

THE RELATIONSHIP BETWEEN POST-CONCUSSION PHYSICAL ACTIVITY AND
CONCUSSION RECOVERY OUTCOMES IN COLLEGE-AGED ADULTS

By

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PUBLIC ABSTRACT

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Context: For years, the most common treatment for a concussion has been periods of prolonged physical and cognitive rest. However, recent research suggests that early post-concussion physical activity may be better at promoting concussion recovery. Research has not yet evaluated the influence of free-living physical activity participation (e.g., daily walking) on concussion recovery outcomes. **Purposes:** The purpose of this study was to assess the relationship between post-concussion physical activity participation and two post-concussion recovery outcomes (symptom reporting and overall recovery time) in college-aged adults with a concussion.

Methods: Participants were included in the study if they completed their initial visit within 72 hours of concussion occurrence, were between the ages of 18-24 years, and completed two follow-up testing visits (visit 2: 8 days after initial visit, visit 3: following full medical clearance). Physical activity participation was measured during the first week after concussion using an Actigraph GT9X Link Physical Activity Monitor and was expressed as Vector Magnitude (VM) counts per minute. Physical activity intensity was also evaluated and expressed as percent time spent in light or moderate-to-vigorous physical activity (MVPA). Symptom reporting was assessed using the Post-concussion Symptom Scale which asked participants to rate 22 symptoms on a 7-point Likert scale. Total symptom severity was determined by adding all Likert scale scores and is out of 132. Symptom severity from visit 2 was used during analysis. Recovery time was the number of days from injury occurrence to unrestricted medical clearance. **Results:** A total of 32 participants (male: 10, female: 22) completed all testing visits, recorded

2446 $\pm$ 441 VM counts per minute, and spent approximately 11.8% of their time performing MVPA. Participants' symptoms gradually improved over time, with the majority of participants recovering in about two weeks. Although participant sex and the symptoms reported at visit 1 were good predictors of visit 2 symptoms, physical activity participation and percent time spent in MVPA had no association with symptom reporting at visit 2. Similarly, physical activity and percent time in MVPA also had no association with concussion recovery time. **Conclusion:**

Although previous research has shown recovery improvements when using physical activity as a concussion treatment, the current study found no association with free-living physical activity participation and symptom reporting or concussion recovery. This suggests that simply increasing physical activity participation throughout the day may not be enough to reduce post-concussion symptoms or shorten recovery time. Future research should not only monitor patients post-concussion physical activity but should also evaluate the influence of other external factors (e.g. social support) on symptom reporting and recovery time.

ABSTRACT

THE RELATIONSHIP BETWEEN POST-CONCUSSION PHYSICAL ACTIVITY AND CONCUSSION RECOVERY OUTCOMES IN COLLEGE-AGED ADULTS

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Context: Prolonged physical and cognitive rest is a popular treatment approach for individuals with a concussion, however this prolonged inactivity has been found to exacerbate symptom reporting and prolong recovery.^{1,2} Research to counteract this phenomenon has utilized early post-concussion physical activity, from which promising results have emerged.³⁻⁵ However, researched physical activity protocols require heavy supervision and are not clinically feasible. Thus, identifying a different approach to track and promote early post-concussion physical activity is necessary. **Purpose:** The purpose of this study was to assess the relationship between post-concussion physical activity participation and two post-concussion recovery outcomes (symptom reporting and overall recovery time) in college-aged adults with a concussion.

Methods: A prospective cohort study design was used to assess the relationship between post-concussion physical activity participation and concussion recovery outcomes. Participants were included if they completed their initial visit within 72 hours of concussion occurrence and were between 18-24 years old. Post-concussion physical activity was measured using an Actigraph GT9X Link Physical Activity Monitor and was expressed as Vector Magnitude (VM) counts per minute. Physical activity intensity was also evaluated and expressed as percent time spent in MVPA. Symptom reporting was represented as severity from visit 2, whereas, recovery time was the number of days from injury occurrence to medical clearance. A hierarchical multiple regression analysis was used to evaluate the relationship between VM counts per minute and symptom severity at visit 2 while controlling for participant sex and symptom severity at visit 1.

Secondly, a linear regression analysis was used to evaluate the relationship between VM counts per minute and concussion recovery time. Exploratory hierarchical and linear regression analyses were also completed evaluating the relationship between percent time in MVPA and the recovery outcomes. **Results:** A total of 32 participants (male: 10, female: 22) completed testing and yielded valid post-concussion physical activity data. Participants averaged 2446 ± 441 VM counts per minute of physical activity, and spent $11.8\% \pm 3.7\%$ of their time performing MVPA. Participants yielded symptom severities of 28 [24] and 2 [8] for visit 1 and visit 2, respectively. Average recovery time was 14.7 ± 7.5 days. A significant hierarchical multiple regression model assessing the relationship between VM counts per minute and symptom reporting at visit 2 was found ($F_{(2,28)}=6.16$, $p=.002$) and accounted for 39.8% of the variance ($R^2=.398$). However, VM counts per minute did not significantly contribute to the model ($B=-.006$, 95% CI: $-.015$, $.002$, $\beta=-.239$, $p=.122$). Likewise, VM counts per minute was not associated with concussion recovery time ($B=-.003$, 95% CI: $-.010$, $.003$, $p=.276$) and did not yield a significant regression model ($F_{(1,30)}=1.23$, $p=.276$). Similar non-significant findings were found for the relationship between percent time in MVPA and symptom reporting ($B=-.580$, 95% CI: -1.59 , $.434$, $\beta=-.180$, $p=.251$) and recovery time ($B=-.385$, 95% CI: -1.129 , $.349$, $p=.292$). **Conclusion:** Results from the current study suggest that simply increasing free-living physical activity participation throughout the day may not be enough to reduce post-concussion symptoms or shorten recovery time. Conversely, healthcare professionals should avoid broad statements simply telling patients to increase their activity levels as this may not provide enough guidance to optimize recovery. Conversely, clinicians recommending post-concussion physical activity should aim to provide more specific guidelines outlining physical active protocols that have previously been shown to improve concussion recovery.

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KEY TO ABBREVIATIONS

AAN	American Academy of Neurology
ACL	Anterior Cruciate Ligament
ADHD/ADD	Attention Deficit Hyperactivity Disorder/Attention Deficit Disorder
AE	Athlete Exposures
ANAM	Automated Neuropsychological Assessment Metrics
ANOVA	Analysis of Variance
ANS	Autonomic Nervous System
ATP	Adenosine Triphosphate
BESS	Balance Error Scoring System
CBF	Cerebral Blood Flow
CISG	Concussion in Sport Group
CT	Computed Tomography
EMS	Emergency Medical Services
FDA	Federal Drug Administration
GPA	Grade Point Average
GSC	Graded Symptom Checklist
HIS	Head Injury Scale
HITS	Head Impact Telemetry System
HS	High School
Hz	Hertz
ICC	Intraclass Correlation Coefficients

ImPACT	Immediate Post-Concussion Assessment and Cognitive Test
IQR	Interquartile Range
KD	King-Devick Test
mBESS	Modified Balance Error Scoring System
MET	Metabolic Equivalent of Task
mTBI	Mild Traumatic Brain Injury
MVPA	Moderate-to-Vigorous Physical Activity
NCAA	National Collegiate Athletic Association
NEISS	National Electronic Injury Surveillance System
NPC	Near-Point of Convergence
OTC	Over the Counter
PCSS	Post-Concussion Symptom Scale
RIO	Reporting Information Online
RPQ	Rivermead Post-Concussion Symptom Questionnaire
SAC	Standard Assessment for Concussion
SCAT	Sport Concussion Assessment Tool
SD	Standard Deviation
SIS	Second Impact Syndrome
SRC	Sport-Related Concussion
VCR	Vestibulocollic Reflex
VM	Vector Magnitude
VMS	Visual Motor Sensitivity
VOMS	Vestibular Ocular Motor Screening

VOR	Vestibulo-Ocular Reflex
VSR	Vestibulospinal Reflex

KEY TO SYMBOLS

$\pm$	Plus or Minus
$\%$	Percentage
$>$	Greater Than
$\geq$	Greater Than or Equal To
$<$	Less Than

CHAPTER I

INTRODUCTION

Overview of the Problem

A concussion is defined as a complex pathophysiological process affecting the brain, which is induced by biomechanical forces.⁶ These head injuries occur between 1.8-3.6 million times annually and are particularly prevalent in collegiate athletics.⁷ Specifically, sport-related concussions (SRC) make up approximately 6% of all collegiate injuries.⁸ Individuals with a concussion may experience an array of post-concussion symptoms, cognitive impairments, and balance deficits which typically resolve within two weeks.^{6,9} However, approximately 15-20% of individuals experience a protracted concussion recovery lasting longer than 30 days.^{10,11} Factors such as athlete sex,¹² age,^{12,13} and previous health history¹⁴ have all been reported to influence concussion recovery time. Additionally, several post-concussion management techniques have been found to influence concussion recovery trajectories.^{1,3,5}

Cognitive and physical rest have been the cornerstone of concussion management practices. Previously this resting period has been employed until individuals are completely asymptomatic, followed by a gradual reintroduction to activity.¹⁵ Cognitive and physical rest are believed to ease discomfort during the acute recovery phase, minimize the excessive energy demands of the brain, and limit chances of a subsequent head injury.¹⁶⁻¹⁸ However, little evidence exists supporting the benefits of post-concussion rest beyond the acute recovery phase. Furthermore, prolonged post-concussion rest has been found to be associated with worse recovery outcomes.^{1,2} Specifically, Thomas et al.¹ found that extending rest periods by an extra 3 days (2 days vs 5 days) negatively impacted post-concussion symptom reporting and recovery

time. Due to this evidence refuting prolonged rest as a management strategy, researchers have begun evaluating alternative management approaches to improve post-concussion recovery.

Current consensus guidelines suggest limiting rest to the first 24-48 hours following injury.⁶ After this point, gradual reintroduction to normal activities of daily living should begin.⁶ Additionally, at this stage other treatment options may be utilized to further promote recovery. Post-concussion physical activity is believed to be one of the most viable treatment options because of its direct effects on cognition and mood.^{19,20} When implementing a physical activity protocol in children with a concussion, researchers found significant improvements in several post-concussion outcomes.³⁻⁵ Specifically, these children recovered 3-15 days faster and reported less post-concussion symptoms than those who were instructed to strictly rest.^{4,5} It should be noted that previous research typically employed treadmill-based physical activity protocol interventions which require direct clinical supervision.³⁻⁵ Unfortunately, this type of intervention is not clinically feasible for all healthcare professionals tasked with managing individuals post-concussion. Identifying an approach that utilizes more general physical activity is warranted, considering, something as simple as promoting more habitual physical activity participation may be sufficient for improving post-concussion outcomes.

Researchers have begun to quantify physical activity participation (e.g., walking) in youth athletes after a concussion.^{21,22} One investigation found an immediate reduction in the total number of steps taken by concussed youth athletes compared to healthy controls (6,663 vs 11,148 per day).²² Despite this initial decline, as recovery progressed athletes slowly returned to similar activity levels as their healthy counterparts.²² Another study found that lower post-concussion physical activity participation was significantly associated with more vestibular impairment after injury.²¹ These preliminary findings may suggest that by simply promoting

greater levels of post-concussion physical activity participation, healthcare providers may improve recovery outcomes. However, this potential link has only been evaluated in concussed youth athletes on a single vestibular assessment. Research is not only needed for an older population (i.e., collegiate athletes) who are not restricted to being in a school setting for several hours, but also need to evaluate the influence of this type of physical activity on other post-concussion recovery outcomes (i.e., symptom reporting and recovery time).

Purposes of the Study

The purpose of this study was to assess the relationship between physical activity participation and two post-concussion recovery outcomes (symptom reporting and overall recovery time) in college-aged adults with a concussion.

Specific Aims and Hypotheses

Specific Aim 1: To evaluate the relationship between post-concussion physical activity participation (VM counts per minute) and symptom reporting (symptom severity at visit 2) in college-aged adults with a concussion.

Hypothesis 1: There will be a moderate, inverse relationship between post-concussion physical activity participation (VM counts per minute) and symptom reporting (symptom severity at visit 2) in college-aged adults with a concussion.

Specific Aim 2: To evaluate the relationship between post-concussion physical activity participation (VM counts per minute) and recovery time (days) in college-aged adults with a concussion.

Hypothesis 2: There will be a moderate, inverse relationship between post-concussion physical activity participation (VM counts per minute) and recovery time (days) in college-aged adults with a concussion.

CHAPTER II

REVIEW OF LITERATURE

Concussion

Definition of Concussion

The definition of a concussion has taken many forms, especially among different healthcare and professional organizations. Although it may be common for concussion and mild traumatic brain injury (mTBI) to be used interchangeably, a concussion is a more specific condition that falls within the umbrella of mTBI.⁶ Thus, using these terms interchangeably is not an idealistic approach. The American Academy of Neurology (AAN) defines a concussion as a trauma-induced alteration in mental status that may or may not involve loss of consciousness.²³ Similar to the AAN, experts within the Concussion in Sport Group (CISG) define a SRC as a complex pathophysiological process affecting the brain, which is induced by biomechanical forces.⁶ The CISG also states that SRCs should be classified as functional disturbances rather than structural injuries due to the inability to physically see damaged structures.⁶ Athletes diagnosed with these injuries may develop transient neurological impairments along with possible manifestation of clinical signs and symptoms. Due to the lack of clear structural damage, clinicians must rely on these patient reported signs and symptoms to help identify when a SRC may be present. Finally, in their definition of SRC, the CISG identify the injury as being caused by a direct or indirect blow to the head resulting in transmitted force to the brain.⁶

Mechanism of Concussion

To fully understand the mechanism of injury for a SRC, the foundation presented by the CISG must be expanded.⁶ When a direct or indirect force is invoked upon the head, the brain may be injured in a coup or contrecoup fashion. A coup injury refers to the brain sustaining

trauma on the same side in which the head is contacted.²⁴ However, when the brain sustains trauma to the opposing side of contact, this is referred to as a contrecoup injury.²⁴ Coup injuries are common when a stationary head is struck by a moving object (i.e., ball, stick), whereas a contrecoup injury is caused from a moving head impacting a stationary object (i.e., ground, wall).²⁴

Player contact has been overwhelmingly reported to be the primary cause of SRCs.^{8,25-27} Specifically, studies have reported anywhere from 46-84% of SRCs are from intentional or unintentional player contact.^{8,25-27} In their analysis of high school collision sports (football, ice hockey, lacrosse), Bartley et al.²⁶ found that the most common SRC causing activities were tackling/checking and being tackled/checked. This finding was again confirmed in a study of youth, high school, and collegiate football athletes.²⁵ However, youth football athletes were found to be 2 times more likely to sustain a SRC from contact with the ground when compared to high school and collegiate football athletes.²⁵ Investigations into other collision sports such as men's lacrosse have yielded high percentages (69%) of player contact SRCs.²⁷ Although player contact is often the mechanism for collision sports, contact with the ground or other objects (i.e., ball, stick) must also be a consideration, especially in those non-collision sports.

Of the non-collision sports with a high incidence of SRC, soccer and women's lacrosse remain the most researched. Concussion producing mechanisms for soccer have been relatively consistent among previous research with player contact being responsible for 59-70% of SRCs.^{8,27,28} Whereas, contact with an object (i.e., ball, stick) has been blamed for 21-38% of soccer SRCs.^{8,27,28} Women's lacrosse is also considered a non-collision sport due to rules and regulations that limit intentional player contact. Zuckerman et al.⁸ indicated that most SRCs (57.7%) reported for this sport were from contact with objects (i.e., stick, ball) rather than other

athletes. This finding in women's lacrosse is rather interesting due to previous research suggesting that most SRCs occur from player contact. Thus, it may be beneficial to evaluate why such differences have been found for lacrosse. Sex differences may be an explanation as to why these differences exist. Researchers have not only evaluated sex differences for mechanism of injury in lacrosse, but also in other common sex-comparable sports.

Overall, females have been reported to sustain more player to object (i.e., equipment) SRCs than their male counterparts. These results were consistent for lacrosse (58.2% vs 17.7%), soccer (33.8% vs 21.8%) and basketball (23.3% vs 20.2%) athletes.⁸ It has been purposed that these findings may be due to females having less neck strength than males, thus being less efficient at decelerating the head before contacting the ground.^{29,30} To help identify the actual forces applied to the head and to objectively evaluate these sex differences, researchers have begun to utilize biomechanical sensors to quantify the magnitude and frequency of impacts sustained by athletes.

A wide array of commercially available devices currently exist to help researchers evaluate these biomechanical forces acting on the head. Devices such as the Head Impact Telemetry System (HITS), the Gforce Sensor and the ShockBox mount directly to popular sporting helmets, while devices like the X-Patch and SimG are mounted directly to the head. These devices measure head acceleration (linear, rotational), frequency of impacts and in some instances the location in which the head was impacted. Table 1 depicts the average magnitude of sub-concussive head impacts sustained by different sports. Specifically pertaining to head impact frequency, Broglio et al.³¹ identified football lineman as sustaining the most head impacts (1068 impacts), whereas receivers, corners, and safeties (283 impacts) sustained the least amount. Quarterbacks sustained the greatest linear (30.0g) and rotational acceleration (1421 rad/s/s) and

receivers, corners, and safeties sustained the least (linear = 25.0g, rotational = 1165.2 rad/s/s),³¹ which is unsurprising due to the nature of these positions. In ice hockey, males have been reported to sustain more head impacts and at a greater magnitude (linear: 31.2g vs 28.3g, angular: 2881.0 rad/s/s vs 1766.8 rad/s/s) than females.³² Similar sex differences have been reported when comparing men's and women's lacrosse athletes (linear: 21.1g vs 14.7g, angular: 3603.1 rad/s/s vs 2327.6 rad/s/s, frequency: 11.5 vs 9.2 impacts).³³ However, these findings are likely due to rule inconsistencies among the two sports, allowing men to legally make contact compared to females who are not allowed to make contact. The final sport commonly found in SRC biomechanical research is soccer. Soccer is evaluated utilizing head mounted impact sensors such as the X-patch. Male soccer athletes have been found to sustain more head impacts over a single season than female soccer athletes (432 impacts vs 296 impacts).^{34,35} Additionally, males also averaged greater linear and rotational forces when compared to females (linear: 20.5g vs 19.1g, rotational: 3687.1 rad/s/s vs 3115.4 rad/s/s).³⁶

Table 1: Sub-Concussive Head Impact Magnitudes by Sport

Sport	Linear Acc. (g)	Rotational Acc. (rad/s/s)
Football ³⁷	20.5	1400.0
Men's Ice Hockey ³²	31.2	2881.0
Women's Ice Hockey ³²	28.3	1766.8
Men's Lacrosse ³³	21.1	3603.1
Women's Lacrosse ³³	14.7	2327.6
Men's Soccer ³⁶	20.5	3687.1
Women's Soccer ^{34,36}	12.5 - 19.1	2093.6 - 3115.4

Researchers have also attempted to utilize these devices to identify SRC causing thresholds. However, due to SRCs occurring differently for every athlete, identifying a threshold has posed tremendous difficulty. Table 2 shows previously reported SRC thresholds. Despite the apparent inconsistencies in SRC thresholds, researchers generally agree that lowering the

acceleration forces and number of head impacts may have potential to reduce the overall incidence of SRCs. Furthermore, the results of these biomechanical studies have not gone unnoticed; several changes have been implemented as a direct result of these findings. These changes may be to reduce the number of contact practices per week or reduction of full padded practices per week. After reducing the number of full contact football practices, athletes experienced significantly lower head impact measures.³¹ Additionally, researchers suggest that head impact exposures can be decreased if teams adopt a helmetless tackling program.³⁸ Researchers should continue to evaluate these head impact biomechanics to reduce the impact forces sustained by the head during contact sports. Information from these devices should be taken into consideration when making policy adjustments for collision sports. In turn this may assist in reducing SRC incidence among collision and other contact sports.

