EXPLORING LONG-TERM EFFECTS OF CONTACT SPORTS PARTICIPATION

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Kinesiology – Doctor of Philosophy

2019

PUBLIC ABSTRACT

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Background: Recent evidence suggests that there may be long-term effects of concussion that occur from participation in contact sports. However, little is known about the long-term effects of participating in contact sports. **Purpose:** The purpose of this dissertation was to 1) to retrospectively compare neurocognitive performance in healthy student-athletes participating in high and moderate levels of contact sports between two seasons of participation, 2) retrospectively compare neurocognitive function in healthy college football athletes participating in high- and low-risk positions two between two seasons of participation, and 3) to compare neurocognitive function, inhibitory control, and single- and dual-task steady-state and tandem gait characteristics between former high school contact sport athletes and control adults. **Methods:** For study 1 and 2 a total of 294 high school athletes (high contact sport: n = 142, moderate contact sport: n = 152) and a total of 80 college football athletes (high-risk position: n = 37, low-risk position: n = 43) completed a baseline neurocognitive assessment at two separate occasions on average two years apart, respectively. For study 3, a final sample of 39 adults (former contact sport athletes: n = 27, controls: n = 12) completed a demographics questionnaire, a neurocognitive assessment, a modified version of the flanker task, and a gait assessment including steady-state and tandem gait during single- and dual-tasks conditions. **Results:** For study 1, indicated there were no significant interactions between the two baseline administrations and contact levels, and no significant improvements in composite scores over time in high school athletes. There were significant differences between high school contact levels for Visual-Motor

Speed and Reaction Time. For study 2, college football athletes in the high-risk positions had worse Reaction Time that improved over time, compared to the low-risk for repetitive head impact exposure group. There were no significant differences for any other composite score. Finally, for study 3, there were no significant differences in neurocognitive function, inhibitory control, or gait characteristics between adult former contact sport athletes and controls when adjusting for previous history of concussion. **Conclusions:** High school athletes participating in high contact sports demonstrated worse scores for Visual-Motor Speed and Reaction Time. College football athletes participating in high-risk positions demonstrated small, but slower reaction times that improved between test administrations compared to the low-risk group. However, adults with former high school contact sport participation for at least two years did not demonstrate worse neurocognitive function, inhibitory control, or any gait characteristic when compared to adults that never participated in contact sports. Future research should continue to investigate the manifestation or progression of declines in cognition or postural control of former high school contact sport athletes' years after high school contact sport participation.

ABSTRACT

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Background: Deficits in neurocognitive function following concussion are widely studied. However, high school and college contact sports participation places student-athletes at risk for sustaining repetitive head impacts below the threshold of concussion, and in some contact sports (i.e., football) the exposure to such impacts is dependent on the position the athlete plays. The long-term effects of such cumulative head impacts are currently unknown. **Purpose:** This dissertation had three aims: 1) to retrospectively compare neurocognitive performance in healthy student-athletes participating in high and moderate levels of contact sports between two seasons of participation, 2) retrospectively compare neurocognitive function in healthy college football athletes participating in high- and low-risk positions at two between two seasons of participation, and 3) to compare neurocognitive function, inhibitory control, and single and dual-task steady-state and tandem gait characteristics between former high school contact sport athletes and control adults. **Methods:** For specific aim 1 there were a total of 294 high school athletes (high contact sport: n = 142, moderate contact sport: n = 152) and for specific aim 2 there were a total of 80 college football athletes (high-risk position: n = 37, low-risk position: n = 43) that completed a baseline neurocognitive assessment at two separate occasions on average two years apart. A final sample of 39 adults (former contact sport athletes: n = 27, controls: n = 12) completed a demographics questionnaire, a neurocognitive assessment, a modified version of the flanker task, and a gait assessment including steady-state and tandem gait during single- and dual-tasks conditions. **Results:** In the high school sample, there were no significant interactions between the two baseline administrations and contact levels (p = 0.124 - 0.766), and no significant improvements in composite scores over time (p = 0.062 – 0.823). There were significant differences between contact levels for Visual-Motor Speed (F (1, 275) = 9.764, p = .002) and Reaction Time (F (1, 275) = 4.988, p = .026). In the college football sample, the high-risk positions had worse Reaction Time ($F_{(1, 77)}$ = 5.158, p = .026) that improved over time ($F_{(1, 77)}$ = 4.117, p = .046), compared to the low-risk for repetitive head impact exposure group. There were no significant differences for any other composite score. In the adult sample, there were no significant differences in neurocognitive function ($F_{(4,33)}$ = .073, p = .990), inhibitory control ($F_{(1,36)}$'s range = .010 – 3.822, range = .058 – .921; $t_{(37)}$'s range = -1.136 – .729, p's = .263 – .538), or single-task ($F_{(3,33)}$'s range = .523 –1.149, p's range = .344 – .670) and dual-task ($F_{(3,33)}$'s range = .470 – 1.506, p's range = .231 – .705) gait conditions between adult former contact sport athletes and controls when adjusting for previous history of concussion. **Conclusions:** High school athletes participating in high contact sports demonstrated worse scores for Visual-Motor Speed and Reaction Time. College football athletes participating in high-risk positions demonstrated small, but slower reaction times that improved between test administrations compared to the low-risk group. However, adults with former high school contact sport participation for at least two years did not demonstrate worse neurocognitive function, inhibitory control, or any gait characteristic when compared to adults that never participated in contact sports. However, future research should continue to investigate the manifestation or progression of declines in cognition or postural control of former high school contact sport athletes' years after high school contact sport participation.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Dr. Tracey Covassin, for providing me with more than enough opportunities to grow as researcher and educator. I appreciate her guidance, mentorship, support, and time that began since the first day I started at Michigan State University.

I would like to thank my committee members Dr. Chris Kuenze, Dr. Matthew Pontifex, Dr. Sally Nogle, and Dr. Erica Beidler for their time and continued support and guidance throughout my dissertation process.

I would like to thank my peers Sport Injury Research Laboratory for your support in my projects and my morale. Also, to my friends both in and outside of the department, you each individually contributed to my positive experience and always making me laugh.

I would also like to thank the Michigan State University Athletic Training Staff. I appreciate you including me in clinical environment, your support in my research goals, and the opportunities for learning you provided.

Finally, to my family, as you have continued to love support me throughout my education and life no matter how dramatic I can be!

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CHAPTER ONE

Introduction

Sport-related concussion (SRC) is a growing health concern especially among high school and college athletes. The incidence of SRC continues to grow due to increased participation in high school sport, as well as increased awareness, education, and legislative initiatives toward this injury.[1-4] Likewise, SRC management practices have improved to include a multifaceted assessment approach to encompass the individualized trajectories of recovery.[5,6] Numerous position and consensus statements recommend a multidimensional assessment that includes a physical examination, symptoms, motor control, mental status, and neurocognitive testing.[5,7] To date, much of the literature surrounding SRC addresses the acute impairments and recovery within these various assessment measures; however, gaps in current literature exist in determining long-term deficits resulting from SRCs within each of these clinical domains.

To gain a deeper understanding of the long-term effects of SRC, researchers have developed research questions to determine the influence previous concussion history has on these various clinical assessments. Specifically, researchers have identified persistent cognitive deficits in athletes with a history of concussion including visual memory, cognitive flexibility, executive functioning, and behavioral inhibition.[8-16] These persistent dysfunctions, however, are present during more sensitive cognitive tasks and may not be identified in computerized neurocognitive tasks (CNT) as their purpose is to act as a screening tool during the diagnosis of SRC.[9,17]

In addition to cognitive tasks, motor tasks have identified adaptations in athletes' ability to maintain postural control acutely after sustaining a concussion,[18-29] and even years post-injury.[27,30,31] Gait is an objective and functional measurement of postural control[19,25,32,33] that has previously identified conservative adaptations in athletes with a history of concussion.[27,34] Gait tasks also allow clinicians to identify more subtle deficits by increasing the difficulty of the motor task (i.e., tandem gait) or dividing participants' attention with a concurrent cognitive task (i.e., dual-task gait).[19,20,24,25,33,35] Both dual-task gait and tandem gait have been used to identify conservative adaptations in gait following a concussion.[19,25,28,36,37]

However, athletes participating in contact sports sustain cumulative head impacts across their athletic careers that may not result in a diagnosed concussion. For example, high school football athletes may endure an average of 15.87 impacts per game or practice,[38] and depending on the position, such impacts occur at relatively low magnitudes.[39] Apart from football, researchers have also began to evaluate head impact exposure[40,41] in contact sports with high rates of SRC (i.e., wrestling, soccer, ice hockey).[3,4] Due to the high incidence of repetitive head impacts in contact sports, it is reasonable that researchers begin to investigate the cumulative effects of repetitive subconcussive head impacts similar to studies determining long-term effects of concussive impacts.

A relationship between participation in high contact sports, like football, and neurological consequences later in life has begun to develop.[42] Recent literature suggests that athletes with a greater exposure to repetitive subconcussive head impacts are at a greater risk for cognitive impairments and lower health related quality of life.[43] Also, former athletes that began participating in high contact sports at earlier ages may exhibit cognitive impairments that are not apparent in former contact athletes whose athletic career began after 12 years old,[44,45] although the results of these current studies are highly controversial and prompt a large debate.[46] Nonetheless, these results warrant a deeper understanding of the long-term effects of contact sport participation, as much of the existent literature is limited to former elite athletes and to cognitive outcomes.

A growing body of literature examines the acute influence of contact sport participation on gait characteristics. Conservative gait adaptations have previously been reported between athletes and non-athletes.[28] Whereas, other authors contrastingly reported no significant differences in any gait characteristic between high and low contact athletes,[32] or changes in gait characteristics relative to head impact exposure across the course of a season.[47] The results of these studies are timely, but this area of research is predominated by football and limited to relatively acute assessments. Therefore influence of cumulative participation in contact sports across multiple seasons on postural control should be explored later in life.

Current evidence suggests that a history of concussion may not be the only cause of long-term impairment in former athletes. The long-term effects of repetitive head impacts that result from contact sport participation are understudied, especially in respect to the multifaceted assessment paradigm used to determine acute impairments that result from SRC. Therefore, more research is needed to continue to develop the current understanding of how participation in contact sports may impact athletes later on in life.

Research Aims

Specific Aim 1: The aim of study one was to retrospectively compare neurocognitive function in healthy student-athletes across two seasons of participation in high and moderate contact high school sports.

H 1.1. High school athletes participating in high contact sports will have worse neurocognitive function compared to moderate contact sport athletes.

Specific Aim 2: The aim of study two was to retrospectively evaluate neurocognitive function in healthy college football athletes participating in high- and low-risk positions at two baseline neurocognitive assessments.

H 2.1. Athletes participating in collegiate football positions with greater repetitive head impact exposure (i.e., defensive line, linebacker, offensive line) will have worse verbal and visual memory, visual motor speed, and slower reaction time compared to positions with lower head impact exposure (i.e., quarterback, wide receiver, defensive back, running back).

Specific Aim 3: The aim of this study was to identify the long-term effects of contact sport participation on neurocognitive function, inhibitory control, and gait characteristics in former contact sport athletes.

H 3.1. Former high school contact sport athletes would have worse neurocognitive function (i.e., verbal memory, visual memory, visual-motor speed, reaction time) compared to adults with no history of previous contact high school sport participation.

H 3.2. Former high school contact sport athletes will have deficits in inhibitory control compared adults with no history of previous contact high school sport participation.

H.3.3. Former high school contact sport athletes will demonstrate adaptations in gait characteristics (i.e., best gait trial time (s), mean gait trial time (s), average gait speed (m/s)) compared to adults with no history of previous contact high school sport participation.

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CHAPTER TWO: REVIEW OF THE LITERATURE

Introduction

Concussions are a complex pathophysiological process leading to acute and persistent outcomes in various clinical domains. The understanding of acute outcomes of a SRC is continuously developing in current literature, and researchers are even identifying persistent or lasting impairments resulting from sport-related concussion (SRC). However, emerging research is identifying potential relationships between long-term impairments and cumulative head impacts that occur in contact sports. Therefore the purpose of this literature review is to examine the effect of high school and college contact sport participation on clinical domains that are commonly evaluated acutely following concussion.

Definition of Concussion

The Consensus Statement on Concussion in Sport[1] defines an SRC as a traumatic brain injury that is induced by biomechanical forces to the head, face, neck, or elsewhere on the body. An SRC may present with a range of signs and symptoms and neurological impairments that typically have a rapid onset and are short lived; however, impairments may develop over minutes or hours and may be prolonged.[1] The overall rate of SRCs occurring in high school sports, recently reported by O'Connor et al.,[2] is 3.89 per 10,000 athlete exposures. In college sports, the overall SRC rate was 4.47 per 10,000 athlete exposures.[3] Kerr et al.[4] reported the overall SRC rate in football as 2.57 – 3.01 per 1,000 athlete exposures in competition and 0.35 – 0.40 per 1,000 athlete exposures in practice for high school and NCAA athletes, respectively. Due impart to increased attention, awareness, and educational initiatives towards this injury, the rate of SRC has significantly increased in recent years.[5] In addition, the typical symptom recovery of SRC is between 7-14 days in high school athletes,[2] yet impairments my persist beyond symptom resolution and may leave lasting effects. However, not all head impacts result in a concussion, and the amount of head impacts athletes endure varies by sport and position.[6-10] Therefore, it may be important to investigate long-term effects of repetitive head impacts as a result of contact sports participation.

Defining Contact and Non-Contact Sports

High school and collegiate sport participation continues to grow.[11,12] As of the 2016-17 academic year, there were 7.9 million athletes participating in both contact and non-contact high school sports.[12] At the collegiate level, there were over 401,000 athletes participating in National Collegiate Athletic Association (NCAA) sports during the 2016-17 academic year.[11] Athletes participating in sports sustain various amounts of head impacts depending on the level of contact in their respective sports and positions. Therefore, researchers have defined contact sports by the incidence of repetitive head impacts.[13] For example, Tushima et al.[13] separated high school sports into high contact, moderate contact, and low contact based on their own reported incidence proportions. The high contact group included wrestling/martial arts, cheerleading, track, and football; the moderate contact group included softball, basketball, and soccer; the low contact group included baseball, volleyball, water polo, tennis, and cross-country.[13] However, the limited sample sizes in certain sports may have influenced group selection, in addition confidence intervals were not provided.

It may be valuable to classify sports into high verses low contact groups using recent epidemiological studies that report sports with the highest incidence of SRC. In high school sports, football (9.21 per 10,000 athlete exposures), boys' lacrosse (6.65 per 10,000 athlete exposures), girls' soccer (6.11 per 10,000 athlete exposures), boys' wrestling (5.76 per 10,000 athlete exposures), girls' lacrosse (5.54 per 10,000 athlete exposures), girls' basketball (4.44 per 10,000 athlete exposures), and girls' field hockey (4.42 per 10,000 athlete exposures) were reported to have the highest SRC rates.[2] These are similar at the collegiate level with men's wrestling (10.92 per 10,000 athlete exposures), men's ice hockey (7.91 per 10,000 athlete exposures), women's ice hockey (7.50 per 10,000 athlete exposures), men's football (6.71 per 10,000 athlete exposures), and women's soccer (6.31 per 10,000 athlete exposures) among the sports with the highest rates of SRC.[3] The Concussion Assessment, Research and Education (CARE) Consortium separated sports into contact (basketball, diving, field hockey, football, ice hockey, lacrosse, soccer, water polo, wrestling), limited-contact (baseball, beach volleyball, cross country/track, fencing, field events, gymnastics, softball, volleyball), and non-contact (bowling, golf, rifle, rowing/crew, sailing, swimming, tennis) sports based on the American Academy of Academics and the NCAA Injury Surveillance System.[14]

Defining Repetitive Head Impacts

The definition of a concussion identifies a range of signs and symptoms that result from a direct or indirect impact to head, neck or torso; however, not all head impacts will result in a concussion. Similar to the rate of SRCs, the occurrence of repetitive impacts also varies between sports. Therefore, it may also be important to differentiate contact and non-contact sports based on these variations in occurrence of repetitive head impacts. Participation in contact sports may cause repetitive head impacts that are below the threshold of a diagnosed SRC, in which some researchers define as "subconcussion".[15] The term "subconcussion" is debated, as 60% of athletes with no diagnosed SRC report experiencing signs and symptoms following head impact over the course of a season,[16] meaning clinical signs and symptoms may in fact be present. These subconcussive events can occur in any sport, but the most widely studied is football. An early study investigating repetitive head impacts in football found that 79.4% of head impacts were below 30*g*.[9] However, the threshold between sustaining a concussion and a head impact that does not produce clinical signs and symptoms of a concussion is unknown. In high school football, athletes sustained an average of 15.87 impacts per game or practice.[6] In college football, the reported median number of impacts per season was 420 [217 – 728] per athlete,[7] yet repetitive impacts are reported to vary by position.[6,7,9]

In both high school and college football, 76% of all impacts occurred in linemen, and the magnitude of the majority of the impacts was reported to be relatively low (20-30*g*).[9] Broglio et al.[6] reported that defensive linemen sustained the greatest number of head impacts compared to offensive lineman and skill players in high school football. In college football, the range of head impacts varies by position, as defensive and offensive linemen and linebackers sustained the greatest number of impacts compared to quarterbacks and wide receivers that sustained the lowest number of impacts.[7] Additionally, defensive line players had greater linear acceleration compared to defensive skill players and offensive linemen, and offensive and defensive lineman had greater rotational acceleration than skill players in high school football.[6] In contrast, defensive and offensive linemen sustained the lowest magnitude of head impacts compared to all other positions in college football athletes, despite the high frequency.[7] This finding is interesting as the magnitudes of head impacts reported in collegiate football players are suggested to be greater than impacts reported in high school football.[9] In a study by Baugh et al.,[17] there were no reported differences in the number of diagnosed SRCs between positions; yet, offensive linemen reported significantly more undiagnosed SRCs and "dingers." These findings may be due to the relatively low magnitude of these repetitive impacts,[9] as well as unfavorable reporting behaviors.[18]

Similar to football, repetitive head impacts below the threshold of concussion occur in other contact sports. In ice hockey, male college athletes sustained a median of 287 [200-446] head impacts and female college athletes sustained a median of 170 [116-230] head impacts throughout one season.[10] In collegiate soccer, females sustained an average of 1.86+/-1.42 head impacts per practice or game (89.6% of all head impacts were headers), with the greatest number of average impacts occurring in midfielders, followed by defenders, forwards, and goalkeepers.[8] However, less is known about the number of impacts that occur in contact sports other that football, especially within the high school level, and therefore more research is needed in this area.

Sport-Related Concussion Management Strategies

General recommendations for SRC management include a multifaceted approach for assessment and diagnosis.[1,19] This approach should involve clinical domains such as symptoms, physical signs, balance impairment, behavioral changes, cognitive impairment, and sleep/wake disturbances.[1] For high school athletes, the most common assessment tools used during SRC management include neurocognitive testing (68.5%), sideline assessments (i.e., Sport Concussion Assessment Tool (SCAT)(40.5%)), symptom scales (35.5%), and balance testing (23.5%).[20]

Traditional neuropsychological assessments include paper and pencil as well as computerized neurocognitive test (CNT) assessments. Neurocognitive assessments are important as they provide an objective component to SRC management.[1,21] The Standardized Assessment of Concussion (SAC) is a brief paper and pencil cognitive assessment that measures orientation, immediate memory, concentration, and delayed recall.[22] Concussed athletes demonstrate significantly lower scores on the SAC when compared to healthy controls,[22] however a recent report identified small effect sizes and no significant differences beyond the acute phase of concussion.[23]

The Immediate Post Concussion Assessment Tool (ImPACT) is a widely used CNT among clinicians. ImPACT is composed of five component scores (verbal memory, visual memory, reaction time, visual motor speed/processing speed, and impulse control),[24] and has demonstrated good construct validity as a screening tool for concussion,[24] good test-retest reliability[25] and the online version has been reported to have 94.1% sensitivity and 69.1% specificity.[26] Similarly, CogState is a reliable CNT that targets alertness, attention, working memory, spatial awareness, memory, and executive functions.[27,28] that has demonstrated adequate construct validity, and is valid in multiple testing settings (i.e., individual, group, supervised), and is able to detect cognitive impairment as a result of mild traumatic brain injury (mTBI).[29,30] The Automatic Neuropsychological Assessment Metrics (ANAM) is a CNT that is commonly used to assess concussion in military settings.[31] Throughput scores, the correct number of scores per minute of available response time, for each of the ten subtests are used to assess reaction time, information processing, and memory.[31] Test-retest reliability following time-points clinically relevant to concussion management ranged from moderate to weak.[31,32] The validity of ANAM determining athletes with a sports related concussion is modest,[32] and this CNT is reported to be worse in differentiating patients with a concussion and other injury in an emergency department.[33]

These clinical assessments, however, were designed to act as screening tools to aid in identification of SRC. Therefore CNTs may not be able to detect subtle cognitive declines beyond SRC assessment. Non-traditional assessments, have been also been used to investigate if cognitive dysfunctions exist following injury, especially in the long-term and are further explored in this literature review.

