ABSTRACT

Cognitive Performance in Collegiate Athletes at Risk for Sub-Acute Blows to the Head

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Sub-acute blows to the head are hits that do not result in the immediate presentation of injury symptoms. However, these blows may pose a greater risk than initially anticipated if repeated, sub-acute brain trauma collectively predicts declines in cognitive performance. Collegiate athletes who play specific positions within their sport are especially at risk of sub-acute blows to the head, which makes them an important population to monitor when determining if there are negative effects of sub-acute blows on cognition and brain health. Electroencephalogram (EEG) data from collegiate athletes on an NCAA Div. 1 men's football team and women's soccer team were analyzed to observe if there were differences in measures of cognitive performance between players at positions of varying levels of risk for sub-acute blows to the head. No significant differences were found between measures of cognitive performance between collegiate athletes in different risk level categories based on their position. While future studies should be done to evaluate the use of position as a proxy for risk to sub-acute blows to the head and to determine the imaging technology needed to detect possible additive changes from sub-acute blows, this preliminary study suggests that head-injury prevention and research may be able to be addressed on a team level.

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COGNITIVE PERFORMANCE IN COLLEGIATE ATHLETES AT RISK FOR SUB-ACUTE BLOWS TO THE HEAD

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CHAPTER ONE

Introduction

Traumatic brain injury (TBI) has garnered a well-deserved amount of attention in research with its considerable prevalence and its extensive effects on health and quality of life. The Centers for Disease Control and Prevention (CDC) reported that 223,135 hospitalizations were related to TBIs in 2019, and 64,362 TBIs led to death in 2020 (CDC, 2022). These statistics do not include TBIs that were treated outside of standard hospital settings, such as in the emergency department, or those that went untreated and unaccounted for (CDC, 2022). Previous estimations have predicted that 1.7 million people sustain a TBI each year, with mild TBIs (mTBIs), such as acute concussions, accounting for around 75% of these cases (Mott et al., 2012). Furthermore, it is important to consider how overall brain health and function extend into every aspect of the human experience. While major trauma to the brain often draws attention with its distinct and pronounced effects, it would be irresponsible to assume that minor levels of brain trauma with no initially apparent repercussions have no effect on brain health at all. While measuring the compounding effects of repeated damage that presents as asymptomatic may pose a significant challenge to systematic research, it is still worth exploring due to the profound long-term effects unidentified brain damage may have on people. This thesis is a preliminary step to studying the possible consequences of repeated minor blows to the head to determine if the summative effects of asymptomatic brain trauma should be considered with a level of concern more like that which is given mTBIs.

Health Problems Associated with Acute and Repeated mTBI

An mTBI, or concussion, is defined as a neurocognitive disorder resulting from a blow to the head that leads to a loss of consciousness for under 30 minutes, post-traumatic amnesia for less than 24 hours, and a Glasgow Coma Scale rating of 13-15 (Blyth & Bazarian, 2010). Due to the varying levels and spread of trauma across the entire brain in mTBIs, the presentation of symptoms can vary considerably. However, the hallmark symptoms associated with mTBIs include cognitive deficits, drowsiness, noise sensitivity, amnesia, problems with working memory, altered mental status, feeling disoriented, headaches, nausea, vision problems, executive dysfunction, irritability, and mood disturbances (Laskowski et al., 2015; Mott et al. 2012). While acute concussions cause symptoms that usually resolve within a few weeks, repeat concussions can lead to a greater risk of having prolonged symptoms (Conder et al., 2020; Eisenberg et al., 2013). Certain injuries can lead to long-lasting symptoms that extend beyond the period of acute injury, which is referred to as Post-Concussion Syndrome (PCS). PCS is defined as concussive symptoms not explained by other causes that extend to months post-injury after a standard presentation of a concussion (Conder et al., 2020). These prolonged symptoms resemble acute concussion symptoms and include headaches, fatigue, vertigo, cognitive deficits, concentration problems, sleep disturbances, irritability, anxiety, issues with balance, visual problems, and retrograde amnesia (Bo & Pearkao, 2021).