Table 2: Reported SRC Producing Thresholds for Football and Ice Hockey Athletes

Study	Sport	Concussions	Linear Acc. (g)	Rotational Acc. (rad/s/s)
Liao et al. ³⁹	Football	24	97.0	5359.4
Guskiewicz et al. ⁴⁰	Football	13	102.8	5312.0
Broglia et al. ⁴¹	Football	13	105.0	7230.0
Broglia et al. ⁴²	Football	20	93.6	6403.0
Beckwith et al. ⁴³	Football	105	102.5	3977.0
Wilcox et al. ⁴⁴	Women's Ice Hockey	9	42.0	4030.0
Duhaime et al. ⁴⁵	Football, Ice Hockey	31	86.1	3620.0

Pathophysiology of Concussion

Regardless of the mechanism of injury, there is an intricate cascade of events occurring in the brain following a SRC. To better understand this process, researchers have commonly utilized animal models to identify what is occurring at the cellular level. Understanding what is occurring in the brain may further explain why athlete's experience the outward signs and symptoms commonly associated with the injury. This insight may also provide a rationalization

as to why clinicians make certain choices throughout the recovery process (i.e., not allowing athletes to return to competition immediately after sustaining a SRC).

The pathophysiological cascade begins immediately following direct or indirect trauma to the brain. Instantly, there is a disruption of cellular membranes causing an efflux in potassium.¹⁷ This initial potassium increase leads to neuronal depolarization, which then stimulates the release of additional potassium causing a cyclical feedback loop. While this is occurring, neurotransmitters specifically glutamate are being released by damaged cells.⁴⁶ Glutamate will not only contribute to the potassium efflux, but will also stimulate the release of calcium within the cells.^{47,48} This increasing amount of calcium will further contribute to the cellular damage that is occurring and may even cause some cells to begin to die.⁴⁸

Due to the overwhelming number of things occurring in the brain cells after trauma, a metabolic mismatch is created. Cells mitochondria are no longer able to produce Adenosine Triphosphate (ATP) fast enough to meet the energy demands for healing, thus signaling glycolysis to begin.⁴⁹ As the process of glycolysis attempts to correct this energy crisis, it

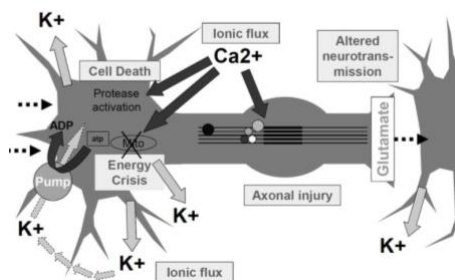


Figure 1: Neurometabolic Cascade of Concussion

Giza, C. C., & Hovda, D. A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery*, 75(suppl_4), S24-S33.

produces a byproduct called lactate.⁴⁹ In extreme cases, large amounts of lactate may break down the blood-brain barrier causing significant cerebral edema.⁴⁹ Figure 1 is a visual representation of the cellular changes experienced after a concussion.

Throughout the acute phase of a concussion, vasoreactivity decreases causing an imbalance between carbon dioxide and oxygen within the cells.⁵⁰ This increase in carbon dioxide along with poor vasoreactivity are believed to be contributing factors for post-concussion symptom reporting.⁵¹ Additionally, this poor vasoreactivity may predispose athletes to a second, more serious head injury if returning to activity before completely resolved.⁵¹ This is problematic because post-concussion symptom reporting has been reported to resolve before these blood flow abnormalities.^{52,53} Thus, caution must be taken when determining return to activity status following a concussion.

Epidemiology of Concussion

Concussions are a common occurrence in athletics and recreational activities at the youth, high school and collegiate level. Specifically, the Center for Disease Control has identified that between 1.6-3.8 million concussions occur annually.^{7,54} Understanding the prevalence of these injuries during specific events provides necessary awareness to participants and healthcare professionals tasked with overseeing such activities. Researchers have utilized several popular injury surveillance systems to report and track the occurrence of injuries, including concussions. National Electronic Injury Surveillance System (NEISS), High School Reporting Information Online (RIO), and Datalys Injury Surveillance Program are only some examples that have been used for youth, high school and collegiate populations, respectively. The information provided by these monitoring systems make it easy to identify factors that may influence concussion prevalence such as sport, age, sex, or event type (practice vs competition).

Researchers have analyzed youth middle school athletes to get a representation of the rate in which youth athletes sustain a concussion.⁵⁵ It was identified that youth have an average concussion incidence rate of 0.75 concussions per 1,000 athlete exposures (AE).⁵⁵ Middle school

football (2.61/1,000 AEs) has been reported to have the highest rate of concussions followed by girls' soccer (1.30/1,000 AEs).⁵⁵ The same study further identified football (4.31/1,000 AEs), girls' basketball (2.61/1,000 AEs), girls' soccer (2.47/1,000 AEs), and boys' baseball (1.02/1,000 AEs) all having a rate above 1.0/1,000 AEs during competitions.⁵⁵ Table 3 shows previously reported concussion prevalence for youth athletes.⁵⁵

Table 3: Youth Athlete Concussion Rates by Sport

Sport	Concussion Rate per 1,000 AEs 95% Confidence Interval			
	Game	Practice	Total	Game vs Practice Rate Ratios
Boys				
Baseball	1.02 (0.00-3.02)	0.40 (0.00-1.17)	0.57 (0.00-1.36)	2.58 (0.16-41.19)
Basketball	0.00	0.25 (0.00-0.75)	0.18 (0.00-0.52)	N/A
Football	4.31 (1.12-7.50)	2.29 (1.29-3.29)	2.61 (1.62-3.59)	1.88 (0.80-4.45)
Soccer	0.60 (0.00-1.96)	0.00	0.15 (0.00-0.45)	N/A
Track	0.00	0.00	0.00	N/A
Wrestling	0.66 (0.00-1.96)	0.46 (0.00-1.09)	0.51 (0.00-1.08)	1.45 (0.13-16.01)
Boys Total	1.12 (0.43-1.81)	0.80 (0.48-1.12)	0.87 (0.58-1.17)	1.40 (0.67-2.92)
Girls				
Basketball	2.61 (0.32-4.89)	0.20 (0.00-0.60)	0.88 (0.18-1.59)	12.77 (1.49-109.31)
Cheer	0.00	0.84 (0.17-1.52)	0.68 (0.14-1.23)	N/A
Soccer	2.47 (0.05-4.90)	0.80 (0.00-1.70)	1.30 (0.34-2.26)	3.11 (0.70-13.89)
Softball	0.00	0.90 (0.00-2.14)	0.68 (0.00-1.62)	N/A
Track	0.00	0.00	0.00	N/A
Volleyball	0.71 (0.00-2.12)	0.22 (0.00-0.66)	0.34 (0.00-0.81)	3.23 (0.20-51.64)
Girls Total	1.18 (0.45-1.91)	0.45 (0.20-0.69)	0.61 (0.36-0.86)	2.63 (1.15-5.99)
Overall	1.15 (0.64-1.65)	0.63 (0.43-0.83)	0.75 (0.55-0.94)	1.83 (1.06-3.15)

Kerr, Z. Y., Cortes, N., Caswell, A. M., Ambegaonkar, J. P., Hallsmith, K. R., Milbert, A. F., & Caswell, S. V. (2017). Concussion Rates in US Middle School Athletes, 2015–2016 School Year. *American journal of preventive medicine*, 53(6), 914-918.

High school athletes also receive increased research attention due to their developing brains and relatively high concussion risk. High school concussions have seen a steady increase over the past two decades, nearly doubling in occurrence.^{56,57} High school athlete concussion risk has been reported to range between 0.1/10,000 AEs to 9.21/10,000 AEs depending on sport. Football (9.21/10,000 AEs), boys' lacrosse (6.65/10,000 AEs) and girls' soccer (6.11/10,000

AEs) athletes are most at risk of sustaining a concussion compared to all other high school sports (see Table 4).⁵⁷ It is not surprising that these contact sports yield the greatest risk due to the large amount of player-to-player contact that occurs. Concussion rates have also been consistently found to be higher during competition compared to practice.⁵⁷ Furthermore, high school football games had a concussion rate as high as 20/10,000 AEs, which was the highest reported rate among all events (see Table 4).⁵⁷

Table 4: High School Concussion Rates by Sport

Sport	Concussion Rate per 10,000 AEs (95% Confidence Interval)			
	Game	Practice	Total	Game vs Practice (Rate Ratios)
Boys				
Baseball	1.22 (0.31-2.12)	0.73 (0.30-1.16)	0.86 (0.46-1.25)	1.67 (0.65-4.31)
Basketball	4.93 (3.49-6.36)	1.72 (1.23-2.21)	2.52 (2.01-3.04)	2.86 (1.90-4.31)
Football	19.87 (17.95-21.80)	6.78 (6.24-7.31)	9.21 (8.64-9.78)	2.93 (2.59-3.32)
Lacrosse	17.51 (13.52-21.49)	2.97 (2.01-3.93)	6.65 (5.41-7.89)	5.90 (3.97-8.75)
Soccer	11.33 (8.46-14.20)	1.48 (0.87-2.08)	3.98 (3.12-4.83)	7.67 (4.74-12.40)
Track	0.82 (0.02-1.63)	0.13 (0.00-0.28)	0.25 (0.07-0.44)	6.32 (1.41-28.25)
Wrestling	10.21 (7.23-13.20)	4.75 (3.78-5.72)	5.76 (4.80-6.73)	2.15 (1.51-3.07)
Boys Total	4.86 (4.17-5.54)	0.85 (0.70-1.00)	1.69 (1.51-1.88)	5.70 (4.56-7.14)
Girls				
Basketball	10.52 (8.23-12.82)	2.22 (1.59-2.86)	4.44 (3.67-5.20)	4.74 (3.31-6.79)
Field Hockey	9.83 (6.74-12.91)	2.47 (1.54-3.40)	4.42 (3.36-5.49)	3.99 (2.44-6.51)
Gymnastic	5.27 (0.00-12.58)	2.28 (0.45-4.10)	2.65 (0.81-4.49)	2.32 (0.47-11.48)
Lacrosse	11.75 (7.55-15.95)	3.44 (2.12-4.76)	5.54 (4.09-6.99)	3.42 (2.02-5.78)
Soccer	17.61 (13.02-21.30)	2.96 (2.04-3.88)	6.11 (4.94-7.27)	5.80 (3.91-8.58)
Softball	6.33 (3.80-8.86)	2.54 (1.57-3.52)	3.57 (2.58-4.56)	2.49 (1.43-4.33)
Track	0.79 (0.00-1.69)	0.33 (0.07-0.59)	0.41 (0.14-0.68)	2.40 (0.60-9.59)
Volleyball	3.67 (2.31-5.03)	2.09 (1.49-2.69)	2.50 (1.93-3.06)	1.76 (1.10-2.81)
Girls Total	7.07 (6.11-8.03)	1.49 (1.27-1.71)	2.64 (2.37-2.90)	4.75 (3.88-5.81)
Overall	8.71 (8.15-9.27)	2.64 (2.48-2.80)	3.89 (3.72-4.06)	3.30 (3.02-3.60)

O'Connor, K. L., Baker, M. M., Dalton, S. L., Dompier, T. P., Broglio, S. P., & Kerr, Z. Y. (2017). Epidemiology of sport-related concussions in high school athletes: National Athletic Treatment, Injury and Outcomes Network (NATION), 2011–2012 through 2013–2014. *Journal of athletic training*, 52(3), 175-185.

Similar to high school football, collegiate football athletes have been found to be at a significant risk of sustaining a concussion (6.71/10,000 AEs).⁸ Specifically, Zuckerman et al.⁸ found that collegiate football athletes had a risk of 30/10,000 AEs during competition and 4/10,000 AEs during practice. However, researchers have found that wrestlers have the overall greatest risk (10.92/10,000 AEs) of any collegiate sport.⁸ Surprisingly, collegiate men's and women's ice hockey (men: 7.91/10,000 AEs, women: 7.50/10,000 AEs), not football were identified as having the next highest risk for sustaining a concussion.⁸ Table 5 shows collegiate concussion rates per 10,000 AEs.

Table 5: College Concussion Rates by Sport

Sport	Concussion Rate per 10,000 AEs (95% Confidence Interval)		
	Game	Practice	Total
Men			
Baseball	1.20 (0.37-2.04)	0.72 (0.22-1.21)	0.90 (0.46-1.34)
Basketball	5.60 (3.45-7.75)	3.42 (2.54-4.31)	3.89 (3.06-4.72)
Football	30.07 (26.43-33.71)	4.20 (3.75-4.64)	6.71 (6.17-7.24)
Ice Hockey	24.89 (21.14-28.63)	2.51 (1.84-3.18)	7.91 (6.87-8.95)
Lacrosse	9.31 (5.66-12.96)	1.95 (1.20-2.69)	3.18 (2.31-4.05)
Soccer	9.69 (6.39-13.00)	1.75 (1.02-2.48)	3.44 (2.53-4.35)
Track	0.00 (0.00-0.00)	0.13 (0.00-0.40)	N/A
Wrestling	55.46 (39.43-71.48)	5.68 (3.92-7.44)	10.92 (8.62-13.23)
Men's Total	9.35 (8.22-10.47)	1.63 (1.39-1.87)	3.23 (2.93-3.54)
Women			
Basketball	10.92 (7.89-13.95)	4.43 (3.36-5.50)	5.95 (4.87-7.04)
Field Hockey	11.10 (4.22-17.99)	1.77 (0.22-3.32)	4.02 (1.99-6.06)
Gymnastics	4.83 (0.00-11.52)	2.43 (0.92-3.93)	2.65 (1.15-4.14)
Ice Hockey	20.10 (15.01-25.18)	3.00 (1.82-4.17)	7.50 (5.91-9.10)
Lacrosse	13.08 (8.15-18.02)	3.30 (2.08-4.52)	5.21 (3.84-6.59)
Soccer	19.38 (15.60-23.16)	2.14 (1.43-2.85)	6.31 (5.25-7.37)
Softball	5.61 (3.77-7.44)	1.75 (0.92-2.58)	3.28 (2.40-4.17)
Track	0.00 (0.00-0.00)	0.51 (0.00-1.09)	N/A
Volleyball	5.75 (3.54-7.96)	2.69 (1.73-3.65)	3.57 (2.64-4.51)
Women's Total	10.81 (9.54-12.09)	1.99 (1.70-2.28)	3.94 (3.58-4.31)
Overall	12.81 (11.97-13.65)	2.57 (2.39-2.75)	4.47 (4.25-4.68)

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: incidence, recurrence, and mechanisms. *The American journal of sports medicine*, 43(11), 2654-2662.

As the above suggests, influencing factors such as sport, event type (practice, competition) and age have been well documented in the literature. Similarly, male and female athletes have been found to yield differing concussion rates. Evaluation of these sex differences often utilize similar sex-comparable sports such as basketball, soccer, baseball/softball, ice hockey, lacrosse, etc. At both the high school and collegiate levels, females were overall at greater risk of sustaining a concussion compared to males (High School (HS) females: 2.64/10,000 AEs, HS males: 1.69/10,000 AEs; college females: 3.94/10,000 AEs, college males: 1.63/10,000 AEs).^{8,57} Previous research has found that females are at a 2.7, 2.5 and 1.6 times greater risk for sustaining a concussion in softball/baseball, basketball and soccer respectively, when compared to males.⁵⁸

Finally, the last influencing factor for concussion risk is the time during an event (e.g., beginning, middle, end) and the time during the season. Athletes are more at risk during the middle of all sporting events compared to the beginning (Relative Risk (RR)- 4.90) and end (RR- 3.28).⁵⁹ This is unsurprising because the middle of events tends to be the longest time-frame of competitions and the most intense during practices. Researchers have yet to evaluate at which time during an athletic season concussions are most prevalent. This gap in knowledge may help to further the understanding of SRCs by athletes, parents, coaches and healthcare professionals.

Despite the identified information presented, athletes continue to significantly underreport these head injuries.⁶⁰⁻⁶² Conway et al.⁶⁰ identified that 91% of collegiate athletes think they can “tough out” a concussion and do not report their injury to a healthcare professional. Athletes also failed to report a concussion out of fear of being taken out of competition (91%) and fear that they would lose future playing time (87%).⁶⁰ Athletes have also cited not being aware they were experiencing a concussion, supporting the need for an awareness

intervention for athletes.⁶³ Additional factors such as school location (urban vs suburban) and athletic trainer availability have been found to contribute to poor athlete knowledge as it relates to concussions.^{61,62} High school athletes attending urban schools had worse knowledge in identifying a concussion than students who attended suburban schools.⁶¹ Additionally, not having access to a full time athletic trainer reduced concussion knowledge.⁶² These awareness problems coupled with athletes resistance to reporting concussion symptoms may suggest that the injury occurs more than initially reported.

