The Effects of Repeated Sub-Concussive Impacts on Reaction Time Across Football Seasons

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The Effects of Repeated Sub-Concussive Impacts on Reaction Time Across Football Seasons

A Thesis
Presented to the Faculty of the
Department of Sports Medicine
West Chester University
West Chester, Pennsylvania

In Partial Fulfillment of the Requirements for
the Degree of
Master of Science

By
Kate A. Gaglias
May 2021

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Abstract

Context: Recent evidence suggests that accumulating head impact exposures may have an effect on neurocognitive function over time. Objective: The purpose of this study was to examine the relationship between HIEs and reaction time (RT) over time. Design: Observational cohort study. Setting: Data collection occurred at a Division III college throughout the 2018 and 2019 competitive football seasons. Participants: Six football players volunteered for this study. Main Outcome Measures: HIEs (95%, 99%, and HIE\text{lin} threshold categories) using helmet accelerometers and ImPACT reaction time (ImP) measurements (baseline (BL), post-season 1 (PS1), post-season 2 (PS2)). Results: A total of 1,411(235.17±237.97) HIEs were sustained by participants in the 2018 season, and increased to 2,118 (353±381.19) in the 2019 season. Dependent t-tests revealed that composite RT significantly improved at the PS2 measurement (0.60±0.08ms) when compared to BL (0.68±0.11ms), (P=.048). Conclusion: Noticeable trends in accumulating HIEs were present within the subject group. Sub-concussive impacts had a greater presence compared to concussive impacts throughout the study period. Changes in reaction time measurements occurred over time, however further research is needed to validate the impact of repetitive HIEs on long-term RT measurements in collision sport athletes. This study contributes to the ongoing research of HIE trends in Division III collegiate football. Word Count: 201 Key Words: head impact exposure, accelerometer, reaction time, football
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Literature Review

Introduction

Sports-related concussions (SRC) occur frequently and have become increasingly prevalent in sport.\(^1\) The presence of signs and symptoms associated with an SRC are individualized, requiring an individualistic management plan for each injury.\(^1\)-\(^3\) However, with a high prevalence occurring in sport, the amount of SRC research conducted has grown within the last decade in order to further knowledge and create evidence-based management plans. This is also a result of recent findings relating an accumulation of SRCs to the disease known as chronic traumatic encephalopathy (CTE).\(^4\),\(^5\) Sub-concussive impacts also play a critical role when it comes to understanding the frequency of head impacts in contact and collision sports.\(^6\)-\(^8\) When sub-concussive hits are sustained, signs and symptoms may not present making this type of head impact unique compared to concussive impacts.

Both sub-concussive and concussive impacts are important components to understanding the increasing frequency of head impact exposures (HIEs) faced by athletes. Particularly in American football, the proper usage of helmets is essential to preventing severe injury.\(^2\) Although no specific design is certain to decrease risk of SRC, they have been at the center of head biomechanics research.\(^9\) By using accelerometer sensors, helmets can aid in the detection of head impact characteristics, providing a better insight to health care providers for both scopes of impacts.\(^9\)-\(^11\)

As a critical ability within athletics, reaction time is one of the many skills that can be impaired after suffering from an SRC.\(^2\),\(^12\) There are many methods of reaction time measurement tools, including computerized tests or physical examinations.\(^13\) Specifically, reaction time can be measured as simple or choice and consists of various stimuli and
With the evolvement of SRC management, reaction time has become an important component to the overall cognitive assessment of SRC.\textsuperscript{12,17}

**Sports-Related Concussion (SRC)**

**Definition**

Due to its complexity, there is presently no clear operational definition of a sports-related concussion (SRC). However, there are multiple characteristics that are used consistently when describing an SRC. In the most recent consensus statement provided by the Concussion in Sport Group (CISG) an SRC represents both the transient and/or immediate symptoms of a traumatic brain injury (TBI).\textsuperscript{2} Although previously deemed a mild traumatic brain injury (mTBI), the CISG now defines an SRC as within the TBI spectrum, rather than just an mTBI.\textsuperscript{2,18} This is due to the pathophysiological response that occurs with an SRC, as it mimics a similar structural change in the brain as a TBI but to a lesser degree.\textsuperscript{2}

**Mechanism of Injury**

An SRC is induced by direct or indirect biomechanical forces transmitted to the head.\textsuperscript{1-3,19-21} It is the head’s dynamic response to that force that results in further injury. These forces can consist of both linear and/or rotational accelerations.\textsuperscript{1,19,22} Linear acceleration is described as the external force impacting the head, face, or neck, while rotational acceleration is the motion of the head that occurs after the external impact. Rotational acceleration can cause shearing forces of the brain, therefore potentially causing further damage or injury.\textsuperscript{6,7,19,23} Once these external forces are sustained, they can transfer internally causing the brain to accelerate and decelerate inside of the skull.\textsuperscript{19,21,22}

Both types of accelerations are commonly seen in American football.\textsuperscript{5-8,10,24} Different sports specific mechanisms that are involved include head to head contact, player contact with
blocking, player contact with tackling, or player to surface contact.\textsuperscript{7,25} However, there is no established threshold of force that is specific to causing injury and studies have shown that forces can range from 55.80-168.71g of linear acceleration, and 163.4-15397.1 rad/sec\textsuperscript{2}.\textsuperscript{11,26-29} These forces can also range depending on the location of impact to the head.\textsuperscript{10,22,30,31} It is also recognized that high accelerated impacts are not necessarily needed to sustain a head injury or SRC; even low magnitudes of both linear and rotational accelerations, when combined with a short duration of impact, can result in high brain tissue strain.\textsuperscript{7,11} Evidence supports that low accelerations can cause an SRC especially with an accumulated frequency of impacts.\textsuperscript{7} Once an individual sustains an SRC, independent of the magnitude of force, that individual is at a higher risk for an additional SRC.\textsuperscript{1,2} Importantly, they are more susceptible to sustaining an SRC caused by an acceleration on a lesser scale.\textsuperscript{7}

\textit{Pathophysiology}

Although there is no threshold of force known to cause injury, once these forces are sustained a neurometabolic cascade can occur.\textsuperscript{1,19-22,32} Upon sustaining an SRC, there is an immediate interruption of the brain function beginning at the cellular level. Immediately following a mechanical injury, cellular membranes are disrupted causing neuronal depolarization.\textsuperscript{21,32} Once the membranes are interrupted, voltage-gated channels are opened, increasing the amount of intracellular potassium.\textsuperscript{21,32} The brain responds by increasing the release of neurotransmitters which results in increased cortisol activation, hyperexcitability, and the initiation of more cellular cascades. This contributes to cell damage and interrupt energy production.\textsuperscript{21} The human body will respond to this cellular change acutely in many ways, producing a neuroinflammatory response.\textsuperscript{21,32} Specifically, SRCs can produce axonal injury, which is the tearing or shearing of axons that occurs due to the mechanical forces of brain
trauma. This can occur in different areas of the brain including the cerebellum, which is the control center of motor coordination and reaction time. If multiple SRCs are suffered, recent evidence has shown an association to the development of chronic traumatic encephalopathy (CTE). Chronic traumatic encephalopathy can be defined as a neurodegenerative disease caused in part by repetitive brain trauma, including both concussive and non-pathologic (sub-concussive) impacts. Like SRC’s CTE can directly affect areas of the brain including the frontal lobe, temporal lobes, and cerebellum, due to their location relative to the skull resulting from sustaining multiple injuries. While CTE has been found to be present in athletes with a history of multiple SRCs in sports involving repetitive head trauma such as football, it has also been found in football athletes who have no known history of sustaining a diagnosed SRC.

