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# Changes in brain oxygenation of rugby players before and after head trauma

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# CHANGES IN BRAIN OXYGENATION OF RUGBY PLAYERS BEFORE AND AFTER HEAD TRAUMA

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**Abstract**

Clinicians often rely on simple neuropsychological and balance tests to diagnose concussion and determine return to sport. These tests are not fully comprehensive and lack a measure of brain physiology, warranting the need for an objective biomarker, especially in sports with frequent head trauma (e.g., rugby). The high number of concussions occurring in recreational sport necessitates an affordable and accurate biomarker to easily assess the severity of trauma. The purpose of the present study was to address this issue, using functional near-infrared spectroscopy (fNIRS) to assess relative changes in oxyhemoglobin ($O_2Hb$), deoxyhemoglobin (HHb), total hemoglobin (tHb) and hemoglobin difference (Hbdiff) in the left and right prefrontal cortex (LPFC and RPFC) during a commonly used concussion test (King-Devick (K-D)). Healthy baseline data (n=22) was compared to data collected following mild head trauma (MHT) during a collegiate rugby game (n=17) and to data collected following significant head trauma (SHT) (player-reported excessive force to the head) during the game (n=5). Major findings indicate that both Hbdiff and $O_2Hb$ were significantly lower in the RPFC following moderate head trauma in comparison to that of baseline (Hbdiff: 2.21 ± 2.03 μmol vs. 0.89 ± 1.16 μmol, $p = 0.02$, $O_2Hb$: 1.96 ± 1.98 μmol vs. 0.78 ± 1.27 μmol, $p = 0.03$). Following significant trauma, Hbdiff was significantly lower and HHb was significantly higher in the RPFC (Hbdiff: 2.51 ± 0.42 μmol vs. 0.79 ± 1.17 μmol, $p = 0.04$, HHb: -0.72 ± 0.34 μmol vs. 0.06 ± 0.45 μmol, $p = 0.04$). Taken together, these findings indicate reduced activation of the RPFC following rugby competition. Interestingly, no significant differences were observed between conditions in K-D results (time to completion, secs) (MHT healthy baseline: 49.29 secs vs. post trauma: 47.33 secs, SHT healthy baseline: 47.34 secs vs. post trauma: 49.02 secs). Since no significant difference was found in K-D scores but there was reduced activation of the RPFC

detected in those subjects who had experienced significant head trauma, our preliminary results indicate that clinicians should rely on more objective assessments of brain activity in addition to the currently used concussion tests for full contact sports such as rugby. Assessing PFC activation via fNIRS may be a viable biomarker for monitoring the physiological state of the brain following a collegiate rugby game.

## Introduction

It is estimated that there are approximately 170 million concussions and 300,000 sport related concussions annually just in the United States (Dessy, 2017). This number is significant, especially considering the fact that many of these injuries are in a population that does not have a fully developed brain. Unfortunately, these numbers are also an underestimation since athletes have a tendency to either not report their symptoms or play through their concussion (McDonald, 2017). Undiagnosed concussions can be incredibly dangerous as athletes who sustain one concussion are three times more likely to sustain another in the same season (Leong, 2014). The dangers of unreported concussions are coming to light as more research on second impact syndrome as well as chronic traumatic encephalopathy (CTE) are being done. One of the biggest areas of conversation around concussions is which assessment is most accurate in diagnosing the injury. Some of the common tests include the SCAT test, imPACT, PCSS, CogSport, CRI and King-Devick (Ventura, 2015), and it is important to note that these tests do not assess any biomarkers in the brain. Magnetic resonance imaging (MRI) is another option for diagnosis, however they are expensive and take a lengthy time to be scheduled and processed. After reviewing research completed by Dessy and Dziemianowicz (2015) it seems that the King-Devick test is one of the most effective in detecting concussions due to using eye movements to activate the vestibular system as well as activating the brain stem. In order for this test to be effective the athlete needs a baseline score which would then be compared to a post head trauma score to diagnose the concussion. This is not a fully comprehensive test, meaning it has to be paired with other tests. Even the best concussion tests are not enough to detect a concussion so most doctors and trainers combine multiple in order to have the most accurate results. Science is still searching for an affordable way to use a human biomarker in order to determine whether or not an athlete has sustained a brain injury.