Beyond PCS, sustaining multiple mTBIs can have long-term mental health outcomes and lasting neurological effects. In a systematic review by Manley et al. (2017) on people who have suffered concussions, including some retired athletes, results showed that having multiple concussions was correlated with poor neurological and mental health outcomes such as depression, cognitive deficits, suicide, and neurodegenerative diseases that can have effects more than ten years beyond the initial injury (Manley et al., 2017). Perhaps the most well-known outcome of repeated TBI is Chronic Traumatic Encephalography (CTE). CTE is a well-known problem in retired professional athletes from sports with high rates of trauma to the head, such as football and wrestling, and is presumed to be linked to repeated mTBI or a significant moderate to severe TBI. While there is some controversy surrounding the understanding of CTE, observed long-term outcomes are related to early dementia, psychiatric problems, personality changes, and neurological impairment (Smith et al., 2019).

With these cases in mind, the need for research done on preventing and combatting long-term post-concussive symptoms and health deterioration is clear. These issues illustrate the need for a better understanding of the outcomes related to the summative effects of repeated brain trauma, with the goal of figuring out if long-term problems may be preventable if there are ways to detect earlier signs of damage. If repeated mTBIs lead to prolonged neurological symptoms, it is also worth considering whether repeated sub-acute blows might lead to negative health and cognitive outcomes as well.

Sub-Acute Blows to the Head

While there is a lot of knowledge regarding the physical and psychological repercussions of acute mTBIs, there is a lack of similar data about the effects of sub-acute blows to the head. There is no widely accepted definition for a sub-acute blow to the head outside of the traditional understanding that TBIs range from mild to severe and the basic understanding of the term meaning a hit that is below the threshold to induce an acute concussion. Nevertheless, sub-acute blows to the head can be understood as more frequent, low-magnitude hits that do not result in the presentation of concussive symptoms. This definition has also been referred to as a “ding” or a “subconcussive” impact in previous studies (Baugh et al., 2015; Rosenthal, 2018). Based on this definition, at the time of a sub-acute impact, there are no concerning symptoms that require clinical intervention. That being said, disorders such as PCS and CTE have shown that the cumulative effects of brain trauma can lead to additional, long-term problems of their own. However, the threshold for the level of trauma needed to have a delayed, collective impact is unclear. This prompts the question as to whether repeated sub-acute blows to the head might also have measurable long-term effects on physiological brain health and cognitive performance.

Electroencephalography (EEG)

To assess the possible impact of repeated sub-acute blows to the head on cognitive function, researchers must determine the kinds of quantitative measures that can be used to detect and monitor neurological changes and outcomes. One possible method is electroencephalography (EEG), which is a non-invasive method of brain imaging used to detect brain waves through the contact of electrodes to the scalp. Data collected from EEG technology can be used to assess brain function and performance.

One of the pioneering technologies for incorporating EEG in an accessible format for athletic environments is the WAVi Headset and WAVi ® Research Platform (WAVi Research, Boulder Co USA). Using the standard International 10-20 System for electrode placement, this portable headset allows quantitative data to be collected in any location, overcoming the barrier of other EEG systems that require transport to a health clinic or a research lab. The effectiveness of the headset in comparison to standard concussion protocols shows concurrent validity in diagnosing acute concussions in collegiate athletes (Clayton et al., 2020). By comparing brain activity at the time of injury and two weeks after a concussion event to a baseline WAVi scan, the researchers were able to observe quantitative changes that occurred after a concussion alongside standard concussion protocol conclusions. Overall, the article suggested that measuring these values is consistent in assessing concussions as well as being related to the duration of post-concussive symptoms and the risk of repeat concussions (Clayton et al., 2020).

The Present Study

This thesis provides a secondary data analysis to the research performed by Clayton et al. (2020) on an NCAA Div. 1 men's football team and women's soccer team with the use of the WAVi Headset to gather EEG data. Extending beyond the original study's focus on acute sports concussions, the goal of this thesis was to further investigate whether the risk of repeated, low-magnitude impacts to the head, as estimated by a player's position on their respective team, are associated with cognitive performance changes. The hypothesis for this project was that within each team, collegiate athletes in positions that are at high risk for sub-acute blows to the head will have lower outcomes on cognitive performance measures as compared to positions with a lower risk for sub-acute blows to the head.

CHAPTER TWO

Methods and Materials

Sample

The sample from Clayton et al. (2020) consists of collegiate athletes from an NCAA Div. 1 men's football team and women's soccer team that were studied from 2013 to 2017. The raw data provided for this project included a total of 239 participants, with 207 participants from the men’s football team and 32 participants from the women’s soccer team.

