussion, the brain recruits additional areas indicative of increased mental processing for a task. Consequently, using fNIRS with SRCs may be beneficial in monitoring an individual over time and may be one step to establishing a return-to-play protocol. Lastly, and pertinent to the current preliminary study, is how fNIRS may help quantify changes in brain haemodynamics in athletes who have sustained repetitive head exposure [46], which may go undetected in a game, match, or season [47], or those who are considered to have subconcussive impacts as they do not demonstrate the signs of a concussion [48–50]. Therefore, the purpose of the current preliminary study was to compare post-match PFC brain haemodynamics, as measured by fNIRS, during the performance of the K-DT with those players identified as possibly having sustained a concussion during a collegiate-level rugby match. It was hypothesized that changes in the K-DT would correspond with changes in the brain's haemodynamic processes, thus establishing a relationship between the fNIRS and concussion tools such as the K-DT. This supports a promising avenue for future research on the usefulness of combining these two forms of assessments, functional and physiological, for sideline assessments and the ongoing monitoring of SRCs.

2. Results

Overall, 22 participants had baseline (pre-season) K-DT+fNIRS assessments (six males and sixteen females; age range: 18–22). Ten participants were categorized as having sustained an injury that required an evaluation by the team's athletic trainer or a worsening K-DT score (categorized in this study as a 'suspected concussion') based on the post-match K-DT time results. Of the ten who were categorized as having sustained an injury that required an assessment or worsening K-DT time, seven were female, and three were male.

There were observable differences identified in the K-DT baseline for all players between (pre-season) test 1 and test 2 ($\chi^2(1) = 6.8$; $p = 0.0093$; $z = -2.7$; $p = 0.0063$; $d = 0.15$) (see Table 1). Additionally, there were observable differences for the players who had a suspected concussive injury (the 'suspected concussion' group) post-match ($\chi^2(1) = 5.0$; $p = 0.0253$; $z = -2.0$; $p = 0.0431$; $d = 0.16$). The inter-class correlation (ICC) was considered excellent for the baseline total, non-concussed players, and players suspected of having a concussive injury.

There were significant O₂Hb differences between the baseline (pre-season) and post-match levels for all suspected concussed players in the right PFC (RPFC) ($t(8) = 250$; $p = 0.0371$; $d = 0.92$) and for suspected concussed females in the RPFC ($t(6) = 2.78$; $p = 0.0319$;

$d = 0.52$) (see Table 2). This was similar for non-concussed males and non-concussed females in the LPFC ($t(4) = -4.73$; $p = 0.0091$; $d = 2.58$) (see Figure 1).

Table 1. King–Devick test scores and player ages for baseline establishment, baseline score, post-match scores, and differences in seconds for total players, players not concussed, and players suspected to have a concussion, as well as inter-class correlation by median values with inter-quartile ranges.

	Total ($n = 22$)	Non-Concussed ($n = 12$)	Concussed ($n = 10$)
	Median [IQR]	Median [IQR]	Median [IQR]
King–Devick test			
Baseline 1	42.2 [48.8 to 54.7] ^b	43.7 [48.9 to 54.0]	40.2 [48.6 to 54.7] ^b
Baseline 2	39.8 [45.4 to 54.6] ^a	40.6 [47.7 to 55.4]	37.4 [45.4 to 53.1] ^a
Baseline	39.8 [45.4 to 53.0]	40.0 [47.1 to 53.5]	37.4 [45.4 to 53.1]
Diff	0.1 [1.2 to 3.3]	−0.9 [−0.8 to 3.2] ^d	1.0 [2.4 to 3.4] ^c
ICC	0.98 [0.95 to 0.99]	0.97 [0.93 to 0.99]	0.99 [0.98 to 0.99]
Post-Match	38.6 [46.8 to 52.4]	38.0 [39.7 to 50.6] ^d	43.6 [50.5 to 57.0] ^c
Diff	−2.4 [−3.7 to 3.0]	0.4 [2.2 to 3.3]	−5.1 [−3.7 to −2.2]
Player age			
Total	19.0 [18.0 to 21.0]	19.0 [18.0 to 21.0]	19.0 [18.0 to 21.5]
Male ($n = 6$)	18.0 [18.0 to 18.8]	18.0 [18.0 to 19.5]	18.0 [18.0 to 18.0]
Female ($n = 16$)	20.0 [19.0 to 21.3]	20.0 [19.0 to 21.3]	19.5 [18.0 to 21.8]

IQR = Inter-quartile [25 to 75] Range; ICC = Interclass correlation coefficient; Significant difference ($p < 0.05$) compared to (a) = Baseline 1; (b) = Baseline 2; (c) = Non-concussed; (d) = Concussed.

Table 2. O₂Hb baseline establishment, post-match results, and differences between total players, non-concussed players, and players suspected to have a concussion, reported as the means with 95% confidence interval.