Cognition

Acute Effects of Concussion on Cognition

It is important to note the general path of cognitive recovery of athletes using computerized neurocognitive test assessments like ImPACT. A systematic review and meta-analysis by Williams et al.[34] reported the average time for recovery on neurocognitive tests was 5 - 7.1 days in college and high school athletes, respectively. Covassin et al.[35] administered ImPACT to a sample of 76 high school athletes that sustained a concussion over the course of two years at baseline and at multiple assessment times throughout their recovery. Athletes with a concussion demonstrated impairments in reaction time during 2 days, 7 days, and 14 days post injury, and returned to their baseline scores after 21 days.[35] Athletes with a concussion also had impaired verbal memory and processing speed composite scores at 7 days post injury, and returned to baseline by 14 days.[35] No significant changes were reported for visual memory composite scores throughout recovery.[35] Similarly, Abbassi et al.[36] administered ImPACT to adolescent athletes at baseline, 3 days, 8 days, and 15 days after sustaining a concussion. The authors reported verbal memory composite scores were significantly worse than baseline at 3 days post injury and returned to baseline at 8 days.[36] There were no other significant differences between baseline and post injury assessments for the other composite scores; however, athletes demonstrated improvements in each composite score across recovery.[36] Kris et al.[37] administered ImPACT to 32 adolescent hockey athletes at baseline and following a concussive injury once they self-reported being asymptomatic, on average 23.8 ± 16.8 days after injury. The authors reported 28.9% of athletes demonstrated composite scores that fell below the reliable change index compared to their baseline performance after they self-reported a resolution of symptoms, suggesting continued neurocognitive impairments.[37] Rieger et al.[38] evaluated cognitive recovery from concussion by administering ImPACT to children and adolescents seen in emergency room acutely after sustaining a concussion (within 72 hours) and at three months post injury, and to athletes that presented with an orthopedic injury at similar time intervals. With the exception of the verbal memory composite score, there were no significant differences in composite scores between the concussion group and the orthopedic injury group at either test administration.[38] The concussion group demonstrated worse composite scores for verbal memory compared to the orthopedic injury group at the acute assessment and at the three-month follow-up.[38]

The results of the aforementioned studies suggest that neurocognitive recovery following a concussion assessed using a CNT may be dependent on the composite of tasks. Henry et al.[39] administered ImPACT to participants 14-22 years old within 1 week of sustaining a concussion, and subsequent follow-up assessments at 2, 3, and 4 weeks. The authors reported variations in neurocognitive recovery depending on the composite domain.[39] Significant improvements in verbal memory scores were noted between week 1 and week 4. Visual memory scores significantly improved between weeks 1 and 2, and weeks 2 and 3.[39] Significant improvements in visual motor speed were also reported between weeks 1 and 3, and weeks 1 and 4.[39] Therefore, researchers consistently reported acute improvements in neurocognitive assessments following a concussive injury; however, some studies also suggest baseline and post-concussion neurocognitive assessments may be influenced by a history of previous concussion and removal from play after sustain a concussion.

Effects of Previous History of Concussion on Cognition

In attempt to determine potential lasting impairments resulting from concussive impacts, researchers have explored the effects of concussion history on cognition that may determine the utility of cognitive assessments in identifying possible long-term impairments of repetitive impacts that result from contact sport participation. A review of the current literature is necessary, as some athletes demonstrate cognitive impairment beyond self-reported symptom resolution compared to their baseline.[37] In addition, early evidence suggests a history of concussion may increase self-reported, spousal/family member reported, and clinically diagnosed mild cognitive impairement.[40]

Athletes with a previous history of concussion may demonstrate cognitive impairments following a subsequent concussion that persist longer compared to athletes with no previous concussion history. Covassin et al.[41] administered ImPACT to high school and college athletes diagnosed with a concussion at baseline, and within 3- and 8-days of injury, and also asked athletes to self-report their previous concussion history (i.e, 0, 1, 2, ≥ 3 previous concussions). Athletes with a self-reported history of ≥ 3 concussions still demonstrated impairments in verbal memory at 8-days compared to their baseline scores; whereas, athletes with a history of 1 or 2 concussions exhibited impairments at 3 days that returned to baseline within 8 days.[41] Similarly, athletes with a self-reported history of 2 or ≥3 concussions presented with worse reaction time scores at 8 days compared to baseline, and athletes with 0 or 1 previous concussions had impairments in reaction time at 3 days that resolved by 8 days following injury.[41] Therefore, a previous history of concussion may influence cognitive recovery in athletes that sustain multiple concussions. However, due to ImPACT's design as a screening tool, may not be able to detect subtle cognitive declines. Therefore, more sensitive tasks have been used to investigate if cognitive dysfunctions persist in athletes with a history of a concussion.[42-48]

For example, Ellemberg et al.[42] administered various neuropsychological tests to female college soccer athletes 6-8 months after sustaining a concussion and to control athletes. Athletes with a previous history of concussion demonstrated significantly worse performance for processing speed in both inhibition time and accuracy during the Stroop Color Word Test compared to controls.[42] In addition, athletes with a history of concussion also performed significantly worse on the Tower of London-DX for planning time and accuracy compared to controls.[42] Reaction time during the Choice Reaction Time task was also worse in athletes with a previous concussion compared to controls.[42] Moore et al.[49] compared cognitive and neuropsychological tasks between college soccer athletes with a history of 1-3 concussions that occurred 27.3±3.6 months prior to testing, soccer athletes with no concussion history, and athletes that participated in non-contact sports.[49] The authors reported significant differences between all groups in committed errors during delayed recall of the Hopkin's Verbal Learning Task-Revised, as soccer athletes with a history of concussion demonstrated the most errors (5.4±0.7), followed by soccer athletes with no history of concussion (0.7±0.1), and then non-contact athletes (0.1±0.1).[49] In addition, during the Oddball task, soccer athletes with a history of concussion demonstrated slower response time (475.0±46.5ms), compared to soccer athletes with no history of concussion (430.3±36.9ms) and control non-contact athletes (433.7±33.2ms).[49] Moore et al.[48] also administered a series of neuropsychological tests to youth athletes that sustained a concussion 2.1±1.9 years prior to testing and controls to assess persistent deficits in sustained attention, working memory, behavioral inhibition, and mental flexibility. Athletes with a history of concussion had worse accuracy and working memory performance during both the N-back task and switch task, and displayed greater impulsivity during the Go-NoGo task.[48] In an investigation of longer-term impairments that persist 34.74±9.2 following concussion, DeBeaumont et al.[44] administered neuropsychological tests that target visual memory and incidental learning to the former college athletes aged 50-65 years. Athletes with a concussion history demonstrated significantly worse performance on the Rey-Osterrieth Complex Figure task than controls, specifically for recognition, immediate recall, and delayed recall conditions.[44] In a sample of 366 retired elite and amateur rugby athletes and non-contact athletes, Hume et al.[50] reported significantly worse performance for cognitive flexibility, executive functioning, and complex attention on the CNS-VS neuropsychological online test in former athletes with a history of one or more concussions compared to former athletes with no previous concussions. In addition, processing speed, composite memory, executive functioning, and cognitive flexibility was worse in former athletes that reported 1 or more previous concussion compared to the US norms.[50]

The flanker task is a neuropsychological assessment commonly administered to athletes with a history of concussion that assesses congruent (symbols in the same direction) and incongruent (symbols in the opposite direction) symbols, and from those an interference effect can be calculated (incongruent – congruent). Moore et al.[46] administered a flanker task to youth athletes with a previous concussion history, which occurred 2.1±1.9 years prior to test administration, and controls. Athletes with a previous history of concussion had more omission errors and performed worse when an incongruent trial followed another incongruent trial, or a worse sequential-congruency effect.[46] Additionally, after making an error, youth athletes with a concussion history performed worse during an incompatible stimulus response mapping trial.[46] Similarly, Pontifex et al.[43] administered ImPACT and the modified flanker task to college athletes with a history of 1.7±1.1 previous concussions, 2.9±2.9 years since the injury, and controls. Athletes with a concussion history had a greater flanker interference effect for reaction time, decreased response accuracy, and decreased post response accuracy compared to the control group, when no such differences were seen in ImPACT or reported symptoms.[43] Parks et al.[47] also had college athletes with a concussion history, 4.2±3.4 years prior to test administration, and controls perform the modified flanker task. Worse response accuracy and greater variability in reaction time was also seen in college-aged athletes with a history of concussion compared to control athletes.[47] Moore et al.[45] administered the flanker task to former athletes, aged 20-29 years, with (7.1±4.0 years prior to test administration) and without a previous history of concussion. Former athletes with a concussion history had worse response accuracy for both congruent and incongruent tasks.[45] A study by DeBeaumont et al.[44] similarly used the modified flanker task, yet evaluated former collegiate athletes that were 50-65 years old. Athletes were separated into two groups: a self-reported previous history of concussion, which ranged from 1-5 and sustained their last concussion 34.74±9.2 years prior to testing, and controls. There were no significant differences between athletes with a history of concussion and controls for reaction time of the incongruent condition and interference effect, or reaction time and accuracy scores for congruent condition.[44] However, athletes with a history of concussion presented with significantly more errors during the incongruent response and accuracy scores for interference effect were significantly worse compared to controls.[44] The results of these studies signify that more specific cognitive tasks may be more beneficial than a screening tool like ImPACT in determining if cognitive dysfunctions exist later in life in former contact sport athletes. Especially, the modified flanker, as deficits were identified during this task but not on ImPACT in the same sample.[43]

Acute Influence of Contact Sport Participation on Cognition

Due to the nature of repetitive head impacts occurring in contact sports, it may be valuable to evaluate the effects on cognition beyond the diagnosis of concussion. Researchers have started to investigate the effect of contact sports participation on cognition in high school collegiate, and professional athletes. Their methodologies include comparisons of CNT scores immediately after a competitive event, baseline comparisons of CNT scores between contact and non-contact athletes, and comparisons of CNT scores in athletes across a season of contact sport participation. Mrazik et al.[51] compared CNT scores in 94 college and professional football athletes between baseline and either post-game, immediately following a competitive event (within 24 hours post-game), or post-concussion, after sustaining a concussion prior to medical clearance to return to full competition. Athletes in the post-concussion group demonstrated significant improvements in verbal memory, visual motor speed, and reaction time on ImPACT.[51] These improvements were not seen in the post-game group. In contrast, the post-game group performed worse in impulse control from baseline (6.0±4.7) to posttest (8.3±5.8).[51] The authors attributed the improved scores seen in the post-concussion group to motivations to return to competition, as a better score would likely influence return-to-participation decisions; however, motivation was not a measured outcome variable.[51] Similarly, Howell et al.[52] administered CNT to female athletes pre and post an Olympic-style boxing tournament (5.2±1.6 days apart). There were no significant differences between test sessions on six of seven CogState domains; however, head impact exposure during the tournament was not recorded.[52] The only domain with a significant change was processing speed during the maze chase task, which improved from pre-tournament (1.23 correct moves/second) to post-tournament (1.40 correct moves/second).[52] These results suggest acute effects of participation in contact sport on cognition may not be present.

In contrast, Tushima et al.[53] retrospectively compared high school football athletes' baseline CNT scores between high contact (i.e, offensive and defensive lineman) and low contact (i.e, receivers and defensive backs) positions. Athletes in the high contact positions reported more total symptoms and performed worse on verbal memory, visual motor speed, and impulse control on ImPACT compared to athletes in low contact positions.[53] However, these results should be interpreted with caution as high school football athletes often play more than one position, and the authors did not collect previous history of football or other contact sport participation.[53] Similarly, baseline CNT scores were compared among high school athletes participating in various levels of contact sports.[13] Athletes participating in high contact sports (i.e., wrestling/martial arts, cheerleading, track, football) performed worse on visual memory, visual processing speed, and impulse control on ImPACT at baseline compared to moderate contact (i.e., softball, basketball, soccer) athletes.[13] High contact athletes also had worse scores on visual memory, visual processing speed, reaction time, and impulse control compared to low contact (i.e., baseball, volleyball, water polo, tennis, cross country) athletes.[13] This study is also not without limitations; specifically, the authors used incidence proportions to delineate contact sport group levels, and did not account for history of participation and participation in multiple sports.[13] Katz et al.[14] compared baseline CNT scores between NCAA athletes participating in contact, limited contact, and non-contact sports. Contact and limited contact sport athletes performed better on visual and verbal memory on ImPACT compared to non-contact athletes, although the authors reported small effect sizes.[14] In contrast, non-contact athletes performed significantly better on reaction time than contact athletes.[14] Therefore, results are inconsistent when comparing high school and college baseline CNT amongst varying levels of contact sport participation.

Other researchers have compared CNT at multiple time points across a competitive athletic season. An early study by Miller et al.[54] compared SAC and ImPACT scores in college football athletes between baseline, mid-season, and post-season test administrations. Scores on the SAC and ImPACT either remained the same or improved throughout the three testing sessions.[54] Broglio et al.[55] similarly assessed CNT scores in high school football and non-contact athletes at baseline, midseason, and post-season. Results revealed no significant declines, however, improvements were seen in learning and working memory speed across time.[55] Similarly, McAllister et al.[56] compared preseason and postseason CNT test scores between Division I contact (i.e., football, ice hockey) and non-contact (i.e., track, crew, Nordic skiing) athletes and reported no significant group by time interactions on ImPACT. Therefore, some studies report no significant deficits in CNT scores following a competitive season of contact sport participation.

The contrasting results reported in the previously mentioned studies may be due to the nature of assessments. CNT tools like ImPACT are intended to act as a screening tool used in the diagnosis of concussion, and therefore not be appropriate in determining subtle impairments.[24] Additionally, some studies that support differences in CNT scores between various levels of contact sport participation only assessed athletes at one time point, especially early in their competitive careers, and had small effect sizes. For example, the CARE consortium study included baseline ImPACT scores of participants that were relatively early in their collegiate athletic career (44% freshman, 21% sophomores, 19% juniors, and 13% seniors).[14] Similarly, in the study by Tsushima et al.[13] athletes were on average 15.22 years old, which is relatively early in their high school career. Therefore, future research should determine if scores change over time depending on the level of contact sport participation.

Acute Effects of Head Impact Exposure on Cognition

Repetitive head impacts are currently evaluated in contact sports using head impact exposure biomechanics, and some researchers have investigated the relationship between head impact exposure biomechanics and cognition. However, a majority of this literature surrounds football athletes. An early investigation by Broglio et al.[57] evaluated the relationship between head impact exposure biomechanics surrounding a concussive event on the day of injury using the Head Impact Telemetry System (HITs) and resulting cognitive declines on ImPACT. The HITs records peak linear and rotational acceleration, head impact location, and HITsp (a non-dimensional measure of head impact severity that combines linear and rotational acceleration with impact duration).[56,57] There were no significant relationships between the changes in ImPACT scores from baseline to post-concussion administration and any cumulative biomechanical variables (peak linear or rotational acceleration, HITsp, cumulative linear acceleration) pre- or post-injury.[57] Despite these non-significant findings following a concussion, the authors did not evaluate the effect of cumulative impacts across seasons, which may provide insight into the effect of repetitive subconcussive head impacts on cognition. However, McAllister et al.[56] recorded head impact exposure using the HITs in college contact sport athletes (e.g., football and ice hockey) over the course of a season, and administered CNT pre- and post-season. The authors reported a significant association between athletes with greater head impact exposure and worse performance on ImPACT; specifically, athletes with greater peak linear acceleration had worse scores on the reaction time composite of ImPACT.[56] Also, athletes with greater peak and sum HITsp, peak linear acceleration, and peak rotational acceleration demonstrated worse performance on the Trail Making Test.[56] These results suggest cumulative head impacts over the course of a season may negatively influence cognitive performance. In contrast, Gysland et al.[58] reported no significant relationships between pre- to post-season changes in ANAM test scores and HITs variables (i.e., total number of impacts, total number of impacts greater than 90*g*, total cumulative magnitude of impacts, total number of impacts to the top of the head) in college football athletes.

Nauman et al.[59] also administered CNT during pre- and post-season assessments while tracking head impact exposure using HITs in high school football athletes over the course of a season. The authors used "flagged" tests, or any composite score of ImPACT outside the reliable change index (RCI), and reported no significant differences in the distribution of athletes being "flagged" at postseason between athletes with over 900 head impacts per season (80%) and athletes with fewer than 600 head impacts per season (52%).[59] However, the authors reported that the distribution of athletes "flagged" with above 50 impacts per week (83%) was significantly different than athletes "flagged" with below 50 impacts per week (48%).[59] Other authors similarly report "flagged" ImPACT scores to report false positive rates in healthy asymptomatic participants. Breedlove et al.[60] reported 54% (n=12/22) of high school football athletes were "flagged" on at least one composite score of ImPACT during in-season assessments. There were 58.3% (n=7/12) of athletes "flagged" on at least one composite score of ImPACT in the high cumulative impact group (above 500 cumulative hits), and 50% (n=5/10) of athletes "flagged" in the low cumulative head impact group (below 500 cumulative hits).[60] Conversely, Resch et al.[61] administered ImPACT to healthy adults and reported 37% of healthy adults had at least one "flagged" composite score outside of the RCI within 7 days of completing a baseline assessment, and 28.9% had at least one "flagged" composite score within 50 days of their baseline.[61] However, the authors did not report if RCI's were due to improvements or worse performance.[61] Despite these findings, it would be valuable for researchers to note the actual changes in each composite score between athletes with high and low head impact exposure, rather than "flagged" composite scores on ImPACT.

Soccer athletes are also known to endure repetitive impacts throughout their career, which are largely attributed to soccer heading.[8] Similar to football athletes, researchers have begun to assess the cumulative effects of repetitive soccer heading on cognition. Di Virgilio et al.[62] administered a CNT (Cambridge Neuropsychological Test Automated Battery (CANTAB)) to 22 amateur soccer athletes (22.0±3.0 years) at baseline, and immediately post-, 24 hours post-, 48 hours post-, and 14 days post-heading protocol involving 20 consecutive soccer headers. Athletes demonstrated worse performance on tasks of short-term memory and long-term memory immediately post-heading protocol compared to baseline, and scores returned to baseline within 24 hours.[62] No other impairments (i.e., attention or processing speed) were found after an acute bout of soccer heading.[62] Similarly, Gutierrez et al.[63] administered ImPACT to high school female soccer athletes pre- and post-15 soccer headers that occurred in three directions (forward, to the left, to the right) and reported no significant differences in any composite score. However, these researchers did not account for a history of cumulative head impacts, and therefore could not assess the cognitive effects resulting from cumulative head impacts over time.[63]

Moore et al.[49] recorded college soccer athletes' repetitive head impacts over the course of a season by asking athletes to self-report the number of soccer headers per game combined with randomized video analysis for validation. The authors also compared cognitive and neuropsychological tasks between soccer athletes with a history of a concussion, soccer athletes with no concussion history, and athletes that participated in non-contact sports.[49] Despite aforementioned differences between soccer athletes with a history of concussion, soccer athletes with no concussion history, and non-contact athletes in HVLT delayed recall and Oddball task response time, there were no significant correlations between any of the cognitive tasks and number of reported soccer header impacts.[49] Similarly, Chrisman et al.[64] recorded youth soccer athletes' head impact exposure over one month of game play; however, ImPACT scores did not significantly change between baseline and follow-up test administrations. Straume-Naesheim et al.[65] also administered CNT at three time points (baseline, follow-up after head impact, at one-year follow-up) in professional soccer athletes. Cogstate was used to compare reaction time during six tasks (psychomotor function, decision-making, simple attention, divided attention, working memory, learning and memory) between athletes that sustained and did not sustain at least one minor head impact.[65] Athletes in the minor head impact group performed significantly worse on reaction time for psychomotor functioning, decision-making, and simple attention.[65] Athletes that sustained at least one minor head impact were further divided into those who reported symptoms and those that did not report symptoms following impact.[65] The symptomatic group had significantly worse changes in reaction time during psychomotor functioning and decision-making compared to controls with no observed head impacts.[65] Finally, athletes that sustained at least one head impact demonstrated a significantly worse change between baseline and one-year follow-up during the decision-making task compared to control athletes with no observed head impacts.[65] These studies primarily evaluated the relationship between cognition and repetitive head impacts in acute instances (e.g., immediately following repetitive head impacts, cumulative head impacts over the course of one season); whereas, it is also important to review current literature surrounding long-term influences on cognition as a result of repetitive head impact exposure. Nonetheless, the inconsistencies in results of the studies investigating the acute effects of repetitive head impacts on cognition warrants more research in this area.