Concussion Diagnostic Procedure

Concussion Sideline Evaluation

Sport-related concussions are complicated injuries to identify and diagnose due to no physical injury being seen. Additionally, these injuries affect every athlete differently causing there to be no perfect identifying measure. Healthcare professionals must often rely on observing a direct blow to the head, or having athletes self-report their post-concussive signs and symptoms. During an event, if an athlete is suspected of having a SRC they should be removed from play immediately and evaluated by a healthcare professional.⁶⁴ Furthermore, if signs such as loss of consciousness, blank vacant stare, or significant balance impairments, are apparent after contact to the head, the athlete should be removed from competition and be further evaluated for a SRC.^{65,66} This removal from play is critical in preventing further, more serious injuries from occurring such as second impact syndrome. Second impact syndrome is a condition in which an athlete sustains a second head injury before completely recovering from previously sustained head trauma.⁶⁷

Intracranial hemorrhage is another concern when a SRC is suspected. Intracranial hemorrhage is a bleed within the skull which can compress the brain causing significant

impairment or even death.^{68,69} This bleeding may be suspected if an athlete's post-concussion signs and symptoms deteriorate significantly which will then warrant immediate activation of emergency medical services (EMS). Diagnostic imaging (i.e., computed tomography (CT)) may then be utilized to identify if any bleeding has occurred within the brain or skull.⁶⁹ A common misconception of diagnostic imaging is its ability to visually identify if a SRC has been sustained. This is due to SRCs being functional in nature and not expressing any identifiable brain damage.⁶ Therefore, the main use for post-concussion neuroimaging is to identify the presence of cerebral hemorrhage or other concerning damage to the skull/brain.

Once an athlete is removed from play with a suspected SRC, a comprehensive sideline evaluation should take place. Ideally, this evaluation should be conducted in a quiet, distraction-free environment which due to the fast-paced nature of athletics may not be feasible. To aid in making sideline assessments thorough and concise, several sideline evaluation tools have been developed. The Sport Concussion Assessment Tool (SCAT), the Balance Error Scoring System (BESS), the King-Devick (KD) test, and the Vestibular Ocular Motor Screening (VOMS) are common sideline assessments created to aid healthcare professionals in quickly identifying if an athlete has sustained a concussion.

Sport Concussion Assessment Tool

The SCAT was created by the CISG in 2004 to help standardize and improve the SRC sideline evaluation process.⁷⁰ The SCAT combines several components of the SRC evaluation (i.e., symptom evaluation, cognitive assessment, neurological functioning) into one succinct document and is currently the most commonly utilized sideline assessment tool.^{6,71} Since 2004, the SCAT has undergone several revisions to reflect current research recommendations. The revisions to the original SCAT include the SCAT2, SCAT3 and SCAT5.

The most recent version, the SCAT5, has undergone significant revisions which mainly consists of adding components such as a new 10-word immediate memory list and alternative digits-backward lists. The SCAT5 includes several sections including an immediate/on-field assessment, office/off-field assessment, athlete background, Glasgow Coma Scale, self-reported symptom evaluation, cognitive and neurological screening, and a balance measure. The athlete background section obtains several demographic information including athlete sex, sport, position, and health history (concussion history, diagnosis of headache disorder, migraines, learning disability, dyslexia, Attention Deficit Hyperactivity Disorder/Attention Deficit Disorder (ADHD/ADD), depression, anxiety, and current medications).

The Glasgow Coma Scale is used to assess the level of consciousness for eye and verbal responses, as well as motor responses.⁷² If athletes are able to open their eyes spontaneously to stimuli, they receive a 4/4.⁷² If athletes are oriented to verbal commands, they receive a 5/5.⁷² Finally, if athletes are able to obey motor commands they receive a 6/6.⁷² These components are then added together to yield a maximum score out of 15.

Athletes then self-report 22 common post-concussion symptoms on a 7-point Likert scale (0 (none) to 6 (severe)). Athletes receive a total symptom score based on the 22 concussion symptoms and a total symptom severity score out of 132. The cognitive screening section includes the Standard Assessment for Concussion (SAC). The SAC is broken into several subcategories (orientation, immediate memory, concentration and delayed recall) which are scored individually then added together to get a total SAC score. Orientation consists of questions (i.e. what is the date day of the week?) in which participants receive a point for every correct answer. Then, athletes were presented a newly added 10-item word immediate memory list, three separate times, and are asked to recite them back in any order. The concentration

section, which consists of the digit backwards test and months of the year in reverse order. During the digit backwards test, athletes are given a string of numbers and asked to repeat them backwards. The digit backwards test starts with a string of 3 numbers (i.e., 4-9-3) and increases to 6 numbers (i.e., 8-4-1-3-5-7) if the strings are answered correctly. The digit backwards test is stopped after two consecutive incorrect answers or correctly completing all strings backwards. In the concentration section, athletes are asked to repeat the months of the year backwards starting with December. The final section of the SAC is the delayed recall, which asks athletes to repeat the original 10 words from the immediate memory test. A total SAC score is calculated by adding each component of the SAC together and has a max of 50. The original version of the SAC had a test-retest reliability of 0.64.⁷³ The validity for each subtest of the original SAC is as follow: Orientation ($r = .36$), immediate memory ($r = .61$), concentration ($r = .68$), and delayed recall ($r = .52$).⁷³ It should be noted that validity and reliability measures do not currently exist for the SCAT5 or the newly added 10-word recall list.

The neurological screening test included several components such as, athletes being able to read aloud and follow instructions without difficulty, having full, pain-free passive cervical spine movement, the ability to move their eyes from side-side and up-and down with a stationary head, performing the finger-to-nose coordination test, and a tandem gait test. The final section of the SCAT5 includes the modified BESS (*mBESS*) which will be discussed at length in the balance section of this document.

During the third international conference, the CISG deemed it necessary to create an age appropriate version of the SCAT directed towards children under the age of 12, thus the Child-SCAT3 was created.¹⁵ During the most recent CISG meeting, the Child-SCAT3 underwent an update and is now the Child-SCAT5.⁶ The Child-SCAT5 includes several components similar to

that of the adult SCAT5, but with more age appropriate language and easier testing procedures to improve patient comprehension. Specifically, the Child-SCAT5 includes a parent-reported and child-reported Health and Behavior Inventory which provides insight into the post-concussion symptoms a child may be experiencing.⁷⁴ The child version also has several distinct differences in the SAC components, including elimination of the time component for orientation, starting with a two-digit string for digits backwards, and changing months in reverse order to days of the week in reverse order.⁷⁴ Finally, the single leg balance position was removed from the balance examination component of the SCAT5.⁷⁴

Despite the SCAT5 being the most commonly used sideline assessment tool, it alone should not be used to confidently diagnose an athlete with a SRC. It is been recommended that medical professionals utilize a multimodal approach consisting of several evaluation metrics to improve the overall sensitivity and specificity of the SRC evaluation process.^{6,75,76} This multimodal approach should be completed for every SRC evaluation and should consist of a symptom inventory, neurocognitive assessment, balance evaluation and vestibular/ocular testing.^{6,77} After conducting this thorough evaluation, healthcare professionals should utilize their results to best determine if a SRC has been sustained. If the athlete is suspected of having a SRC, or if the clinician is unsure of their findings, the athlete should not be allowed to return to activity the same day.

Concussion Symptomology

Following a concussion, individuals present with a wide array of clinical signs and symptoms. These transient symptoms can last several days, weeks, or even months and may significantly impact athlete's activities of daily living during this time. Symptom reporting ranges significantly between individuals, with some athletes reporting several post-concussion

symptoms, or simply endorse a single symptom. However, previous research analyzing post-concussion symptom trends identified that athletes report an average of 4 to 5 symptoms following a SRC.⁷⁸ Of the possible symptoms experienced, headache, dizziness, and difficulty concentrating have been found to be the most commonly reported after a SRC.⁷⁸

Standard of care when evaluating athletes with a suspected SRC involves identifying these post-concussion symptoms. Several symptom scales have been created to augment this process and allow clinicians to track improvements across recovery. The Graded Symptom Checklist (GSC),⁷⁹ Post-Concussion Symptom Scale (PCSS),^{80,81} Rivermead Post-Concussion Symptom Questionnaire (RPQ),⁸² and the Head Injury Scale (HIS)⁸³ have all been previously used in research. However, these existing symptom scales range significantly in not only the symptoms asked but also the scale measuring the severity of the symptoms. Of these symptom scales, the GSC and PCSS are the most adopted by healthcare professionals due to their ease of use and their incorporation on the SCAT5⁷¹ and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT)⁸⁴ respectively. The GSC includes 22 symptoms which are graded on a 7-point Likert scale ranging from 0 (not experiencing) to 6 (severely experiencing). Similarly, the PCSS consists of 22 total symptoms, however, these differ from those on the GSC. These symptoms are also scored on the same 7-point scale as the GSC.

These symptom inventories may be utilized at different stages throughout the evaluation and management of a SRC. Athletes are commonly given a symptom assessment at baseline (pre-season), when a concussion is suspected, and to track recovery after a concussion is diagnosed. Baseline symptom assessment serves as an individualized measure that may later act as a comparison if a concussion is suspected. This is because athletes tend to report concussion like symptoms even in the absence of a concussion.⁸⁵

Significant research has been performed to identify patterns in symptom reporting at baseline and immediately following a SRC. Additionally, premorbid factors that affect symptom reporting have been a popular area of focus for previous research. Factors such as athlete sex, age, and previous medical history have been purposed to influence symptom reporting at baseline and following injury. A closer evaluation into these potential relationships is necessary.

Sex Differences in Concussion Symptom Reporting

At baseline, mixed results exist for the effects of sex on symptom reporting. Several previous studies have identified females as reporting more total symptoms with an overall greater severity at baseline when compared to males.^{80,86-88} However, conflicting results exist suggesting that males endorse more symptoms,⁸⁹ or that there are no difference in symptom reporting at baseline between males and females.⁹⁰ Despite these conflicting results, more evidence is in support of this sex difference, suggesting that athlete sex may need to be considered when completing baseline symptom assessments.

Like the sex differences present at baseline, females have been found to report more symptoms and at greater severity after a SRC when compared to concussed males.^{80,91-95} Specifically, females are more likely to report being dizzy or having sensitivity to light, whereas males more likely report confusion and disorientation.⁹⁶ However, conflicting evidence also exists suggesting there are no differences between males and females in symptom reporting after a SRC.⁹⁶ However, research supporting these similarities are underwhelming, therefore these post-injury sex differences are generally accepted by researchers due to the high support from previous research. These post-injury sex differences suggest that males and females may need differing treatment approaches. Additionally, these differences may also suggest that females may take longer to recover than males due to the increase in symptom reporting after injury.

Age Differences in Concussion Symptom Reporting

Similar to the aforementioned sex differences, researchers have also evaluated the impact age has on symptom reporting. For convenience purposes, this evaluation commonly consists of separating athletes by participation levels (i.e., youth, high school, collegiate) and evaluating this effect on baseline and post-injury symptom reporting. Mixed findings exist when comparing these levels of participation. In a study comparing healthy high school and collegiate athletes, no differences in the number or severity of symptoms were identified during baseline testing.⁹⁷ Despite the lack of difference in symptom total and severity, differences were identified in the type of symptoms reported between these healthy athletes. High school athletes were found to report more somatic and migraine symptoms, whereas college reported higher levels of emotional and sleep related symptoms at baseline.⁹⁷

When assessing these age differences in concussed athletes, Covassin et al.⁹⁴ identified no age differences for either the total number or severity of post-concussion symptoms. These age similarities were again found in more recent research comparing high school and collegiate athletes after SRC diagnosis.⁹⁸ However, when comparing symptom reporting between concussed youth, high school and collegiate football athletes, researchers identified youth as reporting the least number of symptoms (4.76 ± 2.58) compared to high school (5.60 ± 3.16) and collegiate athletes (5.56 ± 3.03).¹⁰ Furthermore, differences were found in the specific types of symptoms endorsed between the three levels of competition. High school and collegiate athletes reported more cognitive and sleep related symptoms than youth athletes.¹⁰ However, caution must be taken when comparing youth athletes to these other levels, as youth may not fully understand the symptoms they are experiencing, or how to represent them accordingly. Because of this reason, the Child-SCAT5 includes a different symptom reporting measure with easier

terminology, along with a parent reported symptom section.⁷⁴

Health History and Concussion Symptom Reporting

The effects of premorbid health conditions on concussion outcomes have become an increasingly popular area of research, specifically as they relate to symptom reporting. Previous history of concussion,⁹⁸⁻¹⁰² Attention Deficit Disorder/Attention Deficit Hyperactivity Disorder¹⁰³⁻¹⁰⁶ and depression^{75,97,107,108} have all been purported to have an impact on symptom reporting. Of these conditions, concussion history has the most inconsistent influence on symptom reporting both at baseline and following SRC. While the link between depression history and symptom reporting has the greatest support.

During baseline symptom assessments, mixed results have been reported for athletes with previous concussion diagnoses. Specifically, athletes with a previously diagnosed concussion have been found to report more symptoms than those without a previous concussion.⁹⁹ Researchers also identified that athletes with 2 or more previous concussions report more symptoms at baseline than those who have no history.¹⁰¹ Researchers also found an increase in baseline symptom reporting with every additional previous SRC.¹⁰⁰ However, these findings were contradicted by Chin et al.⁸⁸ who identified no differences. Similar results were found concluding there were no differences between athletes with and without a history of SRC.¹⁰⁹ Mixed findings also exist for concussion history and symptom reporting after a SRC. Researchers have reported post-concussion symptom reporting differences in athletes with and without a history of a concussion.^{98,102} Furthermore, Covassin et al.¹⁰² identified that athletes with 3 or more previous concussions reported more symptoms one week after sustaining a SRC than athletes without a previous history of concussions. These results have been contradicted in a

sample of collegiate athletes, suggesting no differences in symptom reporting for athletes with and without previous concussion diagnoses.¹¹⁰

The effects of ADHD/ADD on symptom reporting has been well studied.¹⁰³⁻¹⁰⁶ One study identified collegiate athletes with ADHD/ADD as recording a baseline symptom score of approximately 10, whereas those without a history of ADHD/ADD reported a score of only 4.¹⁰³ Researchers again confirmed these findings in a sample of 27,000 healthy high school and collegiate athletes.¹⁰⁴ Similar differences were found in an adolescent sample, concluding that those with ADHD/ADD report approximately twice as many symptoms at baseline than those without the diagnosis.¹⁰⁵ The same study found no difference between adolescents being treated with ADHD/ADD medication and those with ADHD/ADD who were not medicated.¹⁰⁵

Despite this overwhelming amount of research on baseline symptom reporting, little evidence exists for the effects of ADHD/ADD on post-concussion symptom reporting. Gardner et al.¹⁰⁶ found no differences in symptom reporting between concussed athletes with ADHD/ADD and without the diagnosis. Additional research is needed to evaluate if athletes with ADHD/ADD report more symptoms after SRC diagnosis than athletes without this condition. This analysis is needed at every level of competition (youth, high school, college), as these athletes may experience the effects of ADHD/ADD and concussion differently.

Due to the increasing prevalence of depression, research analyzing the effects of these conditions on concussion symptomology have begun to rise. Furthermore, researchers have found that approximately 15.6% of collegiate athletes meet criteria for possible clinical depression, which may alter symptom reporting before and after a SRC.¹¹¹ Covassin et al.⁹⁷ identified a dose response for baseline symptom reporting suggesting that as the severity of depression got worse, more symptoms were reported. Their results found that athletes with mild,

moderate and severe depression reported approximately 13, 14 and 21 symptoms respectively.⁹⁷ Athletes with a history of depression were again found to report more baseline symptoms when directly compared to those athletes without a previous depression diagnosis.⁷⁵ These results are unsurprising, as the symptomology between depression and concussion are similar in nature.¹¹²

Athletes who reported depression related symptoms at baseline were more likely to report these again after sustaining a SRC.¹¹³ Additionally, athletes with a history of depression have been found to report more symptoms than those athletes without the diagnosis.¹⁰⁷ More specifically, athletes with a previous depression diagnosis reported greater post-concussion symptoms 7 and 14 days after sustaining a SRC.¹⁰⁸ When comparing the emotional responses of athletes with a SRC and Anterior Cruciate Ligament (ACL) injury, athletes with a SRC experienced more depressive like symptoms immediately following their injury.¹¹⁴ However, athletes with a ACL injury expressed more long-term depression symptoms, likely due to their recovery taking longer.¹¹⁴ Future research is needed to identify the exact extent in which post-concussion symptom reporting is influenced by previous depression diagnoses. Due to the similarities between depression and concussion symptoms, extreme caution must be taken when evaluating and managing concussed athletes with a history of depression. Further medical referral may be warranted to manage both conditions.

Baseline and Post-Concussion Symptom Factors

The large variability in symptom reporting may provide a challenge for healthcare professionals when evaluating athletes for a SRC. This challenge has prompted researchers to identify symptom groupings commonly reported in conjunction with one another. This research strategy utilizes factor analyses to identify baseline and post-injury symptom factor groupings. These groupings can help predict reporting patterns and implement more guided treatments to

address these predictable symptomologies. A major limitation to previous symptom factor research is the lack of consistency in symptom inventories, and populations studied.

Piland et al.⁷⁹ were some of the first to look at symptom factors, and did so in a sample of healthy athletes. Their results identified a 3-factor structure consisting of somatic, neurobehavioral and cognitive structures for the 16-item and 9-item GSC in healthy athletes. Similarly, Herrmann et al.⁸² identified a 3-factor structure for healthy athletes, however their factors included mood-cognition, general somatic, and visual somatic, which varies slightly from previous research. A larger, more recent factor analysis utilizing the PCSS found a 4-factor structure for healthy and concussed high school and collegiate athletes.⁸⁰ The healthy sample endorsed symptom factors consisting of cognitive-sensory, sleep-arousal, vestibular-somatic, and affective.⁸⁰ The post-concussion group reported cognitive-fatigue-migraine, affective, somatic and sleep-arousal symptom factors.⁸⁰ The specific symptoms included in each of these factors can be found in Table 6 and Table 7.

Table 6: Symptoms Included in the Factor Analysis for Healthy Athletes

Cognitive-Sensory	Symptom Factors		
	Sleep-Arousal	Vestibular-Somatic	Affective
Sensitivity to Light	Fatigue	Headache	Irritability
Sensitivity to Noise	Trouble Falling Asleep	Nausea	Sadness
Feeling Slowed Down	Sleeping Less Than Usual	Vomiting	Nervousness
Mentally Foggy	Drowsiness	Balance	More Emotional
Difficulty Concentrating		Dizziness	
Difficulty Remembering			
Vision Problems			

Kontos, A. P., Elbin, R. J., Schatz, P., Covassin, T., Henry, L., Pardini, J., & Collins, M. W. (2012). A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. *The American journal of sports medicine*, 40(10), 2375-2384.

Table 7: Symptoms Included in the Factor Analysis for Concussed Athletes

Cognitive-Migraine-Fatigue	Symptom Factors		
	Affective	Somatic	Sleep
Headache	Sadness	Vomiting	Trouble Falling Asleep
Dizziness	Nervousness	Numbness	Sleeping Less Than Usual
Fatigue	More Emotional		
Drowsiness			
Sensitivity to Light			
Sensitivity to Noise			
Feeling Slowed Down			
Mentally Foggy			
Difficulty Concentrating			
Difficulty Remembering			

Kontos, A. P., Elbin, R. J., Schatz, P., Covassin, T., Henry, L., Pardini, J., & Collins, M. W. (2012). A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. *The American journal of sports medicine*, 40(10), 2375-2384.