**Signs and Symptoms**

The human body’s pathophysiologic response to brain injury can cause an array of signs and symptoms, which can be broken down into categories of physical, cognitive, emotional, and sleep-related. Specifically, in an SRC physical signs and symptoms can include a headache, nausea, vomiting, balance problems, dizziness, visual impairments, fatigue, sensitivity to light and/or noise, numbness/tingling, and feeling “dazed” or “stunned”. Cognitive signs and symptoms of an SRC can include feeling mentally “foggy”, slowed down, difficulty concentrating, retrograde amnesia, anterograde amnesia, confusion, and slowed response/reaction time. Emotional signs and symptoms can include irritability, sadness, increased emotional state (compared to normal), and nervousness. Sleep-related issues can include increased drowsiness, sleeping more or less than usual, and difficulty falling asleep. A key component to understanding the signs and symptoms of an SRC is that it may or may not involve loss of consciousness. Symptoms may present as a rapid or delayed onset, varying in
the rate to which they resolve. Within the aforementioned symptoms the most common symptoms reported include headache and dizziness, in 92.2% and 68.9% of cases respectively.\textsuperscript{36} The presence of these symptoms varies within each individual; not all are required in order to diagnose an SRC, as any one of these symptoms may present in varying forms.\textsuperscript{2,3} Therefore, an individualistic strategy is required to appropriately diagnose, treat, and manage each SRC.

\textit{Management}

As stated by the CISG, there are specific guidelines that a health care provider should follow to maintain proper management of an SRC.\textsuperscript{2} Once it is suspected that the athlete is suffering from one or more of the clinical signs and symptoms of an SRC, they must be removed from play immediately and not return for the remainder of the day.\textsuperscript{1-3} Upon recognizing the occurrence of a head injury, the gold standard of immediate assessment is the Sport Concussion Assessment Tool 5\textsuperscript{th} Edition (SCAT5), an evaluative tool used particularly in a population of 13 years and older.\textsuperscript{2,37} The SCAT5 is a modified version of the SCAT3 with revisions based on the most recent consensus statement by the CISG. As a sideline and immediate post-injury tool, the SCAT5 is a vital instrument to determine if there is a likelihood of an SRC suffered by the athlete. Taking approximately ten minutes to conduct, the SCAT5 encompasses a combination of cognitive and neurological screenings. This test is recognized by the CISG to be most beneficial as a diagnostic tool immediately post-injury rather than tracking injury progress throughout the span of recovery.\textsuperscript{2,37} For an on-field or immediate post injury assessment, the SCAT5 consists of a red flag and observable signs checklist, Maddock’s questions for memory assessment, the Glasgow Coma Scale (GCS), and a cervical spine assessment. For an off-field or office evaluation, further assessments encompass a full athlete background and previous history of concussion questionnaire, a symptom evaluation checklist, the Standardized Assessment of
Concussion (SAC), and a neurological screening. The SAC is a cognitive screening tool that consists of exercises to assess athlete orientation, immediate memory, and concentration.\textsuperscript{37} The neurological screening consists of the Balance Error Scoring System (BESS) test to assess the athlete’s balance.\textsuperscript{37} Combined, each section within the SCAT5 is an important contribution to the decision-making process for the diagnosis of an SRC.

As recommended by the National Athletic Trainer’s Association (NATA), utilizing a baseline exam is an essential tool for the all-encompassing management plan of an SRC.\textsuperscript{2,3} Recognized as a multifaced approach to assess SRCs, the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is another test that is used as a re-evaluative tool as well as a method to determine cognitive status.\textsuperscript{3,38-42} The computerized neurocognitive test consists of five domains: verbal memory, visual memory, visual-motor speed, reaction time, and impulse control.\textsuperscript{41,42} Literature has demonstrated that there is a high sensitivity (91.4\%) and moderate specificity (69.1\%) of using ImPACT for symptomatic athletes during the acute stage of SRC.\textsuperscript{40} However, as a baseline tool there are mixed results regarding validity of scores. This can be due to confounding factors such as suboptimal participant effort, lack of participant motivation, or purposely avoiding return to play.\textsuperscript{39-41} Underperforming on ImPACT could cause premature return to play if post-injury scores appear to have improved significantly compared to a “false” baseline.\textsuperscript{38} Another confounding factor of using ImPACT is scores of those with learning disabilities, who may underperform on cognitive exams.\textsuperscript{38,41,42} In particular, evidence shows that ImPACT’s invalidity recognition detects an average of 6\% of invalid performance, while missing approximately 20\% of purposeful underperformance.\textsuperscript{38} The literature also demonstrates variable test re-test reliability when utilizing the ImPACT. For example, higher intraclass correlation coefficients (ICCs) were found in visual motor speed and reaction time.
modules, while lower ICCs were prevalent in verbal and visual memory.\textsuperscript{42-44} Overall, while the ImPACT can be used as an SRC management tool a lower percentage of healthcare professionals, in particular athletic trainers, actually utilize this tool.\textsuperscript{45} While the literature reports that this percentage is increasing, lower usage trends could be due to many factors such as limited accessibility, limited experience in neurocognitive testing, lack of knowledge of interpreting the test, and time constraints.\textsuperscript{46-48}

Once an SRC is diagnosed and the athlete is under the care of a medical professional, they are encouraged to continue with cognitive rest until symptoms begin to subside in order to prevent a prolonged recovery period.\textsuperscript{1-3} New evidence also suggests that after a diagnosed SRC, with clearance from a physician, athletes may benefit from subthreshold aerobic exercise during the acute phase.\textsuperscript{49,50} Before an athlete can participate in sport, they also must go through a gradual return to play protocol, usually conducted by the athletic trainer.\textsuperscript{2,51,52} The protocol consists of a step-by-step rehabilitation, symptom-limited strategy.\textsuperscript{2} After an initial minimal period of rest for 24-48 hours, the athlete can go back to activities of daily living as long as they are asymptomatic. Following stage 1, they can progress to light aerobic exercise (stage 2), sport-specific exercise (stage 3), non-contact training drills (stage 4) and a full contact practice (stage 5) before fully returning to game participation.\textsuperscript{2} Throughout each stage, the athlete must remain asymptomatic in order to progress. Using this strategy, research has shown that on average it takes an athlete to recover from an SRC between 10-20 days, including the days of participating in the return to play protocol, however it is difficult for health care providers to predict recovery rates due to individuality.\textsuperscript{2,52,53} It is also important to acknowledge confounding factors to recovery such as age, severity of injury, previous history of SRCs, and psychological factors.
If the athlete’s symptoms are persistent for more than 10-14 days, it is recommended that the athlete be referred for a more individualized management plan.²