Long-Term Effects of Head Impact Exposure on Cognition

Researchers are beginning to evaluate longer-term effects on cognition as a result of contact sports participation, in which athletes sustain repetitive head impacts. Montenigro et al.[66] developed the cumulative head impact index (CHII) to estimate athletes' total head impact exposure by combining self-reported athletic exposure and objective kinematic data from published accelerometer studies in youth, high school, and collegiate athletes.[66] The authors used the CHII to evaluate the relationship between cognition later in life (47.3±13.9 years), using the Brief Test of Adult Cognition by Telephone (BTACT), and head impact exposure, reporting that the risk of impairment increases with a greater amount of head impacts.[66] Specifically, the authors reported that the estimated number of head impacts to occur per person was 545 impacts per season, and the risk for cognitive impairments later in life steadily increased with each additional 1,000 head impacts (i.e., two additional seasons).[66] Also of importance, self-reported history of concussion was not able to predict objective cognitive impairment later in life.[66] This warrants further exploration of the effect of participation in contact sports with high risks of repetitive head impacts at the subconcussive level, on clinical domains later in life. Deshpande et al.[67] similarly evaluated former high school football athletes later in life (i.e., 54 years, 65 years, and 72 years) using Letter Fluency and Delayed Word Recall tests and compared results to non-contact controls. The authors did not account for the cumulative number of repetitive head impacts, and reported no significant differences in either cognitive task between non-contact athletes and non-athlete controls.[67] Hume et al.[50] investigated cognitive function in former elite rugby athletes (41.3±7.5 years), amateur rugby athletes (44.9±8.4 years), and non-contact athletes (42.1±7.7 years), yet did not report cumulative head impact exposure. Athletes that formerly participated in elite rugby had worse performance on complex attention, executive functioning, processing speed, and cognitive flexibility compared to the former non-contact athletes.[50] The elite rugby group also had worse scores for complex attention compared to the amateur rugby athletes; whereas, the former amateur rugby athletes performed worse on executive functioning and cognitive flexibility compared to the former non-contact athletes.[50] Therefore, the few studies evaluating cognitive impairments later in life provide variable results. Despite the significant increase in risk for cognitive impairments with participation in cumulative seasons in sports with repetitive head impacts reported by Montinegro et al.,[66] the reported head impact exposures were limited to estimations from previously reported studies combined with athlete self-reports of previous sport participation, and therefore results should be interpreted with caution.

Age of First Exposure to Contact Sports and Cognitive Impairments

The age at which an athlete started participating in contact sports may also influence cognition, and some researchers have explored the age of first exposure to contact sports and cognitive outcomes later in life. Youth athletes are undergoing critical stages of brain development between 10-12 years in which the rate of myelination and cortical levels are peaking,[68,69] and white matter volume reaching that of adults.[70] This may leave these athletes more vulnerable to repetitive head impacts and injury during critical stages of growth and may interrupt development.[68,71-73] In a sample of 8-13 year old males that participated in one season of youth football with no clinically diagnosed concussion, Bahrami et al.[74] identified a significant relationship between white matter changes and head impact exposure. These results suggested that microstructural changes in the white matter may result from the repetitive head impacts that occur in contact sports even in the absence of a concussion.[74] These microstructural changes in white matter are also apparent later in life, as Stamm et al.[72] reported differences between former NFL athletes that started participating in tackle football before the age of 12 and at 12 years or older. Specifically, when controlling for the duration of play, retired NFL athletes that started participating in football before 12 years old had microstructural alterations that were not apparent in those that started participating at 12 years old or later.[72]

In a study of 42 former professional football athletes aged 40-69 years old from the Diagnosing and Evaluating Traumatic Encephalopathy using Clinical Tests (DETECT), Stamm et al.[75] evaluated the relationship between neuropsychological testing later in life and former athletes' age of first exposure to tackle football. Former athletes that started participating in football before age of 12 demonstrated greater impairments in executive functioning, immediate memory, delayed recall, and estimated verbal IQ compared to those who started participating at 12 years old or later.[75] Despite these reported differences, this study has obtained major criticism as the study limits generalizability, the authors did not report the test scores of the control group, and the authors did not account for the statistically significant differences in premorbid impairments (e.g., learning disability) between groups.[76] Therefore, the results of the study by Stamm et al.[75] investigating the relationship between age of first exposure to football and cognitive functioning should be interpreted with caution.

Solomon et al.[76] assessed neuroradiological, neurological, and neuropsychological outcomes among 45 retired NFL athletes, 46.7±9.1 years old, while also administering a comprehensive medical history exam including former contact sport participation, head injury and concussion history, employment, and premorbid cognitive impairment (i.e., ADHD, learning disability, reading disorder). The neuropsychological tests were used to assess verbal/visual memory, executive function, fine motor speed, sustained attention, working memory, and estimated verbal IQ.[76] The authors reported no significant relationships between years participating in pre-high school football and any neuropsychological assessment while controlling for age, BMI, learning disability, concussion history, and professional football experience.[76] However, Alosco et al.[71] asked 214 former high school, college, and professional football athletes from the Longitudinal Examination to Gather Evidence of Neurodegenerative Disease (LEGEND) to report their previous medical history, athletic history, and complete objective cognitive assessments. Former athletes that started competing in football before the age of 12 were 2-times more likely to have clinically meaningful worse scores on one of the cognitive assessments (BRIEF-A).[71]

Researchers have also begun to investigate lasting impairments resulting from higher levels of competitive play verses the impairments related to age of first exposure to contact sports. Alosco et al.[71] also reported there was no interaction between age of first exposure to football and level of play with any cognitive measure. Similarly, Stamm et al.[75] reported former NFL athletes that started participating in football before the age of 12 had lower duration of play in the NFL, and had significantly worse impairments on all cognitive assessments. These results suggest an earlier onset of competitive sport participation may be a better indicator of clinical impairment than the level of contact sport participation.

Furthermore, the age at which an athlete sustains a concussion is also worthy of investigation.[77] Moore et al.[46] reported the age at which an injury occurs may influence performance on the flanker task, n-back task, switch task, and Go-NoGo task, as athletes with an injury that occurred at a younger age demonstrated worse performance.[46] Similarly, Moore et al.[48] reported negative correlations between the age of concussive injury and cognitive tasks, as athletes that sustained a concussion earlier in life demonstrated worse performance on N-back, more errors during a switch task when requirements for cognitive control increased, and greater impulsivity on go-no go task.

Effects of Continuing to Play with a Concussion

Despite the laws and guidelines requiring immediate removal from play after a suspected SRC,[1,19] a percentage of concussions remain undisclosed by athletes in various levels of play including high school, collegiate varsity, and collegiate club sports.[18,78-81] The most commonly reported motivations for nondisclosure include not wanting to leave a game or practice, not knowing it was a concussion, not knowing it was serious enough, and not wanting to let their teammates down.[18,78-81] Also, not every athlete receives the same standard of care as not all athletic teams are provided with a sports medicine professional trained to recognized and manage a SRC. These factors warrant the need to examine the effect of continuing to play with a suspected concussion on cognitive recovery.

Elbin et al.[82] administered ImPACT to athletes aged 12-19 years following a concussion, while also separating athletes into two groups: 1) immediate removal from play and 2) continued to play with concussion signs or symptoms. Within the first week of injury, athletes that continued to play had worse scores for verbal memory, visual memory, processing speed, and reaction time compared to the athletes that were removed from activity.[82] Within 8-30 days, athletes that continued to play still demonstrated worse performance for verbal memory, visual memory, and processing speed compared to athletes that were removed.[82] In addition, athletes that continued to play with concussion signs and symptoms were more likely to have a protracted recovery than athletes without symptoms.[82] Asken et al.[83] similarly assessed days missed from activity following immediate removal and delayed removal in Division I athletes, reporting athletes with delayed removal had a longer recovery compared to athletes that were immediately removed from activity.[83] However, these studies only report acute impairments as a result of continuing to play with a concussion, warranting more research to better understand long-term effects of continuing to play with a concussion.

Gait and Postural Control

Postural Control

Cognitive impairments may not be the only clinical domain that is impacted as a result of contact sports participation. Postural control, or the ability to maintain postural orientation in response to internal and/or external disturbances, is a biomechanical framework that is commonly assessed following concussion.[84,85] Measures of postural control occur in static and dynamic stance activities and in functional activities such as gait.[84,86,87] Adaptive strategies to maintain postural control have been suggested to occur after sustaining a concussion,[84-86,88-96] and last beyond symptom resolution,[85,86,89,97,98] and even years post-injury.[94,99,100] However, there is limited research investigating the influence of contact sport participation beyond clinically used static and dynamic balance (e.g., Balance Error Scoring System (BESS)).[52,58,95,101-104]

Characteristics of static and dynamic balance and gait are commonly measured with various assessment tools (i.e., full body motion analysis, inertial motion sensors, force plate, electronic walkway),[86,90,92,94,95,105] and outcome variables are dependent on the measurement tool.[93] During full body motion analysis, temporal-distance and whole body center of mass (COM) variables are commonly measured. Temporal-distance variables commonly include average walking speed, cadence, stride length, step width, double support time; whereas, anterior posterior and medial-lateral displacement and peak velocity, and anterior velocity are variables often reported for whole body COM.[86,90,93] Whole body motion analysis provides good to excellent internal consistency for commonly measured gait characteristics across a 5 session testing period (Cronback alpha range = .764 - .967).[105] Variables for inertial motion assessments commonly include head and trunk local dynamic stability estimates, root mean square (RMS) sway, and 95% ellipse sway area.[88,89,92] However, despite finding group differences in concussed and non-concussed athletes, inertial sensor assessments provide low sensitivity and high specificity indicating a high false-negative rate when identifying athletes with a concussion.[88] Force plate assessments provide variables regarding center of pressure (COP) that include medial-lateral and anterior-posterior COP displacement and velocity, which are also used to calculate approximate entropy (ApEn) values.[90,96,97]

Static and Dynamic Balance

Static and dynamic balance is commonly assessed at acute and longer-term intervals following a concussion. Athletes with an SRC were tested during a quiet stance task with their eyes open and hands on their hips for 30 seconds, at both an initial exam (9.5±5.2 days from injury) and after reporting a resolution of symptoms (28.7±22.3 days from injury). During the quiet stance, measured with an inertial sensor system, there were no significant differences between groups for any sway variables.[89] In high school and college athletes with a concussion, BESS scores, a measure of static and dynamic postural stability in three stance conditions (i.e., double leg, single leg, tandem), were worse at 1 day after injury, and significantly improved within 2- and 3-days after a concussion.[91] Similarly, Baracks et al.[88] observed balance deficits in single-leg, double-leg, and tandem-balance in college-aged athletes with an acute concussion, within 72 hours, when measuring postural sway with a 3-axis inertial sensor. Additionally, concussed athletes had faster anterior-posterior COP displacement and velocity compared to controls during static balance with eyes closed, and the differences between athletes with controls in anterior-posterior and medial-lateral COP velocity was still present at return to play, 26 days after injury.[96]

Researchers have also aimed to investigate if changes in static and dynamic balance occur as a result of athletic participation. In a group of healthy female college aged athletes and non-athletes, significant improvements in BESS scores were observed from pre- to post-season, and no differences were reported between groups.[101] Contact sport athletes have also been targeted in an attempt to identify the influence of contact sport participation and repetitive head impacts on static and dynamic balance. In a group of youth football athletes, there were no significant changes in BESS scores or COP, measured on a force plate, between pre- and post-season. The authors also evaluated the relationship between head impact exposure and quiet stance measures; however, no significant relationships were reported.[102] Similarly, female Olympic-style boxing athletes with no reported concussion were assessed before and after a tournament.[52] Comparable to other literature,[101] the athletes' modified BESS (mBESS) scores significantly improved from pre- to post-tournament assessments.[52] This was similarly reported in NCAA Division I football players, in which BESS scores significantly improved after one year of participation.[106] In contrast, a group of college lacrosse players' BESS scores worsened from pre- to post-season, and 32.4% demonstrated worse performance with an increase in score by at least 7 errors. Additionally, there was a significant positive relationship between BESS performance on the foam pad and head impact kinematics; suggesting greater errors were reported in athletes with higher scores for linear acceleration, head impact criteria, and Gadd Severity Index.[104] Head impact variables were also significant predictors of changes in BESS scores in college football athletes with no concussion occurring over the course of a season.

Interestingly, a greater number of head impacts and greater number of previous concussions predicted improvement during BESS; whereas, worse BESS scores were associated with higher cumulative magnitude of head impacts across as season.[58]

Soccer heading also provides opportunity for repetitive subconcussive head impacts; however, results vary with respect to the effect of soccer heading on postural control. When measured with a Biodex Balance System, there were no significant effects on any balance measure across two weeks after an acute bout of soccer heading.[62] Broglio et al.[107] assessed postural control immediately after linear and rotational soccer heading, and reported no significant difference from baseline assessments. In contrast, Haran et al.[103] reported that postural instability significantly increased 24 hours after soccer heading when compared to a control group. Therefore, based on these inconsistencies, static and dynamic stance as a measure of postural control may not be appropriate in identifying long-term impairments as a result of soccer participation.

A recent study evaluated balance regularity with the Sensory Organization Tests (SOT) among former football athletes 40-65 years old.[99] The study included two groups: a concussion group with 2 or more concussions during high school football, and a no concussion history group. The authors reported former athletes in the concussion history group had greater regularity (lower approximate entropy (ApEn)), suggesting a more conservative and less complex adaptation in postural control,[99] which is consistently reported in athletes with concussion.[84,85] ApEn does not directly measure postural stability, but rather quantifies randomness in system output in which a less random output equates to a system that is more constrained.[108] Therefore, a smaller ApEn value is often reported with larger COP amplitude, indicating greater regularity and decreased postural stability.[85,100] Greater regularity was previously reported by Cavanaugh et al.,[84] as athletes with a concussion demonstrated increased regularity or decreased randomness compared to their preseason measures and healthy controls within 48 hours of injury, despite no changes in postural stability between time-points. A further investigation revealed that this increase in regularity persists beyond 3-4 days post-injury,[85] which is inconsistent with research that identifies postural stability measured with static and dynamic balance to returns to baseline acutely following a concussion.[91,109] Lower ApEn values were also reported for anterior-posterior COP in college football athletes with a history of concussion that occurred at least 9 months prior to testing compared to athletes with no concussion history.[97] Similarly, Sosnoff et al.[100] reported differences in COP oscillation regularity between athletes with and without a history of concussion; however, the differences highlighted more adaptive strategies in the medial-lateral direction for athletes with a history of concussion. Gysland et al.[58] also evaluated the effect of subconcussive impacts across a college football season on SOT, reporting that worse scores from pre-season to post-season were associated with a greater number of years playing college football.[58] Therefore, the majority of research suggests there may be a cumulative effect of concussive and subconcussive impacts on postural control, however a study by Murray et al.[110] reported no significant relationships between kinetic data (i.e., RMS, peak excursion velocity, sample entropy) and head impact kinematics between pre- and post-season.

Conservative balance strategies are commonly observed post-concussion;[90,92] although, time since concussive injury may not influence postural control.[100] The aforementioned studies address adaptions in postural control during static and dynamic balance; however, conservative strategies to maintain postural control following a concussion are also observed during different gait conditions.[94]

Gait

Gait is a functional measurement of postural control that is objective and repeatable[86,89,105,111] and aids in identifying more subtle deficits following concussion, especially beyond acute recovery.[86,89,90,92,93,95,98,105,112] Adaptive strategies in maintaining postural control have been identified during gait assessments following concussion.[86,89,90,92-95] In addition, conservative gait patterns are also reported in athletes with a history of concussion;[94,97] however, it may be important to investigate the influence contact sports participation has on postural control during gait due to conflicting evidence in current literature.[95,111]

Single-Task Gait

Single-task gait, or walking with undivided attention, has been assessed following a concussion. Howell et al.[86] identified high school athletes with a concussion had more conservative step lengths acutely after concussion; however, there were no significant differences between concussed athletes and healthy controls.[86] In contrast, when compared to a control group, shorter single-task stride lengths were observed in athletes with a concussion at an initial visit (9.5±5.2 days from injury).[89] However, no differences were noted in single-task gait after symptom resolution, occurring on average 28 days from injury, between groups.[89] Similarly, no significant differences were reported between college aged participants, with a concussion and controls at any time-point across 28 days on any single-task gait variable.[90] Likewise, Fino et al.[92] observed no differences between concussed athletes and healthy controls during the single-task gait condition across six weeks of recovery. One study, conversely, reported significantly lower gait velocity in participants with a history of one or more concussions that occurred on average 6 years from the testing session, although this was measured with an electronic walkway system.[94]

In consideration of athletes competing in sports with varying levels of contact and athletes vs. non-athletes, Parker et al.[95] compared four groups of college aged athletes and non-athletes (i.e., concussed athletes, concussed non-athletes, uninjured athletes, uninjured non-athletes) across 28 days of concussion recovery. During single-task conditions, gait velocity was slower, and medial-lateral COM displacement and peak velocity was greater in athletes compared to non-athletes regardless of concussion.[95] When comparing athletes with varying levels of contact, Howell et al.[111] observed no significant differences in any gait characteristics (i.e., gait speed, cadence, stride length, gait cycle duration) between healthy contact and non-contact athletes. Similarly, Buckley et al.[113] reported limited adverse relationships between gait performance and repetitive head impacts. The only significant predictors of worse performance were lower medial-lateral COP displacement during the anticipatory postural adjustment and transitional phase of gait initiation.[113] However, Parker et al.[95] reported athletes participating in sports that are more likely to sustain chronic subconcussive repetitive head impacts had greater medial-lateral COM displacement compared to athletes participating in sports that are more likely to endure acute high-velocity head impacts. It is important to note operational definitions of these sport groups were not defined in the study.[95] Despite the contrasting evidence identifying significant changes in postural control during single-task gait conditions, attention divided gait has demonstrated the ability to highlight adaptations in gait characteristics following concussion even beyond an initial assessment.[89,90,92]

Dual-Task Gait

Attention divided gait, or dual-task gait, pairs a cognitive and motor task that highlights adaptations in postural control that may not be identified during quiet stance or single-task gait conditions.[86,89,90,92] These adaptations are proposed to result from increased processing demands that require athletes to prioritize either postural control or cognitive performance.[114-117] Both healthy controls and athletes with a concussion demonstrate significant adaptations to gait when a simultaneous mental task is added,[52,86,89,90,93,95,105,111,112] and Catena et al.[118] suggests concussed athletes show signs of greater instability when a cognitive task is added. However, Resch et al.[119] identified improvements in postural control with a longer reaction time and greater errors during the cognitive task when an auditory switch task was performed congruent with a static postural control task in healthy athletes. This data suggests that in healthy athletes, postural control may be prioritized over cognition, although, these tasks were assessed during SOT rather than a gait task.[119] Parker et al.[120] reported no significant differences between concussed athletes' correct responses during cognitive tasks, yet conservative gait adaptations were reported between groups for temporal-distance and COM gait variables.[120] These studies suggest healthy and patient populations may prioritize cognitive and postural control strategies differently.[117]

Specific variables including slower gait velocity, lower cadence, shorter stride length, shorter gait cycle, greater medial-lateral COM displacement, greater medial lateral COM peak velocity, and anterior COM peak velocity are all adaptations in gait that occur in dual-task conditions when compared to single-task conditions.[52,86,95,111] Additionally, a more complex cognitive task or motor task during a dual-task condition may have greater impacts on postural control during gait.[105,115] Dual-task cost, or the percent change from a single- to a dual-task condition, is greater with a more complex cognitive task.[105] Additionally, the percent change between single-task to dual-task conditions significantly greater in adolescent athletes with a concussion compared to healthy controls across two months post-injury.[86] Moreover, adaptations in postural control assessed during a dual-task condition may be identified beyond resolution of impairments in neurocognitive performance.[98]

Similar to single-task conditions, temporal-distance outcome variables are commonly assessed during dual-task gait following concussion. Berkner et al.[89] observed athletes with a concussion had shorter stride lengths compared to the control group during dual-task gait at an initial visit, approximately 10 days from concussion, similar to a single-task gait condition. However, impairments in gait characteristics persisted beyond symptom resolution which was on average 28 days post-concussion, as athletes with a concussion demonstrated slower average gait speed, smaller cadence, and shorter stride lengths while walking in a dual-task condition compared to controls.[89] Fino et al.[92] reported that college athletes with a concussion walked slower compared to controls during a dual-task gait condition. Comparably, Parker et al.[95] assessed college-aged participants in four groups (i.e., concussed athletes, concussed non-athletes, uninjured athletes, uninjured non-athletes) across 28 days after injury. The authors reported that both concussed and non-concussed athletes walked slower (lower gait velocity) than concussed and non-concussed non-athletes.[95] In contrast, Howell et al.[111] reported no significant differences for dual-task temporal-distance gait characteristics (i.e., gait speed, cadence, stride length, gait cycle duration) between healthy athletes in contact and non-contact sport groups. Although, it is noteworthy that during dual-task standing and walking conditions, non-contact sport athletes had significantly better mean cognitive task accuracy, number of total correct responses divided by total number of provided items, compared to contact sport athletes during the Mini-Mental Status Examination.[111] Buckley et al.[113] compared gait between football players, while also measuring repetitive head impacts, and cheerleaders pre- and post-season. There were no significant group by time interactions reported for dual-task stepping characteristics, or COP displacement for gait initiation or gait termination.