A formal Non-Human Subjects Research Determination was obtained from the Baylor Institutional Review Board (IRB) for this project in alignment with the required de-identification procedures. Clayton et al. (2020) conducted the initial study, received IRB approval, and obtained written informed consent from all participants. For this thesis, all data was provided in a de-identified form. To add a player’s position to the previously collected data, publicly accessible data from each NCAA Div. 1 team’s athletic roster were compiled as needed for this project and provided to the WAVi research team to be incorporated into the de-identified dataset. The data is not readily identifiable and was provided by and attained with permission from the WAVi team that worked on the initial study. The original study can be referenced for more details on consent, recruitment, and exclusion procedures for the original sample (Clayton et al., 2020).

As a player’s position on the team was used as a proxy for the risk of sub-acute blows to the head, most of the exclusion criteria for the current study were related to position categorization, position changes across athletic seasons, or a player's position at the time of the WAVi scan. The specific process for using position to assess risk level is detailed in the next section outlining the procedure. Prior to de-identification, initial exclusion criteria were players that were categorized in an undefined position (e.g., "Athlete" for men's football) or changed position each year during the study for more than two years as there was not enough information to assign them to a risk level category. This information was determined through publicly accessible online rosters of each team. According to these criteria, one player from men's football and one from women's soccer were excluded from the data analysis and not provided to the WAVi team for inclusion into the de-identified dataset. In the de-identified dataset, 13 players from men's football and one player from women's soccer were excluded because there was no position data associated with the scan. Nine players from men's football were excluded due to a possible acute concussion as seen from having two scans two weeks apart, which is part of the WAVi acute concussion screening procedure. Participants with acute concussions were excluded to limit confounding factors and allow the study to focus on sub-acute blows to the head that do not result in an acute concussion. Nine players from men's football and three players from women's soccer were excluded because the scan occurred after a position change that also involved a change in the player's risk level category. Lastly, five players from the men's football team were excluded due to artifacts in the WAVi scan related to excessive synch blinks or invalid EEG outputs (e.g., a P300 latency of -1). The final data sample included a total of 200 participants, 171 in men's football and 28 in women's soccer. For men's football, the average age was 20.72 years *(SD = 1.77)*. The average age for women's soccer was 20.63 years *(SD = 1.90)*.

Materials and Measures

Procedure for Grouping by Position

Players were grouped into categories according to their position on their respective team to allow for comparison across players at varying levels of risk for sub-acute blows during data analysis. Each player's position was obtained from the NCAA Div. 1 official team rosters that are publicly accessible on the university's website.

The procedure for categorizing positions on the men's football team was based on previous literature involving position groupings for NCAA Div. 1 college football (Baugh et al., 2015). The nine categories are offensive linemen, defensive linemen, running backs, tight ends, linebackers, defensive backs, wide receivers, quarterbacks, and special teams. The athletic roster referenced for this study listed each player's specialized position as well, so participants were grouped according to the specifications of Baugh et al. (2015) as seen in Table 1. Each position category's respective risk level represents the risk of sub-acute blows to the head, which is covered in the below section on risk determination.

For women's soccer, the four position groupings are forwards, defenders, midfielders, and goalkeepers. More specific roles within these groups were not listed on the athletic roster and therefore there were no further steps to the grouping procedure. Each position category's risk level is also listed in Table 2.

Table 1

Men's Football Position Categories and Risk Level Assignment

Position category	Specialized positions	Risk level	*n*
Offensive lineman	Offensive lineman	3	29
	Center		
	Offensive tackle		
Defensive lineman	Defensive line	3	23
	Defensive end		
	Defensive tackle		
	Nose tackle		
Running back	Running back	2	14
	Fullback		
	Tailback		
Tight end	Tight end	2	12
Linebacker	Linebacker	1	24
	Inside Linebacker		
	Outside Linebacker		
Defensive back	Defensive back	1	26
	Cornerback		
	Safety		
Wide receiver	Wide receiver	1	29
Quarterback	Quarterback	1	7
Special teams	Punter	1	8

Kicker

Long Snapper

Note. The risk level denotes that position category's risk for sub-acute blows to the head, with level three being the highest risk, level two involving moderate risk, and level one including little to no risk.

Table 2

Women's Soccer Position Categories and Risk Level Assignment

Position category	Risk level	*n*
Forward	3	8
Defender	2	7
Midfielder	1	10
Goalkeeper	1	3

Note. The risk level denotes that position category's risk for sub-acute blows to the head, with level three being the highest risk, level two involving moderate risk, and level one including little to no risk.