Epidemiology

Within the United States, approximately 1.6-3.8 million SRCs occur each year.¹⁻³,¹⁵,¹⁶,⁵⁵,⁵⁶ Particularly in the National Collegiate Athletic Association (NCAA), the frequency of SRCs within collegiate sports is constantly increasing. Within the 2009-2010 and 2013-2014 NCAA seasons, a total of 1,670 SRCs were sustained among 17 collegiate sports; with men’s football having the highest prevalence of 603 SRCs.²⁵ Among football student athletes with a diagnosed SRC, 5% experienced recurrent SRCs. Many sports-specific mechanisms contribute to SRC risk; these include player contact while blocking (n=123, 20.4%), player contact while tackling (n=120, 19.9%), player contact while being tackled (n=87, 14.4%), and player contact while being blocked (n=72, 11.9%).²⁵ American football was also reported to have the highest annual national estimate of reported SRCs in the NCAA within those two combined seasons, with an estimate of 3,417.²⁵ Another epidemiological study examined SRC occurrence from the 2011-2012 through 2014-2015 seasons, which also portrayed NCAA collegiate football as ranking high in prevalence categories. Collegiate football had the highest average team-based SRC rate per season (5.63±/− 5.36).⁵⁷ There was a total of 552 SRCs throughout those combined seasons, calculating to a .75 athlete-based concussion rate.⁵⁷ Within those SRCs sustained, 518 total athletes suffered from injury, making the pooled risk for men’s football 5.33% with an annual weight risk of 5.42%.⁵⁷ Within these epidemiological studies, men’s football continued to be high in prevalence compared to other collegiate sports. Among the high school population in the United States, approximately 136,000 SRCS occur annually, particularly during competition rather than practice.⁵³,⁵⁸ Similar to the collegiate level, the high school sport with the highest rate
of sustaining SRCs is tackle football.\textsuperscript{53,59} According to the High School Sports-Related Injury Surveillance Study, during the 2008-2010 academic years football had the highest prevalence of SRCs with 912 sustained out of a total of 1,936 total reported. More specifically, 87.8\% of the SRCs sustained were due to player-to-player contact.\textsuperscript{59} However, these statistics only account for reported SRCs with a known mechanism, and do not account for total number of head impacts. \\

\textit{Sub-Concussive Impacts} \\

A sub-concussive impact is an impact to the head that does not result in a diagnosed SRC.\textsuperscript{5-8,10,60} Although acceleration and deceleration of the brain inside of the skull may occur and have a similar mechanism of an SRC, the difference is that clinical signs and symptoms may not present as they do in a diagnosed SRC. However, although there is no presentation of symptoms there may still be a physiological response by the brain at the cellular level especially with repetitive occurrences.\textsuperscript{6-8,24,61} This suggests accumulating sub-concussive impacts, along with concussive impacts, contribute to the development of CTE and have the most effect physiologically later in life.\textsuperscript{4,5,24,31,61} \\

Sub-concussive impacts fall under the category of head impact exposures (HIEs), along with concussive impacts. Head impact exposures can be defined as any impact to the head, and consists of many confounding components such as frequency and the head’s kinematic response to the impact.\textsuperscript{10,62,63} Repetitive HIEs are prevalent in sport, especially American football, causing more research to be conducted on the measurement of HIEs.\textsuperscript{2,6,10,24,35,63} As there was a previous lack in literature of the connection between sub-concussive impacts, HIEs, and the brain’s pathophysiological response, research has become more consistent within the last decade. \\

\textit{Helmet Accelerometers}
Helmets are a critical piece of equipment to the overall safety and wellbeing for collision sport athletes. Although there is no recent evidence showing that helmets prevent sustaining an SRC, they aid in decreasing the risk for a severe TBI or skull fracture.\textsuperscript{2,3,31,64} They decrease risk by reducing the acceleration of the skull caused by impact; however, as the brain is surrounded by cerebrospinal fluid the helmet cannot necessarily prevent the brain’s acceleration and deceleration inside of the skull.\textsuperscript{31,65} Multiple designs of helmets, specifically for American football have been created in order to prevent further injury beyond the severe TBI spectrum. It is a requirement that the National Operating Committee on Standards for Athletic Equipment (NOCSAE) recertifies helmets annually in order to ensure that they meet the proper safety criteria. Manufactures have mainly focused on dispersing the energy from the linear acceleration of outside impacts as well as increasing shock absorption, however further research needs to be conducted in order to validate that these efforts decrease SRC risk.\textsuperscript{31,66}

The usage of helmet accelerometer technology has become a widespread tool in measuring head biomechanics in sport.\textsuperscript{10,24,26,62,67} This technology has also provided a greater insight into the components of an HIE, particularly for linear acceleration, rotational acceleration and location of impact. The Head Impact Telemetry (HIT) system, a component of the Sideline Response System by Riddell© (Riddell, Chicago, IL) is the most commonly used device to measure HIE characteristics. It is beneficial to use as a clinical tool for data collection to provide insight for health care providers rather than as a diagnostic tool for SRC.\textsuperscript{9,24,62} Multiple studies have examined the characteristics of HIEs for both sub-concussive and concussive impacts, contributing positively to existing research with the assistance of the HIT system. The HIT system also provides insight into how many HIEs athletes are exposed to per season. For example, over a three-season study span with 314 collegiate athletes there was a total of 286,636
HIEs recorded. It was found that on average, each player sustained approximately 420 HIEs per season, with the highest total number of HIEs for a single season being 2,492.\textsuperscript{10} Events causing frequency of HIEs has also been studied, with more HIEs being sustained during practices rather than games.\textsuperscript{10} Other studies using the HIT system have looked more in depth into the measurement of linear and rotational acceleration. There is consistent evidence that during concussive events, the athletes sustained impacts at a high linear and rotational acceleration causing an SRC.\textsuperscript{26,62} In the collegiate setting, concussive impact accelerations averaged to be greater than 55.8g of linear acceleration and ranged from 163.4-15,397 rad/sec$^2$ of rotational acceleration.\textsuperscript{11,26,28} These thresholds of force varied between populations, as youth football athletes were shown to experience similar and increased rotational acceleration than at the collegiate or high school football level.\textsuperscript{26,68} Overall, continuing HIE data collection can aid athletic trainers and other health care providers in identifying sub-concussive impacts, as well as all HIEs, that may not be immediately recognized in an on-field setting.

**Reaction Time**

Reaction time is an important skill within athletic performance, and if impaired can lead to an increased risk of injury.\textsuperscript{15,69} Reaction time is an element of overall motor function, controlled by the brain structure known as the cerebellum.\textsuperscript{20} Physiologically, once the neuro-cascade occurs after sustaining an SRC, the cerebellum and other parts of the brain are affected beginning at the cellular level.\textsuperscript{20,32} As one of the identified symptoms of an SRC, reaction time is an important component to the overall SRC assessment.\textsuperscript{1,2,15,70} Prolonged reaction time is also one of the most sensitive indications that cognitive change has occurred from sustaining an SRC, making its assessment critical for both baseline and post-injury evaluations.\textsuperscript{12,17,70-72} In
some cases, reaction time may still be impaired even after the athlete has become asymptomatic and has fully returned to sport after an SRC.\textsuperscript{17,70,71}

Two main types of reaction time are emphasized when clinically assessed, categorized into simple and choice. Simple reaction time consists of a single stimuli and response, while choice reaction time consists of multiple stimuli and responses.\textsuperscript{14-16,73,74} Choice reaction time also considers accuracy rather than just response time.\textsuperscript{15} As the gold standard tool for neurocognitive assessment for an SRC, the ImPACT encompasses both types of reaction time into one composite score.\textsuperscript{73} One of the benefits of utilizing ImPACT as a reaction time tool is that computerized neurocognitive tests can detect more refined impairments compared to a physical assessment.\textsuperscript{17}

As another computerized neurocognitive exam, the C3Logix (NeuroLogix Technologies, Clevland, OH) encompasses individual scores of both simple and choice reaction times.\textsuperscript{14,16,73-75} The C3Logix was developed as an iPad application, making it’s usage easily accessible and straightforward similar to the ImPACT. Both simple and choice reaction times are measured separately with a correlation of 0.59 between each, showing a moderate positive correlation of the two scores.\textsuperscript{16} In order to measure each form of reaction time, there are a series of repetitive exercises requiring the athlete to use the touch screen. Although consistency has been questioned, using this digital method of measuring reaction time can aid in reducing human error; however, accuracy of results is a limitation with technology.\textsuperscript{73}