Concussion Neuropsychological Testing

During the multimodal concussion evaluation process, it is recommended to include neuropsychological testing to assess for cognitive impairments.⁶ This is because cognitive performance has been shown to be negatively impacted in the presence of a concussion.^{95,115} Neuropsychological testing also adds an objective component to the predominantly subjective evaluation process, thus relying less on athletes to self-report their injuries. This evaluation component may take many forms, ranging from sideline pen and paper tests, to more formal computerized testing protocols. Furthermore, a single assessment may evaluate for several specific aspects of cognitive function often impaired by a concussive injury (i.e., memory, processing speed, concentration, reaction time).^{116,117}

Some of the common pen and paper neuropsychological tests include the SAC, Trail Making Test, and Brief Visuospatial Memory Test-revised..¹¹⁸ The SAC is arguably the most utilized during concussion assessments due to its incorporation within the SCAT.⁷¹ These assessments may be completed with minimal equipment, and are often easily accessible for

clinicians. However, the psychometric properties are subpar when identifying athletes with a concussion. Researchers have identified some pen and paper assessments to have a sensitivity as low as 20% when evaluating for a concussion.¹¹⁹ Although these tests can be useful on the sideline of sporting events, another drawback is the time required to perform these one-on-one assessments.¹²⁰ Due to the lackluster qualities of these tests, computerized neuropsychological assessments were created to help reduce time constraints, and improve testing thoroughness.

Computerized neuropsychological assessments allow clinicians to test multiple athletes at a given time, while ensuring a thorough athlete profile is obtained. Several computerized tests exist including, ImPACT, Automated Neuropsychological Assessment Metrics (ANAM), Cogstate, and Concussion Vital Signs.¹²¹ Of these widely accessible programs, ImPACT is most commonly utilized by clinicians for baseline and post-injury evaluations.^{122,123} Computerized testing has been thought to have several benefits over the pen and paper version, including the ability to utilize different testing versions to reduce practice effects, testing multiple athletes at once, ease of compiling results, and their ability to assess several different domains of cognitive functioning.^{124,125} When directly compared, researchers found computerized assessments to have higher sensitivity than pen and paper versions.¹²⁶ However when evaluating the reliability of these computerized assessments, lackluster performance has been reported for ANAM (Intraclass Correlation Coefficients (ICC)) = 0.14-0.86), Cogstate (ICC = 0.45-0.90) and ImPACT (ICC= 0.23-0.91).¹²³

ImPACT is a 20-minute computerized assessment which evaluates an individual's visual memory, verbal memory, visual motor processing speed, and reaction time. Approximately 90% of athletic trainers have been reported to utilize ImPACT for the neuropsychological component of their concussion evaluation.¹²⁷ This popularity is concerning due to the reported inconsistency

of ImPACT. Specifically, the reliability of ImPACT has been reported to vary, with ICCs of the individual components ranging from 0.23¹²⁸ to 0.91¹²⁹. Intraclass correlation coefficients for each component can be found in Table 8. The large variability in ICCs by each component may be contributed to the different testing protocols and populations utilized by researchers. Register-Mihalik et al.¹³⁰ assessed ImPACT's reliability in collegiate and high school athletes over a 1-3 day period, whereas another study¹³¹ evaluated reliability results in professional athletes 1 year apart. Athlete sex,^{93,95,115} age,^{88,130,132} and premorbid health conditions^{88,133} have been reported to influence neuropsychological performance. Additional factors have been reported to influence ImPACT scores, such as the prior night of sleep¹³⁴ and pre-assessment exercise.¹³⁵ Future analysis on the psychometric properties of neuropsychological testing should aim for consistency in the testing procedures to improve better improve the generalizability of the findings.

Table 8: Previously Reported Intraclass Correlation Coefficients for Each Component of the ImPACT Assessment

Study	Sample	Time Between	Verbal Memory	Visual Memory	Processing Speed	Reaction Time
Broglia ¹²⁸	College	45 days	0.23	0.32	0.38	0.39
Bruce ¹³¹	Professional	1 year	0.54	0.38	0.74	0.52
Register-Mihalik ¹³⁰	College, High School	1-3 days	0.29	0.45	0.71	0.60
Elbin ¹³⁶	High School	1.2 years	0.62	0.70	0.85	0.76
Schatz	College	1.9 years	0.46	0.65	0.74	0.68
Nakayama ¹²⁹	College	45 days	0.76	0.72	0.87	0.67
Cole ¹³⁷	Military	32 days	0.60	0.50	0.83	0.53

Caplan, B., Bogner, J., Brenner, L., Alsalaheen, B., Stockdale, K., Pechumer, D., & Broglia, S. P. (2016). Measurement error in the immediate postconcussion assessment and cognitive testing (ImPACT): systematic review. *Journal of head trauma rehabilitation*, 31(4), 242-251.

Not only have researchers evaluated the psychometric properties of computerized neuropsychological assessments, but population normative values have been reported. Normative values have been reported for healthy and concussed male and female athletes ranging in

competition level and previous health diagnoses. Understanding the effects these factors have on neuropsychological performance is critical to ensure complete accuracy when interpreting baseline and post-injury results.

Sex Differences in Concussion Neuropsychological Performance

Previous research assessing sex differences on neuropsychological assessment focuses more commonly on the ImPACT assessment battery. Specifically, Covassin et al.⁸⁶ found that healthy female athletes performed better on the verbal memory component of ImPACT, but performed worse than males on the visual memory component. Similar findings were again reported in high school and collegiate athletes, with females performing better than males in the verbal memory component of ImPACT.⁹⁷ Despite these differences, mixed findings exist suggesting that males and females perform similarly during baseline neuropsychological testing.^{95,138} Although ImPACT is the most utilized tool to assess for these baseline sex differences, other test results have been reported. When utilizing the SAC, researchers found that high school males performed worse on the orientation component, as well as recorded worse total SAC scores when compared to females.⁸⁹ These results are consistent with those presented by Chin et al.⁸⁸ who found that females outperformed males on almost every component of the SAC. Despite these differences, when utilizing the Child SCAT3 no differences were noted between healthy male and female adolescent athletes.¹³⁸

Despite previous research identifying baseline sex differences in neuropsychological performance, even larger discrepancies between males and females have been reported after injury. Specifically, researchers have identified concussed females as performing worse after injury than their male counterparts.^{93,95,115} When completing ImPACT within 3 days after sustaining a SRC, females performed worse on visual memory, verbal memory and reaction

time.⁹⁵ However, these researchers found no differences for visual motor speed.⁹⁵ Tanveer et al.¹¹⁵ also found these visual memory differences between concussed male and female athletes, although no other post-injury differences were identified. Differences were again found 8 days after SRC, with females performing worse in the visual and verbal memory components.⁹³ Despite the sex differences presented for ImPACT, little to no differences were found when utilizing the SAC after injury.¹³⁹

Additional research should assess for these cognitive differences utilizing other neuropsychological assessments as ImPACT and SAC are not the only commercially available tools to evaluate for a SRC. Results from other assessments may help clinicians and researchers better understand the extent to which the reported sex differences exist or if they can be contributed to measurement error of the assessments. Additionally, researchers should aim to identify how long these post-injury differences are present to better improve injury management.

Age Differences in Concussion Neuropsychological Performance

Athletes may experience physical, emotional, and cognitive maturation differently throughout their athletic careers. This maturation process can significantly impact concussion neuropsychological testing both during baseline measures and following injury. A significant amount of research has attempted to evaluate these differences to determine if more age appropriate measures are needed. For example, the Child-SCAT was derived from this research, which provides a more appropriate evaluation tool for those under 13 years of age.^{74,132} Specifically, Glaviano et al.¹³² identified age differences on the SCAT2 between middle school and high school athletes, with 12-year-old athletes performing worse on the concentration component when compared with 13-18-year-old athletes. Furthermore, age differences were

even found when utilizing the Child-SCAT3 on healthy youth athletes. Athletes age 5-7 years old performed worse on the Child-SCAT3 when compared to youth ages 11-13 years old.¹³⁸

Additional research analyzing age differences in healthy athletes found trends for worse performance in youth ice hockey (Atom and Pee Wee leagues) athletes when compared to those just slightly older (Bantam and Midget leagues).¹⁴⁰ Additional research support for these age differences were identified between high school and collegiate athletes during baseline SCAT testing, where high school athletes having worse performance.⁸⁸ Similarly, when utilizing ImPACT, researchers found differences in processing speed between high school and collegiate athletes.¹³⁰ These age differences are not surprising due to the maturation and developmental differences as well as the emotional immaturity of high school and youth athletes. Additionally, high school and collegiate athletes are at differing stages in academic demands, which may impact their performance on baseline cognitive assessments.

Despite the little amount of research done after injury, researchers have identified some cognitive inconsistencies when directly comparing concussed high school and collegiate athletes.⁹⁴ Specifically, concussed high school athletes performed worse on the verbal and visual memory components of ImPACT when compared to their collegiate counterparts.⁹⁴ Despite these reported age differences, additional research is needed to determine if these cognitive inconsistencies truly exists. Research should continue to identify age appropriate measures when assessing athletes for a possible SRC.

Health History and Concussion Neuropsychological Performance

Athletes who sustain multiple previous concussions may respond to subsequent head injuries differently than athletes with no previous injury. This concept has been the foundation for several studies comparing neuropsychological performance following multiple previous

concussions compared to those with no or few injury events. Like other influencing factors, concussion history has been reported to have mixed effects on cognitive performance. During baseline testing, athletes with a history of multiple past concussions did not differ from those without a previous history.^{75,88,89,139,141} Barker et al.¹⁴¹ further confirmed no cognitive differences between athletes with 0, 1, and 2 previously reported concussions. Despite these reported similarities, conflicting results have identified football athletes with 2+ prior concussions as performing worse than those with fewer previous injuries.¹³³ Similar results were found by Covassin et al.¹⁰² during post-injury neuropsychological testing. They determined that athletes with 3+ prior concussions demonstrated worse cognitive performance and for an extended period of time compared to those with less prior concussions.¹⁰² Although research has identified post-injury differences for athletes with multiple concussions, conflicting results have been reported suggesting little to no differences exist.¹³⁹ More consistent research is needed to determine if short term and long term cognitive differences exist among athletes with multiple past concussions, and if so what is the extent of these impairments.

Unlike the previous factors influencing neuropsychological performance, the effects of ADHD/ADD are understudied. Of the research that exists on ADHD/ADD, the majority are in support of neuropsychological differences during baseline testing.^{88,89,138} Limited research is available analyzing these effects after injury. Future research is needed to evaluate if these differences in neuropsychological performance exist after a concussion diagnosis. The results of this future research may suggest modifications to how the results of these assessments are interpreted.

Little research exists analyzing the effects of depression on baseline or post-injury neuropsychological performance. Putukian et al.⁷⁵ were one of the few to evaluate this effect,

yielding no baseline differences in neuropsychological performance between athletes with and without a history of depression. The only other study to analyze these effects at baseline identified differences in visual memory performance, with those reporting a history of depression performing worse.⁹⁷ Kontos et al.¹⁰⁸ discovered similar effects of depression on visual memory performance following a concussion diagnosis.

Concussion Postural Stability Assessment

Following a SRC, athletes often experience dizziness, vestibular pathology and balance impairments. Because of these common deficits, current consensus statements suggest the use of post-concussion balance assessments. Although often underutilized, post-concussion postural stability testing may provide clinicians with important information about the specific body systems that may be impacted by a SRC.

Post-concussion postural stability assessments have previously been criticized due to their large variability and inability to detect true clinically relevant changes. Specifically, these arguments stem from the commonly utilized BESS assessment. The BESS test is a non-technological postural control assessment, consisting of six total conditions, with 3 completed on a firm surface and 3 on a soft surface (double-leg, single-leg, tandem). During each trial, athletes are asked to be barefoot, have their hands on their hips, and their eyes closed for 20 seconds. The BESS is scored based on the total number of deviations from the starting position, with a maximum score of 10 per trial. A common modification of the BESS is the *mBESS*, which included only completing 3 trials on the firm surface and forgoing the soft surface.

Although the most commonly utilized balance assessment, the BESS is often criticized because it relies heavily on subjective interpretation which may lead to inconsistent results. When evaluating the reliability and validity of the BESS, mixed findings have been reported.

The BESS test has been reported to have a sensitivity of 0.34 and a specificity ranging from 0.91-0.96.¹⁴² When evaluating the reliability of the BESS test, some researchers found ICCs of 0.93 and 0.96 for interrater and intrarater reliability, respectively.¹⁴³ However, other researchers found results much lower (0.69), suggesting variability in the BESS test.

Despite the BESS test being the most popular non-technology based assessment among clinicians, the Romberg Test and the tandem gait are also commonly used to identify balance deficits. The Romberg Test assesses an athlete's postural sway with their eyes open and their eyes closed, with the presence of postural sway indicating a positive test. Despite its ease of use and popularity, no research exists on the validity or reliability of the Romberg Test when evaluating for a SRC. The tandem gait task is a simple gait assessment that includes athletes walking heel-to-toe as fast as they can for 6 total meters. The tandem gait assessment has a within-session reliability of 0.97 and a between session reliability of 0.71.¹⁴⁴

With the progress in technology, several companies have created more objective balance assessment tools that augment the concussion evaluation process. The Biodex Balance System utilizes a standard force plate to assess variations in center of pressure during various stances. A standard force plate, like the one included on the Biodex, is considered the gold standard when evaluating for changes in postural stability. However, due to the high cost and large space requirement, the Biodex is not clinically feasible in most athletic settings. Therefore, the BTrackS was created to address these limitations by providing clinicians with a portable and cost efficient solution. The BTrackS is an Federal Drug Administration (FDA) registered portable force plate used to assess center of pressure excursion during a double leg stance.¹⁴⁵ Participants complete a total of 4 20-second trials with feet shoulder width apart and eyes closed. This balance assessment has recorded high sensitivity (0.90) and specificity (0.64) when evaluating

athletes for the presence of a SRC.¹⁴⁶ Furthermore, research suggests that this device may be better at identifying balance deficits than the BESS test.¹⁴⁶

The final postural stability assessment is the SWAY Balance Mobile Application. SWAY Balance relies on the accelerometers located inside a mobile phone. Athletes hold the phone up to their chest while maintaining their stability in 5 different stances (1. Feet together, 2. Right leg in front of left, 3. Left leg in front of right, 4. Right leg only, 5. Left leg only).¹⁴⁷ After each testing position, athletes performance is represented on a scale of 0 (worst) – 100 (best). The SWAY balance application has been reported to have low to adequate reliability during serial testing ($r = 0.53 - 0.78$).¹⁴⁷ Despite its lower than ideal reliability, SWAY provides clinicians with a portable, objective measure of postural stability. Future research is needed to determine the validity of SWAY when assessing athletes for a SRC. Research is also needed to evaluate the utility of SWAY during sideline SRC assessments.

Factors Affecting Concussion Balance Assessment

Similar to other post-concussion outcomes, athlete sex, age, and concussion history have been purposed to influence balance assessment scores. However, due to the variety of balance assessments, mixed findings have been reported for baseline and post-concussion balance testing. Therefore, caution must be taken when interpreting and identifying factors that impact balance performance.

During baseline balance testing, researcher shows that as athlete age increases, balance performance improves.¹⁴⁸⁻¹⁵⁰ Specifically, when looking at the BESS test, youth athletes recorded significantly more errors (16 errors) than high school (13 errors) and collegiate athletes (12 errors).¹⁵⁰ When assessing these age differences using the BTrackS, Goble et al.¹⁴⁹ found that

as age increased, the amount of postural sway was reduced. Similarly, these age differences were again reported using the Biodex System.¹⁴⁸

Despite the evidence suggesting athlete age may impact baseline balance performance, little research has been done following a SRC. Covassin et al.⁹⁴ identified balance differences between high school and collegiate athletes. Specifically, they found that high school males performed worse than collegiate males on the BESS.⁹⁴ Interestingly, when comparing females, concussed high school athletes performed better than collegiate athletes.⁹⁴ Another post-concussion study utilizing the BESS found that as age increased balance performance decreased.¹⁵¹ The inconsistency of these findings make it challenging to confirm if age differences actually influence balance performance after a SRC.

The effect of sex on balance performance has been commonly assessed in previous research. At baseline, females have predominantly been shown to perform better than their male counterparts.¹⁴⁸⁻¹⁵⁰ However, the reasons for these balance differences are unknown. Conversely, when assessing balance after SRC, males and females recorded similar performances.¹⁵¹ These results may suggest that females incur greater balance impairments after SRC, which then causes their performance to become similar to males.

As previously reported, concussion history has been found to impact several post-concussion outcomes. When assessing its impact on baseline balance performance, researchers have found that those athletes with a history of concussion performed similar to those without a history.^{152,153} Although no differences were found at baseline, research is needed to compare these results in a concussed population. Future research should assess the relationship between concussion history and balance performance immediately following a SRC.

Vestibular/Ocular Motor Assessment

The vestibular system plays an important role in postural stability, spatial orientation, vision stability and sensing head motion.¹⁵⁴ Additionally, within this system are three reflexes tasked with responding to information received by the vestibular system. The Vestibulospinal reflex (VSR) is primarily responsible for maintaining whole body posture and balance, while the vestibulocollic reflex (VCR) is responsible for stabilizing the head.^{155,156} Finally, the vestibulo-ocular reflex (VOR) stabilizes vision during various head movements.^{155,156} Impairments in the vestibular system or any of its reflexes may drastically impact activities of daily living. Unfortunately, dysfunctions in this system are common following a concussion.¹⁵⁷

Researchers have found that approximately 55% of athletes experience vestibular dysfunction after a concussion.¹⁵⁸ Several factors have been linked to increased risk of vestibular dysfunction after a concussion such as, female sex, history of depression, post-injury amnesia, presence of dizziness, blurred vision, or difficulty concentrating.¹⁵⁹ Of the symptoms associated with vestibular impairments, dizziness is most commonly reported (50-85% of cases) by athletes after a concussion.^{80,160} Unfortunately, athletes with vestibular impairments have been found to take longer to recover after a concussion.^{157,161-163} Due to this protracted recovery, it is beneficial to include vestibular assessments within the concussion evaluation process to help guide early directed treatment (i.e., vestibular rehabilitation).