As the original study spanned four athletic seasons (2013-2017), there were some participants who changed positions over the course of the study. These participants were categorized according to the position they spent the greatest number of years playing based on procedures in previous literature related to position categorization (Baugh et al., 2015). The position they spent the most time in will be referred to as their primary position, with all other positions held being secondary positions. There were some exceptions that led to a different categorization or exclusion from the sample. If the EEG scan was performed before a position change, the player's primary position was considered to be their position before the scan. If the scan occurred after a position change to a player's primary position, the player continued to be categorized in that primary position. If the scan occurred after a change to a secondary position with a different risk level, the participant was excluded. If a player spent the same amount of time in two positions of different risk levels, the participant was excluded if the scan occurred after the position change. Players who did not have a primary position due to yearly changes were also excluded from the analysis. These exclusions were made to avoid confounding factors in the cross-sectional analysis that used position as a proxy for the risk of sub-acute blows. The number of exclusions resulting from this process is listed in the description of the sample as seen previously.

Risk Categorization by Position

Player position was used to define a player's risk of sub-acute blows to the head. Each position was labeled with a risk level according to the findings from previous literature such as Baugh et al. (2015), Clark et al. (2018), and Stewart et al. (2018). For both football and soccer, there were three risk levels, with level one being little to no risk for sub-acute blows to the head, level two being moderate risk, and level three being high risk. In general, positions that are at greater risk of overall hits to the head were categorized as being at a higher numerical risk level, whereas positions that do not involve many collisions or hits to the head were categorized as having a lower risk level.

In men's football, risk level three contained the two positions at the highest risk for sub-acute blows to the head which were the offensive and defensive lineman. These positions were determined to be at the highest risk because offensive linemen have been shown to experience frequent, low-magnitude hits and show significantly higher numbers of sub-acute blows and undiagnosed concussions (Baugh et al., 2015). Similarly, offensive and defensive linemen are categorized as the two “non-speed” positions that experience a higher proportion of frontal blows to the head (Clark et al., 2018). Beyond lineman positions, there is limited literature on position-specific rates of head impact. Special teams players were included in the lowest risk level, level one, as their role involves limited contact and has been excluded from other studies on hits to the head (Clark et al., 2018). Level one also included linebackers, defensive backs, wide receivers, and quarterbacks as they were not mentioned in the literature as experiencing significant numbers of frequent, low-magnitude head impacts. Level two, moderate risk for sub-acute blows to the head, included tight ends and running backs, because tight ends are subject to frequent tackles and running backs are likely to receive direct hits, but at a lower frequency than linemen (Clark et al., 2018). The risk designations for the men’s football position categories can be found in Table 1.

For women’s soccer, sub-acute blows to the head were estimated by positions with significant differences in the frequency of heading the ball as determined in a study done by Stewart et al. (2018) on unintentional head impacts in soccer players. Forwards had the high incidence of heading the ball and were therefore categorized in level three for the highest risk of sub-acute blows to the head. They were followed by defenders, who were categorized as level two. The two lowest-risk positions included goalkeepers and midfielders (Stewart et al., 2018). The women’s soccer position risk levels are listed in Table 2.

WAVi Research Platform

EEG data were gathered using the WAVi ® Research Platform and WAVi Headset (WAVi Research, Boulder Co USA). The WAVi Headset uses EEG to provide quantitative information about brain activity, such as voltage and brain wave frequency, through noninvasive measurements of electrical activity from the scalp. The WAVi Headset follows the International 10-20 system for EEG electrode placement with reference electrodes placed at the earlobes. The WAVi Headset is FDA approved for "use in routine clinical and research settings where rapid placement of a number of EEG electrodes is desired" (U.S. Food and Drug Administration, 2017). The original study can be referenced for more details on the full technical specifications of the WAVi device and the EEG acquisition process for the datasets used in this secondary data analysis (Clayton et al., 2020). The WAVi Headset is pictured in Figure 1.

Figure 1: WAVi Headset (WAVi Research, Boulder Co USA) (*About WAVi | WAVi*, n.d.).