Although it has been shown that reaction time declines after suffering an acute SRC, there is still limited research of the effect of sub-concussive impacts on reaction time. Using the C3Logix as a measurement tool after sustaining a concussive impact, results demonstrated that there was a significant decrease in both simple and choice reaction time performance compared
to baseline.\textsuperscript{75} In a study that utilized the HIT system to measure HIEs, it was found that performance on the ImPACT reaction time composite scores post-season had significantly declined compared to baseline. This was also associated with a higher amount of sub-concussive impacts sustained over the course of the season.\textsuperscript{76}

Conclusion:

As SRC research is constantly changing and evolving, it is important to understand both the mechanism and pathophysiology that results in the clinical presentation of signs and symptoms.\textsuperscript{2,32} There are multiple tools that contribute to SRC management plans, which includes utilizing a baseline assessment tool, an acute injury evaluation tool, and following a return to sport protocol once signs and symptoms have resolved.\textsuperscript{1-3} Head impact exposures (HIEs) can be categorized into sub-concussive and concussive, and the accumulation of both can be factors in the development of CTE.\textsuperscript{5,7}

It is important to recognize that helmets do not necessarily prevent SRCs but can reduce the risk of skull fractures and severe TBI.\textsuperscript{2} Utilizing helmet accelerometer technology to recognize head impact characteristics is crucial to understanding the risk of both concussive and sub-concussive impacts.\textsuperscript{26} An important component to head impact characteristics is the linear and rotational acceleration applied to the skull.\textsuperscript{19} While there is no exact known threshold of acceleration that causes specific injury, the accumulation of these impacts can still result in physiological damage even if no signs or symptoms present.\textsuperscript{7,19} The physiological changes that occur may include a decline in motor function, specifically reaction time.\textsuperscript{75,76} Therefore, the purpose of this study is to further investigate the role of sub-concussive impacts and overall total number of HIEs and their effect on athlete reaction time.
The Effects of Repeated Sub-Concussive Impacts on Reaction Time Across Football Seasons

Introduction

Sports-related concussions (SRC) are prevalent within sport and are recognized as a traumatic brain injury (TBI). An SRC can occur from an indirect or direct force transmitted to the head, causing sudden changes in cerebral velocity typically resulting in neurological imbalances. This can elicit clinical signs and symptoms, which may occur immediately or develop over time. Signs and symptoms of an SRC can include headache, dizziness, nausea, confusion, amnesia, behavior changes, decrease in motor function, slowed reaction time or loss of consciousness. The presence of the aforementioned symptoms vary within each individual and therefore requires an all-encompassing clinical strategy. Many tools have been validated to assess head injuries including the Sports Concussion Assessment Tool (SCAT 5), Concussion Recognition Tool (CRT5), and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). These tools utilize an array of neurocognitive tests and clinical evaluations to diagnose and direct management accordingly.

As one of the identified symptoms of an SRC, an area of emphasis in its diagnosis is clinically measured reaction time. Reaction time can be divided into two domains, simple and choice. Simple reaction time consists of a single stimuli and single response, while choice reaction time will have multiple stimuli and responses. Prolonged reaction time is also one of the most sensitive indications that cognitive change has occurred from sustaining an SRC, making its assessment critical for both baseline and post-injury evaluations. Reaction time can be clinically measured using an array of tools, including components from the baseline tool ImPACT.
Head impact exposures (HIEs) can be defined as any impact to the head and consists of both concussive and sub-concussive impacts.\textsuperscript{4,10,62} Although an HIE may result in a diagnosed SRC, not all HIEs will elicit an immediate neurological injury.\textsuperscript{4,10,62} More emphasis has now been placed on investigating the effect of sub-concussive impacts. A sub-concussive impact is defined as an HIE that may not cause obvious signs or symptoms of an SRC, but if accumulated could still result in brain trauma and lead to long-term deficits.\textsuperscript{5,7,8} Sports-related sub-concussive impacts are most commonly seen in high contact or collision sports, such as American football.\textsuperscript{5-8} In particular, football has been studied for its association with the neurodegenerative disease of chronic traumatic encephalopathy (CTE), caused by repetitive concussive or sub-concussive trauma to the brain over time ultimately resulting in neurocognitive deterioration.\textsuperscript{5,6,8}

Helmets are mandatory pieces of equipment at all levels of American football. While there is no supporting evidence to show that they decrease risk of SRC, they are essential in minimizing the risk of skull fractures in collision sports.\textsuperscript{3,7,78} In order to further examine head biomechanics and SRC risk, helmet accelerometer technology is being used to record HIE characteristics including frequency of HIEs, magnitude of force, linear acceleration, rotational acceleration, and location of impact.\textsuperscript{9,26,35,67} Using this technology has revealed the frequency of HIEs sustained by football players and the forces at which they sustain them. For example, within a single season a collegiate football athlete can sustain 420-2,492 HIEs.\textsuperscript{10} Although no specific threshold of force has been established, a concussive impact event can range from 60.51-168.71g of linear acceleration and 163.4-15,397 rad/sec\textsuperscript{2} of rotational acceleration.\textsuperscript{11,26,28} However, lower acceleration impacts combined with higher frequencies have also been shown to result in injury over time.\textsuperscript{7,11} By collecting this data previous studies have been able to obtain a
better understanding of the mechanism and factors that contribute to sports-related head injuries, ultimately leading to suggested prevention strategies.\textsuperscript{26,62}

Recent evidence has shown that recurrent SRCs, as well as increasing number of sub-concussive impacts has an effect on neurocognitive function over time.\textsuperscript{5-8,12,14,76} Although reaction time is shown to be impaired after suffering from an acute SRC, there is a lack of evidence evaluating the role of repeated sub-concussive impacts on reaction time performance.\textsuperscript{13,76,79} Therefore, the purpose of this study is to examine if there is a change in reaction time in collegiate football players over time. In addition, we will determine if a relationship between HIE characteristics and a change in reaction time exists.

Specific Measurable Aims and Hypotheses

1. To compare the total number of HIEs between impact groups (99\%, 95\%, HIE_{lin})

   \textit{Hypothesis 1a: We predict that there will be more HIEs in the HIE_{lin} threshold compared to the 99\% and 95\% thresholds.}

2. To compare baseline and post season reaction time measurements for each individual.

   \textit{Hypothesis 2a: We predict that PS1 reaction time measurements will be lower compared to baseline reaction time measurements indicating a decline in performance.}

   \textit{Hypothesis 2b: We predict that PS2 reaction time measurements will be lower compared to baseline reaction time measurements indicating a decline in performance.}

3. To compare baseline and post season reaction time scores with individual total season number of HIEs.
Hypothesis 3a: We predict that individuals with a higher season total number of HIEs will have a larger deficit in PS1 reaction time measurements.

Hypothesis 3b: We predict that individuals with a higher season total number of HIEs will have a larger deficit in PS2 reaction time measurements.