In addition to temporal-distance outcome variables, COM outcome variables during dual-task gait are often affected. During a dual-task condition using an auditory Stroop test, correctly identifying pitch of a word (high pitch, low pitch) while ignoring if the congruent meaning and pitch matched, Howell et al.[86] observed that adolescent athletes with a concussion had a greater reduction in peak anterior COM velocity compared to controls. This was also observed in young adults with a concussion as they demonstrated significantly less peak COM anterior velocity during a dual-task condition compared to controls at 72 hours after injury.[93] Comparably, during attention divided gait using a question and answer paradigm, participants with a concussion had reduced anterior COM displacement and anterior COM velocity within 48 hours of injury compared to controls.[90]

Adaptations in medial-lateral COM displacement and COM peak velocity are also observed following a concussion. Athletes with a concussion had significantly greater medial-lateral displacement during dual-task gait within 37 hours,[121] and across two months post-injury compared to controls.[86] These results were similarly reported in a study of adolescents and young adults, in which the athletes with a concussion had greater medial-lateral COM displacement across a two-month recovery; however, the differences in the young adult group did not reach significance.[93] In a study of college aged athletes and non-athletes, Parker et al.[95] reported athletes with a concussion demonstrated greater medial-lateral COM displacement compared to non-athletes both with and without a concussion. Interestingly, athletes without a concussion also had greater medial-lateral COM displacement compared to non-athletes with a concussion.[95] Congruent with medial-lateral COM displacement, at two months post-injury, adolescents with a concussion demonstrated significantly greater medial-lateral COM peak velocity compared to control athletes during dual-task gait.[93] Likewise, college aged athletes, both with and without a concussion, had greater medial-lateral COM peak velocity compared to non-concussed controls.[95] Parker et al.[95] further compared outcome variables in athletes participating in sports with a greater likelihood of low-velocity subconcussive impacts to athletes participating in sports with high-velocity head impacts. Athletes in the low velocity repetitive head impact group demonstrated greater medial-lateral COM displacement, however the separation of sports into these groups were not defined.[95]

The aforementioned studies evaluated concussed and non-concussed participants from adolescence to young adulthood across recovery; yet, the studies do not account for athletes' resumption of pre-activity levels. In a study by Howell et al.,[112] the authors analyzed gait characteristics following a concussion at two recovery levels, pre-return to activity and post-return to activity. Specific to the dual-task condition, there were significant improvements in medial-lateral COM displacement, suggesting improvements in postural control; however, after return to pre-injury activity levels, athletes with a concussion demonstrated significantly worse medial-lateral COM control.[112] These data suggest athletes may not be functionally ready to return to activity, and may leave athletes with a concussion vulnerable to further injury.[122]

Tandem Gait

Similar to a dual-task condition, a more complex motor task can also influence gait performance.[105,115] An example of a more complex gait task is tandem gait, or walking in a straight line using a heel-to-toe pattern. Normative values for tandem gait in healthy participants have previously been established,[123-125] and authors have evaluated tandem gait at acute assessments following concussion. Oldham et al.[126] reported that college aged athletes, evaluated acutely following a concussion, took longer to complete a tandem gait task compared to baseline, and these differences were not observed in control athletes. Additionally, greater sensitivity and specificity were reported for tandem gait compared to BESS or mBESS at an acute assessment following a concussion.[126] Similarly, Howell et al.[127] reported slower completion times and significantly lower cadence for tandem gait in concussed athletes within 72 hours of their concussion compared to controls. However, Hanninen et al.[128] evaluated professional ice hockey athletes and reported no significant differences in tandem gait completion times between athletes on the day of their injury and their baseline times or compared to league norms. Similar to the previously mentioned gait studies, tandem gait completion times have been compared between contact and non-contact athletes, and athletes with and without a history of concussion; however, no significant differences were reported.[123]

Catena et al.[118] combined a complex motor task (i.e, obstacle walking) with a concurrent cognitive task, and reported slower gait velocity during the dual-task obstacle condition compared to single task gait in concussed athletes compared to controls. In addition, concussed athletes took longer to complete a stride in dual-task obstacle walking, and had a wider step during obstacle walking.[118] Tandem gait has also been studied during dual task conditions. Howell et al.[127] reported slower tandem gait completion times at 72 hours, 1 week, and 2 weeks after injury in concussed athletes compared to controls. Cadence was also significantly lower in athletes with a concussion across two months of recovery during the dual-task condition compared to controls.[127] In addition, during tandem gait for both single- and dual-task conditions, medial-lateral COM displacement was greater in concussed athletes that took longer to complete the task.[127] These results suggest that a complex gait condition with an added cognitive task may identify lasting deficits in postural control resulting from a concussion. However, studies evaluating dual-task tandem gait are limited to acute analyses.

Vestibular Ocular Motor Impairment

SRC assessments should include a vestibular ocular motor component as patients report vestibular and ocular motor impairments following a concussion.[129-135] Mucha et al.[130] developed the Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate vestibular and ocular motor impairments after sustaining a concussion. During this assessment, patients are asked to report symptom provocation on a scale of 0 (none) to 10 (severe) after a series of 7 components (smooth pursuit, horizontal saccades, vertical saccades, near point of convergence (NPC), horizontal vestibular ocular reflex (VOR), vertical VOR, and visual motion sensitivity (VMS)), and NPC distance while an accommodation task is recorded.[130] Symptom provocation during the VOMS assessment is scored by summing the total symptom provocation score of each component, or by computing the change score (total symptom provocation score – pre VOMS administration symptom score).[129] A clinical cutoff score of ≥ 2 or NPC distance ≥ 5 cm was developed by Mucha et al.[130] to aid in identification of vestibular and ocular impairments following an SRC.

In an investigation of the VOMS across three test sessions in healthy high school athletes, Worts et al.[136] reported minimal provocation of symptoms as no VOMS component yielded scores above the clinical cutoff. In contrast, Elbin et al.[129] administered the VOMS to high school athletes after sustaining a concussion and identified that symptoms were provoked after completing each VOMS component at two acute assessments, within one and two weeks after injury. Specifically, when using total symptoms, athletes reported an increase in provoked symptoms within one week and two weeks of injury for each VOMS component.[129] However, when assessed with change scores, the only VOMS component to provoke symptoms at the second assessment compared to baseline was vertical VOR and VMS.[129] Sufrinko et al.[134] also used the VOMS to identify patients with a concussion that had a greater risk of recovery lasting ≥ 14 days, reporting patients with greater symptom provocation during the VMS component at an initial assessment had an increased risk for a prolonged recovery. Similarly, Anzalone et al.[131] identified concussed athletes, aged 11-19 years, that reported symptom provocation or a clinical abnormality on at least one VOMS component had longer recovery than athletes with no symptom provocation or clinical abnormalities. In another study, Sufrinko et al.[133] administered the VOMS and a CNT to participants aged 14-26 years at two time points, within 1-10 days and 11-20 days of injury, after sustaining a concussion to compare those with high motion sickness susceptibility and no motion sickness susceptibility. No differences between motion sickness susceptibility groups on CNT scores were reported.[133] Also there was no association between motion sickness susceptibility groups and VOMS component scores above clinical cutoff levels at the first assessment; however, patients with high motion susceptibility had a greater risk of VOMS component scores above clinical cutoff levels at the follow-up assessment.[133]

Risk factors for vestibular and ocular impairments following VOMS administration are also studied in current literature. Kontos et al.[137] evaluated risk factors of VOMS outcomes in a sample of healthy college athletes. Athletes were more likely to report symptom provocation above clinical cutoff levels on great than or equal to one VOMS component if they reported a personal history of motion sickness and/or had an immediate family member with a history of motion sickness, or if they were female.[137] Interestingly, histories of migraine or previous concussion were not predictors of symptom provocation above clinical cutoff levels on ≥ one VOMS component.[137]

However, symptom provocation following a vestibular or ocular motor task is not the only indicator of impairment following a concussive impact. Mucha et al.[130] identified greater

NPC distance in concussed athletes compared to healthy controls, with a mean difference of 4.0 cm. Similarly, Elbin et al.[129] reported NPC distance was significantly greater within 1 week and within 2 weeks of injury compared to their baseline assessments in high school athletes with a SRC. In addition, deficits in NPC after sustaining a SRC are reported to relate to adaptations in single-task and dual-task gait.[132] Howell et al.[132] reported concussed athletes with NPC distance ≥ 5 cm walked slower and had shorter stride lengths that was not reported in athletes with NPC distance below clinical cutoff and healthy controls. Interestingly, these ocular motor impairments may not persist over time. van Donkelaar et al.[138] measured NPC distance at baseline in a group of college aged male contact sport athletes and compared scores between those with and without a history of concussion. There were no significant differences in NPC distance between athletes with and without a previous history of concussion.[138] This was similar to the results reported by Kontos et al.,[137] as no risk factors were identified for abnormal NPC outcomes.

Despite the few studies reporting non-significant differences in NPC distance between athletes with and without a history of concussion, recent evidence suggests there is a relationship between adaptations in ocular motor performance and repetitive head impact exposure over the course of a season.[139] Kawata et al.[140] compared NPC distance in healthy adults at acute assessments before and after repetitive soccer heading between a soccer heading group and controls. Adults' NPC distance in the soccer heading group were significantly worse at baseline immediate following soccer heading and at 24 hours after completing the soccer headers.[140] There were no significant changes in NPC distance in the control group across the three test times.[140] In another study, Kawata et al.[141] measured head impact exposure and NPC distance in Division I football athletes, comparing high head impact and low head impact groups throughout a preseason football camp. At baseline, there were no differences in NPC distance between groups; however, athletes NPC distance in the high head impact group worsened across time when measured before and after completing a full-pads practice session.[141] The authors also reported that the differences in NPC distance between high head impact and low head impact groups resolved by the post-season follow-up visit.[141] The results of this study open an area for debate as NPC abnormalities were related to repetitive subconcussive head impacts, yet the limitations of this study include limited methodologies for measuring impairments in convergence by only measuring accommodation distance while not accounting for confounding factors including fatigue and exercise warranting more research.[141,142] Nevertheless, these studies suggest ocular motor impairments exists at acute stages following repetitive head impacts, warranting future investigations of the long-term effects of repetitive head impacts and contact sport participation on vestibular and ocular motor systems.

Health Related Quality of Life

Health Related Quality of Life in Athletes and Non-Athletes

The World Health Organization (WHO) defines health as, not just the absence of physical disease/injury/illness, but complete physical, mental, and social well-being.[143] Therefore, when measuring health related quality of life (HRQoL), or the impact of health on an individual's quality of life, it is important to evaluate health status, self-reported well-being, and life satisfaction.[144,145] Wilson et al. [145] developed a conceptual model of HRQoL that incorporates characteristics of the environment (i.e., psychological, social, physical components of health)[145,146] and of the individual (i.e., symptom amplification, personality motivation, and values preferences). When measuring HRQoL, a holistic approach that includes the disease/injury and resulting impairments or limitations should capture the impact of a disease or injury on patient's daily function using patient reported outcomes.[145,147-149]

Chronic injuries and illnesses of various severity levels can influence multiple domains of HROoL (i.e, physical, functional, emotional, mental, social).[150-158] The effect of current injury and a history of injury on HRQoL was explored in a meta-analysis by Houston et al.[158] The authors reported an overall moderate effect size (0.68) for uninjured athletes having better HRQoL compared to injured athletes, and athletes with a current injury yielded the strongest effect sizes.[158] Comparably, in a sample of 467 Division I and Division II athletes, athletes with a current injury indicated greater physical impairments and decreased well-being compared to athletes with and without a history of injury.[150] Additionally, athletes with a more recent injury reported greater physical impairment compared to athletes with a history of injury that occurred greater than one year prior to survey administration.[150]

HRQoL scores may also be positively influenced by physical activity.[150,159-161] In a meta-analysis of HRQoL of athletes and non-athletes, it was suggested that athletes reported better HRQoL compared to non-athletes; however, these results should be interpreted with caution due to small effect sizes (0.27).[158] Houston et al. 2017[150] reported that college athletes participating in their sport with a current injury demonstrated lower physical HRQoL compared to athletes competing in full participation. However, athletes participating with an injury demonstrated better HRQoL compared to athletes not participating in sport due to injury.[150] Nonetheless, these differences were not present for the mental domain of HRQoL between athletes participating with a current injury and athletes that were out of sport due to injury.[150]

It also may be beneficial to investigate HRQoL beyond current physical activity and athletic participation, by exploring varying levels of participation in contact sports especially of former athletes. For example, former professional football athletes report high injury incidences resulting from participation, and are over 3 times more likely to report osteaoarthritis compared to the general population,[162] which was previously described as a chronic condition that affects HRQoL.[148] Similarly, over 84% of former collegiate football players reported a history of at least one previous concussion, and those with a greater number of previous concussions (i.e., ≥ 3) had worse mental health and depression outcomes.[163] In addition, former Division I college athletes that participated in collision sports had worse HRQoL outcomes than limited contact or non-contact athletes.[149] However, in a study of former female athletes aged 40-70, Stracciolini et al.[164] suggested females that participated in college sports reported better overall health, exercised more than three times per week or daily, were less likely to smoke or do recreational drugs, and lower proportions reported high cholesterol, hypertension, or obesity compared to non-athletes. Although, female athletes had worse mobility scores on the Neuro-QoL and increased anxiety compared to non-athletes.[164] Therefore, more research is needed to understand if former participation in sports at varying contact levels, especially in understudied populations (i.e., former high school athletes), influences HRQoL.

Current evidence suggests HRQoL may be impacted as a result of injury and contact sports participation at higher participation levels. Simon et al.[148] evaluated self-reported HRQoL using the PROMIS (Patient-Reported Outcomes Measurement Information System) in former NCAA Division I athletes and non-athletes, aged 53.36 ± 7.11 years. The PROMIS included scales for anxiety, depression, fatigue, pain interference, sleep disturbance, physical function, and satisfaction with social roles. Higher scores for physical function and satisfaction with social roles indicate better HRQoL, whereas high scores for all other scales suggest worse HRQoL.[148] HRQoL scores were worse in former NCAA Division I athletes that reported significantly more major injuries, chronic injuries, daily limitations, and physical activity limitations compared to non-athletes.[148] Specifically, former collegiate athletes had worse scores for physical function, depression, fatigue, sleep, and pain compared to non-athlete controls.[148]

However, not all former NCAA Division I athletes participated in sports with the same level of contact. A more recent investigation of HRQoL split former collegiate athletes, aged 40-65 years, into three groups (e.g., collision, contact, and limited contact).[149] Using the Short Form 36 Version 2 (SF36v2), athletes in the collision group had worse scores on all eight domains (physical function, role physical, bodily pain, general health, vitality, social functioning, role emotional, mental health) compared to the limited contact group, and worse scores on 7/8 domains (except social functioning) compared to the contact group.[149] The contact group had worse scores on 6/8 domains (i.e., physical function, role physical, bodily pain, general health, role emotional, and mental health) compared to the limited contact group.[149] Similarly, Kerr et al.[165] found former Division I athletes between the ages of 22-51 years, in low or non-contact sports, to have better physical HRQoL composite scores compared to former high contact or collision sport athletes on the Veterans RAND 12-Item Health Survey (VR-12). Yet, no differences were reported in mental HRQoL composite scores between sport types. These results suggest there are differences in HRQoL between former collegiate athletes that competed in varying contact levels, with the greatest differences reported between athletes that participated in collision sports compared to limited contact athletes.

HRQoL scores in former collegiate athletes have also been compared to general populations of the United States. Using the PROMIS, former NCAA Division I athletes had worse scores on the physical function and pain interference scales compared to the US population; whereas, the non-athlete controls had better HRQoL scores on physical function, depression, and pain interference compared to the US population.[148] In contrast, Kerr et al.[165]

reported slightly better scores for physical and mental health compared to the general population. When former Division I athletes were separated into collision, contact, and limited contact groups, athletes in the collision group had worse scores for physical role functioning, bodily pain, social role functioning, and emotional role functioning domains on the SF36v2 compared to the general population.[149] Former athletes in the contact group and limited contact group had better scores for vitality and mental health domains compared to the general population.[149] These results suggest that long-term effects on HRQoL may vary by the type of former athletic activity (i.e., collision sport). The aforementioned studies evaluate HRQoL in former athletes participating in varying levels of contact; however, they do not account for impairments in HRQoL that may result from a history of mTBI, concussion, or repetitive subconcussive head impacts.

Health Related Quality of Life and Mild Traumatic Brain Injury

Early studies suggest no effect of mTBI on HRQoL throughout recovery;[166] however, recent evidence is demonstrating otherwise. Zonfrillo et al. 2014[167] measured HRQoL with the Pediatric Quality of Life Inventory (PedsQL), and suggested 11-13% of patients had decreased HRQoL at 3- to 12-months post-mTBI, respectively. In addition, symptoms resulting from mTBI are suggested to relate to HRQoL, and are commonly studied in adolescent populations.[168,169] A presence of symptoms acutely and longitudinally following mTBI (i.e., 3-12 months post-injury) were reported to predict HRQoL in children aged 8-15 years.[170,171] Worse physical HRQoL, measured with the Child Health Questionnaire (CHQ-PF50), is related to the presence of greater somatic symptoms at 3- and 12-months post-mTBI.[170] In addition, worse scores for psychosocial HRQoL were apparent at 3-months post-mTBI when somatic and cognitive symptoms were reported.[170,171] Similarly, in 5-18 year olds diagnosed with an mTBI in the emergency room, 30.6% (n = 510/1667) had persistent post-concussion symptoms and demonstrated worse HRQoL.[172] Those with persistent symptoms had significantly worse HRQoL scores at each follow-up assessment across 12-weeks compared to those without a mTBI.[172] In addition, a study of mTBI patients aged 13-18 years also found impairments in cognitive and physical HRQoL at an initial visit, and reported patients that developed post-concussion syndrome (i.e., one or more symptoms lasting 1-month or longer) had worse HRQoL scores in all domains (e.g., cognitive, social, emotional, physical) at the initial assesement.[169] Other predictors of poor HRQoL at a 3-month assessment include female sex, older age, Hispanic ethnicity, household income, lower education degree achieved of parents, history of previous concussion, migraine, learning disability, and anxiety.[167,172] At a 12-month assessment, household income, lower education level of parents, and Medicaid verses private insurance all predicted worse HRQoL scores.[167] HRQoL scores are also significantly related to traditional assessment tools for concussion and mTBI (e.g., symptom severity, Balance Error Scoring System (BESS), Standardized Assessment of Concussion (SAC), time loss), and therefore provide a valuable added component to management of such injuries.[147]

HRQoL outcomes are also compared between patients with mTBI and patients with either orthopedic injury, or non-injured controls. Moran et al.[170] suggested adolescent patients with mTBI had worse physical HRQoL at 12-months post-injury compared to adolescents with an orthopedic injury. This study also reported patients' physical HRQoL in the mTBI group remained constant over a 12 month period following injury; whereas, patients in the orthopedic injury group demonstrated improvements in physical HRQoL between 1 and 12 months.[170] In contrast, Pieper et al.[173] reported no differences in HRQoL at 12-months post injury between children aged 5-17 years with mTBI, orthopedic injury, and uninjured controls. However, adolescents in the orthopedic injury group had worse physical HRQoL scores compared to the mTBI group at 1 month post-injury.[173] These results are supported by a recent investigation of collegiate athletes, identifying greater physical impairments closer to the date of injury.[150] It is however noteworthy that Pieper et al.[173] reported a significantly older sample in the orthopedic injury group compared to the mTBI group, and older age is reported to be a predictor of worse HRQoL outcomes in an adolescent population.[167]

There is limited research investigating HRQoL following mTBI in adults. However, Emanuelson et al.[174] reported adults, average age 32 years, had worse scores in all domains of the SF-36 at 3-months and one-year post mTBI. Similar to reports of adolescent populations, adults with a greater number of symptoms also had worse HRQoL scores. In an investigation of adults with mTBI or trauma controls seen in the emergency department, Ponsford et al.[175] reported worse mental HRQoL in mTBI patients within 48 hours, 1-week, and 3-months following their injury compared to controls.

Health Related Quality of Life and Concussion

The literature surrounding HRQoL and concussion is continuously growing, especially with respect to adolescent athletes. Valovich McLeod et al.[176] evaluated HRQoL across different lengths of concussion recovery (e.g., short: 0-7 days, moderate: 8-13 days, prolonged: ≥ 14 days) in adolescent athletes. The authors reported overall HRQoL, measured with the PedsQL, was worse on day 3 and day 10 for athletes with a prolonged recovery.[176] Athletes with prolonged recovery also had worse physical functioning and school functioning scores on day 3 and day 10 compared to athletes with short or moderate recovery, and social functioning was worse on day 3 for athletes with prolonged recovery compared to those in the short recovery group.[176] However, Plourde et al.[177] performed a long-term investigation of HRQoL comparing patients with a concussion history and patients with a history of orthopedic injury that occurred on average 2.7 years prior. There were no significant differences in HRQoL or psychosocial functioning between athletes with multiple concussions, a single concussion, or orthopedic injury.[177] These results however were limited to recall bias and did not account for athletes with variable lengths of recovery. Therefore, the conflicting results warrant more research in this area. In addition to concussion history, and prolonged symptoms and recovery, sex may also contribute to HRQoL outcomes after a concussion in youth athletes. Vassilyadi et al.[178] reported athletes with a concussion had more HRQoL impairments compared to normative data, and female athletes with a concussion had worse HRQoL outcomes compared to males.