Rugby is a sport in which every player on the field experiences some sort of head trauma throughout the game. When the rate of concussions sustained in a rugby game was compared to a football game, rugby was about twice as high (Willigenburg, 2016). It was also found that concussions accounted for 16% of all injuries sustained while participating in collegiate rugby and direct player contact was the most common mechanism of injury (Willigenburg, 2016). Functional near-infrared spectroscopy (fNIRS) could potentially be a useful diagnostic modality due to its portability and the fact that it is easy to use. This tool enables the assessment of cognitive workload in terms of cerebral oxygenation change while performing cognitive tasks (Ayaz et al 2013). Urban (2015) found that as brain activity increases, so do hemoglobin and oxyhemoglobin levels, however, deoxyhemoglobin levels decrease. After head trauma occurs to the brain, it has been shown that brain activity may be altered. The fNIRS was used to compare brain oxygenation in rugby players before and after head trauma.

To address this prevalent issue in sports, a case study using fNIRS to determine relative changes in oxy and deoxyhemoglobin as well as hemoglobin in the prefrontal cortex was conducted. Hemoglobin difference (Hbdiff), total hemoglobin (tHb), oxy and deoxyhemoglobin ($O_2$Hb and HHb) levels were measured while performing the King-Devick concussion test before (as a baseline) and after head trauma from a collegiate rugby match. This research has helped to determine if the changes in Hbdiff, $O_2$Hb, tHb or HHb could be useful biomarkers to assess the physiological state of the brain following collegiate rugby performance and serve as an objective physiological measure to assess concussion/head trauma.

**Purpose**

The purpose of the current investigation was to examine changes in prefrontal cortex activation (PFC) using functional near-infrared spectroscopy following rugby competition. Prefrontal cortex activation was measured while performing the K-D concussion test before and after mild and significant head trauma sustained by athletes in a collegiate rugby match. This research is important as subtle changes in biomarkers may offer guidance on diagnosing injury and informing treatment.

**Literature Review**

The current research on concussions describes the injury as a “brain injury defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces” (McCrory, 2012, p. 179). With this broad of a definition, the process of diagnosis and recovery from this injury is variable and highly controversial. Concussions can present in a multitude of different ways and can be conceived by any sort of “head trauma”; which includes any sort of physical trauma that affects the head/brain. The brain is arguably the most important part of the body, meaning that research in this area is essential to maintaining athletes’ safety. Due to the complex physiological nature of concussions compared to other injuries, which can often be diagnosed by a few physical tests, concussions are not easy injuries to diagnose and recover from.

Although concussions are one of the most dangerous injuries, they are also the most underreported since they cannot be physically seen.

> In a 2004 study of high school football players, it was found that 41 percent of athletes reported that they played through a possible concussion because they did not want to leave the game. It was also found that 66 percent of the athletes didn't report their symptoms because they didn't think the injury was serious enough to do so (McCrea et al., 2004 as cited by Graham 2014).

Another driving factor in not reporting head trauma is the protocol for returning to sports. According to USA Rugby, "If a player shows symptoms of concussion before, during or after a match, that player must be removed from play immediately, not to return to that match. No Exception" (USA Rugby Digital Platform Team, 2022). They also explain that adult rugby players must sit out for a minimum of one week (seven days), and be symptom free before beginning a five day return to play protocol. The current return to protocol looks something like this:

| Day Number | Objective | Example(s) |
|---|---|---|
| 1 | Symptom free with normal activities | school, driving, social interactions |
| 2 | Light aerobic activity | walking, stationary bike |

| | | |
|---|---|---|
| 3 | Moderate activity | Running, light ball drills |
| 4 | Heavy non contact activity | Non contact practice |
| 5 | Full contact practice | As stated |
| 6 | Competition | As stated |

Athletes also may not even know that they have sustained a concussion as symptoms may not present until hours after the incident. Due to the fact that it may take time for symptoms to present, and athletes tend to underreport concussions, it would be beneficial to have an instrument that can detect a concussion without any subjective test or having to wait for symptoms to begin. This would also be useful in managing recovery because the athletes would not have the ability to be dishonest as they could be in a subjective test.