	Baseline ($n = 22$)		Concussed ($n = 10$)		Non-Concussed ($n = 12$)	
	RPFC Mean (95% CI)	LPFC Mean (95% CI)	RPFC Mean (95% CI)	LPFC Mean (95% CI)	RPFC Mean (95% CI)	LPFC Mean (95% CI)
Baseline						
Total	1.7 (1.4–1.9)	2.2 (−4.2–8.5)	1.7 (1.4–1.9) ^{bd}	2.2 (−4.2–8.5)	0.7 (−6.9–8.3) ^c	0.9 (−9.8–11.5)
Male	3.5 (−19.6–26.6)	2.7 (−24.2–29.5)	3.5 (−19.6–26.6)	2.7 (−24.2–29.5)	2.3 (−8.4–13.0)	2.2 (−9.2–13.6) ^f
Female	1.7 (1.4–1.9)	2.2 (−4.2–8.5)	1.7 (1.4–1.9) ^b	2.2 (−4.2–8.5) ^d	0.7 (−6.9–8.3)	0.9 (−9.8–11.5) ^{ce}
Post Match						
Total	1.9 (1.0–2.8)	2.1 (1.2–3.0)	−0.1 (−10.6–10.3) ^a	0.0 (−11.7–11.7)	2.2 (−12.9–17.3)	3.2 (−0.1–6.4)
Male ($n = 3$)	1.8 (0.8–2.7)	2.0 (1.1–3.0)	−0.3 (−6.8–6.2)	−0.2 (−22.3–21.8)	2.2 (−12.9–17.3)	3.2 (−0.1–6.4)
Female ($n = 7$)	0.5 (−0.5–1.5)	0.7 (−0.3–1.8)	−0.1 (−10.6–10.3) ^a	0.0 (−11.7–11.7)	0.2 (−9.9–10.2)	0.3 (−14.8–15.4)

CI = Confidence interval; Significant difference ($p < 0.05$) than (a) baseline; (b) post-match; (c) concussed; (d) non-concussed; (e) male; (f) female.

There was a non-significant negative correlation identified between changes in baseline King–Devick scores and changes in the LPFC and RPFC measurements for the non-concussed (L: $r_{(9)} = 0.29$; $p = 0.932$; R: $r_{(9)} = -0.235$; $p = 0.486$) and concussed (L: $r_{(4)} = -0.645$; $p = 0.167$; R: $r_{(4)} = -0.720$; $p = 0.107$) players (see Figure 2).