The relationship between concussion history and HRQoL has also been investigated in older athletes. Kuehl et al.[179] evaluated HRQoL in athletes that participated in college sports at the time of testing, and reported athletes with a history of ≥ 3 concussions had worse scores for bodily pain and social functioning compared to athletes with a history of 0, or 1-2 concussions. College athletes with a history of ≥ 3 concussions also had worse vitality than athletes with no history of concussion.[179] Similarly, Kerr et al.[165] indicated that former Division I athletes with a history of ≥ 3 concussions had significantly worse HRQoL physical composite scores when compared to athletes with a history of 0, or 1-2 concussions. No significant differences were reported for mental composite scores.[165] Additionally, athletes with a greater number of previous concussions reported higher scores on the Headache Impact Test (HIT-6), suggesting a lingering effect of headaches that impact HRQoL.[179]

Kerr et al.[163] also evaluated HRQoL in former college football athletes aged 33-38 years using the VR-36, and compared the results to the national average. The authors reported 22% and 39% of the participating former football athletes had worse physical HRQoL scores and mental HRQoL scores, respectively, compared to the national US population average.[163] However, significant differences were only found for mental HRQoL in which athletes with a history of ≥ 3 concussions were 2.2-2.5 times more likely to have scores below the national average when compared to athletes with 1-2 previous concussions or no concussion history, respectively.[163] The results of this study may help to explain the conflicting results in adolescent populations, as the differences in HRQoL were only apparent for general mental health and in former athletes with a history of ≥3 concussions.

Health Related Quality of Life and Repetitive Head Impacts

Recent evidence suggests 33% of former college athletes did appropriately report suspected concussions;[18] and at the high school level, the percentages for non-disclosure of suspected concussions or bell-ringer events are even higher.[79] Due to these non-disclosure rates, it may also be important to evaluate HRQoL in sports with high incidence of repetitive head impacts. Chrisman et al.[64] studied head impact exposure and HRQoL in youth soccer athletes that did not sustain a concussion, and reported no significant differences between assessments at baseline and post-one-month of game play. This study, however, was limited to one sport, and does not account for repetitive head impacts sustained throughout an athletic career. In contrast, Grysland et al.[58] reported that an increase in symptoms from pre- to post-season in football athletes was predicted by greater number of head impacts above 90 *g*s, a greater number of impacts to the top of head, and more years of college football participation. Additionally, significant relationships have previously been identified between symptom severity and HRQoL,[168-172] therefore warranting further investigation. Furthermore, studies investigating former athletes with various levels of contact sport participation suggest differences in HRQoL outcomes, yet these studies did not account for repetitive subconcussive head impacts.[149,165]

Likewise, much of the evidence that is investigating the long-term influence of athletic participation on HRQoL is in elite or collegiate athletes; whereas, a large population of former athletes stems from the understudied high school population.[11,12] In efforts to address this knowledge gap, future research should evaluate current HRQoL in former high school athletes.

Conclusions

Current literature identifies acute and lasting impairments resulting from SRC in a multifaceted arena of clinical assessments. However, there is limited evidence suggesting these persistent impairments exist as a result of contact sport participation. Largely, the identification of cognitive impairments in athletes with a previous history of concussion and exposure to repetitive head impacts has predominated current literature.[50,66,67,71,75,76] In addition, assessment tools beyond those used as screening tools for SRC (e.g., modified flanker) may be more appropriate in identifying persistent impairments, especially later in life.[43-47] Moreover, research investigating additional SRC outcomes including adaptive gait strategies,[86,89,90,92-95] vestibular and ocular motor impairments,[129-132,134] and HRQoL[176,178] is growing; and the persistent effects of a previous history of concussion on these clinical outcomes have also been identified.[94,97,163,165,179] Yet, there are gaps in the current understanding of the influence that contact sport participation has on each of these clinical outcomes.

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CHAPTER THREE: THE INFLUENCE OF HIGH SCHOOL CONTACT SPORTS PARTICIPATION ON BASELINE COMPUTERIZED NEUROCOGNITIVE FUNCTION

Abstract

Context: Deficits in neurocognitive function following concussion are widely studied. However, high school contact sports participation places student-athletes at risk for sustaining repetitive head impacts below the threshold of concussion, and the cumulative effects of such impacts are currently unknown. **Objective:** To retrospectively evaluate neurocognitive performance in healthy student-athletes participating in high and moderate levels of contact sports across two seasons of participation. **Design:** Retrospective cross-sectional study. **Setting:** High school. **Patients or Participants:** Two-hundred and ninety-four student-athletes (high contact: n = 142, male n = 120; moderate contact: n = 152, male n = 152). **Main Outcome Measure(s):** Student-athletes were administered a baseline neurocognitive test battery (Immediate Post-Concussion and Cognitive Testing (ImPACT)) at two separate occasions on average 2.21 ± 0.5 years apart. A high contact group (cheerleading, football, ice hockey, soccer, wrestling) and moderate contact group (baseball, basketball, gymnastics, lacrosse, softball, volleyball) were compared on ImPACT composite scores with alpha level set at .05. **Results:** There were no significant interactions between the two baseline administrations and contact levels (p = 0.124 - 0.766). There were no significant improvements in composite scores over time (p = 0.062 – 0.823). There were significant differences between contact levels for Visual-Motor Speed (F (1, 275) = 9.764, p = .002) and Reaction Time (F (1, 275) = 4.988, p = .026). **Conclusions:** Athletes participating in high contact sports demonstrated worse scores for Visual-Motor Speed and Reaction Time. **Key Words:** concussion, youth, sports

Introduction

As of the 2017-18 academic year, over 7.9 million student-athletes were participating in sport at the high school level.[1] However, the National Federation of State High School Associations also reported a decline in football participation and speculates that the risk of concussion and the long-term effects of such injuries may be influencing factors of decreased football particiaption.[1] The overall rate of sport-related concussion (SRC) is 3.89 per 10,000 athlete exposures (AEs) in high school sports,[2] with the highest incidence commonly reported to occur in football, boys' ice hockey, boys' lacrosse, boys' and girls' soccer, wrestling, and girls' basketball.[2-5] The acute neurocognitive effects of a concussion are established in current literature;[6,7] yet, repetitive head impact exposure occurs in the absence of a diagnosed concussion. Little is known about the influence participating in high school contact sports and the cumulative effects repetitive head impact exposure has on neurocognitive function.

The total amount of repetitive head impacts that a high school athlete sustains varies on based on the sport, and researchers primarily focus on recording repetitive head impacts in sports with more contact.[8-10] Some argue that participation in high contact sports leaves athletes at risk for cognitive impairment;[11] however, the acute and long-term effects of repetitive head impact exposure occurring in high school contact sports on neurocognitive function are inconsistent in current literature.[12-18] Football participation has been a focus of study by researchers in an attempt to understand long-term neurocognitive effects of cumulative head impacts.[8,18-27] In high school athletes, no significant neurocognitive declines were reported following one season of participation between football and non-contact athletes.[13] In fact, the authors reported improvements in learning and working memory from pre- to post-season when assessed with CogState, a neurocognitive test battery.[13] Similarly, Rose et al.[18] reported repetitive head impact exposure in football did not predict any cognitive changes from pre-season to post-season. Soccer participation and its effect on neurocognitive outcomes is also studied due to exposure to soccer heading exposure,[28] yielding similar results to those found in football. These results are similarly reported for soccer. soccer athletes.[15,17] In contrast, in an estimate of the cumulative amount of repetitive head impact exposure across a football athlete's career, it's suggested that the repetitive head impact exposure typically sustained in two seasons of participation substantially increases the risk for cognitive impairments.[25] As such, evaluating cognitive impairments after one season of play may not be appropriate in identifying long-term effects.

Evaluations of repetitive head impact exposure and the burden of such repetitive head impacts is limited to the current studies of select high school sports. Tsushima et al.[11] assessed baseline computerized neurocognitive test scores in high school athletes participating in varying levels of contact sports. The high school sports were categorized into high (i.e., wrestling, martial arts, cheerleading, track and field, and football), moderate (i.e., softball, baseball, soccer), and low (i.e., softball, baseball, soccer) contact based on highest risk of concussions in their sample.[11] The high contact group had worse baseline neurocognitive test scores than the moderate contact group on visual memory, processing speed, and impulse control.[11] In addition, the high contact group performed worse on visual memory, processing speed, reaction time, and impulse control compared to the low contact group at baseline.[11] These results suggest neurocognitive impairments may result from contact sport participation. However, the authors only assessed baseline computerized neurocognitive test scores prior to the start of one season, which typically occurs early in a high school athlete's athletic career. Thus limiting the interpretation that such the reported neurocognitive declines are a result of the cumulative effect of high school contact sports participation. Due to previous studies identifying changes in baseline neurocognitive test scores over time,[17,29] an additional test time during athletes' high school athletic career may further elicit a relationship between neurocognitive performance and high school contact sports participation. Therefore, the purpose of this study was to retrospectively compare neurocognitive function in healthy student-athletes across two seasons of participation in high and moderate contact high school sports. We hypothesized that high school athletes participating in high contact sports will have worse neurocognitive function compared to moderate contact sport athletes.

Methods

Research Design

A retrospective cross-sectional design was used for this study. The BLANK University Institutional Review Board determined this study was exempt due to de-identifiable data. Baseline testing took place at four local high schools and occurred in a quiet computer laboratory at each high school. All student-athletes were administered ImPACT at baseline prior to the start of their respective competitive seasons by a certified athletic trainer. All student-athletes were administered ImPACT at a second baseline assessment on average of 2 years following their first baseline assessment. Each baseline assessment took approximately 30 minutes to complete.

Participants

To be included in this study, high school student-athletes were required to complete two separate pre-season baseline assessments approximately 2 years apart. Student-athletes were included in this study if they self-reported previous concussion history, diagnosed learning disability, diagnosed attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD), or a history of treatment for headache and/or migraine. However, significant differences between groups on these factors will be used as covariates due to their influence on baseline computerized neurocognitive test scores.[18,30-33] The level of sport contact was determined from previous studies evaluating high school sports at the greatest risk for sustaining a concussion.[5,34] High school sports were separated into high (football, ice hockey, soccer, wrestling, cheerleading) and moderate (baseball, basketball, gymnastics, lacrosse, softball) contact based on the rate of concussion occurrence in high school sports.[5,34]

Instrumentation

Immediate Post-Concussion and Cognitive Testing (ImPACT): ImPACT is a neurocognitive concussion test that is comprised of three components including demographics, symptoms, and neurocognitive testing. The demographic component includes self-reported age, sex, previous concussion history, learning disability, attention deficit hyperactivity disorder (ADHD), and a history of treatment for headache and migraine. The symptom assessment includes 22-items rated on a 7-point Likert scale from 0 (none) – 6 (severe). The Total Symptom Score is generated by summing the total score of each item, and ranges from 0 to 132. The neurocognitive assessment yields five composite scores (verbal memory, visual memory, visual-motor speed, reaction time, and impulse control) from six subscales (immediate and delayed word recall, immediate and delayed design memory, X's and O's, symbol match, color match, three-letter memory).[35] Invalid baseline assessments; flagged test based on any of the following: X's and O's total incorrect > 30, Impulse Control > 30, Word Memory Learning % correct < 69%, Design Memory Learning % correct < 50%, or Three Letters total letters correct < 8;[36] were not included in this study. ImPACT is reported to be a valid and reliable assessment for concussion, with a sensitivity and specificity of 91.4% and 69.1%, respectively.[35,37]

Statistical Analysis

Descriptive statistics are presented for participant characteristics in frequencies for categorical variables (i.e., sex, ADD/ADHD, learning disability, treatment for headaches, treatment for migraines, concussion history), and means and standard deviations for continuous variables (i.e., age, time interval between baseline neurocognitive administrations). First, participant characteristics compared between groups. Due to the violation of normality, differences in age and time between baseline administrations were assessed with the Mann-Whitney U test. Differences in sex, ADD/ADHD, learning disability, treatment for headaches, treatment for migraines, and concussion history were assessed using chi-square test, and Fishers exact test when expected cell counts were small. Second, separate 2 Group (high contact, moderate contact,) X 2 Time (Season 1, Season 2) repeated measures analysis of covariance (ANCOVA) were used to assess significant interactions between level of contact and time on ImPACT composite scores and the Total Symptom Score. Due to significant group differences, the covariates included sex, age and self-reported diagnosis of ADD/ADHD. All analyses were performed using SPSS with significance set a priori to $p < .05$.

Results

A total of 294 athletes (high contact: n = 142, 48.3%; moderate contact: n = 152, 51.7%) completed two separate neurocognitive baseline assessments, on average 2.21 ± 0.5 years apart. The majority of athletes competed in football (n = 94/142, 66.2%) and soccer (n = 36/142, 25.4%) in the high contact group, and basketball (n = 39/152, 25.7%) and lacrosse (n = 33/152, 21.7%) in the moderate contact group (Table 1). Descriptive statistics are reported in Table 2. Sex, age, and ADD/ADHD were significantly different between the two groups at the first baseline administration. Age was significantly different between groups at the second baseline administration. There were no other significant differences between participant characteristics at either baseline administration (Table 2).

Table 1. Athlete Sport Participation

High Contact (n = 142) n (%)			Moderate Contact (n =152) n (%)		
Cheerleading	5	(3.5)	Baseball	22	(14.5)
Football	94	(66.2)	Basketball	39	(25.7)
Ice Hockey	3	(2.1)	Gymnastics	7	(4.6)
Soccer	36	(25.4)	Lacrosse	33	(21.7)
Wrestling	4	(2.8)	Softball	24	(15.8)
			Volleyball	27	(17.8)

Table 2. Participant Characteristics at each Baseline Assessment

	High Contact (n = 132) n (%)		Moderate Contact (n = 148) n (%)		*p*
Sex (*male)*	110	(83.3)	66	(44.6)	<.001
Time Interval, *years* (M(SD)	2.21	(0.5)	2.22	(0.5)	.929
First Baseline Administration					
Age, *years* (M (SD))	14.09	(0.6)	14.41	(0.7)	<.001
ADD/ADHD	13	(9.8)	2	(1.4)	.004
Learning disability	0	--	1	(0.7)	1.000
Treatment for headaches	13	(10.4)	19	(13.3)	.590
Treatment for migraines	11	(8.8)	14	(9.8)	.946
Concussion history					.920
1	15	(11.4)	20	(13.5)	
2	4	(3.0)	2	(1.4)	
≥ 3	0	--	1	(0.7)	
Second Baseline Administration					
Age (*years*, M (SD))	16.27	(0.8)	16.58	(0.8)	.001
ADD/ADHD	9	(8.1)	6	(4.3)	.317
Learning disability	1	(0.8)	0	--	.471
Treatment for headaches	11	(9.3)	18	(13.0)	.460
Treatment for migraines	8	(6.8)	13	(9.4)	.590
Concussion history					.939
1	26	(21.3)	33	(23.1)	
2	9	(7.4)	10	(7.0)	
≥ 3	4	(3.3)	1	(0.7)	

After adjusting for age, sex, and self-reported ADD/ADHD, the results from a series of repeated measures ANCOVAs revealed no significant within-subjects main effect for time for the Verbal Memory (Wilks' Lambda = .996, F (1, 275) = 1.010, p = .316, partial eta squared = .004), Visual Memory (Wilks' Lambda = 1.00, F (1, 275) = .050, p =.823, partial eta squared = .000), Visual-Motor Speed (Wilks' Lambda = .987, F (1, 275) = 3.519, p =.062, partial eta squared = .013), and Reaction Time (Wilks' Lambda = .996, F (1, 275) = 1.114, p = .292, partial eta squared = .004) composite scores, and Total Symptom Score (Wilks' Lambda = .990, F (1, 275) = 3.472, p = .063, partial eta squared = .012) indicating no significant improvements in scores between the two baseline administrations (see Table 3).

The results indicated that the main effect for level of contact was not significant for Verbal Memory (F (1, 275) = 1.937, p = .165, partial eta squared = .007), Visual Memory (F (1, 275) = 1.719, p = .191, partial eta squared = .006), and Total Symptom Score (F (1, 275) = 2.375, p = .124, partial eta squared = .009). However, there was a main effect between contact levels for Visual-Motor Speed (F (1, 275) = 9.764, p = .002, partial eta squared = .034) and Reaction Time (F (1, 275) = 4.988, p = .026, partial eta squared = .018). Moderate contact athletes performed better on Visual Motor Speed and had faster reaction time compared to high contact athletes.

The current study did not reveal any significant interactions between contact level and time for Verbal Memory (Wilks' Lambda = .994, F (1, 275) = 1.538, p = .216, partial eta squared = .006), Visual Memory (Wilks' Lambda = .999, F (1, 275) = 0.214, p = .664, partial eta squared = .001), Visual-Motor Speed (Wilks' Lambda = 1.000, F (1, 275) = .088, p = .766, partial eta squared = .000), or Reaction Time (Wilks' Lambda = .998, F (1, 275) = 0.438, p = .508, partial eta squared = .002) composite scores. Similarly, there was no significant interaction between contact level and time for Total Symptom Score (Wilks' Lambda = .991, F (1, 275) = 2.375, p = .124, partial eta squared = .009).

Table 3. ImPACT Composite Scores Across Two Baseline Assessments in High and Moderate Contact Athletes

Composite Score	High Contact M±SD		Moderate Contact M±SD	
	First Baseline	Second Baseline	First Baseline	Second Baseline
Verbal Memory	83.62±8.6	85.32±10.7	84.53±9.2	88.02±8.9
Visual Memory	73.52±13.5	76.56±12.3	74.93±12.1	78.07±12.9
Visual-Motor Speed	33.70±6.0	38.71±6.6	36.83±6.7	41.12±6.7
Reaction Time	0.63±0.1	0.60±0.1	0.61±0.1	0.58±0.1
Total Symptom Score	3.64±6.2	4.02±6.7	4.66±6.7	5.34±8.1

Discussion

The purpose of this study was to examine differences in neurocognitive performance between high school student-athletes participating in high and moderate contact sport levels across two seasons of participation. Overall, the results of this study suggest that there were no significant changes in neurocognitive performance over time, which was demonstrated in each of the composite scores. However, there were significant differences in neurocognitive performance between high school student-athletes in high and moderate contact sports. Moderate contact athletes performed better on Visual Motor Speed and had faster reaction time compared to high contact athletes..

Neurocognitive assessments are a common practice during concussion baseline assessments, and are reported to be a reliable measure of neurocognitive function when administered in long-term intervals.[29,38] Despite the reliability reported across one- and two-years, neurocognitive scores are suggested to change over time. Brett and colleges[29] identified significant improvements in Verbal and Visual Memory, Visual-Motor Speed, and Reaction

Time across two years in high school student-athletes. Such improvements seen in neurocognitive scores in high school athletes are often attributed to the period of maximal cognitive maturation occurring in adolescents between 8-15 years old,[39] justifying the recommendations for re-administration of baseline assessments every two years. In the current study, each group's composite scores improved from the first to second baseline administration; however, after adjusting for age, sex, and self-reported ADD/ADHD the improvements were not significant. The differences between the current study and previous work by be due to the nature of the assessment tool. The neurocognitive assessment was developed as a screening tool used during concussion management, and outcomes are typically evaluated with composite scores that inherently limit identification of variability between sessions and groups. Therefore, future investigations should aim to use more sensitive assessment paradigms to determine if significant neurocognitive impairments result from multiple seasons of high school contact sport participation.

The results of the present study showed small, yet significantly better scores for Visual-Motor Speed and Reaction Time in moderate contact sport athletes compared to high contact sport athletes. Researchers have previously reported differences in Reaction Time across sports,[40] and also between athletes and non-athletes.[41] Specifically, high school athletes demonstrated faster Reaction Times than non-athletes.[41] However, in comparisons of high school athletes participating in various levels of contact sports at an initial baseline assessment, high contact sport athletes exhibit slower Reaction Time and worse Visual-Motor Speed compared to those in high and moderate contact sports.[11,42,43] The authors of previous studies suggest such differences may be a result of cumulative repetitive head impacts. Yet athletes were administered neurocognitive baseline assessments early in their high school athletic career, inherently limiting their exposure to repetitive head impacts, thus weakening the assumption that the difference between groups is due to repetitive head impact exposure. In contrast, these differences may be caused by other factors including age of first exposure,[44,45] academic achievement or aptitude,[46] or effort during assessments.[47] However, research is lacking in these areas necessitating further investigation.

Previous research has indicated differences in symptom reporting between athletes participating in different contact levels, and between athletes and non-athletes. Specifically, high school athletes participating in low contact sports displayed higher symptom scores compared to high and moderate contact athletes.[11,42] In addition, high school non-athletes report higher symptom scores compared to high school athletes.[41] Differences in perception and modulation of pain between athletes and non-athletes[48,49] and differences in reporting behaviors between sport types[50] offer potential explanations for previously reported distinctions in baseline symptom reporting. However, in the current study, there were no significant changes in the total symptom scores and no differences were reported between high and moderate contact athletes. Our non-significant findings are supported by the recent study of soccer and lacrosse athletes by Sandel and colleagues,[51] who reported no significant differences in baseline symptom reporting between sport types.