With recent research identifying high prevalence of vestibular dysfunction after concussion, several assessment tools have been created to augment the evaluation process. Of these assessments, the VOMS, Near-Point of Convergence (NPC), and the KD are most commonly utilized by healthcare professionals. The VOMS evaluates vestibular and ocular impairments through symptom provocation. Although found within the VOMS assessment, NPC

can be utilized as a stand along test which measures near sighted visualization which is often used when reading.¹⁶⁴ Finally, the KD test is a rapid number naming assessment which incorporates saccadic eye movement, attention and processing speed.¹⁶⁵ The KD test takes less than 2 minutes to complete and is commonly utilized during a sideline concussion evaluation. Although these tests help provide an insight into vestibular impairments after a suspected concussion, research supporting their utility varies tremendously.

Vestibular/Ocular Motor Screening (VOMS) Assessment

The VOMS battery aims to assess vestibular and ocular motor function through post-concussion symptom provocation. This assessment includes 7 components: 1) smooth pursuits, 2) horizontal saccades, 3) vertical saccades, 4) NPC 5) horizontal VOR, 6) vertical VOR, and 7) visual motion sensitivity (VMS). Participants rate symptoms of headache, dizziness, nausea and foginess on a scale of 0 (none) to 10 (severe) prior to testing, and then again after each of the 7 components. The NPC is an ocular assessment which reports the distance (in centimeters) a single target is away from the nose when two distinct figures are seen. The VOMS¹⁶⁶ and NPC¹⁶⁷ measure have both been shown to be reliable with high internal consistency. When utilizing VOMS and NPC, clinical cutoff scores have been established to help identify an abnormal assessment. A symptom provocation score of >2 for a given VOMS component, or a NPC distance of $>5\text{cm}$ are considered abnormal and thus a concussion may have been sustained.¹⁶⁸ Research has found that a positive VOMS assessment has been associated with concussion recovery delays.¹⁶¹

During administration of the VOMS assessment, several factors have been found to influence results. Specifically, females and athletes with a history of motion sickness report greater symptom provocation during baseline VOMS administration.¹⁶⁶ These sex differences

have also been found in concussed athletes,^{169,170} which is unsurprising due to females generally reporting more post-concussion symptoms than males.¹⁷¹ Despite these identified differences, no other factors have been found to influence VOMS scores. Specifically, concussion history had no association with VOMS results during baseline¹⁶⁶ and post-concussion testing.¹⁷⁰ Research is needed to evaluate the effects of age on VOMS scores in healthy and concussed athletes.

Near-Point of Convergence (NPC) Assessment

Although NPC is found within the VOMS, healthcare professionals may utilize this measure as a stand-alone assessment within their concussion evaluation protocol. Although abnormal scores are common after concussion, research has failed to identify risk factors (i.e., sex, age, concussion history) that may also influence NPC outcomes. Specifically, males and females have been found to perform similarly on NPC both at baseline and after a concussion.^{166,170} Additionally, athlete age as well as previous history of concussion, motion sickness, ADHD/ADD, or motion sickness have no influence on NPC results.^{166,170} The lack of factors influencing NPC results is beneficial to ensure an accurate evaluation is obtained, which may then only to be influenced by true vestibular impairments. Future research should assess NPC results outside of the VOMS assessment to ensure accurate results are obtained.

King-Devick (KD) Assessment

Finally, the KD test is a popular sideline assessment which takes under 2 minutes to complete. This assessment asks patients to read strings of numbers out loud as fast as possible in a left-to-right, top-to-bottom fashion.¹⁶⁵ A slower post-injury time represents a positive finding further suggesting the athlete may have a concussion. This interpretation method is based on the premise that there is a notable learning effect with the KD test, and it should be considered abnormal if an athlete's time does not improve.^{172,173} Despite this simple interpretation strategy,

the KD test has yielded good reliability ($ICC = 0.91$)^{174,175} and high sensitivity (0.98) and specificity (0.96) when evaluating for a concussion.¹⁷⁵ Due to its high psychometric properties and the KD test taking less than 5 minutes to complete, it may be best utilized during a sideline concussion assessment. Previous research examining risk factors and baseline KD scores identified sex and age differences, with females and older athletes performing better than their counterparts.¹⁷⁶ However, this study only included athletes ages 8-14 years old thus making it hard to generalize these findings to high school and collegiate athletes. Additional research is needed to evaluate if these risk factors influence KD outcomes in healthy high school and collegiate athletes. Research should also assess the relationship between these risk factors and KD results in athletes with a concussion.

Management of Concussion

On-field/Sideline Concussion Management

Although early concussion evaluation techniques are crucial to athlete safety, proper injury management strategies may alter the overall trajectory of an athlete's recovery. These management practices should begin immediately following a thorough concussion assessment. As previously mentioned, current consensus statements recommended that a successful concussion assessment should incorporate a symptom inventory, cognitive assessment, vestibular screening and balance testing.^{6,77} This assessment along with initial injury management strategies may vary depending on the location (i.e., sideline, off-field setting) of the evaluation and the time since injury.

Specifically, on the sidelines, if a concussion is suspected the athlete should not be allowed to return to activity within the same day as the suspected injury.^{6,77} Research is now suggesting that athletes who are not removed from play immediately after their concussion may

experience a protracted recovery.¹⁷⁷⁻¹⁸⁰ Specifically, Charek et al.¹⁷⁹ identified a dose response relationship between removal from play after a concussion and overall recovery time. They found that athletes who played up to 15 minutes after sustaining a concussion were 5 times more likely to experience a protracted recovery compared to those athletes who were removed immediately.¹⁷⁹ Additionally, athletes who continued to play longer than 15 minutes were 12 times more likely to see a delay in recovery than athletes who were removed immediately.¹⁷⁹ Some reasons for athletes not being removed from play after a suspected concussion may include, an improper injury evaluation, no medical personnel onsite, or athletes not disclosing their head injury. Regardless of the reason, athletes returning to play with a suspected concussion may have life threatening consequences.

Second Impact Syndrome

Second Impact Syndrome (SIS) has previously been defined as sustaining a second head injury while not yet recovered from an existing head injury (often a concussion).¹⁸¹ However, the true existence of this phenomenon has been heavily debated and its anatomical impacts are largely theorized. Second impact syndrome is believed to lead to a loss of regulation of the brain's blood supply.¹⁸¹ This uncontrolled blood supply typically leads to an influx of blood within the cranium which increases pressure on the brain and brainstem.¹⁸¹ Depending on the amount of cerebral edema present, complications may occur such as respiratory failure or even death.¹⁸¹ Researchers continue to debate if the purposed definition of SIS is an accurate representation of the mechanisms occurring within the brain. Because of this, the true prevalence of SIS remains unknown. However, the consequences of this syndrome appear to be severe, further suggesting that athletes should not be allowed to return to contact sports too rapidly after

a concussion. While withholding concussed athletes from their sport may be beneficial, it is not the only management technique that should be done immediately following a concussion.

Acute Concussion Management

Following a concussion, current medical practices recommend including a period of cognitive and physical rest. This period of rest is believed to ease discomfort during the acute recovery phase, minimize the excessive energy demands of the brain, and limit chances of a subsequent head injury.¹⁶⁻¹⁸ Because of these purposed benefits, previous consensus statements recommended a much longer resting period after a concussion.^{15,182} Specifically, athletes were recommended to rest until their concussion symptoms completely subsided, regardless of their duration. This extended rest period is still currently one of the most widely utilized concussion treatments available.¹⁸³ However, this recommended treatment is based on limited research support, with several details remaining unknown. Post-concussive rest currently lacks a true definition along with the optimal duration to yield the fastest recovery.

Researchers have begun to study the unknowns surrounding rest and are starting to suggest that prolonged cognitive and physical rest may not be an idealistic treatment strategy when managing athletes with a concussion.^{1,2,5} Thomas et al.¹ found that even extending rest periods by an extra 3 days (2 days vs 5 days) negatively impacted post-concussion symptom reporting and recovery time. Similar results were found when comparing post-concussion rest to post-concussion physical activity.⁵ Specifically, athletes in the active group recovered 3 days faster than those in the resting protocol.⁵ Although important, these findings only include youth and adolescent athletes, future research should evaluate the utility of rest in collegiate and adult athletes. Research should also assess the effects of prolonged rest on post-concussion outcomes in an adult population. Strong randomized clinical trials are lacking in the collegiate setting and

would provide information on the benefits of limiting rest in an older population. Although prolonged rest has previously demonstrated negative effects, a shorter, more controlled duration (24-48 hours) of rest may be necessary immediately after injury to ease initial discomfort and prevent a subsequent head injury.

Following a more controlled resting approach, athletes should be encouraged to start slowly returning to their normal activities of daily living provided concussion symptoms are not exacerbated.^{6,77} Additionally, athletes should still refrain from participating in any contact sports or activities that may increase their risk of a subsequent head injury. In conjunction with this gradual return to daily activity, several treatment options have been purposed to improve post-concussion outcomes and promote recovery.

Subacute Concussion Management

Several post-concussion treatment approaches have been previously utilized to manage athletes with a concussion, this includes medication/supplementation, academic accommodations, vestibular therapy, cognitive and physical rest, and aerobic exercise.¹⁸⁴ When utilizing concussion treatments, it is recommended to take a targeted approach based on the specific symptomology and impairments presented by the athlete.¹⁸⁵ For example, an athlete presenting with vestibular dysfunction may benefit from various forms of vestibular therapy, whereas they may not respond well to aerobic exercise. Selecting the optimal treatment approach may pose a significant challenge, therefore researchers should continue to evaluate current treatment options and attempt to identify new innovative methods for treating a concussion.

Academic Accommodations

Following a concussion, youth, adolescent and collegiate athletes often experience complications that carry over to their academic responsibilities. Specifically, high school athletes

have been found on average to miss between 1-4 days of school following a concussion.^{58,186} The number of missed school days was highly associated with the symptom burden experienced by the athlete.^{187,188} Therefore providing academic accommodations to lessen post-concussion symptoms may help athletes return to school faster and miss less schoolwork. However, despite missing school, high school athletes did not notice declines in academic performance as measured by changes in grade point average (GPA).^{186,189} This consistency in academic performance suggests that current academic accommodations along with a gradual return to learn process may successfully aid athletes when transitioning back into the classroom. It should be noted however, that allowing athletes too much time away from school may add undesired stress as the number of missed assignments and exams increases.

Although several things may be interpreted as an academic accommodation, research has shown that allowing time for cognitive rest, giving less homework, allowing more time to complete schoolwork, and less school attendance are most commonly utilized for athletes with a concussion.^{186,190} Of these accommodations, allowing students to miss school was perceived by athletes as being most beneficial.¹⁸⁹ Additionally, athletes also believed that not participating in physical education class and having open communication with their teachers were beneficial during their concussion recovery.¹⁸⁹ Despite this flexibility during school, only half of concussed high school athletes stated they were satisfied with the academic accommodations provided.¹⁸⁹ Research should continue to evaluate effective and beneficial ways to return athletes to the classroom in a safe and effective manner. Furthermore, research should evaluate what academic resources athletes feel would benefit them the most during their concussion recovery.

Medication and Supplementation

To date, no FDA approved pharmacological agents have been developed to specifically treat concussions. However, common practice when utilizing medication to treat athletes with a concussion is to match the pharmacological agent to the symptoms expressed by the athlete. It has been reported that up to 89% of healthcare professionals utilize over the counter (OTC) medications to help manage the various post-concussion symptomologies.¹⁹¹ Caution must be taken when utilizing medications for athletes with a concussion as this may mask true clinical recovery making return to play decisions difficult for healthcare professionals.

When medication is to be used to manage symptoms of a concussion, common practice suggests waiting until athletes are beyond the acute injury phase. Researchers have found that approximately 10 days post-injury is the most common time to start utilizing a pharmacological intervention.¹⁹² As mentioned, pharmacological interventions should be paired with the symptomology expressed after sustaining a concussion. Previous research has evaluated neurostimulant medications for athletes with cognitive-fatigue symptoms, anti-depressants for athletes with mood symptoms, and sleep medication for those with changes in sleeping habits.¹⁹¹ Despite current research evaluating the utility of pharmacological interventions such as the ones listed, results remain inconclusive. Further studies should continue evaluating the success of various medications when treating symptoms of a concussion. Additionally, it is critical to understand all potential side effects of these medications to ensure they are not adding to the unwanted symptom burden experienced by athletes.

Vestibular and Ocular Motor Therapy

Vestibular dysfunction after concussion has been well documented.^{158-160,162} Due to this prevalence, various forms of vestibular and ocular motor therapy may be utilized to augment the

recovery process. Vestibular therapy may take many forms based on the specific impairments and symptoms an athlete experiences. Dizziness is one of the most commonly reported symptoms following a concussion.^{80,160} Those that experience prolonged dizziness may benefit from a wide array of vestibular therapies including visual motor sensitivity and stationary exertional activity.^{168,193,194} Additionally, VMS training may also benefit those athletes that present with dizziness or vertigo like symptoms. This form of training often involves athletes focusing on one fixed point while moving their head in various directions.¹⁹⁴ Patients warranting VMS training often experience increased symptomologies when exposed to visually disorienting environments such as sporting events, malls or restaurants.

Another large component of vestibular therapy may involve postural control or balance activities. When the vestibular system is impaired, prolonged balance deficits may be likely, further warranting retraining. Specifically, this retraining focuses on sensory organization to help navigate between visual, somatosensory and vestibular information to maintain postural control.^{194,195} Sensory organization training may involve gradually increasing scenarios with eyes open or closed, on a soft or firm surface, while moving the head in various directions. Specifically, research is needed to evaluate the effectiveness of this specific type of vestibular therapy and its impact on concussion recovery.

Previous research evaluating the effectiveness of vestibular therapy is most prominent in patients suffering from vestibular impairments not related to concussion injuries. Specifically, research has commonly involved individuals with migraines,^{196,197} central vestibular dysfunction,¹⁹⁶ and those with VMS.¹⁹⁸ However, when assessing vestibular therapy in athletes with a concussion, positive outcomes were noticed. Schneider et al.¹⁹⁹ found that concussed athletes experiencing dizziness were 4 times more likely to receive medical clearance after

completing 8 weeks of vestibular therapy compared to those who did not complete this treatment. Favorable results were also found by Hoffer and colleagues²⁰⁰ in a sample of military personnel with post-concussion dizziness. Vestibular therapy remains a viable option for those who report dizziness or other related impairments following a concussion. However, additional research is needed to determine when to refer patients for vestibular therapy. Research is also needed to determine which athletes respond best to vestibular therapy (i.e., sex, age, health history) and under what circumstances.

Physical Activity and Aerobic Exercise

Utilizing physical activity in concussion management has previously been a controversial topic. This is likely due to previous research citing an increase in post-concussion symptoms following various bouts of physical activity.²⁰¹⁻²⁰³ Additionally, physical activity participation may predispose athletes to sustaining a second head injury if not monitored closely. Despite this, emerging research has begun to challenge the status quo of prolonged rest after a concussion diagnosis. In doing this, researchers are evaluating how physical activity may be leveraged to reduce symptom reporting, improve post-concussion assessments, and promote recovery. Positive research findings are suggesting that physical activity after concussion may be the most promising concussion treatment to date.

Following a concussion, there is little evidence to support a specific time to begin physical activity after a concussion.⁶ However, current consensus statements recommend a brief period (24-48 hours) of physical and cognitive rest immediately after sustaining a concussion.⁶ After this short rest period, athletes should begin a gradual return to normal activities of daily living including light physical activity.⁶ Athletes who begin light physical activity are instructed to progress at a rate that does not exacerbate their post-concussion symptoms.⁶

Including physical activity in post-concussion management strategies is based on a foundation of positive research findings. These research findings primarily focus on youth and adolescent athletes with adults being less represented. Specifically, when comparing post-concussion physical activity to prolonged rest, Leddy and colleagues⁴ found significant differences in overall recovery time. Participants in the physical activity group recovered in approximately 8 days compared to the rest group who recovered in approximately 24 days.⁴ These differences were again confirmed by Leddy et al.³ in a similar study comparing post-concussion activity to a placebo group. This comparison found that athletes in the physical activity group recovered 4 days faster than those in the placebo group who received a stretching protocol.³ Another study utilizing a similar sample of concussed adolescent athletes included three groups with varying post-concussion protocols (physical activity, rest, placebo stretching group).⁵ Their findings mimicked those presented by Leddy and colleagues,^{3,4} with the physical activity group recovering 3-4 days faster than the rest group.⁵

These studies utilizing physical activity after a concussion rely heavily on treadmill-based protocols. Research utilizing treadmills established a pretreatment exercise tolerance to ensure accurate prescriptions were given. These pretreatment assessments must be completed by a trained professional, which is not feasible for every athlete with a concussion. Although previous studies provide important foundational knowledge, the clinical feasibility is questionable. This is particularly true for those athletes who do not have access to medical facilities or exercise equipment to complete the prescribed protocol. Therefore, researchers have started exploring more feasible options to evaluate and incorporate physical activity after concussion.

Sufrinko and colleagues²¹ were the first to measure physical activity in free-living conditions utilizing actigraphy. Results from this investigation suggest that physical activity increases throughout concussion recovery.²¹ Additionally, their findings supported a positive association between VOMS scores and physical activity levels after concussion.²¹ The only other study to utilize actigraphy compared concussed athletes' physical activity to that of healthy controls.²² Concussed athletes were found to take fewer steps during the first two days after their injury when compared to healthy athletes. Similarly, healthy athletes recorded higher physical activity intensity than concussed athletes.²² Results from these studies confirm that concussed athletes limit their daily physical activity, which in turn may decrease recovery outcomes. Despite these findings, research has yet to evaluate the association between actigraphy results and concussion recovery time. Additionally, research is needed to determine if daily physical activity levels affect post-concussion symptom reporting. Future research should aim to fill these gaps in knowledge and identify a more feasible way to incorporate physical activity as a post-concussion treatment.

Typical Concussion Recovery

Despite the array of available treatment options, athletes with a concussion tend to recover in approximately 10-14 days.^{6,204} This assumes that health care professionals utilize appropriate injury management techniques and do not negatively impact concussion recovery. Although recovery may be influenced by poorly chosen management strategies, several other factors have been reported to influence concussion recovery. Specifically, athlete sex,¹² age,^{12,13} and health history^{102,129} may all contribute to a protracted recovery. In addition, several situational factors (i.e., immediate removal from play,^{177,178,180} sleep quality,²⁰⁵ post-concussion symptom burden^{12,206,207}) have also been noted to influence concussion recovery.

Not only do female athletes report greater post-concussion symptoms and worse cognitive outcomes following a concussion, but they have also been found to take longer to recover than their male counterparts.^{171,184,208,209} When evaluating recovery time among sex comparable sports, female soccer and basketball athletes noticed the largest difference from their male counterparts.²¹⁰ However, despite this available evidence, mixed findings suggest no recovery differences exist between male and female athletes.^{98,211,212} Caution should be taken when attempting to predict recovery for males and females due to these mixed findings.