Methods

Experimental Design

The design of this study was a retrospective cohort study. Data collection from the 2018 and 2019 football pre-season and regular seasons were examined, collected during all team practices and games. The independent variable was the number of head impact exposures (HIEs) sustained by each participant in the 95%, 99%, and HIE_{lin} threshold categories. The dependent variable was the change in participant reaction time measurements collected through the Immediate Post-Concussion Assessment and Cognitive Test (ImP). Helmet accelerometer technology (Riddell Insite©) was used to record the number of HIEs throughout the season, monitored daily. The HIE_{lin} group measured all HIEs in the form of linear acceleration and location of impact only, therefore duration of impact and rotational acceleration were not measured for hits below the 95% threshold. The impact groups of 95% and 99% were pre-determined using the Insite© software, delineating linear and rotational acceleration, location of impact, and duration of impact. Reaction time was measured using the computerized test ImPACT. As one of the five components measured by the ImPACT test, only the RT scores will be used for the purpose of this study. The ImPACT was taken by participants at three different points in time: baseline (BL) in August 2018 prior to the beginning of pre-season, post-season 1 measurement (PS1) in November 2018, and post-season 2 measurement (PS2) during the fall
2020 season. For all subjects who participated in the aforementioned football competitive seasons and who continued to be student athletes in the 2020-2021 school year, the PS2 ImPACT scores served as a two-year follow-up RT measurement.

Participants

A total of six National Collegiate Athletic Association (NCAA) Division III collegiate football players were recruited for this study. Determination of participants was based upon if they have head impact data from the previous two football seasons. All recruited subjects wore the Riddell Speed© or SpeedFlex© helmets equipped with accelerometer technology during the 2018 and 2019 competitive seasons. Before obtaining informed consent, participants were educated on the procedures of the study and their role as subjects. Both West Chester University and Ursinus College Institutional Reviews Board of Human Subjects approved this study.

Instrumentation Procedures

Helmet Accelerometer Technology

As part of the clinical protocol for collegiate football players at their institution, HIEs were recorded during the 2018 and 2019 seasons using accelerometer technology. The Riddell InSite© technology consists of an online software that works cohesively with helmet accelerometers to record data at a constant rate while the helmet is being worn. This software is based on the Riddell Sideline Response System (SRS) (Riddell, Chicago, IL). The linear accelerometers record an on-field history of head impacts and location of impacts, transferring that data to the Insite© software. All HIEs recorded by Insite© are separated into categories of low, medium, and high magnitudes of linear acceleration, which are within the HIE_{lin} threshold group. The approximate ranges for each category include: (low=15-28G’s, medium=29-63G’s, and high >63G’s). Insite© also works as a sideline alert system; handheld devices can be used
on the sidelines to alert athletic trainers of significant single impact exposures (a 99% hit) or an accumulation of multiple impact exposures (a 95% hit) for those with the accelerometers installed into their helmets. These thresholds were determined by a pre-calculated algorithm (Principal Component Score (PCS) :

\[ PCS = 10 \cdot ((0.4718 \cdot s_{GSI} + 0.4742 \cdot s_{HIC} + 0.4336 \cdot s_{LIN} + 0.2164 \cdot s_{ROT}) + 2) \]

that takes into account linear acceleration, rotational acceleration, duration of impact, and location of impact. \(^{35}\) These alerts are derived from impacts in the HIE\(_{lin}\) group.

In the event that a 99% hit occurs and alerts the handheld monitor, it was a recognized protocol that the athletic trainer must evaluate that participant who sustained the 99% hit for a potential SRC. The athletic trainer assessed if the participant is experiencing any signs or symptoms of an SRC, and if potential injury was suspected the concussion management plan was activated. If no signs and symptoms are reported, that participant must not return to play for 15 minutes until they are reassessed; if during the reassessment they still are not displaying signs or symptoms of an SRC, they were permitted to return to play. When a 95% alert occurs, it signifies that the participant has sustained multiple hits throughout a 7-day period that surpasses the pre-determined threshold. The same protocol occurred for a 95% hit as with a 99% threshold hit.

The accelerometer technology was installed within each Riddell Speed© or Speedflex© helmet prior to the first day of contact practice. All helmets were certified by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) prior to the beginning of pre-season. The athletic trainers, along with equipment managers fit each subject with the proper helmet size prior to the start of pre-season practices. Proper fitting was based upon guidelines provided by Riddell©. Using a Wi-Fi connection, the handheld devices “checked in” each
helmet with an installed accelerometer daily at practices or games. At the end of each event, the devices were connected to a computer or laptop to upload HIE data directly to the online software, called the Insite© Training Tool (ITT) where each participant’s data was displayed.

*ImPACT*

The ImPACT (ImPACT Applications Inc., San Diego, CA) is a computerized neurocognitive test used as an SRC management tool, as well as a method to determine cognitive status after injury. As a multifaceted approach, the ImPACT consists of domains of verbal memory, visual memory, visual motor-speed, impulse control, and reaction time. These domains are integrated into six test modules: Word Memory, Design Memory, X’s and O’s, Symbol Match, Color Match, and Three Letters. Composite scores for each domain, as well as individual module scores, are provided at the end of the exam in the clinical report. Specifically, the modules that measure RT are 1) X’s and O’s, 2) Symbol Match, and 3) Color Match. Within the X’s and O’s module, reaction time is calculated for both correct (XOcorrect) and incorrect (XOincorrect) responses to the stimulus. Within the Symbol Match module, reaction time is calculated for each correct match (SMcorrect), and for correct symbol recall (SMhidden). Within the Color Match module, reaction time is calculated for correct matches (CMcorrect) and commissions (CMcom). The composite RT score is comprised specifically of only XOcorrect, SMcorrect, and CMcorrect.

Each subject completed the ImPACT in its entirety before the first day of contact practice, which was scheduled during the sports medicine department pre-participation exam period. Due to the COVID-19 pandemic, following local and state social distancing guidelines this exam was taken on the subject’s own computer at home. The exam was taken in a quiet room on the subject’s own personal computer, and they were provided with instructions via
email on how to complete it. If needed, participants were also provided with a computer mouse. The exam time was approximately 20-25 minutes to complete. At the start of taking the ImPACT each subject provided demographic information, completed a symptom checklist, and reported previous concussion history. Once completed, the subjects were instructed to notify the principle investigator who then obtained their score from the ImPACT clinical report. To validate efficient exam completion, the examiner observed the cognitive efficacy index value (CIE). The CIE provides a score that represents the correlation between accuracy and speed of the symbol test to determine effort of completion; if the subject only completed with submaximal effort the score would be reported as less than 0.20, requiring them to complete it again in 24 hours. The new ImPACT reaction time (ImP) scores were assessed to evaluate for change compared to the previously recorded scores from the 2018 and 2019 seasons. The aforementioned test module RT scores were also assessed and compared to previous scores.

**Statistical Analysis**

For the purpose of this study, the IBM Statistical Package for the Social Sciences (SPSS) was the data analysis software used. Descriptive statistics were performed to determine the change in reaction time throughout the season by subtracting the PS1 and PS2 values from the baseline values to give us ΔImP. A negative number indicated that the scores improved, and a positive number represents a decline in performance. To determine if there were differences from baseline, dependent t-tests were performed between PS1 and BL, and PS2 and BL. To also examine if there were differences in each individual ImPACT module RT scores using dependent t-tests for BL, PS1, and PS2. To determine if there are differences in HIEs between seasons, dependent t-tests will be performed for HIE_{lin}, 99%, and 95% threshold categories. An apriori of p<0.05 will be set as the level of significance for all tests.
Results

Descriptive data for all subjects can be found in Table 1. The average age of all participants was 20.67±.52 years and included field positions of offensive linemen (OL) (2), defensive linemen (DL) (1), and defensive backs (DB) (3). Table 2 includes the overall total HIEs and threshold data. The composite ImP scores for BL, PS1, and PS2 measurements can be found in Table 3, and the individual ImP scores from each module are shown in Table 4.