This study is not without limitations. First, our study was a retrospective investigation of baseline neurocognitive scores of high school athletes from a sample of schools within the state of Michigan. Therefore, the results of this study are not generalizable to the entire high school population. In addition, this was a retrospective investigation; therefore, we do not know the previous history of sport participation or activity levels prior to either baseline administration. It is possible that athletes could have participated in multiple sports that vary in the level of contact or activities that were not recorded within their baseline assessments, or outside of school sanctioned events. Also, this investigation was limited to high and moderate contact sport athletes; athletes participating in non-contact sports were not included in this investigation. Athletes participating in all high school sports are typically administered baseline neurocognitive assessments at least one time during their athletic career. However, those participating in sports with lower levels of repetitive head impact exposure, and sports with lower risk for concussion may not be re-assessed at a second baseline administration. Therefore, we could not compare the results to non-contact athletes. Lastly, this study investigated how multiple seasons of contact sport participation may influence baseline neurocognitive testing, and did not directly measure repetitive head impact exposure. Therefore, future research should further investigate if higher head impact exposure influences neurocognitive performance.

Conclusions

The current study investigated the effect that participating in multiple seasons of contact sports has on neurocognitive baseline assessments. The results suggested that high school student-athletes participating in high and moderate contact sports did not demonstrate significant improvements in any of the neurocognitive composite scores. In addition, high school student-athletes participating in high contact sports performed worse on Visual-Motor Speed and Reaction Time compared to moderate contact sport athletes. Given that we found differences between moderate and high contact athletes on two neurocognitive composite scores, future research should further evaluate the effect that contact sport participation has on neurocognitive function.

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CHAPTER FOUR: THE INFLUENCE OF COLLEGE FOOTBALL POSITION ON COMPUTERIZED NEUROCOGNITIVE FUNCTION

Abstract

Context: Football athletes are exposed to cumulative repetitive head impacts throughout their athletic career, yet the exposure to such impacts is dependent to the position the athlete plays. Deficits in neurocognitive function as a result of football participation is debated, and the effect of position played in college football on neurocognitive performance outcomes is understudied. **Objective:** To retrospectively evaluate neurocognitive function in healthy college football athletes participating in high and low risk positions at two baseline neurocognitive assessments. **Design:** Retrospective cross-sectional study. **Setting:** College football. **Patients or Participants:** Eighty college football athletes (high risk: n = 37, low risk: n = 43). **Main Outcome Measure(s):** College football athletes were administered two separate baseline neurocognitive test assessments (Immediate Post-Concussion and Cognitive Testing (ImPACT)) on average 2.84 ± 0.9 years apart. A high-risk for repetitive head impact exposure group (defensive line, offensive line, linebacker) and low-risk group (defensive back, quarterback, running back, safety, special teams, tight end and wide receiver) were compared on ImPACT composite scores and total symptom scores. Alpha level was set apriori to .05. **Results:** Football athletes in high risk positions had worse Reaction Time ($F_{(1, 77)} = 5.158$, $p = .026$) that improved over time ($F_{(1, 77)} = 4.117$, $p = .046$), compared to the low-risk for repetitive head impact exposure group. There were no significant differences for any other composite score or total symptom score. **Conclusions:** College football athletes participating in high-risk positions demonstrated small, but slower reaction times that improved between test administrations compared to the low-risk group. **Key Words:** concussion, sports, reaction time

Introduction

In collegiate sports, the overall rate for a sport-related concussion (SRC) is 4.47 per 10,000 athlete exposures (AEs), with the highest rates occurring in men's wrestling (10.92 per 10,000 AEs), men's ice hockey (7.91 per 10,000 AEs), women's lacrosse (7.50 per 10,000 AEs), and men's football (6.71 per 10,000 AEs).[1] However, these rates may be higher due to suspected SRCs that remain undisclosed or undiagnosed. Over a third of former collegiate athletes did not disclose a suspected concussion, with football athletes indicating the highest prevalence of non-disclosures.[2] Athletes that continue participating with a SRC are at greater risk for protracted neurocognitive recovery;[3,4] whereas, less is known about the longer-term implications of such impacts in which a SRC is missed or remains undiagnosed.

Moreover, athletes participating in contact or collision sports (i.e., football) sustain repetitive head impacts that do not result in SRC, and the existence of neurocognitive deficits resulting from exposure to contact sports that enable cumulative head impact exposure is unknown. The number of head impacts that an athlete sustains in across one season of football participation is dependent on the level and position of play.[5-8] For example, linemen and linebackers sustain a greater amount of total head impacts in games and practices compared to other football positions.[5,8] Yet, the cumulative effect of exposure to repetitive head impacts occurring in different college football positions on neurocognitive function is unknown. Gysland et al.[9] assessed collegiate football athletes' symptoms and cognitive function pre- and post-season while collecting repetitive head impact exposure variables across one season. The authors reported an increased total number of symptoms in athletes with a greater number of severe head impacts and more years of football participation.[9] However, no head impact exposure metric predicted neurocognitive test performance.[9] Additionally, McAllister et al.[10] reported that college contact athletes that sustained greater peak acceleration across a season had worse Reaction Time during a neurocognitive assessment. Therefore, a subset of athletes that regularly sustain repetitive head impacts may have worse neurocognitive outcomes. Based on the previously reported differences in total head impacts sustained by different positions, football provides a unique opportunity to assess if exposure to a larger amount of head impacts affects neurocognitive function.

In a recent report by Tsushima et al.,[11] baseline neurocognitive test scores were compared between high and low contact positions in high school football. High contact players (e.g., offensive and defensive linemen) had worse function on verbal memory, processing speed, impulse control, and total symptoms compared to low contact players (e.g., receivers and defensive backs).[11] However, based on the average age of participants (14.9 years), and that baseline testing occurred at the beginning of a single season, likely early in their high school athletic career, it is hard to attribute these positional differences to playing football. In addition, positional differences in neurocognitive function have not been assessed at the in college level. Inherently, continued participation in football beyond high school exposes athletes to an increase in the total number of head impacts sustained throughout their career. Montenigro et al.[12] suggested that the estimated repetitive head impact exposure occurring in each additional two seasons of football participation significantly increases the risk for cognitive impairment. These results warrant further investigation into the cumulative effects that participation in college football, specifically in different positions, has on neurocognitive function. In addition, these studies did not account for positional differences in repetitive head impact exposure. As such, the aim of this study is to retrospectively evaluate neurocognitive function in healthy college football athletes participating in high- and low-risk positions at two baseline neurocognitive assessments.

We hypothesize that college athletes participating in football positions with greater repetitive head impact exposure (i.e., defensive line, line backer, offensive line) will have worse neurocognitive performance outcomes compared to positions with lower repetitive head impact exposure (i.e., quarterback, wide receiver, defensive back, running back).

Methods

Research Design

A cross-sectional design was used to retrospectively examine baseline neurocognitive function. The Michigan State University Institutional Review Board determined this study was exempt due to de-identifiable data. Baseline neurocognitive assessments were first administered to athletes at the start of their freshman or transfer year. A second baseline neurocognitive assessment was administered at the start of their junior or senior year. All college football athletes were administered baseline ImPACT tests in a quiet room by a certified athletic trainer, and was completed prior to the start of football season. Each test administration took approximately 30 minutes to complete.

Participants

Computerized neurocognitive data from a pool of NCAA Division I athletes who participated in college football from 2012 – 2018 was used in this study. To be included in this study, athletes were required to complete a computerized neurocognitive battery at two baseline assessments (e.g., freshman or transfer, junior or senior) prior to the start of each football season. Athletes were separated into high-risk (e.g., greater repetitive head impact exposure) and low-risk groups (e.g. lower repetitive head impact exposure) based on repetitive impact exposure previously published at various football positions.[7,8,11] The high-risk group is operationally defined as defensive line, line backer, offensive line, and the low-risk group is operationally defined as defensive back, quarterback, running back, safety, special teams, tight end and wide receiver based on current evaluations of head impact exposure in collegiate football.[8,9,13] Participants were included in this study if they self-reported previous concussion history, diagnosed learning disability, diagnosed attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD), or a history of treatment for headache and/or migraine. However, significant differences between groups on these factors will be used as covariates due to their influence on baseline computerized neurocognitive test scores.[14-18]

Instrumentation

Immediate Post-Concussion and Cognitive Testing (ImPACT): ImPACT is a web-based computerized neurocognitive battery commonly used in the diagnosis of concussion. ImPACT is comprised of demographics, neurocognitive composite scores (i.e., verbal memory, visual memory, reaction time, motor processing), and a total symptom score. Demographics include self-reported age, sex, previous concussion history, learning disability, ADD or ADHD, and a history of treatment for headache and migraine. The composite scores are calculated from subscales including immediate and delayed word recall, immediate and delayed design memory, X's and O's, symbol match, color match, and three-letter memory. Invalid baseline assessments that include X's and O's total incorrect > 30, Impulse Control > 30, Word Memory Learning % correct < 69%, Design Memory Learning % correct < 50%, or Three Letters total letters correct < 8, were not included in this study.[19] The total symptom score is derived from the post-concussion symptom scale that includes 22 items rated on a 7-point Likert scale from 0 (none) – 6 (severe). ImPACT has a previously reported 91.4% sensitivity and 69.1% specificity during an acute diagnosis of concussion.[20]

Statistical Analysis

Descriptive statistics are presented in means and standard deviations for continuous variables (i.e., age, time interval between baseline neurocognitive administrations) and categorical variables are presented in frequencies and percentages (i.e., sex, ADD/ADHD, learning disability, treatment for headaches, treatment for migraines, concussion history). First, participant characteristics were compared with independent *t*-tests (age, time between baseline administrations), and chi-square and Fishers exact test when expected cell size was less than 5 (ADD/ADHD, learning disability, treatment for headaches, treatment for migraines, and concussion history) to determine homogeneity between groups. Second, ImPACT composite scores were analyzed with separate 2 (Group: high-risk, low-risk) X 2 (Time: season 1, season 2) repeated measures analysis of covariance (ANCOVA). Due to the significant group differences in age at the first baseline administration, age was used as a covariate. Statistical analyses will be performed in SPSS and significance will be set a priori at $p < .05$.

Results

Eighty NCAA Division I football athletes (high-risk: n = 37/80, 46.3%; low-risk: n = 43/80, 53.7%) were administered baseline neurocognitive assessments at two times on average 2.84 ± 0.9 years apart during their college football career. The average age of all football athletes at the first baseline administration was 18.13 ± 0.6 years, and at the second baseline administration 20.95 ± 1.0 years. The only significant difference between high-risk and low-risk athlete demographics was for age at the first baseline administration ($t_{(1, 78)} = -2.063$, $p = .042$). All participant characteristics are presented in Table 4.

Table 4. Self-Reported Participant Characteristic at each Baseline Assessment

	High-Risk (n = 37) n (%)		Low-Risk (n = 43) n (%)		*p*
Time Interval, *years* (M(SD))	2.98	(1.0)	2.72	(0.9)	.225
First Baseline Administration					
Age, *years* (M (SD))	17.97	(0.5)	18.26	(0.7)	.042
ADD/ADHD	5	(13.5)	3	(7.1)	.574
Learning disability	2	(5.4)	2	(4.7)	1.000
Treatment for headaches	2	(5.6)	0	--	.227
Treatment for migraines	2	(5.4)	2	(4.7)	1.000
Concussion history					.955
1	5	(13.5)	7	(16.3)	
2	3	(8.1)	1	(2.3)	
Second Baseline Administration					
Age, *years* (M (SD))	21.00	(1.0)	20.91	(1.0)	.679
ADD/ADHD	9	(24.3)	6	(14.0)	.369
Learning disability	1	(2.7)	4	(9.3)	.366
Treatment for headaches	0	--	2	(4.7)	.497
Treatment for migraines	0	--	2	(4.7)	.497
Concussion history					.365
1	5	(13.5)	5	(11.6)	
2	1	(2.7)	7	(16.3)	
≥ 3	1	(2.7)	1	(2.3)	

After adjusting for age at the first baseline administration, the results from a series of ANCOVA's revealed no significant within-subjects main effects for time for the Verbal Memory (Wilks' Lambda = .975, F (1, 77) = 1.944, p = .167, partial eta squared = .025), Visual Memory (Wilks' Lambda = .979, F (1, 77) = 1.627, p = .206, partial eta squared = .021), Visual Motor Speed (Wilks' Lambda = 1.000, F (1, 77) = 0.024, p = .876, partial eta squared = .000), and Reaction Time (Wilks' Lambda = .993, F (1, 77) = 0.554, p = .459, partial eta squared = .007) composite scores, or Total Symptom Score (Wilks' Lambda = 1.000, F (1, 77) = 0.000, p = .989, partial eta squared = .000) (see Table 5).

There were no significant between-subjects main effects for risk of repetitive head impact exposure group for the Verbal Memory (F (1, 77) = 0.740, p = .392, partial eta squared = .010), Visual Memory (F (1, 77) = 0.973, p = .327, partial eta squared = .012), Visual Motor Speed (F (1, 77) = 1.077, p = .303, partial eta squared = .014) composite scores, or Total Symptom Score (F (1, 77) = 1.968, p = .766, partial eta squared = .001) between high- and low-risk collegiate football athletes. There was a significant main effect for repetitive head impact exposure group (F (1, 77) = 5.158, p = .026, partial eta squared = .063), in which college football players in the high risk group had slower reaction times than the low risk college football players.

In regards to the interactions between time and risk of repetitive head impact exposure, there were no group differences for the Verbal Memory (Wilks' Lambda = .999, F (1, 77) = 0.090, p = .765, partial eta squared = .001), Visual Memory (Wilks' Lambda = .999, F (1, 77) = 0.059, p = .808, partial eta squared = .001), Visual Motor Speed (Wilks' Lambda = .981, F (1, 77) = 1.486, p = .227, partial eta squared = .019) composite scores, or Total Symptom Score (Wilks' Lambda = .999, F (1, 77) = 0.050, p = .824, partial eta squared = .001). There was a significant interaction between time and risk of repetitive head impact exposure group for Reaction Time (Wilks' Lambda = .949, F (1, 77) = 4.117, p = .046, partial eta squared = .051), in which football athletes in the high-risk positions had slower reaction times at the first baseline assessment compared to the low-risk group at the first baseline administration.

Table 5. ImPACT Composite Scores Across Two Baseline Assessments in High- and Low-Risk College Football Positions

Composite Score	High-Risk Position M±SD		Low-Risk Position M±SD	
	First Baseline	Second Baseline	First Baseline	Second Baseline
Verbal Memory	84.78±10.9	84.32±12.1	86.05±10.4	85.53±11.7
Visual Memory	76.35±14.4	75.89±13.2	77.72±11.3	78.74±10.5
Visual-Motor Speed	36.87±6.0	40.13±6.9	38.96±6.6	40.96±6.6
Reaction Time	0.66±0.1	0.62±0.1	0.60±0.1	0.61±0.1
Total Symptom Score	2.30±3.5	3.51±5.1	1.77±3.4	3.28±4.6

Discussion

The purpose of this study was to retrospectively compare neurocognitive function between college football athletes participating in positions at both high- and low-risk for repetitive head impact exposure at two baseline assessments. This is the first study, to date, to compare positional differences in neurocognitive function of college football athletes. The results of this study suggest that college football player position does not influence baseline neurocognitive function. However, the results indicate that football athletes participating in high-risk positions demonstrated small, but significantly slower Reaction Time compared to the low-risk group at the first baseline administration.

College athletes who participated in more years of football have been reported to have worse Reaction Time. Whereas, our results indicated that there was an interaction between group and the two baseline assessments for Reaction Time. College football athletes participating in positions at risk for greater repetitive head impact exposure had slower Reaction Time compared to the low risk group. In our study, the high-risk positions were primarily composed of offensive and defensive linemen whose job is to quickly respond off of the line of scrimmage. Inherently, these positions undergo vigorous training at the collegiate level to protect the quarterback against defensive players, or try to tackle the quarterback before the ball is thrown or running back before they cross the line. Therefore, intentional variations in football training may provide a potential explanation as to why these positional differences are seen in Reaction Time for college football athletes.

Although there were differences between high- and low-risk groups on Reaction Time, there were no other differences in neurocognitive function (i.e., Visual Memory, Verbal Memory, Visual-Motor Speed) between college athletes participating in high- and low-risk positions. In contrast, the findings of Tsushima et al.[11] identified differences between high- and low-risk positions for Verbal Memory, Visual Motor Speed, and Total Symptom Score. Nevertheless, the baseline neurocognitive scores reported by Tsushima et al.[11] were of high school athletes and were likely administered early in their football career, decreasing the chances that the differences are due to football exposure. In addition to the differences in cognitive maturation between high school and college football athletes, the total number of impacts per season that a football player sustains is lower at the college level.[5,8] Also, athletes participating in high school football are often shifting between multiple positions, and may play on both sides of the line. Thus, the differences seen between high- and low-risk positions at the high school level, that were not reported in the current study, may be a result of a greater number of cumulative head impacts experienced in high school football and do not persist in college-aged athletes. Finally, as repetitive head impact exposure was not directly measured in either of these studies, it is possible that the inconsistencies be due to the magnitude rather than the multitude of repetitive head impacts.[10] Therefore, future research should further explore if positional differences in neurocognitive function exist as a result of high school and college football participation while recording real-time head impact exposure. It is also noteworthy that many studies investigating neurocognitive effects of football participation are limited to assessments that were developed to be a screening tool used during concussion management, and therefore may not highlight actual cognitive decline. As such, more sensitive assessment paradigms should be included in future investigations to determine if neurocognitive impairments result from multiple seasons of football participation, and if there are differences between athletes participating in different positions.

The current study indicated that neurocognitive function did not change between the two baseline assessments that were administered greater than two years apart. The results of the current study are consistent with previous research that does not identify significant changes in neurocognitive function after participating in college football. Mrazik et al.[21] reported no significant differences in neurocognitive test outcomes between a baseline assessment and post-game assessment in college and professional football. Similarly, previous researchers report no pre- to post-season impairments in cognition for collegiate football athletes.[9,22] Finally, previous researchers also suggest that there are no significant differences in neurocognitive function in high school[23] or college[24] football athletes with and without a history of concussion; suggesting that participation in football may not negatively impact cognitive function regardless of previous concussion. In contrast, researchers suggests that neurocognitive function on Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time improves over one and two years of high school athletes.[25,26] These improvements in neurocognitive function found in high school athletes may be due to the period of cognitive maturation that does not occur in college aged athletes.[27] Congruent with previous research, our results suggest that neurocognitive function of college football players remains stable over time.

This study is not without limitations. First, our sample size was small and football athletes were from a pool of collegiate athletes from only one institution limiting the generalizability of the results. In addition, to be included in the analysis, college football athletes needed two computerized neurocognitive baseline tests that were completed with at least two seasons of participation between administrations. Accordingly, the analysis did not include football athletes that did not complete a second baseline administration or those that did not continue to participate in football beyond two years. Also, as this was a retrospective design, we were unable to collect each athlete's previous sport participation history. Therefore, we were not able to account for athletes that participated in multiple positions or contact sports during their high school or college football prior to their first baseline assessment. Finally, athletes were grouped based on findings from previously reported repetitive head impact exposure. In the current study, we did not record athletes' repetitive head impact exposure and cannot definitively report that athletes in the high-risk group were exposed to a greater number of repetitive head impacts.

Conclusions

This was the first comparison, to date, of neurocognitive function between college football athletes participating in high- and low-risk positions at two baseline assessments. The results suggest that football athletes in high-risk positions had slower Reaction Time than low-risk positions. We found no other significant differences in neurocognitive function between groups across the each baseline administration, and no significant with-in subject declines; suggesting that at least two years of college football participation does not result in neurocognitive declines. To identify if long-term cognitive impairments result from participating in different college football positions, athletes should be followed years after cessation of their sport participation.

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CHAPTER FIVE: A PILOT STUDY INVESTIGATING THE INFLUENCE OF HIGH SCHOOL CONTACT SPORT PARTICIPATION ON A MULTIFACETED ASSESSMENT PARADIGM

Abstract

Context: Participation in high school contact sports places athletes at risk for sustaining repetitive head impacts and concussion. The persistent effects of concussion on cognition are currently being debated; however, there e limited studies that investigate the long-term effects associated with high school contact sport participation. **Objective:** To compare neurocognitive function, inhibitory control, and single and dual-task steady-state and tandem gait characteristics between former high school contact sport athletes and control adults. **Design:** Cross-sectional study. **Setting:** Former high school contact sport athletes. **Patients or Participants:** Forty healthy adults (former high school contact sport: n = 27, 33.74 ± 2.9 years male: n = 20/27, 74.1%; control: n = 13, 35.08 ± 3.3 years, male: n = 6/13, 46.2%). **Main Outcome Measure(s):** Participants were administered a demographics questionnaire, a neurocognitive assessment (Immediate Post-Concussion and Cognitive Testing (ImPACT)), a modified version of the flanker task, and a gait assessment including steady-state and tandem gait during single- and dual-tasks conditions. Alpha level was set a priori to .05. **Results:** There were no significant differences in neurocognitive function ($F_{(4,34)}$ = .068, p = .991). For inhibitory control, there was a significant group difference in which controls had better response accuracy ($F_{(1,37)}$ = 4.546, p = .040) than former high school contact sport athletes. In addition there were no significant differences in steady-state ($F_{(3,34)}$'s range = .805 –1.349, p's range = .275 – .500) or tandem ($F_{(3,34)}$'s range = 0.678 – 1.219, p's range = .318 – .571) gait conditions. **Conclusions:** Adults with former high school contact sport participation for at least two years did not demonstrate worse neurocognitive function, inhibitory control, or any gait characteristic when compared to

adults that never participated in contact sports. However, due to inconsistences in current literature future research should continue to investigate the manifestation or progression of declines in cognition or postural control of former high school contact sport athletes' years after high school contact sport participation.