Procedure

Each participant performed a WAVi scan in a non-injured state to provide a baseline for their cognitive function in the case of a future injury and for the purpose of the study performed by Clayton et al. (2020). Beyond this baseline scan, it is important to note that the protocol for an acute concussion is to complete one scan at the time of the injury and a second scan around two weeks later. However, participants that sustained an acute concussion were excluded from this secondary data analysis, and therefore all the data included for this study contain only baseline EEG data. All participants were scanned using the WAVi Headset while performing an oddball audio P300 protocol in combination with a physical reaction test to the auditory oddball tone. The auditory P300 test is an eyes-closed, two-tone paradigm used to assess cognitive performance by measuring electrophysical markers called event-related potentials (ERPs) which are EEG brain potential changes that are time-locked to an external stimulus. The P300 response is a type of ERP with positive polarity (P for positive) that occurs 300 milliseconds after the stimulus. For the oddball audio P300 protocol, a series of 240 tones were played over headphones across a four-minute period. 40 of the tones were “oddball” tones of a higher frequency (2777 Hz) than the 200 common tones (1000 Hz) (Clayton et al., 2020). When the subject hears the oddball tone, they also click a mouse to provide data regarding their physical reaction time. EEG acquisition, preprocessing, and extraction were completed by the original research team and additional procedural specifications can be found in Clayton et al. (2020). From these tests, the WAVi Headset collects several EEG parameters and measures of cognitive function that are defined by EEG outputs such as

P300 ERPs, P300 latencies, spectral analysis, and peak frequencies. The five outcomes investigated for this project are listed in Table 3.

Table 3

EEG Parameters and Measures of Cognitive Function

Parameter abbreviation	Parameter description	Units
P300 voltage	Maximum voltage of the average P300 waveform	µV
P300 latency	Minimum latency of the average P300 waveform	ms
PFOC	Peak alpha frequency in the occipital and central regions	Hz
FOAR	Frontal occipital alpha ratio	
FRAM	Frontal alpha magnitude	µV

Analysis of Data

To compare cognitive performance between different risk levels, the determined position categories were sent to the WAVi research team to be added to the de-identified dataset that was provided for this secondary data analysis. The data for the men’s football team and the women’s soccer team were analyzed independently due to their distinct position categorization procedures as well as sport-specific positions and types of blows to the head. Within each team, a multivariate analysis of variance (MANOVA) was performed comparing the three levels of risk for sub-acute blows to the head (high, moderate, and little to no risk), as determined by position category, on the cognitive performance parameters of P300 voltage, P300 latency, peak alpha frequency in the occipital and central regions (PFOC), frontal occipital alpha ratio (FOAR), and frontal alpha magnitude (FRAM). All statistical analyses were carried out in SPSS (IBM Corp., 2021).

CHAPTER THREE

Results

Multivariate normality was confirmed by assessing distributions for both men's football and women's soccer data. The histograms for the five EEG outcomes tested did not show any outliers that required additional attention. To begin, correlations between the parameters to be included as dependent variables in the MANOVA were calculated. For men's football, two significant correlations were found. First, there was a negative correlation between P300 voltage and P300 latency, $r(169) = -.15$, $p = .046$. Secondly, there was a positive correlation between P300 voltage and FRAM, $r(169) = .17$, $p = .027$. The rest of the parameters were not significantly correlated, as seen in Table 4. For women's soccer, none of the parameters were significantly correlated, as seen in Table 5.

Table 4

Pearson Correlations Between Parameters for Men's Football

	P300 voltage	P300 latency	PFOC	FOAR	FRAM
P300 voltage	1				
P300 latency	-.15*	1			
PFOC	.01	-.06	1		
FOAR	-.12	.03	-.11	1	
FRAM	.17*	-.06	-.14	.10	1

** Correlation is significant at the 0.05 level (2-tailed).*

Table 5

Pearson Correlations Between Parameters for Women's Soccer

	P300 voltage	P300 latency	PFOC	FOAR	FRAM
P300 voltage	1				
P300 latency	.03	1			
PFOC	-.04	.33	1		
FOAR	-.15	-.26	-.10	1	
FRAM	.30	-.02	-.30	.01	1

Note. There were no significant correlations between parameters for women's soccer.

Tables 6 and 7, for men's football and women's soccer respectively, list the means and standard errors for each parameter in each risk level grouping.

Table 6

Mean and Standard Error of Parameters for Men's Football

Parameter	Risk level 1	Risk level 2	Risk level 3
P300 voltage (μV)	14.94 (0.54)	15.01 (1.02)	13.36 (0.73)
P300 latency (ms)	305.28 (3.47)	312.77 (6.61)	296.16 (4.72)
PFOC (Hz)	10.26 (0.10)	10.06 (0.19)	10.34 (0.14)
FOAR	.70 (0.02)	.70 (0.04)	.67 (0.03)
FRAM (μV)	15.75 (0.54)	16.46 (1.03)	16.23 (0.73)

Note. Standard errors are listed in parentheses.