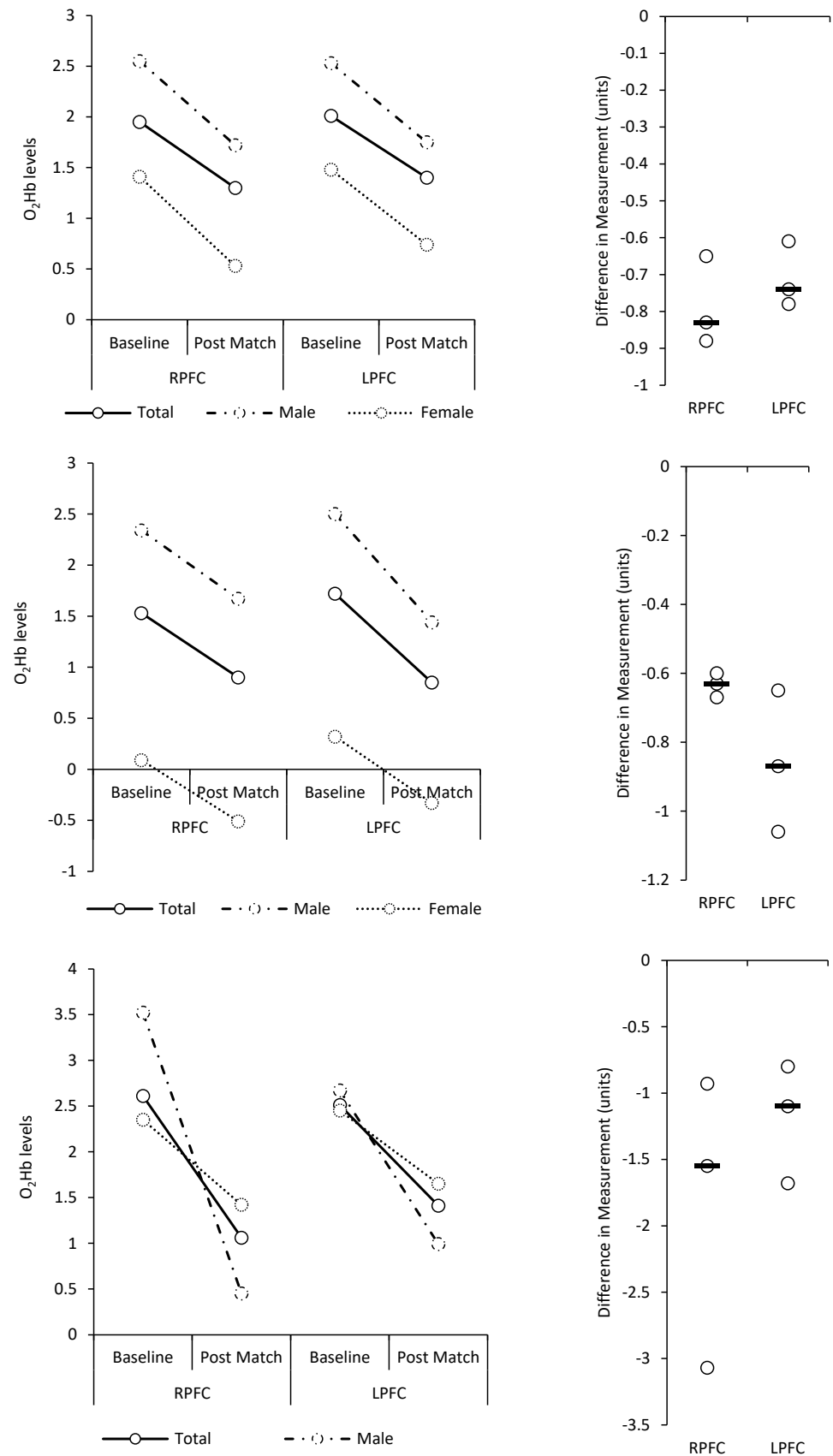


Figure 1. O₂Hb establishment, post-match results, and differences between total, male, and female participants for right prefrontal cortex (RPFC) and left prefrontal cortex (LPFC). (**Top**) Baseline total vs. post-match total; (**Middle**) Baseline non-concussed vs. post-match non concussed; and (**Bottom**) Concussed baseline vs. post-match concussed.

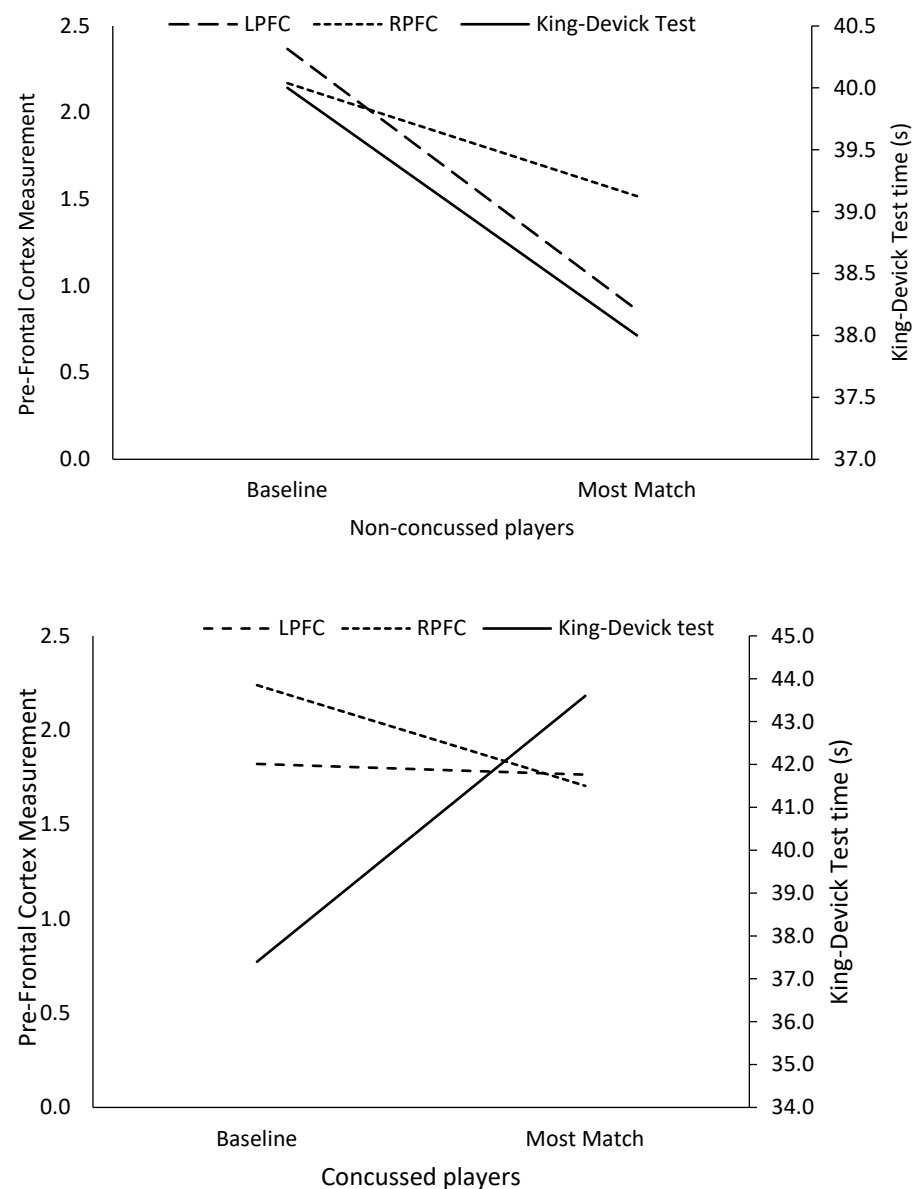


Figure 2. Changes in mean scores of King–Devick test, left prefrontal cortex (LPFC), and right prefrontal cortex (RPFC) for baseline and post-match measurements for concussed and non-concussed players.