Currently, in sports such as collegiate rugby and even in the National Collegiate Athletic Association (NCAA), the governing body for intercollegiate sports, multiple tests are needed to conclude that an athlete has a concussion and there is no protocol for exactly which tests are to be used. Decisions on creating a protocol in each institution depend on their clinical standards of care, finances, resources and time available. The NCAA has tried to give loose guidelines on concussion testing, including history, symptom evaluation, cognitive and balance assessment, however these recommendations are not requirements (Clugston, 2019, p. 1248). For most other injuries there are a few set tests that all clinicians use when diagnosing them however this is not the case for concussions.

In a newer area of concussion testing, clinicians are using tests that evaluate the vestibular system of an athlete. This part of the inner ear can be greatly impacted by concussions and it is involved with controlling balance as well as eye movements. These new diagnostic tests have been developed to target this area in their evaluation, one of these tests being the King-Devick (K-D) test which uses saccadic eye movements to activate this system. The K-D test has been a beneficial tool in diagnosing concussions and has even been found to detect unreported concussions. In a study with a group of rugby players the K-D test time increased compared to the baseline score following a witnessed concussion as well as following an unrecognized concussion. The test ended up identifying 17 concussions that were unrecognized at first (Gardner, 2014). Although research is still emerging surrounding the K-D test, it is currently considered one of the best diagnostic tests for concussion which is a testament to how new research in this area truly is.

After analyzing the literature it seems that research needs to be conducted on; minimizing the amount of tests needed to diagnose the concussion by creating guidelines, decreasing subjectivity and increasing accuracy. Investigations are starting to look for a biomarker that could indicate head trauma. Currently there is some speculation on what these biomarkers could be, "Evidence from human and animal studies in more severe traumatic brain injury demonstrate induction of a variety of genetic and cytokine factors, such as insulin-like growth factor-1 (IGF-1), IGF binding protein-2, fibroblast growth factor, Cu-Zn superoxide dismutase, superoxide dismutase-1 (SOD-1), nerve growth factor, glial fibrillary acidic protein (GFAP), and S-100. In addition, biochemical serum and cerebrospinal fluid biomarkers of brain injury have been proposed as means by which cellular damage may be detected if present. There is currently insufficient evidence, however, to justify the routine use of these biomarkers clinically." (Marshall, 2001). Unfortunately, blood tests or spinal taps are not feasible to be used in athletics to diagnose concussions and these biomarkers are only speculations for severe trauma. Another biomarker that has been looked into has been oxygenation in the brain following head trauma which can be measured by a tool called functional near-infrared spectroscopy (fNIRS). The fNIRS was first used to measure oxygenation in the brain in 1977 by F.F Jobsis and has continued to grow in its applications since then (Karim, 2012). "Functional near-infrared spectroscopy (fNIRS) is a non-invasive method to measure brain activities using the changes of optical absorption in the brain through the intact skull. fNIRS has many advantages over other neuroimaging modalities such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), or magnetoencephalography (MEG), since it can directly measure blood oxygenation level changes related to neural activation with high temporal resolution" (Tak, 2014). Since this tool is noninvasive, less expensive and can be accessible, it could potentially be a breakthrough in concussion diagnosis.

There have already been a few studies using fNIRS to analyze its ability to measure brain oxygenation following head trauma. In a study by Amoyt (2020), the research group measured the cerebral vascular reactivity in patients with traumatic brain injuries using the fNIRS as well as an fMRI. He found that cerebral vascular reactivity or brain activity can be measured using fNIRS and fMRI however each modality has its own advantages and disadvantages. fMRI is the most common with high resolution and can be co-localized with structural images. On the other hand, fNIRS has better temporal resolution, has a low cost and can be easily used in outpatient facilities. It has been shown that the oxygen changes that are detected by the fNIRS determine the capacity that the brain is working. In a study related to current concussion diagnostics, Storey (2021) measured the changes in oxygenation in the brain during a K-D test in pediatric patients by giving them tasks which required varying amounts of focus and therefore brain activation. It was found that “preliminary experimental results demonstrate that fNIRS can reliably detect changes in cerebral blood oxygenation that reflect the cognitive workload associated with a given task” (Storey, 2021). In another study by Bishop and Neary (2017), they used the fNIRS during rest and again during a hypercapnia test to measure oxygen levels of hockey and football players. The conclusion of the study was that noninvasive prefrontal hemoglobin concentrations hold the potential for monitoring sports concussions and recovery.