HIE Data Comparisons

Dependent t-tests were performed to examine for differences in HIE data for the 2018 and 2019 seasons. There were no statistical differences in total HIEs sustained between the 2018 football season (235.17±237.97) and the 2019 football season (353±381.19), (P=0.20). However, HIEs notably increased from 1411 to 2118 in the 2019 season. Dependent t-tests did not reveal differences in the 99% category between the 2018 (1.33±1.37) and 2019 seasons (2.5±3.73), (P=0.54). Within the 99% HIE threshold category, 8 were sustained in the 2018 season and increased to 15 HIEs in the 2019 season. There were no differences in the 95% category between the 2018 season (24±32.38) and 2019 season (17±15.23), (P=0.64); although the number of 95% HIEs decreased from 224 to 100 HIEs in the 2019 season.

Reaction Time

Dependent t-tests were conducted to examine the differences in ImP RT scores between BL, PS1, and PS2. The results revealed that composite RT significantly improved at the PS2 measurement (0.60±0.08ms) when compared to BL (0.68±0.11ms), (P=.048). There were no significant differences in the composite RT scores between BL (0.68±0.11ms) and PS1 measurements (0.61±0.09ms), (P=0.60). When examining the individual ImPACT modules that measure RT, dependent t-tests revealed no significant differences in BL when compared to PS1
or PS2 respectively for measurements of XOcorrect, XOincorrect, SMcorrect, or SMhidden (Table 4). Dependent t-tests revealed there was a significant improvement in CMcorrect at BL (0.89±0.22ms) vs. PS1 (0.75±0.14ms), (P=.031) and BL (0.89±0.22ms) vs PS2 (0.71±0.19ms), (P=.027).

Discussion

Repetitive HIEs are present in high contact and collision sports, and have been reported throughout the literature.\textsuperscript{2,10,61,63} While SRCs have the highest incidence rate in American football, sub-concussive impacts are also prevalent, and have been increasingly studied in sport.\textsuperscript{25,60} Recent evidence suggests that the accumulation of SRCs, as well as sub-concussive impacts, may be related to long-term neurodegeneration.\textsuperscript{5,7,61} Specifically, reaction time deficits may indicate change at the neurocognitive level.\textsuperscript{12,70,71} The purpose of this study was to examine the accumulation of HIEs over two competitive football seasons, and determine if they contributed to changes in player reaction time.

A total of six subjects participated in this two-year follow-up study. All subjects were recruited from a previous study where data collection occurred during the 2018 football competitive season.\textsuperscript{80} Player positions allocated for this follow-up study included OL, DL, and DB. These positions were chosen for this study based on evidence in the literature of being more prevalent to a higher accumulation of HIEs in competitive football.\textsuperscript{81} In particular, linemen have been shown to sustain the most HIEs in both practice and game settings, with offensive linemen receiving up to 75\% of total team impacts.\textsuperscript{29,81} There is consistent evidence to support positional HIE seasonal averages ranging from 417-871 HIEs per collegiate season, specifically for the aforementioned positions.\textsuperscript{10,30,61,81}
Williams et al reports that total season impacts could range from 3,312-90,054 HIEs.\textsuperscript{26} While this study’s subject group accounts for only 5.2% of the full collegiate roster, it is consistent with the literature of seasonal team HIE norms.\textsuperscript{10,35,82} A total of 1,411 (235.17±237.97) HIEs were recorded for the 6 subjects in the 2018 season, which increased to 2,118 (353±381.19) in the 2019 season (Figure 1). Although we did not see a statistically significant difference between seasons, it is important to note that there was an increase of total number of HIEs. We were implored to then individually examine the intricacies of each subject and remarked that they were notable. Total season impacts within individual subjects ranged from 44-1084 HIEs. In total throughout both competitive seasons, three SRCs were sustained by two subjects (subject 1 and subject 4), which may have impacted this data.

Subject 1 had the lowest accumulation of HIEs within the subject group for both competitive seasons (Table 2). Subject 1 also had zero HIEs in the 99% and 95% threshold categories during both seasons (Figure 2). This subject is an outlier within the data, and is not consistent within the literature indicating that collegiate football players can sustain between 223-1,354 impacts over the course of one competitive season.\textsuperscript{26,30,83} When examining this subject’s SRC history, subject 1 sustained a total of two SRCs; one during each competitive season. Both concussive events were registered by the accelerometers as HIEs of lower magnitude (15-28 G). Both events also resulted in decreased playing time due to prolonged SRC symptoms, which could contribute to decreased seasonal HIE accumulation. The literature demonstrates that concussive events can occur from impacts of a wide-ranging magnitude. This subject’s event provides an example of an SRC resulting from low magnitude or from the accumulation of sub-concussive impacts.\textsuperscript{11,67}
Subject 4 revealed to have the highest accumulation of HIEs, with the largest increase between seasons (Table 2). In the 2018 season, this subject also sustained an SRC due to an observable accumulation of 95% impacts. This was recorded during the subject’s previous study participation, and it was noted that subject 4 was continually educated on the affect of accumulating HIEs. On average, this subject sustained 104.5 HIEs per week prior to his injury, which subsequently decreased to 54.2 HIEs per week post-injury. It is important to note that this subject accounted for 49.4% of total subject HIEs in 2018, and increased to 51.2% of total subject HIEs in 2019. As an OL, this is consistent with the literature that OL positions on average sustain a higher amount of HIEs in a competitive season. Compared to the 2018 season, this subject had increased HIEs the following year in the 99% threshold group. However, they also had decreased HIEs in the 95% threshold group (Figure 3). Subject 4 did not sustain an additional SRC during the 2019 season. Overall, when examining this small sample of American football players we were able to demonstrate consistent HIE trends, SRC impact characteristics, and sub-concussive exposures. There were individual variations within the subject group, which were highlighted to portray the intracacies that may have contributed to our overall findings.

Eckner et al supports the use of reaction time measurements as one of the many all-encompassing tools for the assessment of an SRC. Evidence shows that an impairment in reaction time is a cognitive symptom of an SRC, and may represent the most sensitive indication of change at the neurocognitive level. In addition to the examination of overall HIE data, our focus was to determine if there was a relationship between reaction time performance and HIE accumulation over time. McAllister et al reported poorer ImPACT reaction time measurements in subjects with a higher accumulation of HIEs.
45 non-contact athletes, a statistically significant relationship was found between post-season ImPACT reaction time composite scores and peak linear acceleration. From those results, a conclusion was drawn that there is potentially a connection between cognitive performance and frequency of HIEs. This study aimed to interpret similar findings. However, when examining RT composite scores in this study we found that composite scores actually statistically improved when compared to baseline, specifically for the two-year follow up measure (Table 3). Although no statistical significance was found for PS1 compared to baseline, there was a global improvement among the subject group for both measures. We were careful to examine specific factors in highlighted subjects that may have impacted this trend.

Subject 1 demonstrated the highest improvement in both post-season RT composite scores compared to baseline (Table 3) (Figure 4). In total, this subject had taken the ImPACT five times since their initial baseline test in August of 2018 after sustaining two documented SRCs. When we further examined this subject’s post-injury ImPACT scores there was also an improvement in RT. Subject 4 also showed improvements in composite RT scores over time, although not as large of an interval compared to subject 1 (Table 3) (Figure 4). When examining subject 4’s post-injury ImPACT scores, we saw similar trends of RT improvement as we did with subject 1. It is important to note that SRC protocol requires that the subjects must be asymptomatic before they take the post-injury ImPACT assessment. Therefore, these subject’s post-injury composite scores may not reveal true SRC related deficits immediately after a concussive event, and instead reflect the affect of rest and graded return to activity.