3. Discussion

This preliminary study measured post-match brain haemodynamics, as measured by fNIRS during the administration of the K-DT, between players categorized as having a ‘suspected concussion’ and those ‘not suspected of having a concussion’ during collegiate-level rugby. Although the fNIRS can be used with a variety of tasks, such as Sudoku [51], dual-task gait [52], and the Stroop task [32], amongst others, the impetus for using the K-DT as the task for the fNIRS measurements is that it is sensitive to SRCs in a variety of sports [1,35,38,53–56]. To the best of the authors’ knowledge, this is the first study to compare baseline (preseason) with post-match haemodynamic (fNIRS) and K-DT data.

3.1. Overall Findings

The results from the K-DT assessments exhibited a slowing of the time between the baseline (pre-season) and post-match tests for those suspected of having sustained a concussion (37.4 s vs. 43.6 s) and notable differences between the non-concussed players

and suspected concussed players post-match (38.0 s vs. 43.6 s). These results align with previous research on the differing baseline to post-match K-DT times for individuals with concussions in collegiate athletes, rugby, Australian football, boxing, and mixed martial arts [35,39,53–61]. The K-DT indirectly evaluates visual-motor coordination, language, and cognitive function and is sensitive to changes caused by concussions [33,34]. These have a wide range of cortical interconnections for target position and accuracy in areas including the parietal cortex and frontal regions such as the frontal eye fields and the dorsolateral PFC [62–66]. Thus, changes seen between pre- and post-head injury K-DT times may be associated with changes in brain haemodynamics in these regions and potentially sensitive to the measurements obtained with fNIRS. As such, fNIRS may be an appropriate tool to measure this haemodynamic response, particularly changes between baseline and post-head injury results, with the K-DT used as a task. This combination, K-DT+fNIRS, may provide an additional approach for concussion recognition and possible monitoring.

The result from the fNIRS in the current study revealed that the haemodynamic response, oxygenated haemoglobin (O₂Hb), in the RPFC was significantly reduced in the concussed group between the baseline (pre-season) and post-match tests. This was also seen in the female group but not the male group. This was not the case in the non-concussion group, which showed an increase, albeit not meaningful, in the activation of both the right and LPFC. Furthermore, there was no correlation between the K-DT and RPFC and LPFC post-match for those categorized as non-concussed and concussed. However, in the non-concussed group, faster K-DT reading times were associated with lower O₂Hb levels in both the RPFC and LPFC. In the concussed group, slower K-DT reading times were observed, aligning with previous research, with a more pronounced decrease in RPFC O₂Hb. It was hypothesized that changes in K-DT performance would correspond with changes in the brain's haemodynamic processes, establishing a relationship between the fNIRS measurements and concussion tools such as the K-DT. Based on the results, it can be assumed that the slowing of the K-DT times is only partially impacted by O₂Hb levels. Therefore, this highlights the need to examine other mechanisms which may contribute to K-DT performance, such as the vestibulo-ocular system, language function, and attention [33–36]. The small and unbalanced sample size of the 'suspected concussion' group (seven females and three males) limits its generalisability, and the results may be driven by the female participants. Future research should consider potential sex-based differences in haemodynamic responses to SRCs. However, quantifying SRC severity for such comparisons remains challenging. A further exploration of these sex differences is discussed below.

Cortical or cerebral haemodynamics have been reported to be affected by SRCs, or mild traumatic brain injuries, with changes showing decreases in cerebral blood flow, and this is shown by the results of the current study [5,6,67,68]. Interestingly, previous research with moderate and severe brain injuries has shown initial hypoperfusion that gives way to hyperaemia and eventual vasospasm [69,70]. A study by Bishop et al. [71] determined, via fNIRS, whether changes in cerebral haemoglobin can be an objective indicator to assess concussions in those who were 1 to 3 days post-injury, 4 to 6 days post-injury, and 7 to 14 days post-injury [71]. The participants were university-aged athletes in collegiate ice hockey, football, and junior hockey leagues. Their study did not use a neurocognitive test such as the Stroop; instead, they measured O₂Hb levels at rest and during breath-holding tasks. The results demonstrated that during the 5 min rest period, which was prior to the breath-holding sessions (20-s holds), the O₂Hb levels were lower for those who were 7 to 14 days post-injury when compared with those at the 1 to 3 days and 4 to 6 days post-injury category, reflective of a change in time in O₂Hb levels. However, these levels were not notably different from those of the non-concussed controls. Furthermore, and more

important in comparison to the current study, Bishop et al. [71] did not have initial baseline measurements for comparison, making it challenging to compare their findings to the findings of the current study. Kontos et al. [72] assessed post-concussive participants and matched controls with fNIRS and several computerized neurocognitive tests [72]. Similar to Bishop et al. [71]’s study, there were no baseline pre-season measurements [71]. Kontos et al. [72]’s study showed that those in the concussion group demonstrated decreased activation in word memory, design memory, symbol match, and X and O tasks compared to the control group [72]. This was an interesting result as they used the Immediate Post-concussion Assessment and Cognitive Test (ImPACT), which has the aforementioned neurocognitive tasks as a component, albeit not similar to the K-DT [72].