In order to evaluate this modality, a sport with consistent head trauma was considered appropriate. Rugby is a sport in which little to no protective gear is used and the headgear is minimal compared to the helmets used in other high contact sports. In this sport there is constant trauma to the body and head from tackling other players directly as well as hitting the ground. During a front-facing tackle, the average velocity of both the ball carrier and tackler are about 5.1 m/s (11mph) and 5.7 m/s (12.7mph) respectively in the 0.5s period before impact (Hendricks 2017). Since force is calculated using the force = mass x acceleration this amounts to considerable forces acting on wherever the athlete is hit, and if that is the head then it makes sense why there are so many concussions in rugby.  In a study conducted by Damien (2016); it was determined that forwards, adjustables and outside backs had 161, 89 and 41 tackles respectively per game. It was also said that defenders initiate the contact most often. This means that in a 50/50 possession game the athletes are getting hit about 80, 45 and 20 times by one or more defenders. It can be assumed that from hitting the ground and/or another player this many times with the force mentioned in the previous study, players will sustain some sort of head trauma in every match. Also, with the fact that concussions are widely underreported due to the strict rules and "tough" mentality in mind, this sport can result in a scary amount of head trauma. The challenge of undiagnosed concussions is not only a problem in rugby as mentioned earlier, it is a sport-wide problem and needs to be addressed.

After analyzing the current research in the area of concussion diagnostics, it is clear that there is not a singular test that can diagnose a concussion or manage recovery and there is no definitive biomarker that correlates to head trauma. Also, athletes have a tendency to underreport symptoms and due to the nature of current testing, concussions can easily go undiagnosed. The fNIRS may provide a solution to the problem, however, there is not enough research with this device and sports. In an effort to evaluate the diagnostic potential of the fNIRS, rugby is the best sport due to the undeniable head trauma from each game, and the K-D test is the perfect test as it is the most researched/popular brain activating test for assessing concussions.

**Hypotheses**

1. fNIRS will be an affordable and accurate tool to identify head trauma in collegiate rugby players and potentially other athletes.

   *Rationale: fNIRS has better temporal resolution, has a low cost and supposedly easy to use. (Amoyt, 2020)*

2. Oxyhemoglobin levels will decrease and deoxyhemoglobin levels will increase during the K-D concussion test in collegiate rugby athletes following head trauma.

*Rationale: In a pediatric study as brain activation increased it was found that hemoglobin and oxyhemoglobin levels increased however deoxyhemoglobin levels decreased. (Urban, 2015)*

## Methodology

*Please note that all protocols in this experiment were IRB approved

### *Participants*

Thirty-one rugby athletes between the mens and womens UNI rugby teams filled out a history form with questions about their time participating in rugby and their history of concussions. The athletes sat in a chair in a quiet room and had the fNIRS set up with 8 optodes on the left side of the PFC and 8 on the right side. Each athlete then performed the K-D concussion test three times; once as a practice and twice to see how fast they could perform the test while maintaining accuracy. The fastest time was then taken as a baseline score in seconds. The data was analyzed in excel and an average number was taken for each of the biomarkers; Hbdiff, $O_2Hb$, tHb and HHb. Following a rugby match where the athletes endured numerous tackles, the athletes were retested within an hour following the match, using the same procedure and their scores were recorded as “moderate head trauma” (in the study this ended up being 17 athletes who recorded a baseline and had a moderate head trauma score). Athletes who were removed from the game due to a suspected concussion had their data identified using an asterisk on the data sheet and their injury was recorded as “significant head trauma” (after the season there were five athletes that fit into this category). All post game data was then compared with the athlete's baseline.