Subject 2 showed the least structured improvement in composite scores between both post-season measurements and baseline (Table 3) (Figure 4). While PS1 only improved by .01ms, PS2 remained the same as BL (Table 3). This is consistent in Farnsworth et al’s findings, which
reports that an athlete’s ImPACT score should not change in-between testing periods if an SRC has not been sustained. If a change in scores occurs without injury, then it may indicate measurement error.\textsuperscript{84} When examining the specific ImPACT modules, this subject stood out as one who demonstrated the most consistent decline in performance on both post-season measurements, specifically on XOincorrect and SMhidden (Table 4). This subject did not sustain an SRC within the 2-year study period, but did experience a substantial increase in both the total HIE and 95% threshold impacts between seasons (Table 2). When examining these individual modules we did not find statistical significance of decline or improvement in performance. However, we did find statistically significant improvement in CMcorrect for both PS1 and PS2 measurements compared to baseline (Table 4). As this is one of three modules used in the ImPACT algorithm to calculate RT composite scores, we can conclude that this specific module may have contributed to the overall subject improvement in composite measurements. We were curious to find that four out of the six subjects showed some aspect of decline in performance on SMhidden (Table 4). As one of the scores calculated from the “symbol match” ImPACT module, SMhidden represents the average RT for memory recall of the symbols within the module.\textsuperscript{85} However, SMhidden is not used in the algorithm for calculating RT composite scores. Therefore, if there was a decline in performance within this specific module, it may not be reflected in subject composite scores.\textsuperscript{85}

With computerized neurocognitive testing being part of the multifaceted approach to managing SRCs, it is recognized in the literature that the validity of the baseline test is important in order to interpret changes in cognitive function after injury.\textsuperscript{38-41} There may also be a learning curve associated with repeating neurocognitive assessments over time, possibly attributing to the trends that we found in this subject group.\textsuperscript{43,86} The literature reports varying test-retest reliability
for the ImPACT test.\textsuperscript{43,44,84} There has been ranging intraclass correlation coefficients (ICCs) reported, showing higher ICCs for visual motor speed and reaction time modules compared to lower ICCs for verbal and visual memory.\textsuperscript{42-44,87} This indicates that there may be a higher reliability index in motor speed and reaction time modules, and a lower reliability index in verbal and visual memory modules. Maerlander et al also reported similar findings of differences within test domains, revealing significant practice effects of repeat ImPACT testing more evident on memory composite scores than speed composite scores.\textsuperscript{86} While that study was conducted over the course of four years, we cautiously acknowledge that this two-year follow-up study may have shown similar practice effects. Broglio et al used multiple computerized SRC assessments including the ImPACT, testing participants at baseline, day 45, and day 50.\textsuperscript{44} The authors of that study reported lower reliability coefficients than what was previously reported in the literature, and acknowledged that they excluded any invalid baseline assessments from the study.\textsuperscript{44} To conclude, while there is varying evidence to support the consistency of ImPACT scoring, the literature suggests there are many contributing factors that may have affected the scores acquired from our sample group.

This study had limitations that may have affected our overall findings. Due to our small sample size, there was a low statistical power which ultimately may have impacted our ability to identify trends. Although each subject’s ImPACT assessment met the CEI criteria for performance effort, it is important to acknowledge that the clinical report identified subject 1’s initial baseline test in August of 2018 during the previous study as invalid. This may have skewed this subject’s post-season data, and ultimately made this subject an outlier. However, this subject was still included in our data collection out of necessity. We aimed to have multiple tools measure reaction time, originally including the usage of both the ImPACT and C3Logix.
However, in order to follow COVID-19 social distancing guidelines we were not able to utilize the C3Logix, and instead relied solely on the ImPACT as it could be taken remotely. Utilizing only the ImPACT presents as another limitation due to the varying literature of test validity. Another limitation was the lack of HIEs sustained when reaction time measurements were collected during the fall 2020 season. Due to the COVID-19 pandemic, the subjects of this study were participating in non-contact football practice during their PS2 measurement. Therefore, HIE data was not able to be utilized from the 2020 season and the subjects had no recorded HIEs within eleven months from their previous season. This absence of head impacts, along the extended time in-between contact seasons, could have impacted the RT scores within the data collection.

Future studies should include a larger subject population to allow for greater statistical power. A larger study group would provide greater insight into sub-concussive trends within a team population as seen in other observational studies. Additionally, there may be more noticeable trends in reaction time measurements which could be further examined based on subject position and level of play. It may also be beneficial to use a different reaction time tool such as the C3Logix to attempt to minimize potential test re-test validity. A future study utilizing helmet accelerometer data collection and reaction time assessments could provide health care professionals with greater insight on HIE accumulation and their impact on overall neurocognitive performance.

Conclusion

The goal of this observational cohort study was to examine the relationship between sub-concussive impacts and reaction time in Division III collegiate football athletes within a two-year period. We were able to demonstrate noticeable trends in accumulating HIEs within the
subject group. Overall, sub-concussive impacts had a greater presence compared to concussive impacts throughout the study period. This is consistent with the current literature that lower magnitude impacts are sustained more frequently in competitive football. We were also able to demonstrate changes in reaction time measurements over time. Further research however is needed to validate the impact of repetitive HIEs on long-term RT measurements in collision sport athletes. This study contributes to the ongoing research of HIEs, sub-concussive impacts, and long-term neurodegeneration in athletes.
## Appendix A: Table 1. Subject Demographics

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Appendix B: Table 2. Overall HIEs and Threshold Data Across Competitive Seasons

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<th>Subject</th>
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<td>2019</td>
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<td>2.5±3.73</td>
<td>17±15.23</td>
</tr>
</tbody>
</table>

Appendix C: Table 3. Composite Reaction Time Measurements Across Seasons
### Appendix D: Table 4. Individual Module Reaction Time Measurements Across Seasons

<table>
<thead>
<tr>
<th>Subject</th>
<th>Baseline (BL) (ms)</th>
<th>Post-Season 1 (PS1) (ms)</th>
<th>Post-Season 2 (PS2) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.83</td>
<td>0.64</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.59</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>4</td>
<td>0.71</td>
<td>0.66</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td>0.53</td>
<td>0.5</td>
<td>0.48</td>
</tr>
<tr>
<td>6</td>
<td>0.62</td>
<td>0.5</td>
<td>0.54</td>
</tr>
<tr>
<td>Mean/SD</td>
<td>0.68±0.11</td>
<td>0.61±0.09</td>
<td>0.60±0.08*</td>
</tr>
</tbody>
</table>