Several studies have utilized fNIRS for people with long-term post-concussion symptoms [73–76], with one determining how averaging data within regions can better differentiate between post-concussion and healthy controls [73], two studies measuring changes with repetitive transcranial magnetic stimulation and the use of fNIRS [74,76], and one study assessing cortical communication deficits in adults with persistent post-concussion symptoms [75]. A recent study [46] that employed fNIRS and the K-DT examined the effect of repeated head impacts during a high school soccer season on cortical activation, which also included a complex tandem gait test. They reported that the greater amount of average head impact load resulted in a greater activation post-season compared to pre-season during both the K-DT and tandem gait test, but only during the most challenging aspects for each, the third card on the K-DT, and on the tandem gait test for the task involving walking backwards with one’s eyes closed. Interestingly, a greater number of average head impacts, a longer time taken to complete the K-DT, or components such as errors and swaying in the tandem gait test had no effect. The authors noted that the performance-based assessments (K-DT and tandem gait test) were not as sensitive as haemodynamic metrics, measured via fNIRS, in identifying changes in the brain with repeated head impacts.

Interestingly, it appears there is conflicting evidence as to brain activation changes during such cognitive tasks following concussions. For example, Kontos et al. [72] measured changes in frontal cerebral O₂Hb levels (inferior frontal, dorsal-lateral pre-frontal, and frontal regions) in symptomatic post-concussion participants ($F = 4$, $M = 5$, 22.73 ± 1.32 years) with an average time since injury of $21 (\pm 12)$ days and reported decreased activation when compared to controls ($F = 4$, $M = 1$, 22.00 ± 0.28 years) during computerized neurocognitive testing [72]. It is also important to note that the cognitive performance scores were lower for concussed participants on the word memory, design memory, and symbol match tasks than those for the controls. On the contrary, Urban et al. [77] compared relative fNIRS brain oxy- and deoxy-haemoglobin concentrations among youth ($F = \text{four}$, $M = \text{one}$, 15.8 ± 1.3 years) within two weeks of a concussion when compared with concussion-free controls ($F = \text{ten}$, $M = \text{four}$, 15.8 ± 1.7 years). Despite a similar task performance, it was reported that those in the concussion group had altered brain activation patterns (including hyperactivation, added activation, and/or a lack of activation) across frontal and parietal brain regions while performing single and dual tasks [77]. It may be the case that the concussion group is using more reserved resources during the cognitive task when compared to the control group (i.e., a heightened neural effort for the same behavioural performance output). Conversely, decreased activation along with a similar mental output would indicate a greater efficiency. All of that being said, it is clear that concussions can cause altered cerebrovascular responses during cognitive tasks. In addition, behavioural performance scores may also vary.

3.2. Effect of Exercise on Brain Haemodynamics and K-DT Times

It may also be essential to note that the intensity of exercise may also have impacted post-game O₂Hb levels [78]. The most consistent findings regarding the intensity of exercise and brain haemodynamics suggest that during moderate-intensity exercise, there is an increase in cerebral blood flow. This increase may lead to increased post-exercise activation and promote improved cognitive performance. That being said, as exercise approaches higher or near-maximal intensities, resources are moved away from areas that require cognitive processing (including the PFC) and toward regions of motor and sensory function (this response has been termed hypofrontality). Assuming a sport such as rugby is performed at a high intensity, it could be argued that following the rugby game, the failure to observe a rebound effect during cognitive testing may be due to hypofrontality and fatigue induced during the game [78].

The performance of the K-DT following moderate to high levels of exercise was examined by Rist et al. [79]. The results showed that the performance was improved following a bout of high-intensity exercise at an 80% predicted maximal heart rate but not at a moderate level of a 65% predicted maximal heart rate. These were measured following 15 min of the exercise session. However, this study did not re-evaluate performance after the 15 min time frame nor concurrent O₂Hb levels, and previous studies reporting on similar findings did not involve a controlled environment controlling for the level of intensity [35,80,81].

The effect of acute high-intensity exercise on cognitive performance is poorly understood [82], and future studies need to adequately measure match or game exercise components with cognitive performance with consideration to environmental conditions, such as temperature, humidity, and player hydration and nutrient levels.

3.3. Effect of Fatigue on Brain Haemodynamics and K-DT Times

Rugby consists of multiple bouts of high-intensity running, which are separated by low-intensity activities with players tackling and getting into rucks and mauls; as such, they require strength, power, and endurance [83,84]. Therefore, fatigue occurs as the match continues [85,86]. The fatigue that occurs may be another possible explanation for the reduced O₂Hb activation [87–89]. This study did not use GPS or other quantifying devices to measure physical or energy demands. However, it is assumed that the participants in the current study were not near maximal capacity, and the post-match measurements were conducted between 30 and 45 min after the match's conclusion, so the aforementioned research may not apply to the current study. Interestingly, Tsubaki et al. [87] reported O₂Hb decreases immediately after post-exercise rest with individuals exercising at a 30% VO₂ peak for 20 min, but increased shortly thereafter with a slow decrease over time but not superseding the baseline value [87]. These divergent findings from the literature and the current study may suggest the possibility of the post-match reduction being due to an over-recovery of cortical O₂ levels, in which blood is shunted to recovering musculature, the development of post-exercise hypotension [88,89], or changes in fluid or hydration levels [90] and body temperature [91]. However, these reflect changes in volume as opposed to O₂Hb content. Nonetheless, future research would need to better understand the changes in O₂Hb post-exercise over several hours.