### *Study Design*

### *functional Near-Infrared Spectroscopy (fNIRS)*

All fNIRS recordings during the King-Devick task were performed using a non-invasive, portable 8 channel continuous dual wave-length (760 and 850 nm) system (Octamon, Artinis Medical Systems, Netherlands). This device consists of four LED optodes and one receiver placed over the left PFC (LPFC) and right PFC (RPFC), respectively (8 x 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 naison point (depressed area between the eyes, above the bridge of the nose). The optodes were 3.5 cm from the receiver and relative changes for oxyhemoglobin ($O_2Hb$), deoxyhemoglobin (HHb), total hemoglobin (tHb), and hemoglobin difference (Hbdiff) were measured within each K-D test using the first 10 seconds defined as 0 μmol. Following data collection (all data sampling at 10 Hz), a 0.1 Hz low-pass filter was applied to the data to reduce artifacts. The data was then averaged and analyzed in GraphPad Prism 9.0.2.

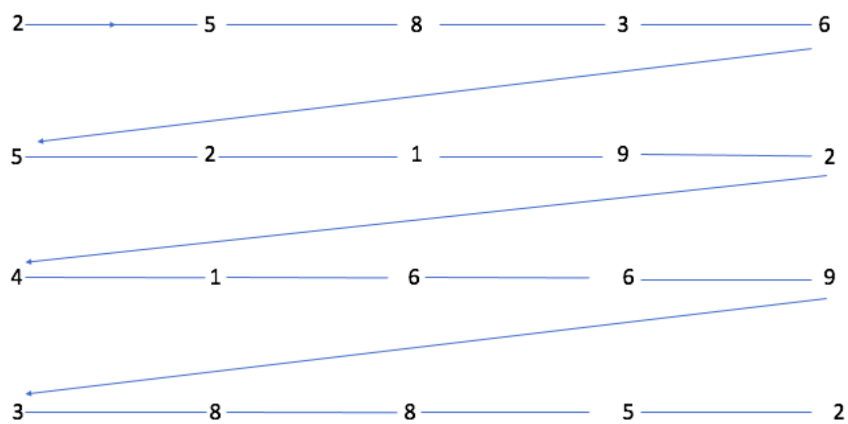
***King-Devick***

The K-D test is a saccadic eye movement test used to evaluate the function of the vestibular system in order to determine whether or not an athlete has sustained a concussion. This is a rapid number naming task where the athlete reads numbers aloud from left to right and top to bottom (as one would read a book) while maintaining perfect accuracy. In this study, the test was administered using an iPad where the athlete tapped the screen to view the test and start their time and tapped the screen when they were done to end the timer. The test consists of three cards; a demonstration card and two test cards. If a mistake was made on a card then that card's score was considered void. The fastest time of the two test cards was recorded as the baseline score. After a match or following a suspected concussion, the athlete was retested using the same procedure and the new post trauma score was compared to each athlete's individual baseline score.

***Statistical Analysis***

All results are expressed as means ± standard deviations. Brain oxygenation changes from baseline within each trial (baseline and post-rugby competition) were analyzed using data from the right PFC (RPFC averaged channels 1-4) and left PFC (LPFC averaged channels 5-8). Paired student T-tests were used to compare K-D times to completion and LPFC and RPFC for $O_2Hb$, HHb, tHb and Hbdiff. Data were analyzed using GraphPad Prism 9.0.2 and statistical significance was set at $p < 0.05$.

EXAMPLE OF K-D DEMONSTRATION




EXAMPLE OF KING-DEVICK TIMED TEST

6 5 8 9 2

4 1 9 7 9

5 7 2 4 1 6

4 8 3 7 5

6 2 8 7 1

**Results:**

***King-Devick Results:***

No significant differences were found between the pre and post trauma K-D test times to completion (see Tables 2 and 3 below). Interestingly, in the SHT group; three subjects increased their K-D times while two subjects decreased their times compared to their respective baselines. This indicates that the K-D test score did not determine whether or not an athlete sustained any head trauma and it also did not determine the severity of head trauma an athlete experienced.