When assessing the impact of age on recovery time, researchers have also reported mixed results. Specifically, Zuckerman et al.²¹³ identified youth athletes aged 13-16 years old as taking longer to recover compared to athletes 18-22 years old. Similarly, another study found that collegiate athletes were faster to recover compared to high school athletes.⁹⁴ However, a large number of previous studies have found no recovery differences between youth, high school and collegiate athletes.^{98,108,207,214} Due to the mass evidence refuting these age differences, it is unlikely that athlete age influences post-concussion recovery.

Athletes with ADHD/ADD or a learning disorder are not at a greater risk for protracted recovery compared to those without the medical condition.²¹⁵ However, other preexisting factors such as history of concussion have yielded mixed results. Athletes with 3 or more previous concussions have been found to take longer to recover than those with less concussions.¹⁰² Furthermore, these similar recovery differences have been found in a wide array of previous literature.²¹⁶⁻²¹⁹ Despite this evidence, researchers have found no significant recovery differences in athletes with and without a history of concussion.^{178,215,220,221} Although research opposing recovery differences remains plentiful, researchers should continue evaluating the effects that multiple concussions have on recovery outcomes. Results of this type of research may help

identify ways to improve management strategies, specifically for those athletes with multiple previous concussions.

Although several personal factors have been purposed to influence concussion recovery, several situational factors have been found to also impact recovery time. Immediately following a concussion, athletes who report a greater number of symptoms have been shown to take longer to recover from their concussion.^{160,206,220-225} Of the factors purposed to influence recovery, the influence of post-injury symptom burden has the strongest supporting evidence. Additionally, athletes who are removed immediately from play tend to recover faster than those athletes who continue to participate through their concussion.^{177,178,180} Finally, research has started evaluating the effects of post-concussion sleep quality on recovery time. Researchers have found that athletes who report good sleep quality after their concussion recovered faster than those with poor sleep quality.^{226,227} It should be noted however, that this does not evaluate quantity of sleep but rather the overall quality. Additional research is needed to not only identify the effects of sleep on concussion recovery, but also the influence a concussion has on the change in sleep habits.

Protracted Concussion Recovery

It should be apparent that several factors may contribute to a delay in concussion recovery. Regardless of these theorized factors, approximately 15% of athletes have been found to experience a protracted recovery lasting longer than 30 days.¹⁰ These long-term complications may have significant impacts on an athlete's activities of daily living and overall quality of life. Furthermore, athletes who experience significant recovery delays often report developing symptoms associated with clinical depression.^{228,229} It is critical for healthcare professionals to

utilize successful management strategies to promote normal concussion recovery and prevent the advancement of major psychological conditions (i.e., depression).

Similar to the management strategies used in the subacute phase of concussion recovery, athletes with a protracted recovery may benefit from an array of treatment options. Of the treatment options available, aerobic exercise has arguably shown the most improvements for athletes with delayed recovery.^{230,231} Research utilizing sub-symptomatic aerobic physical activity has primarily been utilized in youth athletes who experience post-concussion impairments longer than 30 days after injury.^{230,231} Researchers have found that youth who partake in aerobic exercise notice a greater rate in symptom reduction and were more likely to return to sport than those who did not receive the treatment.^{230,231} The recent development of aerobic physical activity as a treatment option may significantly improve the way in which clinicians manage athletes with a concussion.

Physical Activity

Physical activity is defined as “any bodily movement produced by the contraction of skeletal muscle that increases energy expenditure above a basal level”.²³² Rates of energy expenditure are commonly utilized to classify the intensity of a given physical activity and can be broken down into light, moderate or vigorous activities.²³² The energy expenditure used to determine intensity is expressed as multiples of the Metabolic Equivalent of Task (MET) where 1 MET is the rate of energy expended while at rest.²³² A light activity requires less than 3.0 METs, whereas a moderately intense activity requires 3.0-6.0 METS and a vigorously intense activity requires more than 6.0 METS.²³² As suggested by its broad definition, physical activity can take many forms and may be interpreted differently by everyone. Additionally, it should be

noted that “routine” levels of physical activity vary based on an individual’s age and current health status.

Physical activity is particularly important for proper physical maturation in youth and adolescents. Because of this, the child and adolescent population is encouraged to participate in 60 minutes of moderate to vigorous physical activity per day.²³² Furthermore, a minimum of 3 days per week should include muscle and bone strengthening activities.²³² Although these recommendations are straight forward, most children and adolescents fail to reach this weekly benchmark.²³² Specifically, 85% of high school females and 70% of high school males failed to meet weekly minimum physical activity recommendations.²³² This may be attributed to advancements in technology and increased video game usage. Failing to meet these physical activity recommendations as children may result in poor health later in life.

As adults, it is recommended to partake in at least 150 to 300 minutes of moderate physical activity per week.²³² However, this could be substituted for 75 to 150 minutes of vigorous activity per week.²³² Adults are also recommended to partake in moderate to vigorous muscle strengthening activities at least 2 times per week.²³² Similarly, pregnant women should complete 150 minutes of moderate physical activity per week while consulting their physician.²³² Despite these recommendations for adults, approximately 80% of adults fail to meet these minimum weekly goals.²³² The low level of compliance from adults is rather concerning due to the missed health benefits from participating in physical activity.

Health Benefits of Physical Activity

Previous research has long investigated the mental and physical benefits of frequent physical activity participation. Some of these health benefits may be noticeable immediately, whereas other health improvements may not be apparent until later in life. Specifically,

individuals who frequently exceed the weekly physical activity recommendations may reduce their risk for major health conditions (i.e., heart disease,²³³ cancer²³⁴ and clinical depression^{235,236}) as well as see improvements in other aspects of daily life (i.e., sleep quality,²³⁷ mood,^{19,20} and cognition^{19,20}).

While participating in physical activity, several health benefits may manifest immediately and last for several hours. Researchers have found that after a bout of physical activity, individuals noticed significant improvements to their mood.^{20,238} Specifically, these mood boosts included decreased stress, improved self-esteem, and reduction of depressive thoughts.^{19,239} Furthermore, immediate cognition and memory improvements were noted after participating in a bout of physical activity.^{19,240,241}

Not only does a single bout of physical activity have its transient health benefits, but routine participation can significantly impact an individual's long-term health. Researchers have identified more subtle health improvements like improved sleep quality^{237,242} and lower blood pressure²⁴³ as being common with routine physical activity. Additionally, regimented physical activity has been found to improve a variety of chronic health conditions such as low back pain,^{244,245} migraine headaches,²⁴⁶ and clinical depression.^{235,236} Although physical activity has been shown to have benefits for a variety of health conditions, it should likely not be used as the only form of treatment for these individuals.

As mentioned, most children and adults fail to meet minimum physical activity recommendations, thus limiting their opportunity to inherit these health benefits. As a result, sedentary behaviors are becoming inherently common further leading to negative health outcomes. Increased sedentary time may contribute to developing heart disease,²⁴⁷ stroke,²⁴⁸ and type 2 diabetes.²⁴⁸ Continued research is needed to determine the barriers individuals may face

when choosing not to complete routine physical activity. Furthermore, research should continue to track physical activity participation and quantify activity levels in those individuals not meeting the weekly recommendations. This information may then be utilized to better associate sedentary behaviors with poor health outcomes.

Physical Activity Monitoring

Previous research has employed several quantifiable techniques to assess physical activity levels in youth and adult populations. These techniques include self-reported surveys, direct observation, and accelerometry. Due to the advancements in technology, accelerometry has become the preferred method due to its ease of use for researchers and participants. In addition, accelerometry relies less on patient reported physical activity data, which may be less accurate. Furthermore, accelerometry has been shown to be highly sensitive in detecting changes in physical activity.²⁴⁹ However, caution must be taken when utilizing commercially available accelerometers due to their potential to inconsistently monitor physical activity participation.

When utilizing accelerometry to measure free-living physical activity, several factors must be taken into consideration to ensure success during the collection process. The initial step is to determine which accelerometer-based device is best suited to meet the needs of researchers. The body location (e.g., wrist, waist, thigh) of the accelerometer also plays a large role in the data collection process and may influence the results obtained. The final consideration when using accelerometry is determining the optimal software parameters during the data collection and reduction processes. These parameters can range tremendously and are largely dependent on the chosen accelerometer.

Accelerometers

Although several research grade and commercially available accelerometers exist, researchers tend to favor a select number of these devices because of their quality, accessibility, and ease of use. Of these devices, consumers are most familiar with brands like Fitbit, and Apple, whereas devices like the ActivPAL and those produced by Actigraph are marketed strictly for research purposes. Because of their popularity, research mainly focuses on these brands when quantifying physical activity levels using accelerometry. Therefore, emphasis will be placed on these physical activity brands for the current review.

The company Fitbit produces a wide array of wrist worn physical activity monitors designed for consumers to monitor and track their daily habitual physical activity. These monitors can produce outputs with information on heart rate, step count, sedentary time, sleep quality, and sleep quantity. Researchers have found Fitbit to be a valid and reliable measure of habitual physical activity.²⁵⁰ However, in other previous research, Fitbit devices were found to have larger variability when compared to research grade devices.^{250,251} Additionally, Fitbit was often found to overestimate physical activity data such as step count,²⁵¹⁻²⁵⁵ and energy expenditure,^{250,256} while underestimating MVPA.^{250,255} Thus caution may need to be taken when interpreting physical activity outputs from Fitbit activity monitors.

The Apple Watch is a wrist worn, complex accelerometer that produces similar outputs to that of a Fitbit, while also providing the accessibility of a smartphone. This device is often more desired for its advanced smartphone capabilities, thus making it more expensive than that of a Fitbit. Likely due to its advanced technology, research is finding that the Apple Watch may be more accurate at measuring physical activity participation than Fitbit.²⁵⁷⁻²⁶⁰ Additionally, the Apple Watch has been shown to be correlated to research grade devices when measuring several

aspects of activity participation.^{261,262} Despite this correlation, the Apple Watch has been found to be inconsistent when computing energy expenditure,^{256,257,263-265} and heart rate.²⁵⁶ Although this commercially available device has been shown to be one of the most accurate at measuring physical activity participation, inconsistencies still exist. Therefore, when possible researchers should utilize the physical activity monitor that best measures the variables of interest.

Although Fitbits and Apple Watches are most utilized by consumers, ActivPAL and Actigraphs are designed to be utilized by researchers to monitor specific physical activity characteristics. The information produced by these accelerometers is plentiful and far exceeds that of Fitbits and Apple Watches. The ActivPAL is a small accelerometer that adheres to the middle of the thigh and defines body position into either standing, sitting, lying, or stepping.²⁶⁶ This device also calculates METs, energy expenditure, cadence, and time spent in MVPA.²⁶⁶ Research utilizing this device has found it to be a valid and reliable measure of sedentary behavior and MVPA.²⁶⁶⁻²⁶⁹ Previous research has also found the ActivPAL to be similar to the criterion measure for determining time spent in sedentary, standing, light and walking behaviors.²⁷⁰ However, this monitor significantly underestimated step count by at least 25%.²⁷⁰ Future physical activity research should continue utilizing the ActivePAL when measuring body position. However, when aiming to measure step count, the ActivePAL may not be the optimal physical activity monitor.

Actigraph

Actigraph Corporation has produced a number of research grade accelerometers designed to monitor physical activity in free-living conditions. The Actigraph wGT3X-BT and Actigraph GT9X Link physical activity monitors are arguably the most research supported Actigraph models to date. Both monitors can be worn around the waist, thigh, ankle or the wrist and

provide a significant amount of physical activity information.²⁷¹ This information may include METs, energy expenditure, steps, activity intensity, and sedentary time. The Actigraph wGT3X-BT utilizes a 3-axis accelerometer to measure activity data, whereas the GT9X Link monitor incorporates the same accelerometer with the addition of a gyroscope to help measure movement, rotation and body position.²⁷¹

Of the currently available Actigraph monitors, the GT9X Link monitor is one of the most popular because of its small size, complex functionality, and inclusion of a gyroscope. This device primarily measures physical activity via an internal accelerometer which detects changes in acceleration.²⁷² These fluctuations in acceleration cause a change in voltage of the device's internal electric flow.²⁷² The voltage changes are then digitized and filtered through a band-pass filter to eliminate artificial vibrations unrelated to body movement.²⁷² Once this process is complete, the information is processed to represent an individual's physical activity participation. Furthermore, research has found the GT9X Link monitor to be a valid and reliable measure of physical activity.^{273,274} When determining the optimal wear position for the Actigraph monitor (i.e., waist, ankle, thigh, or wrist), the wrist has been shown to be the patient preferred body location.^{275,276} However, the waist has been shown to be a more accurate placement when compared to the wrist.²⁷⁷ Previous physical activity research has utilized Actigraphs in a wide range of individuals such as youth,²⁷⁸ adolescents,²⁷⁹ and adults.²⁵⁴ Furthermore, research has utilized Actigraphs for individuals with an array of medical conditions such as diabetes,²⁸⁰ heart disease/failure,^{281,282} stroke,²⁸³ and much more.

Physical Activity After Concussion

As previously stated, aerobic physical activity has been shown to improve several aspects of concussion recovery including decreased symptom reporting and reducing return to play

time.^{3,4,21} Despite the majority of this previous research including prescribing treadmill based aerobic physical activity, researchers have also begun utilizing accelerometers to measure daily physical activity participation in those with a concussion.^{21,22} Unsurprising, researchers saw a gradual increase in physical activity participation as athletes recovered from their concussion.²¹ They also found that concussed adolescents who completed more daily physical activity throughout their recovery performed better on vestibular assessments than those who completed less activity.²¹ Another study utilizing accelerometers found that during the first 2 days after a concussion, injured athletes recorded almost half as many steps as their healthy controls.²² However, this previous research fails to evaluate the link between daily physical activity participation and other important post-concussion outcomes such as symptom reporting or recovery time. This information may help to identify if promoting more daily physical activity after a concussion can improve recovery outcomes.

Conclusion

Concussions are a complex injury that affect athletes differently based on a number of different influencing factors. Due to these injuries impacting athletes differently, recovery patterns are often challenging to predict. Despite this, typical concussion recovery is between 10-14 days. When recovery falls outside this timeframe it may negatively influence an athlete's daily activities, mental state, and overall quality of life. To help augment recovery and prevent delays, several post-concussion treatments currently exist. Of the purposed treatments, sub-symptomatic physical activity has been shown to be one of the most effective to date. However, research evaluating the effects of physical activity on post-concussion outcomes involve supervised laboratory studies. There is a critical need to identify a physical activity treatment that can be utilized by clinicians without requiring direct supervision. Daily habitual physical activity

has been shown to decrease following a concussion.²² Additionally, decreases in daily post-concussion physical activity has been shown to negatively impact vestibular outcomes.²¹ However, research has yet to identify if decreases in daily post-concussion physical activity influences symptom reporting or overall recovery time. Furthermore, previous research has yet to evaluate this link between daily physical activity and post-concussion outcomes in adults after a concussion.

CHAPTER III

METHODOLOGY

Experimental Design

A prospective cohort study design was used to assess the relationship between post-concussion physical activity and concussion recovery outcome measures. The independent variable was physical activity participation (VM counts per minute) completed by participants after concussion diagnosis. The dependent variables included symptom reporting (symptom severity visit 2) and concussion recovery time (days). This study was approved by the Michigan State University Institutional Review Board and was conducted August 2019 – April 2020.

Operational Definitions

Concussion

All concussion diagnoses were made by a healthcare professional (e.g., certified athletic trainer, physician) utilizing the operational concussion definition provided by the 5th International Concussion in Sport Group.⁶ The International Concussion in Sport Group defines a concussion as a complex pathophysiological process affecting the brain, induced by biomechanical forces.⁶ Additionally, the following criteria were used when diagnosing individuals with a concussion: 1) observed and/or reported mechanism of injury; and 2) the presence of at least one or more of the following: a) on-field signs (e.g., disorientation/confusion, loss of consciousness, balance difficulties, amnesia), b) symptoms (dizziness, nausea, headache), and/or c) any impairment on sideline assessments (e.g., SCAT5).

Recovery Time

Participant recovery time was classified as the number of days from injury occurrence to full unrestricted clearance by a healthcare provider. Athlete recovery was also confirmed during

a third visit in which participants completed tests commonly utilized during a return to play assessment (symptom assessment, VOMS, ImPACT, *mBESS*)

Vector Magnitude (VM) Counts Per Minute

A common output utilized by Actigraph is referred to as a VM count. Vector Magnitude counts are derived from a complex process utilizing the raw accelerometer signal obtained by a combination of three movement planes captured by the Actigraph GT9X Link monitor.^{272,284} For the current study, the Actigraph GT9X Link monitor was preset to collect data at a sample frequency of 30 Hertz (Hz). This means a physical activity measurement was collected every 0.033 seconds and summarized over a 1 minute epoch (300 measurements summarized every minute).^{272,285} Additionally, physical activity data passes through a passband filter, where non-human vibrations and artifacts are filtered out and removed.²⁸⁵ In summation, an activity count is dependent upon the frequency and intensity of an individual's movement.²⁸⁵ Thus, greater daily counts represents greater physical activity participation.

Participants

Participants were recruited from one National Collegiate Athletic Association (NCAA) Division I University, along with one NCAA Division III University, both within the state of Michigan. These Universities were selected based on convenience, location, and willingness to participate in the study. Certified Athletic Trainers and Medical Doctors agreed to assist with the study and utilized the International Concussion in Sport Group definition when evaluating their patients for study eligibility.⁶ After concussion diagnosis, individuals were asked by the healthcare provider if they would be willing to learn more about the current study. If willing, concussed individuals were contacted by researchers to evaluate their fit for the study and their

meeting of inclusionary and exclusionary criteria. Eligible participants provided informed consent, and the referring healthcare provider received monetary compensation for their referral.

Inclusionary Criteria

Participants were considered for inclusion in the current study if they were between the ages of 18-24 years, diagnosed with a concussion, and completed their first visit within 72 hours of their concussion occurrence.

Exclusionary Criteria

Participants were excluded if they had an additional diagnosed concussion within the past 6 months, were currently taking any central nervous system active prescription medication, had a history of moderate or severe traumatic brain injury, or had a history of brain surgery.

Participants with a current cardiovascular disorder or lower extremity injury were also excluded due to these conditions' potential impact on physical activity participation.