3.4. Clinical Application

The clinical application of using the K-DT for SRCs has been established, and numerous studies have already been published [35,53–55,57]. However, the clinical application of fNIRS with SRCs needs further research. In addition, the combination of the K-DT+fNIRS also requires further investigation, and neither one should be utilized as a stand-alone pro-

cedure for assessing concussions. Moreover, combining K-DT+fNIRS could form a battery of tests used to diagnose and manage SRCs and may be utilized with other previously established assessments.

3.5. Limitations

Several limitations must be considered when interpreting the current results. These include this study's small sample size (especially those in the suspected concussion group), which may limit its external validity. That being said, there is a paucity of studies on concussions and fNIRS, so the results may provide initial findings to help guide future research. It is clear future research should include larger sample sizes and consider more finite participant details, such as aerobic fitness level [92], age [93], exercise effect [78,87–89], fatigue [78,87–91], and sex [94], all of which may have an impact on concussion severity. Furthermore, including the fNIRS measurement of other cortical sites would help provide additional insight into the impact of concussions globally and on cognitive performance. It is important to note that since the fNIRS we utilized measured a limited and superficial brain area, our results may differ from those of other studies, whereby different measurement techniques were utilized (e.g., fMRI) or other brain areas were monitored.

4. Materials and Methods

A prospective observational cohort study was conducted on one team of 15 female collegiate rugby players over a 2-match time frame and one team of 15 male collegiate rugby players over a 3-match time frame, respectively, during the 2021 season. Prior to the start of data collection, potential participants were informed about the study by the team captain who had previously met with the researchers. A team meeting was scheduled with all players being informed about the study's aims and data collection procedures. All members of the two teams were invited to participate in the study. A total of 22 rugby players were enrolled and tested at baseline (pre-season) (6 males, age range 18–22 yrs.; 16 females, age range 18–22 yrs.). Written consent was obtained from the players before enrolment. The university's ethics committee approved all procedures (IRB 22-0020).

All participants ($n = 22$) completed an initial baseline (pre-season) iPad-based K-DT+fNIRS assessment. Over the course of the season, all participants were invited to complete at least one post-match K-DT+fNIRS assessment. The K-DT+fNIRS was for research purposes and not for clinical use. It must be noted that the team's assigned athletic trainer, who was external to the university at which the study was conducted and employed at a sports medicine rehabilitation clinic, took baseline (pre-season) SCAT6 measurements on all players and used these results for comparison when assessing players suspected of concussions. These results were not used in this preliminary study as the aim was to use only the K-DT and fNIRS.

4.1. Instruments

4.1.1. fNIRS

All fNIRS recordings during the K-DT (task-DT) were performed using a non-invasive, portable 8-channel continuous dual wavelength (760 and 850 nm) system (Octamon, Artinis Medical Systems, Elst, The Netherlands). This device consists of four LED optodes and one receiver placed over the LPFC and RPPC, respectively (8×2 configuration). Optode placement was based on the modified international electroencephalogram 10/20 system. The measurement was kept consistent throughout the study by positioning the headband 2 cm over the nasion point (depressed area between the eyes, above the bridge of the nose). The optodes were 3.5 cm from the receiver, and relative changes in O_2Hb were measured within each K-DT using the first 10 s, defined as 0 μmol . Following data collection (all data

samples were taken at 10 Hz), a 0.1 Hz low-pass filter was applied to the data to reduce physiological artifacts.

4.1.2. King–Devick

The K-DT is an iPad-based, timed, rapid-number naming task that involves the participant reading several rows of numbers (from left to right and top to bottom) as fast as they can without error over three successive iPad test screens, with a short rest break between screens, which captures afferent visual function, attention, indirect saccadic movements of the eyes, and visual fixation [17,18,95]. The combined time (in s) for the participant to read the numbers on the three successive test screens provides the total K-DT time. At baseline (pre-season testing), the K-DT is completed twice, with the faster of the two trials being recorded as the baseline time. In this study, these are referred to as T1 (time 1) and T2 (time 2). Slower total time or any errors recorded post-head injury compared to baseline have been shown to be related to SRC [35,53–55,57,96]. The K-DT has a reported interclass correlation of 0.92 to 0.97 [55,96].

4.2. Procedure

4.2.1. Baseline Protocol

After completing a health history and concussion history questionnaire, participants were instructed on the testing order. The health history questionnaire screened for age, height, body mass, major illness, prescription and non-prescription medications, and years of rugby experience. Participants were excluded from the study if they had any known behavioural, psychological, or neural disorders. The concussion history questionnaire screened for dates of any previous concussions, the sport in which the concussion occurred, if a hospital was visited and if they had lost consciousness, description of symptoms, and length of time to return to play. No participant reported a history of a diagnosed concussion. Following the questionnaires, the fNIRS head cap (see Figure 1) was placed on the participant, and the baseline (pre-season) K-DT was completed.