***fNIRS Results:***

The RPFC Hbdiff and $O_2$Hb were significantly lower following MHT while the RPFC HHb increased and the RPFC Hbdiff decreased following SHT. This indicates reduced $O_2$ extraction and activation of the RPFC following either moderate or significant head trauma. Although not significant, other interesting findings following MHT were: In the LPFC there was a decrease in $O_2$Hb, tHb and Hbdiff and in the RPFC there was a decrease in tHb. In the SHT group, there was an increase in HHb in the LPFC. (see Table 1).

***fNIRS Data and Graphs:***

Moderate Head Trauma; N=17

**Table 1:**

| ***Right Prefrontal Cortex $O_2Hb$ (μmol)*** | | ***P-value*** | ***Left Prefrontal Cortex $O_2Hb$ (μmol)*** | | ***P-value*** |
|---|---|---|---|---|---|
| Baseline | Post-Game | | Baseline | Post-Game | |
| 1.96 | 0.78* | 0.03 | 2.02 | 1.01 | 0.08 |
| ***Right Prefrontal Cortex HHb (μmol)*** | | | ***Left Prefrontal Cortex HHb (μmol)*** | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| -0.25 | -0.11 | 0.44 | -0.18 | 0.11 | 0.68 |
| ***Right Prefrontal Cortex tHb (μmol)*** | | | ***Left Prefrontal Cortex tHb (μmol)*** | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| 1.71 | 0.67 | 0.07 | 1.83 | 0.91 | 0.07 |
| ***Right Prefrontal Cortex Hbdiff (μmol)*** | | | ***Left Prefrontal Cortex Hbdiff (μmol)*** | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| 2.21 | 0.89* | 0.02 | 2.20 | 1.12 | 0.10 |

Significant Head Trauma; N=5

| *Right Prefrontal Cortex $O_2Hb$ (µmol)* | | *P-value* | *Left Prefrontal Cortex $O_2Hb$ (µmol)* | | *P-value* |
|---|---|---|---|---|---|
| Baseline | Post-Game | | Baseline | Post-Game | |
| 1.79 | 0.85 | 0.17 | 1.85 | 1.07 | 0.36 |
| *Right Prefrontal Cortex HHb (µmol)* | | | *Left Prefrontal Cortex HHb (µmol)* | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| -0.72 | 0.06* | 0.04 | -0.55 | -0.01 | 0.08 |
| *Right Prefrontal Cortex tHb (µmol)* | | | *Left Prefrontal Cortex tHb (µmol)* | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| 1.06 | 0.91 | 0.82 | 1.31 | 1.05 | 0.75 |
| *Right Prefrontal Cortex Hbdiff (µmol)* | | | *Left Prefrontal Cortex Hbdiff (µmol)* | | |
| Baseline | Post-Game | | Baseline | Post-Game | |
| 2.51 | 0.79* | 0.04 | 2.40 | 1.08 | 0.18 |