Table 7

Mean and Standard Error of Parameters for Women's Soccer

Parameter	Risk level 1	Risk level 2	Risk level 3
P300 voltage (μV)	21.90 (1.72)	15.29 (2.35)	22.29 (2.20)
P300 latency (ms)	277.54 (5.55)	269.14 (7.57)	285.00 (7.08)
PFOC (Hz)	10.18 (0.22)	9.93 (0.30)	9.89 (0.28)
FOAR	.52 (0.06)	.66 (0.07)	.49 (0.07)
FRAM (μV)	16.43 (1.41)	15.03 (1.92)	19.28 (1.80)

Note. Standard errors are listed in parentheses.

A MANOVA was performed on each dataset, separately for men's football and women's soccer, to determine if there were differences in the EEG parameters of interest between players categorized in different levels of risk based on their position on their respective team. For men's football, multivariate tests for risk levels showed no significant difference in the tested parameters based on risk level, *F*(10, 328) = 1.34, *p* = .208; Wilk's lambda = 0.92, partial eta squared = 0.04. Similarly, for women's soccer there was no significant difference among the parameters based on risk level, *F*(10, 42) = 1.18, *p* = .331; Wilk's lambda = 0.61, partial eta squared = 0.22.

Furthermore, there were no significant effects for tests of between-subject effects on the men's football data. There were no significant effect of risk level on P300 voltage, *F*(2, 168) = 1.69, *p* = .187, partial eta squared = 0.02; P300 latency, *F*(2, 168) = 2.33, p = .101, partial eta squared = 0.03; PFOC, *F*(2, 168) = 0.72, *p* = .489, partial eta squared = 0.01; FOAR, *F*(2, 168) = 0.69, *p* = .505, partial eta squared = 0.01; or FRAM, *F*(2, 168) = 0.23, *p* = .773, partial eta squared = 0.01.

There were also no significant effects for tests of between-subject effects on the women's soccer data. There is no significant effect of risk level on P300 voltage, *F*(2, 25) = 3.12, *p* = .061, partial eta squared = 0.20; P300 latency, *F*(2, 25) = 1.17, *p* = .326, partial eta squared = 0.09; PFOC, *F*(2, 25) = 0.40, *p* = .673, partial eta squared = 0.03; FOAR, *F*(2, 25) = 1.56, *p* = .231, partial eta squared = 0.11; FRAM, *F*(2, 25) = 1.41, *p* = .264, partial eta squared = 0.10.

CHAPTER FOUR

Discussion

Overall, there were no significant differences in cognitive outcomes between players in different levels of risk to sub-acute blows based on their position for both men's football and women's soccer. Additionally, risk level did not have a significant effect on any of the individual EEG outcomes. Therefore, the hypothesis that position categories determined to be at high risk for sub-acute blows to the head would have lower outcomes on measures of cognitive performance was not supported. These results suggest that for both collegiate men's football and women's soccer, there does not seem to be a particular position that experiences significantly worsened cognitive function related to the risk for sub-acute blows to the head based on the position they play on their team.

These results suggest that the cumulative effects of experiencing higher rates of sub-acute blows do not lead to significant differences in cognitive performance. In application, the lack of significant differences in these results may signify that the accumulation of sub-acute blows is not worse for a specific position, and therefore, preventative measures for cognitive health can continue to be done in a team-focused approach as opposed to a position-specific approach.

Beyond the current study, research on this topic is still necessary as other explanations of these results should be explored in greater detail. These findings might also be attributed to the statistical and procedural capabilities permitted by the design of this study. In addition, the foundation of the interpretation of these results depends on position being a reliable proxy for the risk of sub-acute blows, as there was no direct measure of sub-acute blows in the original dataset. Beyond that, there is still not a feasible or very well-supported method of measuring or estimating sub-acute blows to the head. Previous literature has associated both football and soccer positions with various measures of head trauma such as white matter structure, neural recruitment, post-impact symptoms, participation in full-contact practice, concussions, and soccer headings (Baugh et al., 2015; Bunc et al., 2017; Clark et al., 2018; Weiner et al., 2022). However, this thesis is one of the few attempts to use position as a proxy for sub-acute blows to the head. Nevertheless, other studies that have attempted to use position as a proxy include the one done by Baugh et al. (2015) which found that sub-acute hits were significantly greater for offensive linemen compared to other football positions and was the study on which the men's football risk determination for this thesis was based. As such, these results should be interpreted as preliminary research, with the goal of laying the foundation for increasing our understanding and ability to study sub-acute blows to the head, especially for collegiate athletes.