4.2.2. Identification of Players Suspected of Concussion

Watching or monitoring players can be problematic during a game, especially in rugby, American football, and soccer. Identifying a player who may have sustained a concussion during play in these sports and similar sports is difficult due to the rapid speed of play, player pileups, if the injury is sustained away from the ball, and if the game is in a field that hampers adequate visualization [97]. Those sports and leagues at the elite level, such as the National Football League (NFL), have established the use of multi-positioned video and spotters around the field to observe players. For example, the NFL has a certified athletic trainer (AT) situated in a video booth to view a video monitor and report on player behaviour and mechanism of injury to the medical staff with a recommendation to assess a particular player [98]. Unfortunately, this is usually unavailable at the non-elite level, such as collegiate or non-collegiate club rugby and high school sports. At this level, there is typically a reliance on one or a few athletic trainers who monitor play and assess players for injuries, including SRC [99]. In these situations, a side-line assessment is administered when a player sustains a head injury or displays signs and symptoms of an SRC. A recent study by Jain et al. [46] to determine whether repeated head impacts during a high school soccer season resulted in cortical activation using fNIRS and the K-DT utilized video, impact accelerometers, and observations, respectively. However, the authors noted that they were challenged with malfunctioning equipment, and estimates had to be used. In the current preliminary study with collegiate rugby and no access to video, players were viewed by research assistants (student athletic trainers), the principal investigator (MH), a professor and certified athletic trainer since 2000, and the teams' assigned athletic trainer (external to

the university at which the study was conducted). Please note that the K-DT+fNIRS were utilized for research purposes only, and no decisions on playability or recommendations for further medical assessment were made.

During matches, if a player was witnessed to have sustained a direct head, neck, or indirect body impact that appeared to cause a quick or violent head movement, the team's athletic trainer assessed the player using the SCAT6 protocol. Based on the findings of the SCAT6 or other clinical findings, the athletic trainer decided on the continuation of play or their removal from play. Over the course of the matches observed in this study, no player was deemed to have sustained a concussion by the team's athletic trainer. However, as noted above, those who did require the athletic trainer's evaluation (a player witnessed by observers) were then re-assessed after the match (post-match) with the K-DT+fNIRS. These players were categorized as having a 'suspected concussion'. This term was used as a category due to nomenclature.

In addition, and for comparison, several random participants who had not sustained a head injury and, therefore, were not subsequently assessed by the athletic trainer but had participated for a similar number of minutes in the match as the injured players were asked to be re-evaluated with the K-DT+fNIRS post-match as well for a control group comparison. These random players were those who had volunteered to be in the study and were subsequently asked by the PI after the match if they would be willing to be re-evaluated at that particular match. These players could not be selected pre-match because of the possibility that they may not participate in the entire match due to various factors such as injury, performance, and coaching decisions. However, upon volunteering, they were re-evaluated with the K-DT+fNIRS after the match. If one of these participants performed worse (slowing of time in s) on the K-DT post-match, they were also included in the category of 'suspected concussion' for the analysis. This protocol was established to better understand the relationship between K-DT (slowing) changes and brain haemodynamics measured by the fNIRS. Including post-match K-DT+fNIRS testing on players not witnessed to have sustained an impact provides insight into haemodynamic changes during play, which could result from fatigue, repetitive subconcussive impacts, or an impact not witnessed by the sideline viewers. As noted above, the K-DT has its greatest diagnostic accuracy 0–6 h post-concussion, with worsening of performance time (slower post-concussion versus baseline) varying from 3.5 to 5 s, with the developer recommending that any suspected post-match-concussion injury K-DT greater than 1 s should be further evaluated to rule out concussion [37–40]. Therefore, if a player did perform worse on the K-DT, whether witnessed to have possibly sustained an SRC or randomly asked to sit for a post-match K-DT+fNIRS, they were categorized in the 'suspected concussion' group for analysis. All post-match tests were completed within 30 to 45 min of the final whistle in the match (see Figure 3).

To evaluate the relationship between fNIRS and the K-DT, a participant was categorized as having a 'suspected concussion' if one or both two of the following were met: (1) a player was witnessed to have sustained a direct head, neck, or indirect body impact that appeared to cause a quick or violent head movement warranting an assessment by the team's athletic trainer; and (2) if a participant who was not identified as possibly having sustained a concussion during the match performed worse (slowing) on the K-DT post-match as recommended by the developer [37–40].