Key Words: concussion, sports, adults, neurocognition, inhibition, gait

Introduction

Contact sport participation places athletes at risk for sport-related concussion (SRC)[1-7] and repetitive head impact exposure.[8-20] The risk of long-term neurodegenerative impairments (e.g., chronic traumatic encephalopathy, Alzheimer's Disease) resulting from concussions and repetitive head impact exposure occurring in contact sports has gained heightened attention.[21-24] A SRC is defined as a traumatic brain injury resulting from biomechanical forces that may elicit short-term neurological impairment and presents with a range of clinical signs and symptoms.[25] Whereas, not all head impacts result in a clinically diagnosed SRC.[26,27] Therefore, in addition into investigating long-term impairments in cognitive and postural stability outcomes as a result of concussion,[28-32] research should also aim to investigate the influence exposure to repetitive head impacts as a result of contact sport participation has on such functional outcomes.

Recent evidence has identified a relationship between repetitive head impact exposure and structural damage that is independent of concussion history,[33-35] and is present even in former athletes.[36] Others suggest these structural changes may also relate to the age of first exposure to contact sports,[37] yet these results are controversial necessitating future research.[38] While, functional impairments as a result of repetitive head impact exposure are also commonly discussed in current literature. Previous studies investigating repetitive head impact exposure in contact sports, including soccer and football, reported athletes demonstrated immediate cognitive impairment as a result for participation without exhibiting signs and symptoms of a concussion.[39,40] In addition, a relationship between repetitive head impact exposure and cognitive impairment has been reported in former athletes beyond an acute assessment to later stages in life.[40] Preliminary results of a study by Montenigro et al.,[13] suggest a dose-response exists between repetitive head impact exposure and cognitive deficits, such that an additional two seasons of repetitive head impact exposure resulted in mood, behavioral, and cognitive deficits in former high school and football athletes. However, these results are based on estimates of self-reported athletic exposure and previously reported helmet accelerometer data that was not related to the study's sample.[13] Other authors report no association between former football participation and later in life cognitive impairments.[41] Assumptively, these differences may be attributed to many factors some of which include but are not limited to the sensitivity of test instruments, sport and social exposure, limitations in recall bias, and differences in patient demographics between samples. Where the contrasting results have caused a great debate, and warrants further investigation of long-term cognitive outcomes in former contact sport athletes.

The modified flanker task is an example of a test instrument that was sensitive enough to identify deficits in inhibitory control in athletes with a history of concussion, even years after sustaining the injury.[29,31,42] Inhibitory control is a higher order cognitive function that requires inhibition of distracting stimuli while attending to task relevant information[43] and is demonstrated to have deficits in athletes with an acute SRC[44] that persists to later in life.[28,29] In an older sample of former contact athletes aged 50-65 years old, worse response accuracy during an incongruent condition and an interference effect for response accuracy (e.g., worse performance during an incongruent task compared to a congruent condition) of the modified flanker task was identified in those with a previous history of concussion compared to controls.[28]

However, it may be valuable to identify if these results are present in former contact sport participants with high levels of repetitive head impact exposure independent of a previous history of concussion, and identify if alterations in inhibitory control exist at a mid-stage of life.

Existing literature is dominated by investigations of cognitive impairments resulting from concussion and contact sport participation; whereas additional long-term deficits are also reported in postural control of former contact athletes.[32] After sustaining a concussion, adaptive strategies are suggested to occur to maintain postural control,[45-56] and such adaptations are reported to exist years post-injury.[32,54,57] In addition, balance performance acutely following contact sport participation is beginning to be established. Within 48 hours of participating in a final game of a football season, 42.2% of athletes exceeded the reliable change index compared to baseline on the Balance Error Scoring System (BESS) test suggesting a cumulative negative effect of participation, indicating a balance impairment.[58] Adding an attention-dividing cognitive task also highlights impairments in postural control, especially during a gait task (e.g., dual-task gait).[59] In athletes recovering from a recent concussion, deficits found during dual-task gait persist beyond cognitive recovery,[60] and may be more appropriate to identify deficits in gait in the long-term. Some researchers have identified gait deficits in athletes and non-athletes during dual-task conditions;[55] whereas, conflicting evidence suggests no differences between athletes of different sport classifications.[61] These results may be explained by the positive influence current sport participation and physical activity have on postural control.[62,63] Little is known about the influence repetitive head impact exposure in contact sports has on postural control in the long-term. In addition, increasing the complexity of the motor task combined with the divided-attention condition, may elucidate adaptations in postural control in former contact sport athletes, as impairments have previously been established across two-months of recovery in samples of concussed athletes.[64]

Therefore, in addition to the work evaluating deficits in cognitive function resulting from contact sport participation, more research is needed to understand the long-term effects of contact sports participation on gait. As such, the purpose of this study was to identify the long-term effects of contact sport participation on neurocognitive function, inhibitory control, and gait characteristics in former contact sport athletes. We hypothesize that former high school contact sport athletes will have worse neurocognitive function, deficits in inhibitory control, and adaptations in gait characteristics compared to adults with no history of previous contact high school sport participation.

METHODS

Participants

This cross-sectional laboratory study included two groups (experimental group n = 27, control group n= 13), with the experimental group including adults aged 30-40 years who participated in contact sports during high school. Contact sports were defined as football, ice hockey, martial arts, rugby, soccer, and wrestling. Participants with a history of participation for two or more years in these contact sports during high school were included. This requirement is based on the findings of Montenigro et al.[13] identifying a significantly greater risk of clinical impairments later in life with each additional two years of football participation based on estimates of cumulative repetitive head impact exposure. The targeted participant population for the control group included adults from 30-40 years of age with no history of high school sport participation. Participants were recruited from local sporting events (i.e., youth, high school, or college sporting events), flyers, and word of mouth. Participants were excluded based on the following factors: participation in high school contact sports for less than two years, history of non-sports related traumatic/mild traumatic brain injury (i.e., car accident), lower extremity deficiency or injury that may affect normal gait patterns, neurological disorders (e.g., meningitis, epilepsy, brain surgery), cardiovascular disease, current central nervous system medications, and alcohol or substance use within the past 24 hours. The total time to complete testing took approximately 2 hours.

Instrumentation

Demographic Questionnaire: The demographic questionnaire included age, date of birth, sex, race, total years of education, highest level of education reached, height, weight, handedness, medical history (speech therapy, diagnosed learning disability, ADD/ADHD, dyslexia, previous concussion history), prior night's sleep, former sports participation history, concussion or "bell-ringer" event history, and injury history. Each participant was also administered the Tegner Physical Activity Scale to measure self-reported current physical activity levels.

Immediate Post-Concussion Assessment Tool (ImPACT): The Immediate Post-Concussion Assessment Tool (ImPACT) is a web-based computerized neurocognitive assessment battery commonly utilized during concussion screening. ImPACT is made up of five neurocognitive composite scores (i.e., verbal memory, visual memory, reaction time, motor processing, impulse control). Subscales that make up these composite scores include immediate and delayed word recall, immediate and delayed design memory, X's and O's, symbol match, color match, three-letter memory, and the post-concussion symptom scale and takes approximately 30 minutes to complete.[65] ImPACT has a previously reported 91.4% sensitivity and 69.1% specificity during an acute diagnosis of concussion.[65]

Modified Flanker: Inhibitory control was assessed using a modified version of the Eriksen flanker test[66-68] that has previously been administered following SRC.[28-31,42,69] Participants were instructed to identify a centrally located letter as accurately as possible using a button assigned to the target letter stimulus, among a lateral array of letters that were either congruent (e.g, "D D D D D") or incongruent (e.g., "D D B D D" or "B B D B B") to the centrally presented letter. All stimuli were 1.5 cm tall and presented on a computer screen using PsychoPy (1.85.92, Peirce, 2009). All participants complete a set of 40 practice trials prior to the experimental trials. Following the practice trials, participants completed two blocks of 80 trials for a total of 160 trials. Participants were provided perceptually similar letters for each block of trials (e.g., block 1: E – F, block 2: M – N) and button letter assignments were switched at the midpoint of the block to ensure high degree of task difficulty (e.g., left button press for "D" during the first 40 trials of block 1, then right button press for "D" on second 40 trials of block 1). The target letter stimulus occurred with equal probability for congruency (e.g., 50% congruent trials). The total stimulus duration was 155 ms, with the flanking stimuli present for 55 ms prior to target stimulus onset, and all stimuli remained on the screen for 100 ms. The response window was 1000 ms, and a variable inertial interval (ITI) of 2300, 2400, 2500, 2600, 2700 ms. Task performance variables included reaction time, response accuracy, coeffient of variance of reaction time, standard deviation of reaction time and interference cost.

Gait: A 10-camera motion capture analysis system (Vicon Motion Systems Ltd., UK) was used to measure torso movement kinematic data and an associated force plate (Advanced Mechanical Technology, Inc., Watertown, MA). Torso movement was defined as movement of the entire torso during a trial during each quiet stance task and was assessed across a 100-point time series. A total of 8 clusters were affixed to the thorax, sacrum, bilateral mid-thigh, lateral mid-calf, and forefoot. Joint centers were digitized at the medial and lateral malleoli, medial and lateral knee joint lines, bilateral anterior superior iliac spine, and L5/S1, T12, and C7/T1. After calibration in Vicon, virtual pelvic markers were identified through a stylus on Motion Monitor (Innovative Sports Training, Inc., Chicago, IL). Motion Monitor is a motion analysis software program used to help process kinematic data. Once a virtual marker set was established kinematic data was collected at a sampling rate of 240Hz and kinetic data was sampled at a rate of 1200 Hz. Data was filtered with a 4^{th} order Butterworth filter with a cutoff of 100 Hz for kinetic data and 14.5 for kinematic data and ensemble curves were generated for each task. A total of three trials for each task will be performed.

Procedures

Institutional review board (IRB) approval was obtained prior to data collection. Participants reported to the laboratory for a single session and were asked to complete the following task in a randomized order: demographic questionnaire; cognitive assessments; postural control tasks under four conditions: 1) single-task walking, 2) dual-task walking, 3) single-task tandem gait, 4) dual-task tandem gait.

<u>Gait:</u> During both walking conditions, participants were verbally instructed to walk barefoot at a self-elected comfortable speed. A target was placed 8-meters in front of the participant, and participants were instructed to walk through the target and return to the starting position. During the dual-task walking condition, participants were given the same verbal cues as single-task walking condition while also being cued to complete cognitive tasks. The cognitive tasks include: spelling a 5-letter word backward, serial subtraction from a randomly presented 2-

digit number by 6 or 7, and stating the months in reverse starting with a random month. Participants performed one mental task per dual-task trial. Practice effects from one trial to the next were avoided by randomly selecting the form of cognitive task used, and using no duplicate cues. Cognitive task performance was assessed by calculating the accuracy rate (total number of correct answers/total number of tasks provided). Outcome variables included best gait trial time (s), mean gait trial time (s), average gait speed (m/s), and total COM medial-lateral displacement (m).[46]

Tandem Gait: During both the single-task and dual-task tandem gait conditions participants were verbally instructed to walk forward barefoot along a 3-meter long sports tape with an alternate heel-to-toe step pattern by approximating the heel and toe on each step.[70] After completely passing the 3-meter tape, participants turned and returned to the start with the same heel-to-toe step pattern. Participants were verbally instructed to complete the trial as fast as they could without stepping off the line, separating the heel and toe, and not touching test administrator. Trials were completed until three successful trials are recorded, and failed trials were not included. During the dual-task tandem gait, participants were given the same verbal cues as single-task tandem gait while also being cued to complete the cognitive tasks previously described. Outcome variables will include best tandem gait trial time (s), mean tandem gait trial time (s), average gait speed (m/s), and total COM medial-lateral displacement (m).

Statistical Analysis

All continuous variables were expressed as means ± standard deviation and median [IQR], and categorical variables were presented as frequencies and percentages. Group differences in ImPACT performance (i.e., verbal memory, visual memory, reaction time, motor processing) were analyzed with a multivariate analysis of covariance (MANCOVA), adjusting for previous concussion history. For the flanker task, group differences were analyzed with separate 2 (group: experimental, control) X 2 (congruency: congruent, incongruent) repeated measures MANCOVAs for task performance (response accuracy, reaction time, standard deviation of reaction time, intra-individual coefficient of variation of reaction time), adjusting for previous concussion history. In addition, independent *t*-tests were used to identify interference effect (incongruent – congruent) between groups (experimental, control) for each performance measure. For steady-state and tandem gait tasks, group differences for single- and dual-task conditions were analyzed using separate MANCOVAs, with height and previous history of concussion included as a covariate. The dependent variables included best gait trial time, average gait trial time, and average gait speed. The independent variable was group (previous contact sport verses control). To compare differences between each of the dual-task cognitive test forms, we performed an ANOVA among all participants, and performed a multivariate ANOVA between groups (experimental, control) for each cognitive task. Significance was set a priori to $p \leq .05$. Post-hoc comparisons included Bonferroni corrected t-tests to control for multiple comparisons when appropriate.

Results

A total of 40 adults (34.18 ± 3.1 years) participated in the study, including 27 former contact sport athletes (male: n = 20/27, 74.1%; 33.74 ± 2.9 years) and 13 controls (male: n = 6/13, 46.2%; 35.08 ± 3.3 years). Adults in the former contact sport group were significantly taller than adult controls (p = .039). There were no other significant differences in participant characteristics between groups (p's < .05). See Table 6 for a complete list of participant characteristics. Former contact sport athletes primarily participated in football (n = 12/27, 44.4%), girls' soccer (n = 6/27, 22.2%), and boys' soccer (n = 5/27, 18.2%). All previous contact sport participation of adults in the former contact sport group is reported in Table 7. In addition to previous contact sport participation, adults were asked to self-report their history of previous concussion, “bell-ringer” events, and if they recalled leaving a game or practice with any of the following signs or symptoms: headache, dizziness, confusion, difficulty remembering, sensitivity to light or sound, balance problems, trouble falling asleep. Forty-eight percent (n = 13/27) of former contact sport athletes reported leaving a high school game or practice with signs and symptoms of a concussion, 41.7% (n = 11/27) reported experiencing at least one “bell-ringer” as a result of high school contact sport participation, and 22.2% self-reported at least one concussion that occurred during high school contact sport participation. One adult in the control group self-reported a previous history of concussion (See Table 8).

Table 6. Demographic Variables of Former Contact Sport Athletes and Controls

	Former Contact Sport (n = 27)	Control (n = 13)	*p*
	M ± SD		
Age, *years*	33.74 ± 2.9	35.08 ± 3.3	.209
Height, *cm*	177.16 ± 8.5	171.00 ± 8.7	.039
Weight, *kg*	92.41 ± 18.4	82.75 ± 16.7	.118
BMI, *kg/m²*	29.24 ± 4.2	28.32 ± 5.5	.602
Tegner Activity Scale (range, 1-10), Median [IQR]	5.00 [4.0 – 6.8]	6.5 [5.0 – 7.0]	.228
	n (%)		
Sex, *male*	20 (74.1)	5 (41.7)	.155
Handedness, *right*	24 (92.3)	12 (92.3)	1.000
Race			.707
Asian	2 (7.4)	2 (15.4)	
Black or African American	1 (3.7)	---	
Hispanic	1 (3.7)	1 (7.7)	
White	23 (85.2)	10 (76.9)	
Highest Degree Earned			.219
Associate Degree (other vocational degree)	1 (3.7)	---	
Bachelor's Degree	5 (18.5)	2 (15.4)	
Master's Degree	18 (66.7)	6 (46.2)	
Doctorate, Professional (MD, JD, DDS)	3 (11.1)	5 (38.5)	
Combined Family Income			.228
< $25,000	2 (7.4)	1 (7.7)	
$25,000 – 50,000	6 (22.2)	2 (15.4)	
$50,000 – 75,000	4 (14.8)	3 (23.1)	
$75,000 – 100,000	1 (3.7)	4 (30.8)	
$100,000 – 150,000	10 (37.0)	3 (23.1)	
$150,000 +	3 (11.1)	---	
Decline to respond	1 (3.7)	---	

Table 7. Previous High School, Youth, and Club or Recreation Contact Sport Participation of Former Contact Sport Athletes [a]

Sport	n (%)
High School	
Football	12 (44.4)
Boys' Ice Hockey	3 (11.1)
Girls' Ice Hockey	2 (7.4)
Martial Arts	2 (7.4)
Rugby	3 (11.1)
Boys' Soccer	5 (18.5)
Girls' Soccer	6 (22.2)
Wrestling	3 (11.1)
Youth	
Football	10 (26.3)
Boys' Ice Hockey	4 (10.5)
Girls' Ice Hockey	3 (7.9)
Martial Arts	3 (7.9)
Rugby	---
Boys' Soccer	9 (23.7)
Girls' Soccer	5 (13.2)
Wrestling	4 (10.5)
Club or Recreation	
Football	3 (7.9)
Boys' Ice Hockey	2 (5.3)
Girls' Ice Hockey	2 (5.3)
Martial Arts	2 (5.3)
Rugby	4 (10.5)
Roller Derby	1 (2.6)
Boys' Soccer	3 (7.9)
Girls' Soccer	5 (13.2)
Wrestling	---

[a] Total percentages may be greater than 100% as former contact sport athletes may have participated in more than one contact sport.

Table 8. Self-Reported History of Concussion and "Bell-Ringer" Events of Adults with (n = 27) and without (n = 13) Previous High School, Youth, and Club or Recreation Contact Sport Participation

	Previous Concussion	"Bell-Ringer"	Remember Leaving Game or Practice with Signs or Symptoms [a]
High School			
Previous Contact Sport			
Yes	6 (22.2)	11 (40.7)	13 (48.1)
Unsure	8 (29.6)	5 (18.5)	3 (11.1)
Control	---	---	---
Youth			
Previous Contact Sport			
Yes	2 (7.4)	6 (22.2)	4 (14.8)
Unsure	8 (29.6)	6 (22.2)	2 (7.4)
Control	---	---	---
Club or Recreation			
Previous Contact Sport			
Yes	4 (14.8)	4 (14.8)	5 (18.5)
Unsure	3 (11.1)	3 (11.1)	2 (7.4)
Control	---	---	---
Other			
Previous Contact Sport			
Yes	2 (7.4)	5 (18.5)	4 (14.8)
Unsure	5 (18.5)	3 (11.1)	1 (3.7)
Control			
Yes	1 (7.7)	---	---

[a] Signs or Symptoms include: headache, dizziness, confusion, difficulty remembering, sensitivity to light or sound, balance problems, trouble falling asleep

Neurocognitive Function

After adjusting for previous concussion history, no significant differences were detected with the MANCOVA for the neurocognitive composite scores between adults that did and did not participate in high school contact sports (Wilks' Lambda = .992, $F_{(4,34)}$ = .068, p = .991, partial eta squared = .008). See Table 9 for neurocognitive composite scores of each group.

Table 9. Composite Scores of Neurocognitive Function in Former Contact Sport Athletes and Controls

Composite Score	Former Contact Sport (n = 27)	Control (n = 13)
Verbal Memory		
Mean ± SD	84.56 ± 10.5	85.15 ± 11.5
Median [IQR]	87.00 [74.0 – 93.0]	82.00 [74.5 – 96.0]
Visual Memory		
Mean ± SD	70.48 ± 12.9	71.38 ± 9.9
Median [IQR]	70.00 [59.0 – 82.0]	72.00 [63.0 – 79.0]
Visual Motor Speed		
Mean ± SD	38.35 ± 8.2	38.72 ± 8.5
Median [IQR]	38.03 [33.0 – 44.5]	40.80 [32.6 – 45.3]
Reaction Time		
Mean ± SD	0.67 ± 0.2	0.68 ± 0.1
Median [IQR]	0.62 [0.57 – 0.72]	0.64 [0.58 – 0.77]

Flanker Task

Reaction Time. Analysis of flanker reaction time measures revealed a significant main effect for congruency (Wilks' Lambda = .146, $F_{(1,37)} = 216.723$, $p < .001$, partial eta squared = .854) indicating participants had faster reaction time for congruent trials (μ = 472.34 ± 56.6 milliseconds) compared to incongruent trials (μ = 521.12 ± 56.3 milliseconds). When adjusting for previous concussion history, there was no significant main effect for group on reaction time ($F_{(1, 37)} = .001$, $p = .975$, partial eta squared = .000). In addition, the group X congruency interaction for reaction time was not significant when adjusting for previous concussion history (Wilks' Lambda = .990, $F_{(1,37)} = .382$, $p = .540$, partial eta squared = .010). All behavioral data is presented in Table 10.