*King- Devick Data:*

Moderate Head Trauma; N=17

**Table 2:**

| Baseline | Post-Game | ***P-value*** |
|---|---|---|

| | | |
|---|---|---|
| 49.29 | 47.33 | 0.15 |

Significant Head Trauma; N = 5

**Table 3:**

| Baseline | Post-Game | ***P-value*** |
|---|---|---|
| 47.34 | 49.02 | 0.45 |

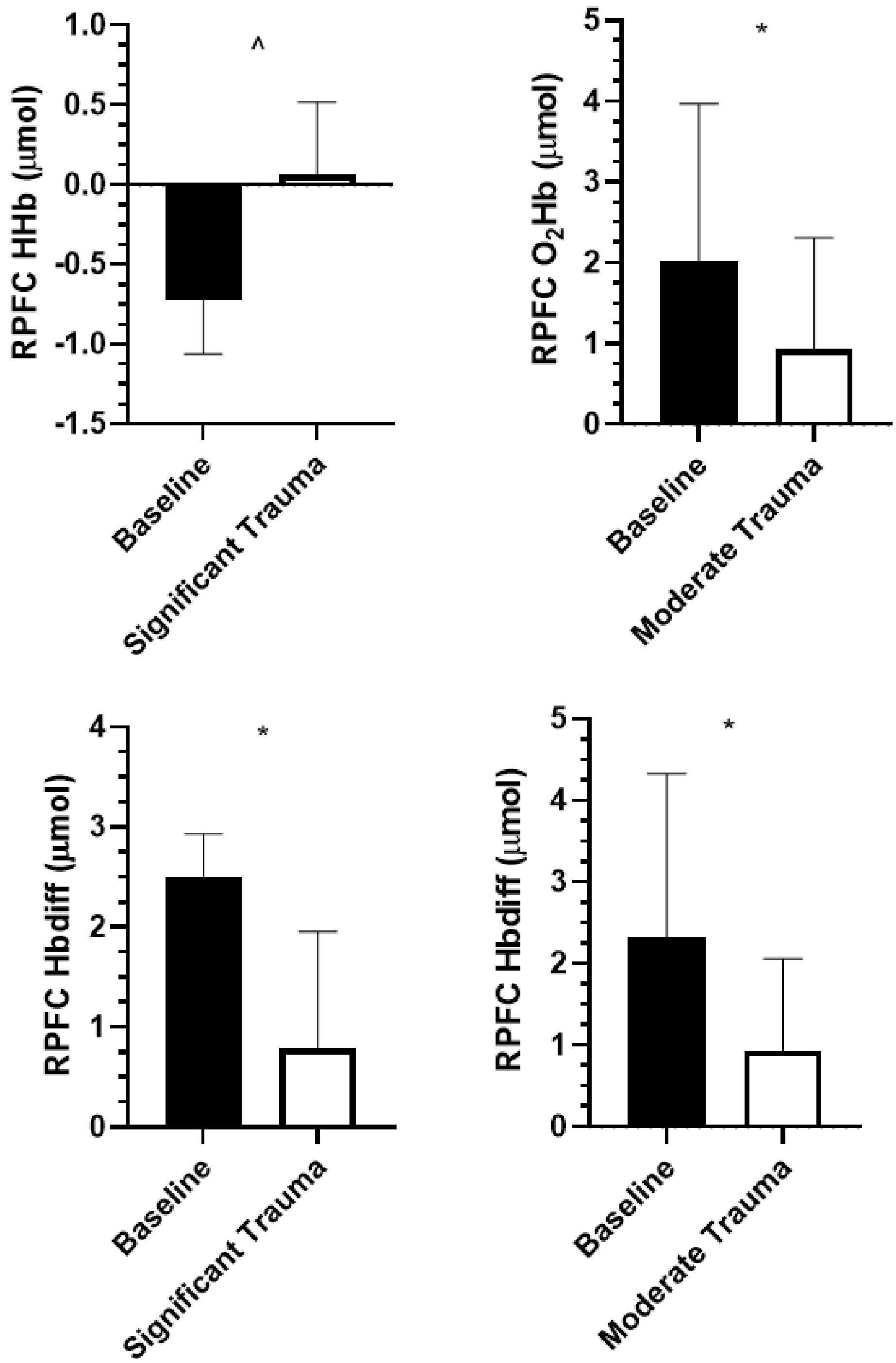



**Figure 1.** PFC $O_2$Hb responses during baseline and following moderate or significant head trauma. A significant difference in right prefrontal cortex HHb and Hbdiff was observed post significant head trauma while a significant difference in right prefrontal cortex $O_2$Hb and Hbdiff

was observed post moderate head trauma. Hbdiff, hemoglobin difference; HHb, deoxyhemoglobin; $O_2$Hb, oxyhemoglobin; RPFC, right prefrontal cortex.