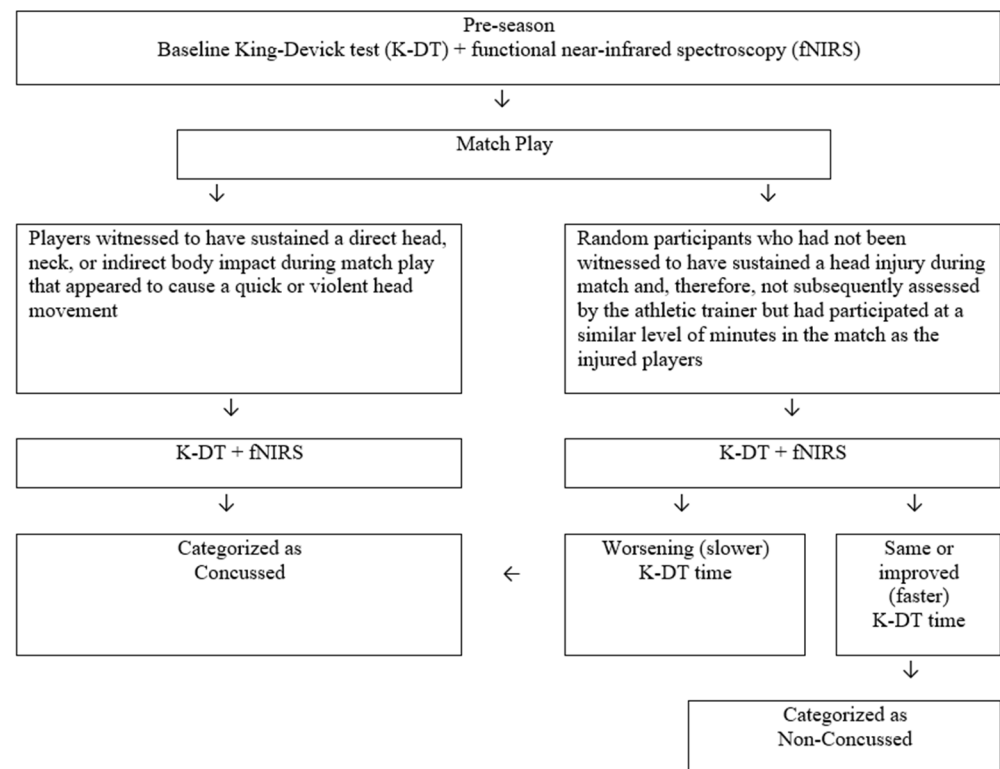


Figure 3. Procedure protocol for participants categorized as concussed or non-concussed. This protocol was established to provide an understanding into haemodynamic changes during play, which could result from fatigue, repetitive sub-concussive impacts, or an impact not witnessed by the sideline viewers.

4.3. Statistical Analysis

All data were downloaded onto a Microsoft Excel spreadsheet and analysed with SPSS (IBM SPSS Statistics for Windows, Version 26.0.0, Armonk, NY, USA: IBM Corp). Data were checked for normality and homogeneity of variance using Shapiro–Wilk test of normality. If tolerances were not met, equivalent non-parametric tests were utilized. The King–Devick test ($W(23) = 0.907$; $p = 0.0358$), player age ($W(28) = 0.794$; $p = 0.0001$), and O_2Hb ($W(68) = 0.938$; $p = 0.0021$) data were identified to be non-parametric and were analysed with a Friedman repeated measures ANOVA on ranks. A Wilcoxon signed-rank post-hoc test was conducted with a Bonferroni correction applied if notable differences were observed. These data were reported as median with 25th to 75th IQR. The fNIRS ($W(21) = 938$; $p = 0.2014$) data were identified to be parametric and were compared using a *t*-test. These data were reported as a mean with 95% confidence interval (CI). Cohen’s effect size (*d*) was utilized to calculate practically meaningful differences between playing positions and for different levels of participation. Effect sizes of <0.19, 0.20–0.60, 0.61–1.20, and >1.20 were considered trivial, small, moderate, and large, respectively [100].

Test–retest reliability was calculated using intra-class correlation coefficient (ICC), with 95% CI, to examine agreement between baseline (pre-season) first and second (time 1 = T1, time 2 = T2) test scores for total, non-concussed players, and players with suspected concussion post-match and at established baseline. The model used was a test–retest repeatability study using a two-way mixed model with absolute agreement for a single rater/measurement. This was chosen because (a) the study refers to the repeatability between consecutive sessions taken by the same instrument under the same conditions; (b) the use of a two-way mixed-effects model is recommended as appropriate to ensure testing reliability with multiple scores from the same rater that cannot be regarded as

randomized samples; and (c) absolute agreement should always be chosen for test–retest reliability [101,102]. The ICC was interpreted as poor (< 0.50), moderate (0.51 to 0.75), good (0.76 to 0.90), and excellent (> 0.91) levels of reliability [60]. The level of significance was set at $p \leq 0.05$. A Pearson correlation coefficient (r) was undertaken to assess the linear relationship between the changes in the K-DT and the measurements of the LPFC and RPFC.

5. Conclusions

In conclusion, those in the suspected concussion group had a decreased cognitive performance and a notable change in PFC activation compared to at baseline. In contrast, the non-concussed control group displayed no meaningful change in PFC activation and no change in cognitive performance scores at the post-match time point. The slowing of K-DT times with the concussed group aligned with previous research, and the changes seen in the fNIRS for this same group were apparent and might reflect a relationship between the two instruments. Overall, the changes in the fNIRS represent a possible acute adjustment in brain haemodynamics and provide insight into how concussions can negatively impact cognitive performance, and future research should examine its relationship to other cognitive assessments. Lastly, future research should continue to investigate the use of commonly used neuropsychological tests and fNIRS in the assessment and recovery of patients with SRCs.

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