Sample Size Estimation

A power analysis using G*Power 3.1 was completed (effect size $f_2 = .13$, a-priori level 0.05, statistical power of 0.8) and indicated that 78 participants would be needed to reach statistical power. Due to the preliminary nature of this study and its specific enrollment criteria (within 72 hours of concussion diagnosis), this sample size was unobtainable. Therefore, a minimum recruitment goal of 20 participants was established based on previous research with similar study designs.^{21,22}

Instrumentation

Post-Concussion Symptom Evaluation

The current study utilized a post-concussion symptom evaluation which required participants to self-report 22 common post-concussion symptoms (i.e., headache, dizziness,

difficulty concentrating, etc.) on a 7-point Likert scale (0 (none) to 6 (severe)) based on how they are feeling at the time of testing. Post-concussion symptom total was represented as the total number of symptoms endorsed out of 22, whereas symptom severity was calculated by adding the Likert scale scores of all reported symptoms for a max score of 132. The current study utilized the PCSS during all testing visits (<72 hours, 8 days later, cleared by healthcare provider) . The post-concussion symptom evaluation was used during the last visit only to ensure full clinical recovery was achieved by each individual as determined by previously published reference values.⁸⁵ This symptom scale has been shown to be a valid tool when assessing individuals for a concussion.²⁸⁶ See Appendix A for the post-concussion symptom evaluation utilized for this study.

Actigraph GT9X Link Physical Activity Monitor

Participants were asked to wear an Actigraph GT9X Link Physical Activity Monitor (Actigraph Corp, Pensacola, FL) on their non-dominant wrist for approximately the first week after their concussion. Participants were instructed to only remove the monitor during water activities (e.g., bathing, swimming) or any activity that may significantly damage the device. Physical activity participation was monitored starting no earlier than 48 hours post-concussion and no later than 72 hours after injury. Data acquired from the monitors was collected in raw form, with a sample frequency of 30 Hz, and was processed using ActiLife Software (Actigraph Corp, Pensacola, FL). Monitor wear time was validated using the Choi²⁸⁷ algorithm. A wear time of ≥ 480 minutes/day for at least 4 consecutive days (minimum three weekdays and weekend day) was considered a valid wear period.²⁷³ Actigraph monitors have previously been shown to be valid and reliable at measuring physical activity under free-living conditions in young and active adults.²⁷³ Additionally, the non-dominant wrist has been shown to be an adequate and

patient preferred anatomical placement for measuring activity in free-living conditions.^{276,288} To evaluate the relationship between physical activity participation and recovery outcomes, physical activity participation was represented as VM counts per minute. In addition, cut points provided by Montoye et al.²⁸⁹ were used to classify physical activity participation as either light physical activity or MVPA based on the number of VM counts that occurred per minute during the data collection period. Percent time spent in MVPA was calculated and reported as physical activity demographic information for participants. See Appendix B

Daily Questionnaire

Participants completed a daily online questionnaire between the first two visits. The questionnaire utilized the Qualtrics platform and took no longer than 5 minutes to complete. This questionnaire included questions regarding self-reported cognitive activities performed throughout each day by participants. Specifically, these questions identified the total time (in minutes) spent on homework and in class between visits. Additionally, individuals were asked to self-report any time (in minutes) spent exercising each day. Minutes of cognitive activity and exercising were evaluated for potential impact on post-concussion symptom reporting. Participants completed the daily questionnaire at 8:00pm via a texted link to the questionnaire. See Appendix C

Vestibular/Ocular Motor Screening (VOMS)

The VOMS is a brief screening tool that assesses vestibular and ocular motor function and symptom provocation. The VOMS includes 7 components: 1) smooth pursuits, 2) horizontal saccades, 3) vertical saccades, 4) NPC, 5) horizontal VOR, 6) vertical VOR, and 7) VMS. Participants were asked to rate symptoms of headache, dizziness, nausea, and foginess on an 11-point Likert scale (0 (none) to 10 (severe)) prior to VOMS administration and after each of

the 7 VOMS components. Each VOMS component was scored separately and was done by adding the provocation of the 4 included symptoms (headache, dizziness, nausea, foggiess). Each of the VOMS components are scored out of a maximum of 40. The VOMS has previously demonstrated high internal consistency.¹⁶⁸ For the current study, the VOMS was completed during the final visit when participants were cleared by a healthcare professional to ensure full clinical recovery was obtained. This was determined by utilizing previously published reference values for healthy individuals.¹⁶⁶ See Appendix D for the VOMS assessment.

Immediate Post-Concussion Assessment and Cognitive Test (ImPACT)

The ImPACT battery is a computerized neuropsychological assessment tool commonly employed following a suspected concussion. ImPACT takes approximately 20 minutes to complete and includes several different versions to limit possible practice effects. The assessment consists of patient demographics, symptom assessment, and cognitive testing modules. The testing modules evaluate individuals in four main areas including verbal memory, visual memory, visual motor speed, and reaction time.²⁹⁰ Composite scores for these cognitive components are presented at the conclusion of the testing battery. The ImPACT battery was administered during the final visit when participants were cleared by a healthcare professional to confirm full clinical recovery was obtained. Previously published baseline reference values were used to confirm recovery.¹⁰³ See Appendix E for the ImPACT battery.

Modified Balance Error Scoring System (mBESS)

The mBESS consists of three stances on a firm surface; double-leg stance, single-leg stance on their non-dominant leg, and tandem stance in a heel-to-toe pattern.^{291,292} During each stance, participants were asked to stand quietly for 20 seconds with their eyes closed and hands on their hips. A trained researcher then counted errors during each of the 3 stances, which

included: opening the eyes, lifting hand(s) off the iliac crest, stepping, stumbling, or falling, moving the hip into more than 30° of flexion or abduction, lifting the forefoot or heel, and remaining out of the test position for more than five seconds. Participants received a point for every error that was made during the 3 trials. Each stance was scored individually, and each error performed by the participant resulted in a single point added to their score. If a participant performed multiple errors at a given time, one error was recorded, and they were told to quickly return to the testing position. The higher the score on the *mBESS*, the worse the individual performed. The *mBESS* test has an intra-tester reliability coefficients from .80 to .89.²⁹³ The *mBESS* was completed during the final visit when participants were cleared by a healthcare professional to ensure full clinical recovery was obtained compared with previously published reference values.¹⁵⁰ See Appendix F for the *mBESS* assessment.

Procedures

Participants with a diagnosed concussion were contacted within 72 hours of sustaining their injury to assess interest in participating in the study. Interested participants met with researchers to discuss study details and provide informed consent. After consent was obtained, participants completed their first of three visits with a member of the researcher team. Visit 1 was completed within 72 hours of concussion occurrence and took approximately 15 minutes to complete. Visit 1 consisted of patient and injury demographics, and the post-concussion symptom evaluation. At the end of visit 1, participants received an Actigraph GT9X Link Physical Activity Monitor which they were instructed to wear on their non-dominant wrist for 7 consecutive days. Participants were instructed to wear this monitor during all waking hours except for water-based activities and contact activities that may damage the device. Physical activity participation was monitored starting no earlier than 48 hours post-concussion and no

later than 72 hours post-concussion. This is due to physical rest being commonly recommended for the first 48 hours after injury.⁶

Between visit 1 and visit 2 participants completed the daily Qualtrics questionnaire. A link to the questionnaire was distributed to each participant at 8:00pm, and they completed it based on their current day. Participants then returned for visit 2 approximately 7 days (± 1 day) after visit 1 and again completed the post-concussion symptom evaluation. After visit 2, participants returned their physical activity monitor to researchers. Participants continued to be managed by their respective healthcare provider until they received full medical clearance.

Once cleared, participants returned for their final testing visit. Visit 3 consisted of the post-concussion symptom evaluation, ImPACT, VOMS, and *mBESS*. Results obtained during this visit were not utilized for analysis; rather, these results were used to confirm that full clinical recovery was obtained by each participant. Furthermore, to confirm recovery was obtained, results from visit 3 were compared to previously published reference values for healthy individuals.^{85,103,150,166} Once confirmed, participant's total recovery time (total days from injury occurrence to full medical clearance) was utilized for analysis.

Data Analysis

All statistical analyses were conducted using SPSS version 24.0 (IBM Corporation, Armonk, NY). Descriptive statistics were identified for demographic information, physical activity participation and all post-concussion outcomes (symptom reporting, recovery time). Participants not meeting Choi²⁸⁷ validation recommendations were removed from analysis. Additionally, participants with a Z-score of ± 3.0 were removed from analysis. An *a-priori* alpha level was set at $p = 0.05$ for all analyses.

Specific Aim 1

A hierarchical multiple regression analysis was utilized to assess the relationship between physical activity participation and post-concussion symptom reporting. Physical activity participation served as the independent variable while symptom reporting served as the dependent variable. Physical activity participation was represented as the VM counts per minute between visit 1 and visit 2. Whereas symptom severity from visit 2 was utilized for symptom reporting. Participant sex and total symptom severity from visit 1 were served as covariates for this analysis due to their previously reported influence on post-concussion symptom reporting.^{93,95,98,102,107}

An exploratory hierarchical multiple regression analysis was completed to assess the relationship between percent time spent in MVPA and post-concussion symptom severity at visit 2. Similar to the previous analysis, participant sex and symptom severity from visit 1 served as covariates during analysis.

Specific Aim 2

A linear regression analysis was utilized to assess the relationship between daily physical activity participation and concussion recovery time. Physical activity was the independent variable and was expressed as VM counts per minute. Recovery time was the dependent variable and was defined as the total number of days from injury occurrence to full medical clearance as determined by a medical doctor. Visit 1 symptom severity was assessed as a possible covariate for this analysis due to its previously reported impact on concussion recovery time.²⁰⁶ A Spearman Rank Correlation analysis was used to evaluate this possible relationship between symptom severity at visit 1 and recovery time.

An exploratory linear regression analysis was completed to assess the relationship between percent time spent in MVPA and concussion recovery time. Similar to the previous analysis, visit 1 symptom severity was assessed as a possible covariate.

CHAPTER IV

RESULTS

Demographic Information

A total of 46 college-aged adults with a concussion were enrolled in the current study. Of the enrolled participants, one participant (2.2%) was later excluded due to not reaching full medical clearance within the study timeframe. Additionally, 10 participants (21.8%) did not meet Choi²⁸⁷ validation for Actigraph wear time and were excluded from analysis. Finally, three participants (9.1%) were removed from analysis due to their symptom reporting (visit 2 severity) and recovery time results being classified as outlier values relative to the distribution among our sample ($z\text{-score} > 3.0$).

A final sample of 32 (69.6%) participants were included in the analyses for the current study. The sample included 10 (31.3%) male and 22 (68.8%) female participants who were 19.8 ± 1.4 years old. Combined, participants averaged 2.5 ± 1.2 years in college with every undergraduate academic class well represented. Table 9 includes academic class breakdown as well as other detailed participant demographics.

Table 9: Participant Demographics

Demographic Variable	n (%)
Age, M(SD)	19.8 (1.4)
Sex	
Male	10 (31.3)
Female	22 (68.8)
Athletic Participation	
Division I	10 (31.3)
Division III	6 (18.8)
Non-Athlete	16 (50.0)
Academic Class	
Freshman	9 (28.1)
Sophomore	7 (21.9)
Junior	8 (25.0)

Table 9 (cont'd)

Senior	7 (21.9)
Grad	1 (3.1)
Medical Diagnoses	
ADHD/ADD	5 (15.6)
Depression/Anxiety	7 (21.9)
Previous Concussion	17 (53.1)

Post-Concussion Outcomes

During visit 1, participants reported a median symptom total of 13 [7] (range: 0-22) yielding a median total severity of 28 [24] (range: 0-81). Headache (31/32, 96.9%), sensitivity to light (30/32, 93.8%), and difficulty concentrating (29/32, 90.6%) were the most commonly reported symptoms, while vomiting (0/32, 0.0%), numbness (6/32, 18.8%) and sleeping less (9/32, 28.1%) were least reported. When returning approximately one week later for visit 2, participants reported a median of 2 [6] (range: 0-18) symptoms and a median total severity of 2 [8] (range: 0-44). Similarly, headache (16/32, 50.0%), difficulty concentrating (10/32, 31.3%), and fatigue (10/32, 31.3%) were most commonly reported at visit 2. Once cleared by their respective healthcare provider, participants returned for their final visit where they averaged no post-concussion symptoms (total: 0 [2], range: 0-5; severity: 0 [2], range: 0-7). The median concussion recovery time for participants was 11.5 [9] (range: 8-38 days), with 19 (59.4%) participants recovering within 14 days and 13 (40.6%) participants taking longer to recover. Table 10 and Table 11 depict symptom reporting categorized by participant sex, sport participation level (Division I, Division III, and non-athlete) and previous medical diagnoses for visit 1 and visit 2, respectively. Table 12 shows concussion recovery time information for all participants.

Table 10: Participant Symptom Total and Severity Reported at Visit 1

	Symptom Total		Symptom Severity	
	Mean $\pm$ SD	Median [IQR]	Mean $\pm$ SD	Median [IQR]
Sex				
Male	11.8 $\pm$ 5.5	12.5 [9]	23.2 $\pm$ 13.3	25.0 [24]
Female	13.9 $\pm$ 4.0	13.5 [6]	36.2 $\pm$ 21.4	30.5 [40]
Athletic Participation				
Division I	12.3 $\pm$ 5.9	13.0 [6]	26.9 $\pm$ 18.7	25.5 [15]
Division III	12.2 $\pm$ 4.4	11.0 [9]	24.2 $\pm$ 4.4	11.0 [9]
Non-Athlete	14.3 $\pm$ 3.6	14.5 [6]	38.4 $\pm$ 21.9	33.0 [38]
ADHD/ADD				
No	13.3 $\pm$ 4.6	13.0 [6]	31.9 $\pm$ 20.6	28.0 [24]
Yes	12.8 $\pm$ 4.3	14.0 [8]	33.4 $\pm$ 17.9	26.0 [32]
Depression/Anxiety				
No	13.0 $\pm$ 4.7	13.0 [7]	32.1 $\pm$ 19.8	28.0 [26]
Yes	14.0 $\pm$ 4.1	14.0 [5]	32.4 $\pm$ 22.4	25.0 [14]
Previous Concussion				
No	13.3 $\pm$ 3.4	13 [5]	33.4 $\pm$ 20.2	28.0 [22]
Yes	13.2 $\pm$ 5.4	14.0 [8]	31.1 $\pm$ 20.4	28.0 [24]

Table 11: Participant Symptom Total and Severity Reported at Visit 2

	Symptom Total		Symptom Severity	
	Mean $\pm$ SD	Median [IQR]	Mean $\pm$ SD	Median [IQR]
Sex				
Male	0.8 $\pm$ 1.3	0.0 [2]	1.0 $\pm$ 1.7	0.0 [3]
Female	4.8 $\pm$ 5.3	3.0 [8]	9.6 $\pm$ 13.6	3.0 [11]
Athletic Participation				
Division I	2.2 $\pm$ 2.4	1.5 [3]	3.0 $\pm$ 3.9	1.5 [5]
Division III	0.5 $\pm$ 0.8	0.0 [1]	0.5 $\pm$ 0.8	0.0 [1]
Non-Athlete	5.5 $\pm$ 5.8	4.0 [9]	11.8 $\pm$ 15.3	5.0 [25]
ADHD/ADD				
No	3.4 $\pm$ 4.7	1.0 [6]	6.5 $\pm$ 11.9	1.0 [7]
Yes	4.2 $\pm$ 5.8	3.0 [9]	9.0 $\pm$ 13.9	3.0 [21]
Depression/Anxiety				
No	3.4 $\pm$ 4.4	1.0 [6]	6.8 $\pm$ 11.6	1.0 [9]
Yes	4.1 $\pm$ 6.2	3.0 [2]	7.3 $\pm$ 14.1	3.0 [3]
Previous Concussion				
No	5.4 $\pm$ 5.9	3.0 [9]	10.7 $\pm$ 15.1	4 [13]
Yes	1.9 $\pm$ 2.8	1.0 [3]	3.6 $\pm$ 7.3	1 [4]

Table 12: Participant Concussion Recovery Time (Days)

	Mean $\pm$ SD	Median [IQR]
Sex		
Male	12.4 $\pm$ 6.7	10.5 [4]
Female	15.7 $\pm$ 7.7	14.0 [9]
Athletic Participation		
Division I	13.6 $\pm$ 5.1	12.0 [9]
Division III	14.8 $\pm$ 8.3	11.0 [13]
Non-Athlete	15.3 $\pm$ 8.7	12.0 [8]
ADHD/ADD		
No	15.2 $\pm$ 7.9	12.0 [9]
Yes	12.0 $\pm$ 3.7	11.0 [7]
Depression/Anxiety		
No	15.1 $\pm$ 8.1	12.0 [10]
Yes	13.1 $\pm$ 4.5	11.0 [6]
Previous Concussion		
No	16.1 $\pm$ 8.6	13.0 [6]
Yes	13.5 $\pm$ 6.4	11.0 [10]

A Shapiro-Wilks test revealed that symptom total ($p < .001$) and symptom severity ($p < .001$) from visit 2 along with concussion recovery time ($p < .001$) were not normally distributed. Separate Mann-Whitney U analyses revealed no differences for ADHD/ADD diagnosis (symptom severity: $U = 61.50$, $p = .749$; recovery time: $U = 53.50$, $p = .465$), depression/anxiety diagnosis (symptom severity: $U = 76.00$, $p = .590$; recovery time: $U = 84.00$, $p = .872$), or concussion history (symptom severity: $U = 83.00$, $p = .084$; recovery time: $U = 104.00$, $p = .372$) in visit 2 symptom severity or concussion recovery time. Additionally, a Kruskal-Wallis analysis revealed no differences between Division I athletes, Division III athletes, and non-athletes for visit 2 symptom severity ($H(2) = 5.158$, $p = .076$) and concussion recovery time ($H(2) = .048$, $p = .976$). Similarly, males and females did not differ in concussion recovery time ($U = 73.50$, $p = .135$), however significant differences were noted for visit 2 symptom severity ($U = 51.00$, $p = .014$) with females reporting worse symptom severity. Results from a Spearman Rank

Correlation analysis indicated a significant relationship between symptom severity from visit 1 and symptom severity from visit 2 ($r_s = .354, p = .044$).

Daily Questionnaire

Between visit 1 and visit 2 participants completed the daily questionnaire assessing self-reported minutes spent in class, studying, and exercising. Participants reported a 7-day median of 517 [444] minutes (8.6 [7.4] hours) spent in class. Additionally, they reported a median of 443 [349] minutes (7.4 [5.8] hours) studying over the 7-day period between visit 1 and visit 2. When combining these reported cognitive activities, participants spent a median of 1,025 [675] minutes (17.1 [11.3] hours) studying or in class over the reporting period. Participants were also asked to self-report daily minutes spent exercising. On average, participants self-reported spending a median of 71 [173] minutes (1.2 [2.9] hours) exercising between visit 1 and visit 2. Results from the daily questionnaire can be found in Table 13. A Shapiro-Wilks test revealed that total minutes of cognitive activity (in class and studying) was not normally distributed ($p = .026$) and a Spearman's rank correlation analysis revealed it had no significant association with symptom severity at visit 2 ($r_s = .182, p = 0.33$) or concussion recovery time ($r_s = .301, p = 0.11$).