* = statistical significance
<table>
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<tr>
<th>Subject</th>
<th>XOcorrect (ms)</th>
<th>XOincorrect (ms)</th>
<th>SMcorrect (ms)</th>
<th>SMhidden (ms)</th>
<th>CMcorrect (ms)</th>
<th>CMcom (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>2.3</td>
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<tr>
<td></td>
<td>0.56</td>
<td>0.94 †</td>
<td>1.5</td>
<td>2.19</td>
<td>0.79</td>
<td>1.21 †</td>
</tr>
<tr>
<td>2</td>
<td>0.49</td>
<td>0.38</td>
<td>1.58</td>
<td>1.45</td>
<td>0.77</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td>0.42 †</td>
<td>1.55</td>
<td>1.63 †</td>
<td>0.77</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td>0.41 †</td>
<td>1.73 †</td>
<td>1.67 †</td>
<td>0.73</td>
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<tr>
<td>3</td>
<td>0.52</td>
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<td>1.94</td>
<td>2.09</td>
<td>1.12</td>
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<td>1.05</td>
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<tr>
<td>4</td>
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<td>1.35</td>
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<tr>
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<td>2.48 †</td>
<td>1.66 †</td>
<td>0.73</td>
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<td>0.47</td>
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<td>2.33</td>
<td>1.27</td>
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<tr>
<td>5</td>
<td>0.42</td>
<td>0.41</td>
<td>1.66</td>
<td>1.73</td>
<td>0.61</td>
<td>0.57</td>
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<td>2.14 †</td>
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</tr>
<tr>
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<tr>
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<td>1.45</td>
<td>1.06</td>
<td>0.6</td>
<td>0.5 †</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>0.38</td>
<td>1.78</td>
<td>1.5</td>
<td>0.57</td>
<td>0.55 †</td>
</tr>
<tr>
<td>Mean /SD</td>
<td>0.50±0.08</td>
<td>0.48±0.17</td>
<td>1.89±0.28</td>
<td>1.77±0.37</td>
<td>0.89±0.22</td>
<td>0.10±0.23</td>
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<tr>
<td></td>
<td>0.47±0.05</td>
<td>0.40±0.07</td>
<td>1.82±0.49</td>
<td>1.63±0.34</td>
<td>0.75±0.14*</td>
<td>0.17±0.26</td>
</tr>
<tr>
<td></td>
<td>0.48±0.05</td>
<td>0.46±0.24</td>
<td>1.80±0.31</td>
<td>1.74±0.56</td>
<td>0.71±0.19*</td>
<td>0.48±0.45</td>
</tr>
</tbody>
</table>

*= statistical significance
†= decline in performance compared to baseline
Appendix E: Figure 1. Overall Total Head Impact Exposures Across Seasons
Appendix F: Figure 2. Subject 1 Head Impact Exposure Frequency Across Seasons

![Graph showing head impact exposure frequency across seasons for Subject 1. The graph compares the number of impacts for different threshold categories (HIElin, 99%, 95%) in 2018 and 2019.]
Appendix G: Figure 3. Subject 4 Head Impact Exposure Frequency Across Seasons

![Graph showing Head Impact Exposure Frequency Across Seasons]

- **Subject 4 Head Impact Exposure Frequency Across Seasons**

  - **Threshold Category**: HIElin, 99%, 95%
  - **Years**: 2018, 2019
  - **# of Impacts**

<table>
<thead>
<tr>
<th>Threshold Category</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIElin</td>
<td>1200</td>
<td>500</td>
</tr>
<tr>
<td>99%</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>95%</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Appendix H: Figure 4. Overall Subject Reaction Time Measurements

![Graph showing reaction time measurements for different subjects and time periods.](image)

- **Baseline (BL)**
- **Post-Season 1 (PS1)**
- **Post-Season 2 (PS2)**
Appendix I: Letter of Approval from West Chester University Institution Review Board

TO: Kate Gaglias and Katherine Morrison
FROM: Nicole M. Cattano, Ph.D.
       Co-Chair, WCU Institutional Review Board (IRB)
DATE: 9/10/2020

Project Title: The Effects of Repeated Sub-Concussive Impacts on Reaction Time Across a Football Season
Date of Approval: 9/10/2020

☑ Expedited Approval

This protocol has been approved under the new updated 45 CFR 46 common rule that went in to effect January 21, 2019. As a result, this project will not require continuing review. Any revisions to this protocol that are needed will require approval by the WCU IRB. Upon completion of the project, you are expected to submit appropriate closure documentation. Please see www.wcupa.edu/research/irb.aspx for more information.

Any adverse reaction by a research subject is to be reported immediately through the Office of Research and Sponsored Programs via email at irb@wcupa.edu.

Signature:

Co-Chair of WCU IRB

WCU Institutional Review Board (IRB)
IORG#: IORG0004242
IRB#: IRB00005030
FWA#: FWA00014155

West Chester University is a member of the State System of Higher Education
Appendix J: Informed Consent Form

Project Title: The Effects of Repeated Sub-Concussive Impacts on Reaction Time Across a Football Season

Investigator(s): Kate Gaglias; Katherine Morrison

Summary of Study: Your completely voluntary consent is being sought for the participation in this study. The purpose of this study is to examine the total number of Head Impact Exposures (HIEs) throughout a competitive football season and examine if there is an effect on athlete reaction time. The expected duration of your participation will be approximately 20-25 minutes. Participants will complete the Immediate Post Concussion Assessment and Cognitive Test® (ImPACT) via their personal computer. Reaction time scores will be compared to your ImPACT scores from previous seasons. Participants will benefit by gaining a better understanding of their individual total HIE rates as they participate in competitive football. There are no anticipated risks as a participant of this study.

Would you like to take part in this Master’s Thesis Study? If you would like to take part, West Chester University and Ursinus College require that you agree and sign this consent form. You may ask Kate Gaglias any questions to help you understand this study. If you don’t want to be a part of this study, it won’t affect any services from West Chester University or Ursinus College. If you choose to be a part of this study, you have the right to change your mind and stop being a part of the study at any time.

1. What is the purpose of this study?
   o The purpose of this study is to examine the total number of Head Impact Exposures (HIEs) throughout a competitive football season using helmet sensor technology. We will also examine if there is a change in reaction time pre versus post season. Additionally, we will compare individual reaction time scores over a two-year period with total season number of HIEs.

2. If you decide to be a part of this study, you will be asked to do the following:
   o Two-Year Follow-Up Measurement
     - Immediate-Post Concussion Assessment and Cognitive Test® (ImPACT), a computerized test that takes approximately 20-25 minutes to complete.

3. Are there any experimental medical treatments?
   o No

4. Is there any risk to me?
   o None

5. Is there any benefit to me?
   o Benefits to you may include: Subjects will gain an understanding of their head impact exposure rates during the competitive season. The data will be provided to them to identify when they are experiencing high volumes of hits and frequent location impacts. Subjects can also gain a better understanding of their individual reaction time measurements.

6. How will you protect my privacy?
   o Data that was previously recorded using Riddell InSite© Technology and stored on a handheld device was uploaded to the Insite© Training Tool website.
o Your records will be private. Only Kate Gaglias, Katherine Morrison, and the IRB will have access to your name and data.
o Your name will not be used in any reports.
o Records will be stored:
  • in a locked cabinet in the SMC Floy Lewis Bakes Center, which will also be kept locked.
o Records will be destroyed once the data is fully integrated into the Master’s Thesis

7. Do I get paid to take part in this study?
o No

8. Who do I contact in case of research related injury?
o For any questions with this study, contact:
  • Primary Investigator: Kate Gaglias at 631-532-9180 or kg941023@wcupa.edu
  • Secondary Investigator: Katherine Morrison at 610-436-3293 or kmorrison@wcupa.edu

9. Will my data be used in the future?
o Data collected will only be used for the purpose of this study. If any additional future use is required, participants will be notified.

For any questions about your rights in this research study, contact the ORSP at 610-436-3557.

I, ______________________________ (your name), have read this form and I understand the statements in this form. I know that if I am uncomfortable with this study, I can stop at any time. I know that it is not possible to know all possible risks in a study, and I think that reasonable safety measures have been taken to decrease any risk.

Subject/Participant Signature __________________________________ Date:________________
Witness Signature ___________________________________________ Date:________________
References


80. Jennings N. *The Utilization of Helmet Accelerometer Sensors to Measure Head Impacts in American Football Players Throughout the Season.* West Chester, PA: Sports Medicine Department, West Chester University; 2019.