**Discussion:**

The lack of significance between the KD test in relation to head trauma is a crucial discovery as the test is considered one of the most accurate in the diagnosis of a concussion/head trauma, however this was not the case in the current study. As mentioned earlier, the importance of reporting concussions and diagnosing them when they occur is imperative to avoid further damage to the brain. This new data should be considered in the future; if possible, medical providers should use more than just the K-D test when determining whether the athlete sustained significant head trauma or a concussion. There could be several reasons that the K-D test was not accurate. Since the evaluation was within an hour following matches or injury, the athletes could have more endorphins which could decrease pain levels and increase attentiveness during this test. The timing of this test could be looked into in order to see whether or not it impacts results following head trauma. Another factor that was discovered could be a learning effect with the test. After the first exposure to the activity, athletes will know what to expect. In a study by Oberlander (2017), it was concluded that, "Providers using the K-D test for serial assessment of concussion in adolescents should be cautious in interpreting the results due to a large learning effect. Incorporating multiple measures can ensure accurate detection of sport concussion" (p.439). However, for the purpose of the fNIRS evaluation, the K-D test has proven to be a beneficial tool in activating different parts of the brain including the PFC to allow for oxygen readings. That said, it may also be the case that this is not the best test, so the fNIRS may need to be tried with other concussion tests in the future to determine which one works the best. More research needs to be done on the K-D test as diagnosing concussions accurately is imperative for athletes lifelong well being.

It is clear that since Hbdiff decreased, $O_2Hb$ decreased and deoxyhemoglobin (Hhb) increased, there is a decrease of oxygen and therefore activation in the right prefrontal cortex following head trauma and the potential for the same to be true for the LPFC with more research. This lack of oxygen in the PFC could explain why after an athlete sustains head trauma they feel dizzy or light headed. Another interesting comparison that was found was that symptoms of mild cerebral hypoxia (lack of oxygen in the brain), which include inattentiveness, poor judgment, memory loss and a decrease in motor coordination, were similar to symptoms of a concussion which consist of, balance problems, feeling hazy or foggy, confusion and memory problems (CDC). This similarity in symptoms is yet another indicator of why it is important to report a potential concussion since cerebral hypoxia is known to cause brain degeneration. CTE could also potentially be related to this lack of oxygen. If an athlete sustains head trauma repeatedly over an extended period of time and oxygen levels continue to be affected, the brain degeneration from hypoxia could play a role in the development of CTE.

There was also a trend in data (as shown in the figures above) where the more severe the head trauma was, the more the levels of $O_2Hb$ and Hbdiff seemed to decrease in the RPFC compared to the baseline. It should be noted that this was not a significant drop however this seemed to be a trend. This is another interesting finding and an area of research to investigate more in the future. The magnitude of the difference in oxygen levels from baseline to post head trauma could indicate the level of injury and the amount of time needed to fully recover. If this was the case the test could be repeatedly administered during the return to play period of concussion protocol to determine when the athlete can be cleared to return to their sport. The application of this tool would also eliminate the ability for athletes to be dishonest in their symptoms. Despite the frustration from the athlete, this could prevent permanent brain damage as well as provide an objective diagnosis. Since concussions can not be seen, having this evidence of an injury would help athletes feel more validated in how they are feeling and help them understand the importance of sitting out to recover. This implication shows that oxygenation in the PFC could be the biomarker that indicates a concussion/head trauma. Based on the data from the current experiment, the fNIRS could be implicated in sports as a reliable and cost efficient source to diagnose head trauma. This would also be an economical draw for many institutions who spend thousands of dollars on insurance and medical bills for their athletes to receive MRI's and other treatments. A one time investment in a tool that provides quality data in concussion diagnostics and management would save a significant amount of money over time. Overall, the findings with this tool are exciting but more data is needed to determine the effectiveness of the fNIRS.

**Conclusion:**

It can be concluded that the fNIRS has potential to be better than any current concussion test to diagnose head trauma by assessing human biomarkers. The areas that seemed to have the most reliable data from the baseline to post trauma scores were in the RPFC and were specifically HHb, Hbdiff and $O_2$Hb levels. It was also observed that the degree of head trauma could potentially be correlated to the degree of head trauma that the athlete experienced. All of this data could be used in diagnosing concussions, in recovery and in the return to play process. Oxygen levels in the brain could be the biomarker that the medical field has been searching for to assess the health and stability of the brain. Another big finding was that the K-D concussion test might be less accurate than anticipated in determining whether or not an athlete has sustained a head injury. This information should definitely be considered by athletic trainers and medical staff. This test should be used with caution and at the very least be paired with other concussion tests. Since this was a case study with a small sample size, further testing needs to be conducted.

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