As research on the effects of sub-acute blows to the head on brain health is still in its developing stages, attempts to promote brain health in athletes should err on the side of preventing the possibility of summative effects of sub-acute blows, which can go hand in hand with prevention strategies for concussions and severe TBIs. Until further research determines whether or not there are significant position-based risks, a team-based approach can ensure that all players are protected from possible trauma. That being said, the idea that a certain position could be more at risk for long-term neurological changes due to repeated sub-acute blows to the head should not be dismissed. As of now, avenues for the early detection of cognitive decline in collegiate athletes are limited. Future studies may be able to better detect possible additive effects of repeated sub-acute blows and provide a precedent to shift preventive and post-injury care to add additional protections for those most at risk.

Some limitations of the current study were the result of the design and measurement challenges of the original study. The main challenges were that there was no direct measurement of sub-acute blows, this study consisted of a cross-sectional analysis due to a lack of consistent longitudinal data, and there were unequal sample sizes between the teams. In terms of risk level determination, it should be noted that there may be differences in the positions that are at most risk for acute concussions versus those at risk for sub-acute blows to the head. In this study, the focus was sub-acute, so the risk of acute concussions was not considered. The current study used the most recent brain scan possible in an attempt to allow for the most accumulation of possible damage from repeated, sub-acute trauma. However, time restraints resulting from players joining and graduating from the team across the course of the five-year study may not have given enough time to detect possible changes related to the summative effects of sub-acute blows. For the statistical analyses, the small sample size for women's soccer limited the statistical power to look for significant differences across the risk categories. It is important to note that for women's soccer, none of the parameters were correlated. However, a MANOVA was still performed to mirror what was done on the larger dataset from the men's football team. Lastly, the provided dataset did not include demographic information and the original study also did not report demographic information, so that was not considered in this study.

As mentioned before, the lack of statistical significance does not mean that position-based differences do not exist. As a result, additional studies should be done to provide a stronger foundation for research regarding sub-acute blows and detecting if repeated sub-acute blows have summative effects on brain function. First, it is necessary to determine which positions have the most sub-acute blows and if a player's position on their team is the best proxy for measuring sub-acute blows. Despite the challenge of not having any immediate physical or psychological symptoms from a singular sub-acute blow to the head, technological advancements may be able to provide a quantitative method of counting sub-acute blows through the development of sensors that could be positioned in places like a player's helmet.

Next, future research also needs to be done to develop better methods of detecting if there are effects of repeated sub-acute blows. Asymptomatic sub-acute blows to the head are harder to detect in traditional neuroimaging settings as changes may only be evident over long periods of time and only if the consequences of the sub-acute blows summate to a measurable level. As a result, possible symptoms and consequences may only be detectable across longer periods of time with a combination of diagnostic tools. While an EEG headset may be the most accessible at the location of an athletic event, more detailed technology may be required to sense more minute, subtle, or longitudinal changes.

An additional consideration for future studies is to investigate the impact of gender differences in relation to sports-related sub-acute blows to the head. Performing a study on both a men's football team and a women's soccer team prompts an important discussion about the gender differences in risks and outcomes for sports-related head trauma. When it comes to mTBIs, previous research has shown that female athletes sustain acute concussions at twice the rate as sport-matched male athletes (Dick, 2009; Lincoln et al., 2011). This also is significant when considering that preliminary research has shown that there may be gender-related differences in white matter changes in response to repetitive trauma, with female soccer players experiencing greater levels than their male counterparts (Rubin et al., 2018). As future research develops, these considerations suggest that gender is an important factor to be considered in sports-related head injury outcomes.

In conclusion, the study of sub-acute blows to the head in collegiate athletes and the summative effects of repeated head injuries are relevant and necessary avenues of neuroscience research. As technological advancements and innovative studies continue to improve the detection of physiological and cognitive changes in the brain, sports-related research can continue to help improve safety and promote favorable long-term health outcomes for athletes.

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