Response Accuracy. Analysis of flanker response accuracy measures revealed a significant main effect for congruency (Wilks' Lambda = .595, $F_{(1,37)} = 25.155$, $p < .001$, partial eta squared = .405) indicating participants had better response accuracy for congruent trials (μ = 95.26 ± 8.6 % correct) compared to incongruent trials (μ = 89.94 ± 7.7 % correct). When adjusting for previous concussion history, there was a significant main effect for group on response accuracy ($F_{(1, 37)}$ = 4.546, p = .040, partial eta squared = .109). However, the group X congruency interaction for response accuracy was not significant when adjusting for previous concussion history (Wilks' Lambda = .991, $F_{(1,37)}$ = .334, p = .567, partial eta squared = .009).

Standard Deviation of Reaction Time. Standard deviation of reaction time analyses revealed no significant main effect for congruency (Wilks' Lambda = .966, $F_{(1,37)}$ = 1.322, p = .258, partial eta squared = .034). In addition, when adjusting for previous history of concussion, there was no significant main effect of group ($F_{(1, 37)}$ = 1.730, p = .197, partial eta squared = .045) or group X congruency interaction (Wilks' Lambda = .979, $F_{(1,37)}$ = .789, p = .380, partial eta squared = .021).

Intra-individual Coefficient of Variation of Reaction Time. Intra-individual coefficient of reaction time analyses revealed no significant main effect for congruency (Wilks' Lambda = .926, $F_{(1,37)}$ = 2.963, p = .094, partial eta squared = .074). In addition, when adjusting for previous history of concussion, there was no significant main effect of group ($F_{(1, 37)}$ = 2.370, p = .132, partial eta squared = .060) or group by congruency interaction (Wilks' Lambda = .969, $F_{(1,37)}$ = 1.172, p = .286, partial eta squared = .031).

Interference Cost. There were no significant differences in interference cost for reaction time ($t_{(38)}$ =.698, p = .495), response accuracy ($t_{(38)}$ = -.853, p = .399), standard deviation of reaction time ($t_{(38)}$ = -1.074, p = .290), or intra-individual coefficient of variation of reaction time ($t_{(36)}$ = -1.391, p = .172).

Table 10. Modified Flanker Task Performance Measures of Former Contact Sport Athletes and Controls

Measure	Former Contact Sport (n = 27)	Control (n = 13)
	M ± SD	
Reaction Time, *ms*		
Congruent	467.70 ± 60.4	473.23 ± 48.0
Incongruent	520.02 ± 60.3	521.35 ± 47.0
Collapsed	492.96 ± 59.8	496.80 ± 46.8
Interference Cost	52.32 ± 18.7	48.12 ± 16.5
Response Accuracy, *% correct*		
Congruent	93.84 ± 10.0	98.56 ± 1.7
Incongruent	88.19 ± 8.3	94.33 ± 4.5
Collapsed	91.02 ± 8.8	96.44± 2.8
Interference Cost	-5.65 ± 5.3	-4.23 ± 3.9
Standard Deviation of Reaction Time, *ms*		
Congruent	101.33 ± 30.0	85.62 ± 20.8
Incongruent	101.28 ± 25.6	91.48 ± 16.9
Collapsed	105.63 ± 25.1	92.63 ± 16.1
Interference Cost	-0.05 ± 16.5	5.85 ± 15.8
Intra-individual Coefficient of Variation Reaction Time, *ms*		
Congruent	0.21 ± 0.05	0.18 ± 0.04
Incongruent	0.19 ± 0.04	0.18 ± 0.03
Collapsed	0.21 ± 0.03	0.19 ± 0.03
Interference Cost	-0.02 ± 0.03	-0.01 ± 0.03

Gait Characteristics

The results of the MANCOVA revealed no significant differences in single-task steady-state gait characteristics between adults that did and did not participate in contact sports in high school when controlling for height and previous history of concussion, (Wilks' Lambda = .934, $F_{(3,34)} = .805$, $p = .500$, partial eta squared = .066). In addition, there were no significant differences in dual-task steady-state gait characteristics in adults that did and did not participate in contact sports in high school when controlling for the covariates (Wilks' Lambda = .894, $F_{(3,34)} = 1.349$, $p = .275$, partial eta squared = .106). Steady-state gait characteristics are presented in Table 11.

Table 11. Steady-State Gait Characteristics of Former Contact Sport Adults and Controls

	Former Contact Sport (n = 27)	Control (n = 12)
Single-Task		
Best Trial Time, *s*		
Mean ± SD	16.99 ± 2.2	16.28 ± 2.0
Median [IQR]	16.78 [15.7 – 17.7]	16.01 [14.6 – 17.9]
Average Trial Time, *s*		
Mean ± SD	18.37 ± 2.4	17.88 ± 2.4
Median [IQR]	17.83 [16.8 – 19.8]	18.34 [15.6 – 19.3]
Average Gait Speed, *m/s*		
Mean ± SD	0.94 ± 0.11	0.98 ± 0.13
Median [IQR]	0.93 [0.87 – 1.00]	1.00 [0.86 – 1.08]
Dual-Task		
Best Trial Time, *s*		
Mean ± SD	18.06 ± 2.4	17.56 ± 2.3
Median [IQR]	17.32 [16.7 – 19.4]	17.84 [15.5 – 18.3]
Average Trial Time, *s*		
Mean ± SD	18.95 ± 2.72	18.22 ± 2.6
Median [IQR]	18.24 [17.2 – 20.5]	18.57 [15.9 – 19.3]
Average Gait Speed, *m/s*		
Mean ± SD	0.86 ± 0.11	0.89 ± 0.12
Median [IQR]	0.88 [0.78 – 0.93]	0.86 [0.83 – 1.01]

The results of the MANCOVA revealed no significant differences in single-task tandem gait characteristics between adults that did and did not participate in contact sports in high school when adjusting for height and previous history of concussion (Wilks' Lambda = .903, $F_{(3,34)}$ = 1.219, p = .318, partial eta squared = .097). In addition, there were no significant differences in dual-task steady-state gait characteristics between adults that did and did not participate in contact sports in high school when controlling for the covariates (Wilks' Lambda = .944, $F_{(3,34)}$ = 0.678, p = .571, partial eta squared = .056). Tandem gait characteristics are presented in Table 12.

Table 12. Tandem Gait Characteristics of Former Contact Sport Adults and Controls

	Previous Contact Sport (n = 27)	Control (n = 12)
Single-Task		
Best Trial Time, *s*		
Mean ± SD	21.97 ± 4.1	23.47 ± 4.0
Median [IQR]	21.28 [20.2 – 24.4]	23.07 [19.6 – 26.7]
Average Trial Time, *s*		
Mean ± SD	22.85 ± 4.1	25.47 ± 3.5
Median [IQR]	22.04 [20.4 – 26.0]	25.20 [22.2 – 28.2]
Average Gait Speed, *m/s*		
Mean ± SD	0.27 ± 0.05	0.24 ± 0.03
Median [IQR]	0.27 [0.23 – 0.29]	0.25 [0.21 – 0.27]
Dual-Task		
Best Trial Time, *s*		
Mean ± SD	23.91 ± 4.3	26.84 ± 3.2
Median [IQR]	24.63 [19.7 – 26.5]	26.87 [24.6 – 29.5]
Average Trial Time, *s*		
Mean ± SD	25.51 ± 4.3	28.48 ± 3.8
Median [IQR]	25.63 [21.5 – 28.2]	27.90 [25.9 – 30.9]
Average Gait Speed, *m/s*		
Mean ± SD	0.24 ± 0.04	0.22 ± 0.03
Median [IQR]	0.24 [0.21 – 0.28]	0.22 [0.19 – 0.23]

Mean cognitive task accuracy performance for the dual-task gait conditions was significantly different between the three cognitive task conditions ($F_{(2,111)} = 4.787$, $p = .010$), where all participants were most accurate for month recitation backward (98.79 ± 4.1 % correct), compared to serial subtraction (91.34 ± 15.5 % correct, $p = .022$) and spelling a 5-letter word backward (91.18 ± 13.7 % correct, $p = .020$). Cognitive task accuracy did not differ between spelling a 5-letter word backwards and serial subtraction conditions ($p > .05$). In addition, there were no significant differences in mean cognitive task response accuracy detected during the dual-task gait conditions (Wilks' Lambda = .983, $F_{(3,32)} = .782$, $p = .513$. partial eta squared = .068), when adjusting for previous concussion history. Comparisons of cognitive task conditions between former contact sport athletes and controls are presented in Table 13.

Table 13. Comparison of Dual-Task Cognitive Task Condition between Former Contact Sport Athletes and Controls

Cognitive Task Condition	Previous Contact Sport (n = 27)	Control (n = 11)
	M ± SD	
Month Recitation Backward, *% correct*	98.33 ± 4.9	99.79 ± 0.7
Serial Subtraction, *% correct*	93.56 ± 6.9	89.62 ± 24.5
Spell 5-Letter Word Backward, *% correct*	89.13 ± 15.1	94.89 ± 9.7

Discussion

Declines in cognition and postural control that are present in adulthood of former athletes may result from participating in contact sports during developmental stages.[32,71,72] Our goal was to compare neurocognitive function, inhibitory control, and gait characteristics during single- and dual-task conditions between healthy adults that formerly participated in high school contact sports and controls. Our findings suggest that adults that participated in contact sports for at least two years in high school do not present with worse neurocognitive function, when measured with ImPACT, or decrements in inhibition, when measured with a modified version of the flanker task compared to healthy control adults. In addition, former high school contact sport adults did not display any significant adaptations in any gait characteristic during single- and dual-task conditions of steady-state gait or tandem gait.

Participation in contact sports may yield persistent negative effects on neurocognitive function.[73] However, studies suggesting such declines, like the results reported by Hume et al.[73] are limited to elite athletes in single sports. In the current study, we found no significant differences in neurocognitive function between adults that formerly participated in high school contact sports for at least two years and controls. These results disagree with recent evidence reported by Katz et al.[74] suggesting differences in neurocognitive function between collegiate athletes participating in high, limited, and non-contact sports, in which high and limited contact athletes displayed better neurocognitive outcomes compared to non-contact athletes. These results demonstrated little clinical relevance based on changes being within the reliable change index;[74] however, they support the findings of the current study that neurocognitive function is not negatively influenced by contact sport participation.

Our results for the flanker task replicated previous results in that participants had faster reaction time and better response accuracy for congruent trials compared to incongruent trials.[29-31,42,44] In addition, former contact sport athletes in our sample had worse response accuracy compared to control adults. Previous literature has shown acutely, high school and college athletes with a concussion display worse response accuracy that is persistent up to one month after injury when compared to controls.[44] Similarly, in youth athletes aged 8-10 years old, those with a history of concussion (2.1 ± 1.9 years from testing) had worse response accuracy compared to controls.[69] In college aged adults, participants tested on average 4.2 ± 3.2 years from their most recent concussion had worse response accuracy compared to healthy controls.[42] Similarly, Pontifex et al.[29] reported worse response accuracy for athletes with a history of concussion compared to controls, when tested 3.6 ± 3.2 years from their last injury. Moreover, adults ranging from 20-29 years old with a history of concussion that occurred on average 7.1 ± 4.0 years from flanker administration demonstrated worse response accuracy compared to adult controls.[29] These deficits related to concussion history may also persist into later adulthood, as retired former athletes with a history of concussion had a significantly worse interference effect for response accuracy compared to controls.[28] Therefore, the modified flanker task is a more sensitive assessment in identifying long-term deficits in higher order cognitive function as a result of concussion or contact sport participation when compared to neurocognitive assessments that are typically used during concussion management.

Persistent effects of concussion are also reported to relate to postural control,[32] and potentially leave patients with a history of concussion at risk for subsequent musculoskeletal injury, especially in athletics.[75] However, research investigating how a history of concussion may influence an adults' postural control later in life is limited. One study by Schmidt et al.[32] identified deficits in postural control in 40-50 year old retired football athletes with a history of concussion compared to controls. Whereas, there were no significant adaptations reported after one single football season in Division I football athletes using similar metrics.[76] Yet, the researchers detected such adaptations in postural control using nonlinear metrics that have limited clinical utility.[32] In the current study, we found no significant difference in single- or dual-task tandem gait characteristics. Our results are similar to those reported by Howell et al.,[61] in which there were no significant difference in single- or dual-task gait characteristics between collegiate collision/contact and non-contact athletes. In addition, a recent study by Buckley et al.[61] did not report any significant relationships between head impact kinematics and dynamic postural control during single- and dual-task conditions. Together, these results support our findings that contact sport participation may not influence postural control in adulthood. Despite the similar gait patterns reported by Howell et al.,[61] the authors found non-contact athletes demonstrated better response accuracy during the serial subtraction cognitive task during gait compared to collision/contact athletes. Whereas, our findings indicate that there were no significant differences in response accuracy for any cognitive task during dual-task gait conditions between adults that formerly participated in contact sports compared to controls. However, consistent with previous research,[61] we did find that response accuracy varied between each of the cognitive tasks in our total sample. Therefore, future research should consider the identifying cognitive tasks that may be more sensitive to highlight gait adaptations during dual-task conditions. Our study did not produce significant differences in gait between former contact sport athletes and controls; nonetheless, the significant findings by Schmidt et al.[32] and inconsistencies reported in current literature coupled the limited focus of the persistent effects of concussion and repetitive impact exposure as a result of contact sport participation warrant continued investigation.

Limitations

Our study was not without limitations. First, our sample size was small and the distribution of former contact sport athletes and controls was not equal. In addition, our neurocognitive assessment was developed for use during concussion management and designed to identify neurocognitive impairments acutely after a concussion. Therefore, this assessment tool may not have been sensitive enough to determine if neurocognitive declines exist in adulthood as a result of contact sport participation. Also, this was a cross-sectional design that required adults to recall previous concussions and bell-ringer events years beyond sustaining the injury. In addition to recall bias of previous concussion history, we did not assess repetitive head impact exposure that the adults in the former contact sport group sustained during their high school contact sport participation. As such, it would be beneficial to follow athletes that are participating in contact sports while recording their incidence of repetitive head impact exposure into adulthood to identify if any significant declines in nuerocognition, inhibition, or gait exist years after participation. Finally, we assessed adults between 30-40 years old; whereas, current significant cognitive and postural control declines are reported in older retired athletes. Therefore, the influence that high school contact sport participation has on cognitive and postural control outcomes may not manifest until later in life. More research is needed in the mid-range of adulthood.

Conclusion

Overall, based on the results of our small sample in this pilot study, there are no apparent detrimental effects of playing high school contact sports on cognition or postural control in the mid-range adulthood. Adults, aged 30-40 years that formerly participated in at least two years of contact sports during high school did not perform worse on any neurocognitive, inhibitory control, or gait performance outcome when compared to adults that never participated in contact sports. However, as this was a cross-sectional design and due to the conflicting evidence surrounding negative outcomes resulting from early contact sport participation, future research should continue to investigate the development or progression of declines in cognition or postural control of athletes years after high school contact sport participation.

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CHAPTER SIX: SUMMARY AND CONCLUSIONS

Summary

The purpose of this dissertation was to examine the long-term effects of contact sport participation. Specifically, we assessed 1) the influence of high school contact sports participation on neurocognitive function, 2) the influence of collegiate football position on neurocognitive function and 3) the influence of high school contact sport participation in former adult contact sport athletes on a multifaceted assessment. For the first two aims, a retrospective comparison between two baseline neurocognitive assessments that were administered on average greater than two years apart was completed. For the last aim, a cross-sectional pilot study was conducted to compare neurocognitive function, inhibitory control, and gait characteristics between adult former high school contact sport athletes and controls.

The Influence of High School Contact Sports Participation on Neurocognitive Function

Prior studies demonstrated that there are differences in neurocognitive function in high school athletes that are dependent on the level of contact experienced in their sport. Specifically, Tsushima et al.[1] found athletes participating in high contact sports had worse baseline neurocognitive test scores than the moderate contact group on visual memory, processing speed, and impulse control.[1] In addition, the high contact group performed worse on visual memory, processing speed, reaction time, and impulse control compared to the low contact group at baseline.[1] The results of the first paper of this dissertation implied that in our sample of 294 athletes (high contact: n = 142, 48.3%; moderate contact: n = 152, 51.7%) there were no significant changes in neurocognitive function or symptom reporting between the two baseline administrations in the total sample, after adjusting for age, sex, and self-reported ADD/ADHD. In addition, there were no significant group differences in Verbal Memory, Visual Memory, or symptom reporting between high and moderate contact athletes. However, there were significant differences for Visual-Motor Speed and Reaction Time, in which moderate contact athletes performed better on Visual Motor Speed and had faster Reaction Time compared to high contact athletes. There were no significant interactions between contact level and time for neurocognitive function or symptom reporting between the two baseline administrations that took place on average two years apart. Overall, the results of the first portion of this dissertation implied that, although there were significant differences in two neurocognitive composite scores between high and moderate contact sport athletes, participating in high school high contact sports does not negatively influence neurocognitive function.

The Influence of College Football Position on Neurocognitive Function

Football is a high contact sport in which athletes are subject to cumulative repetitive head impacts throughout their career, with repetitive head impact exposure being dependent on the football position played. [2] In a study of high school athletes, it was reported that football athletes in positions with higher contact players (e.g., offensive and defensive linemen) had worse function on verbal memory, processing speed, impulse control, and total symptoms compared to lower contact players (e.g., receivers and defensive backs).[3] However, to date no study has evaluated differences in neurocognitive function between different positions in college football. In the second study of this dissertation, healthy college football athletes participating in high- and low-risk football positions were retrospectively evaluated on neurocognitive assessments at two baseline time points.

There were no significant within-subject changes in neurocognitive function or symptom reporting between the two baseline administrations. There were no significant between-subjects main effects for risk of repetitive head impact exposure group for the Verbal Memory, Visual

Memory, Visual Motor Speed or in symptom reporting between high- and low-risk collegiate football athletes. However, there was a significant main effect for repetitive head impact exposure group, in which college football players in the high risk group had slower reaction times than the low risk college football players. In addition, the only significant interaction was between time and group for Reaction Time, wherein low-risk positions had faster reaction times than high-risk positions at the first baseline administration.

The Influence of High School Contact Sport Participation in Former Adult Athletes on a Multifaceted Assessment

Previous researchers have reported persistent effects of concussion resulting from contact sport participation on cognitive[4-6] and postural control[7] outcomes in adult retired athletes. In the third study of this dissertation, there were no significant differences in neurocognitive function or inhibitory control between adult former contact sport athletes and controls. In addition there were no significant differences in single-task or dual-task gait conditions in between groups.

Limitations

The first two studies of this dissertation are limited to retrospective baseline administrations of high school and college athletes. As such, we were unable to collect each athlete's previous sport participation history, and could not account for those that participated in multiple contact sports or multiple positions within each sport during their high school or college football career prior to the first baseline assessment. In addition, in the first two studies, athletes were grouped based on findings from previously reported repetitive head impact exposure. In the current studies, we did not record athletes' repetitive head impact exposure and cannot definitively report that athletes in the high contact or high-risk groups were exposed to a greater number of repetitive head impacts. Lastly, neurocognitive function was assessed using a tool that was designed to identify deficits in neurocognitive function acutely after a concussion, and therefore may not be sensitive enough to highlight impairments resulting from exposure to contact sport participation.

In the third study, our sample size was small and the distribution of former contact sport athletes and controls was not equal. In addition, adults were required recall previous concussions and bell-ringer events years beyond sustaining the injury, subjecting our results to recall bias. Also, similar to the first two studies, we did not assess repetitive head impact exposure that the adults in the former contact sport group sustained during their high school contact sport participation. Future research should aim to track athletes that are participating in contact sports into adulthood while also recording repetitive head impact exposure to determine long-term effects of contact sport participation. Finally, our study included adults aged 30-40 years old; where, current deficiencies in cognitive and postural control are reported in older retired athletes suggesting the effects of high school contact sport participation may not manifest until later in life. Therefore, more research is needed in the mid-range of adulthood to determine if there are lasting effects of contact sport participation.

Strengths

The first two studies provide a unique addition to the existing literature evaluating the influence of contact sport participation and football position on neurocognitive function. Previous studies found differences in neurocognitive function between high, moderate, and low contact high school athletes,[8,9] and differences in neurocognitive function between high- and low-risk football positions in high school athletes.[3] However, in each of these previous reports, high school athletes were assessed at only one time that occurred during baseline assessment. Baseline neurocognitive assessments typically occur early in an athlete's career and therefore these differences in neurocognitive scores cannot be attributed to participating in contact sports at this level. In our first two studies we compared two baseline assessments that were at least two-years apart, and therefore were able to account for cumulative contact sport participation of at least two competitive seasons. In addition, our second study adds to current literature as we investigated adults aged 30-40 years old that were former high school athletes. To date the long-term effects of contact sport are currently studied in older retired athletes that participated at elite levels. Therefore, our inclusion of former high school athletes in the mid-range of adulthood begins to address this gap.

Conclusions

Overall, based on the results of the three studies included in this dissertation, we did not find any obvious harmful effects of high school contact sports participation or different college football positions neurocognitive function. In addition, we did not find any persistent impairment in neurocognitive function, inhibitory control, or gait characteristics in former high school contact athletes in their mid-range of adulthood. However, future research should further evaluate the effect that contact sport participation, and more specifically repetitive head impact exposure, has on neurocognitive function. To identify if there are long-term effects that result from participating in high school contact sports or different college football positions, researchers should follow athletes years after their sport participation ceases and explore the development or progression of declines in cognition or postural control.

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