Table 13: Summary of Self-Reported Responses to Daily Questionnaire

	Males Median[IQR]	Females Median[IQR]	Total Median[IQR]
Total Minutes in Class	395 [411]	523 [575]	517 [444]
Total Minutes Studying	405 [104]	530 [420]	443 [349]
Total Minutes in Class + Studying	801 [494]	1184 [865]	1025 [675]
Total Minutes Exercising	130 [175]	45 [176]	71 [173]

Physical Activity Participation

Participants' PA participation was monitored starting 48-72 hours after concussion occurrence. More specifically, participant's physical activity started being recorded 54.5 ± 8.8

hours after sustaining their injury. On average, participants recorded 2446 ± 441 VM counts per minute and spent $11.8\% \pm 3.7\%$ of their time in MVPA. A Shapiro-Wilks test indicated that VM counts per minute ($p = .302$) and percent time in MVPA were normally distributed ($p = .485$). Therefore, an independent samples t-test was completed and no differences were found for VM counts per minute ($t_{(30)} = -1.00, p = .325$) or percent time in MVPA ($t_{(29.9)} = -1.45, p = .158$) between male and female participants (see Table 14). Additionally, an Analysis of Variance (ANOVA) revealed no significant differences between Division I athletes, Division III athletes, and non-athletes for VM counts per minute ($F_{(2,29)} = .914, p = .412$) or percent time spent in MVPA ($F_{(2,29)} = 2.096, p = .141$) (see Table 15). Detailed post-concussion physical activity participation for all participants can be found in Table 16.

Table 14: Post-Concussion Physical Activity by Participant Sex

	Mean (SD)	Median [IQR]	Min - Max
% Time in Light Activity			
Males	89.3% $\pm$ 1.9%	89.0% [3.0%]	86.8% - 92.5%
Females	87.7% $\pm$ 4.3%	89.0% [4.3%]	77.7% - 95.5%
% Time in MVPA			
Males	10.7% $\pm$ 1.9%	11.0% [3.0%]	7.5% - 13.3%
Females	12.3% $\pm$ 4.3%	11.0% [6.3%]	4.5% - 22.3%
VM Counts Per Minute			
Males	2330.0 $\pm$ 333.7	2287.8 [359.9]	1861.1 - 3023.1
Females	2498.4 $\pm$ 480.3	2430.4 [744.6]	1698.7 - 3637.1
Steps Per Minute			
Males	13.4 $\pm$ 1.8	13.3 [2.7]	11.2 - 17.2
Females	13.5 $\pm$ 2.3	13.8 [3.4]	9.0 - 18.6

Table 15: Post-Concussion Physical Activity by Athletic Participation

	Mean (SD)	Median [IQR]	Min - Max
% Time in Light Activity			
Division I	89.6% $\pm$ 3.4%	89.8% [4.9%]	84.1% - 95.5%
Division III	89.4% $\pm$ 2.4%	89.6% [4.2%]	85.6% - 92.1%
Non-Athletes	86.9% $\pm$ 4.0%	87.5% [4.3%]	77.7% - 93.6%
% Time in MVPA			
Division I	10.4% $\pm$ 3.4%	10.2% [4.9%]	4.5% - 15.9%
Division III	10.6% $\pm$ 2.4%	10.4% [4.2%]	7.9% - 14.4%
Non-Athletes	13.1% $\pm$ 4.0%	12.5% [4.3%]	6.4% - 22.3%
VM Counts Per Minute			
Division I	2302.0 $\pm$ 393.8	2251.8 [664.8]	1698.7 - 2945.0
Division III	2427.4 $\pm$ 324.5	2404.6 [523.6]	2006.1 - 2945.4
Non-Athletes	2542.5 $\pm$ 500.7	2488.7 [708.4]	1861.1 - 3637.1
Steps Per Minute			
Division I	13.0 $\pm$ 2.3	13.2 [3.2]	9.0 - 16.6
Division III	13.3 $\pm$ 1.4	13.6 [2.4]	11.2 - 14.7
Non-Athletes	13.9 $\pm$ 2.4	13.8 [4.0]	10.4 - 18.6

Table 16: Post-Concussion Physical Activity by All Participants

	Mean (SD)	Median [IQR]	Min - Max
% Time in Light Activity	88.2% $\pm$ 3.7%	88.6% [5.3%]	77.7% - 95.5%
% Time in MVPA	11.8% $\pm$ 3.7%	11.4% [5.3%]	4.5% - 22.3%
VM Counts Per Minute	2445.7 $\pm$ 441.4	2348.2 [648.4]	1698.7 - 3637.1
Steps Per Minute	13.5 $\pm$ 2.2	13.6 [2.9]	9.0 - 18.6

Evaluation of Specific Aims

Specific Aim 1

A hierarchical multiple regression analysis was utilized to assess the relationship between post-concussion physical activity participation (VM counts per minute) and symptom severity one week after injury. As previously noted, a significant association was found between symptom severity at visit 1 and visit 2 ($r_s = .354$, $p = .044$). Additionally, a significant difference was also identified between males and females for symptom reporting at visit 2 ($U = 73.50$, $p =$

.135). These result further confirm the need to covary for participant sex and visit 1 symptom severity for this analysis. Therefore, the regression model included an independent variable of VM counts per minute, a dependent variable of symptom severity at visit 2, and covariates of sex and visit 1 symptom severity. The first model included participant sex and visit 1 symptom severity, which yielded a significant model ($F_{(2,29)} = 7.57, p = .002$) and accounted for 34.3% of the variance ($R^2 = .343$). After adding VM counts per minute, the model remained significant ($F_{(2,28)} = 6.16, p = .002$) and accounted for 39.8% of the variance ($R^2 = .398$). However, the R^2 change related to the addition of VM counts (5.5%) was not independently statistically significant ($F \text{ change }_{(1,28)} = 2.54, p = .122$). Furthermore, in the final model only visit 1 symptom severity was significant in predicting symptom severity at visit 2 ($B = .315, 95\% \text{ CI: } .125, .504, \text{ beta} = .525, p = .002$), participant sex ($\text{beta} = .220, p = .170$) and VM counts per minute ($B = -.006, 95\% \text{ CI: } -.015, .002, \text{ beta} = -.239, p = .122$) were not statistically significant.

An exploratory hierarchical multiple regression analysis was completed to evaluate the relationship between percent time spent in MVPA and symptom severity at visit 2. Participant sex and symptom severity at visit 1 again served as covariates. Similar to the previous analysis, a significant first model was found ($F_{(2,29)} = 7.57, p = .002$) accounting for 34.3% of the variance ($R^2 = .343$). The second model produced was also significant ($F_{(3,28)} = 5.57, p = .004$) and accounted for 37.4% of the variance ($R^2 = .374$) with a R^2 change of 3.1% ($p = .251$). However, percent time spent in MVPA was not a significant contributor to the model ($B = -.580, 95\% \text{ CI: } -1.59, .434, \text{ beta} = -.180, p = .251$).

Specific Aim 2

A linear regression analysis evaluated the relationship between post-concussion VM counts per minute and the overall number of days to reach full medical clearance. No

demographic variables were found to have an association with concussion recovery time, therefore no covariates were included in the analysis. The linear regression analysis revealed a non-significant model ($F_{(1,30)} = 1.23, p = .276$) which accounted for 3.9% variance ($R^2 = 0.39$). Vector Magnitude counts per minute was not a significant predictor of overall concussion recovery time ($B = -.003, 95\% \text{ CI: } -.010, .003, p = .276$).

An exploratory linear regression analysis was completed to evaluate the relationship between percent time spent in MVPA and concussion recovery time. Similar to the previous analysis, a non-significant model was found ($F_{(1,30)} = 1.15, p = .292$), accounting for only 3.7% of the variance ($R^2 = .037$). Percent time spent in MVPA did not have a significant relationship with concussion recovery time ($B = -.385, 95\% \text{ CI: } -1.129, .349, p = .292$).

CHAPTER V

DISCUSSION

Overview of Study

The purpose of the current study was to evaluate the relationship between post-concussion physical activity participation and two recovery outcomes such as symptom reporting and recovery time. Although a significant multivariate regression model was identified for visit 2 symptom reporting, post-concussion physical activity did not make a significant contribution to the model, indicating no significant association between the physical activity participation and symptom reporting. Rather, only symptom reporting at visit 1 was a significant contributing factor. Post-concussion physical activity participation also had no relationship with overall concussion recovery time. Similarly, the exploratory analyses evaluating the relationship between physical activity intensity found no association with the recovery outcomes. Despite the lack of statistically significant findings, results from the current study suggest that simply increasing free-living physical activity levels may not be enough to promote recovery after a concussion. Rather, as previous research indicates, more structured physical activity may be needed.

Specific Aim 1

The current study found no relationship between physical activity participation and symptom reporting in individuals with a concussion. Following their concussion, participants averaged 2446 ± 441 VM counts per minute of physical activity. These results are consistent with those presented by Sufrinko et al.²¹ who monitored physical activity levels (VM counts per minute = 2550 ± 490) in adolescent athletes (12 – 19 years old) after a concussion. Their analysis along with another similar study noticed a gradual increase in post-concussion physical activity

throughout recovery.²¹ This increase in activity over time was hypothesized by researchers to occur as post-concussion symptoms diminished.²¹ Although the current study did not measure activity changes over time, no relationship was found between average physical activity participation and symptom reporting one week after injury. By utilizing average activity participation over the course of a week, it is possible that several factors may have influenced these findings such as participant characteristics (i.e., participant sex), amount of social engagement, and intensity of cognitive activities.

Participants in the current study reported similar symptom types and severities to previous research with females reporting a worse post-concussion symptom burden than males.^{80,91,93,94,294} Although not statistically different, female participants also recorded slightly higher post-concussion physical activity results than males (females: 2498 ± 480 , males: 2330 ± 334 VM counts per minute). This finding is similar to those presented in adolescent athletes after a concussion.²¹ Furthermore, Eime et al.²⁹⁵ also found that females self-reported greater levels of non-sport physical activity participation than males. The combination of these inherent sex differences for physical activity and symptom reporting conflict with the idea that greater activity participation may lead to lower post-concussion symptoms. Therefore, the current study's non-significant findings may have been influenced by the combination of these slight differences between males and females.

The current study monitored participants' post-concussion physical activity; however we did not monitor social engagement (i.e., spending time with friends or family) or the intensity of cognitive engagement over the study period. Social support has been shown to be a critical component to concussion recovery.²⁹⁶ Specifically, 89%, 78%, and 65% of collegiate athletes rely on family, friends, and teammates for support while recovering from their concussion,

respectively.²⁹⁶ Moreover, athletes who reported high levels of satisfaction with their support network had lower post-concussion anxiety symptoms.²⁹⁶ This association may suggest that a greater social support network may decrease post-concussion symptom reporting. Conversely, the feeling of social isolation has also been reported by athletes after a concussion.²⁹⁷ This feeling of social isolation is often a result of prolonged periods of rest, severe symptoms forcing someone to avoid loud environments, or falling behind in school.²⁹⁷ Athletes feeling socially isolated may choose to not seek help from a support network resulting in a worse recovery experience. It may be likely that the concept of a strong social support network may be equally, if not more important than the physical activity pathway previously shown to improve post-concussion symptom reporting.³ Thus for the current study, it is possible that the more sedentary participants spent more of their time seeking social and emotional support after their injury than engaging in physical activity.

Although participants were asked about the duration of time spent in class and studying, the intensity of these cognitive activities were not evaluated. Strenuous cognitive activity has previously been linked to an increase in post-concussion symptom reporting.²⁹⁸ Brown et al.²²⁰ also found that athletes who did not reduce their cognitive load after sustaining a concussion experienced symptoms longer than those who immediately reduced their cognitive activity. Although the current study tried to account for the quantity of time spent in class and studying, the intensity of these tasks was not assessed. Similarly, participants were not asked about other cognitive activities they performed such as watching tv, playing video games, or texting. Although the effects of screen time on post-concussion symptom reporting have been understudied, research suggests significant screen time may be associated with eye strain symptomologies.²⁹⁹ Therefore, participants who continued to utilize their devices for an extended

period of time may have exacerbated their symptoms. Future research is needed to parse out the effects of emotional support, social engagement, cognitive load, and physical activity on post-concussion symptom reporting. Only then can researchers find the ideal balance between these activities and further optimize patient care after a concussion.

Specific Aim 2

The current study found no significant association between post-concussion physical activity and concussion recovery time. Participants in the current study had a final recovery time of approximately 15 days. This average recovery time aligns well with the current belief that most college-aged adults recover from a concussion within two weeks.^{6,204} Despite this typical timeframe, several factors have been suggested to influence recovery duration such as patient sex,^{171,184,208,210} symptom severity at time of injury,^{12,206,207} and not being immediately removed from play following injury.^{177,178,180} The current study found no sex differences for recovery time which conflicts with previous studies suggesting that females take longer to recover.^{171,184,208,209} However, the majority of research indicating these differences were primarily shown in convenient samples of youth and adolescent athletes.^{171,184,209} Additionally, participants' symptom severity at visit one was not associated with concussion recovery time. This may be due to visit one not being close enough to injury occurrence. Participants were required to complete their first visit within 72 hours of sustaining their injury, and participants averaged an initial visit of approximately 54.5 hours (2 days 6 hours) from their concussion. The time between injury occurrence and visit one may have allowed some of the initial symptoms to be reduced or completely subside. Finally, participants were not asked if they continued to participate in sports after sustaining their concussion. Thus, it is possible that some participants may have altered their recovery length by choosing to continue playing after sustaining their

concussion. Future physical activity research should ask participants if they were removed from play immediately after their concussion in an attempt to control for this influential factor.

The non-significant findings for the current study conflict with those presented by Suffrinko and colleagues²¹ who reported an association between VM counts per minute and vestibular performance. Similarly, they also found slightly greater improvements in visual memory and processing speed for those athletes with greater VM counts per minute.²¹ However, their analysis included adolescent athletes rather than adults, which makes direct comparison challenging due to differences in developmental such as emotional and physical maturity. Adolescent individuals may also be required to attend an entire day of school which is different than the schedule of college-aged individuals. Participants in the current study likely had more freedom in their daily schedule to choose to participate in more sedentary or physically based activities. Additionally, adolescents typically live with a parent or guardian who can supervise the post-concussion physical activity recommendations given by a healthcare provider. Conversely, college-age individuals must hold themselves accountable when following the instructions provided by an overseeing clinician. Therefore, it may be necessary to set different post-concussion physical activity recommendations for adolescent and adult aged individuals.

Previously, researchers have employed various post-concussion physical activity programs in attempts to modify and improve the pathophysiological process occurring within the brain after a concussion. After a concussion there are varying levels of impairment to the autonomic nervous system (ANS) which will alter the ability to regulate and control cerebral blood flow (CBF).^{17,300-302} This inability to regulate CBF has been found to be a contributing factor in post-concussion symptom reporting and subsequent recovery duration.^{50,303} It should be noted that an increase in CBF is not necessarily the desired outcome as research has also shown

an association between increased CBF and symptom development.⁵⁰ Rather, by improving the ANS and its ability to regulate CBF, symptom reporting and concussion recovery may be improved. Previous findings suggest that physical activity may improve autonomic dysfunction as well as improve CBF regulation within the brain.³⁰⁴ Although previous research has shown favorable results using physical activity as a concussion treatment approach, the question remains; Are these improvements only seen after MVPA, or would any intensity of physical activity be sufficient to improve concussion recovery?

This study was the first to explore the association between free-living physical activity intensity and concussion recovery duration. Participants in the current study spent 88% of their time performing light activities and only 12% of their time in MVPA, which is unlike previous research utilized more structure and the potential for more intense physical activity in their protocol.³⁻⁵ Specifically, Leddy et al.^{3,4} utilized a 20 minute protocol requiring participants to maintain a heart rate at 80% of their pre-established symptom provoking threshold. This protocol allowed participants to set their own personal intensity tolerance, some of which may have reached moderate-to-vigorous physical activity levels. After employing this protocol, researchers found significant recovery time improvements compared to athletes who did not receive the treatment.⁴ However, our exploratory analysis found no significant relationship between free-living physical activity intensity (percent time in MVPA) and concussion recovery time. Although not stated by Leddy et al.^{3,4} it is possible that their participants intensity thresholds were higher than the recorded physical activity intensities in the current study. Therefore, future research evaluating post-concussion physical activity should monitor and report participant heart rates to allow for better comparisons of structured and free-living physical activity protocols.

Research is also needed to identify if a physical activity intensity threshold exists for promoting a more successful concussion recovery.

Clinical Implications

Results from this preliminary study may help identify some tangible strategies clinicians may utilize in their clinical practice when managing individuals with a concussion. This study identified that acute symptom severity may be an adequate predictor of subacute symptom reporting. For approximately every three-point increase in symptom severity at visit 1, participants could expect a one point increase in symptom severity at visit 2 ($B = .315$). Clinicians should aim to educate patients about avoiding activities that may significantly exacerbate acute concussion symptoms. Moreover, some degree of cognitive and physical rest is necessary during the first 48 hours following injury as indicated in current concussion consensus statements.^{6,77} It may also be necessary for healthcare providers to recommend that patients with high acute symptom severities seek advanced medical attention to help limit symptom longevity.

Following the first 24-48 hours post-injury, individuals should begin to gradually increase their cognitive and physical activity to improve recovery outcomes.⁶ The current study may insinuate that simply increasing free-living, non-strenuous physical activity may not be enough to improve post-concussion recovery. Therefore, it may not be adequate enough for healthcare professionals to simply tell patients to “increase physical activity throughout your day”. Rather, clinicians may need to provide more guidance to patients as to the optimal intensity and mode (i.e., treadmill, elliptical, free-living physical activity) needed to be beneficial for recovery. These specific directions may help patients better understand what physical activity they should and should not be performing with a concussion. In addition to promoting early post-concussion physical activity, healthcare professionals should clearly outline when patients

should avoid physical activity. Patients should avoid physical activity if it drastically increases symptom severity or if the physical activity puts them at risk of sustaining another concussion (i.e. contact sports).

Limitations

This study was not without limitations. Although 46 participants were enrolled, 14 were excluded from the final analysis. Because of this, the current study may have not had enough participants to reach statistical power. The participants included in analysis were from two Michigan Universities, thus posing a challenge to the generalizability of the study. Additionally, participants were asked to self-report several pieces of information such as time spent in class and studying, as well as what time they woke up and went to bed. It is possible that participants did not remember the exact time these events took place, which may have led to recall bias. Another limitation of the study is the inability to account for external factors that may have influenced symptom reporting or recovery time. Specifically, participants were not asked about social activities or other cognitive activities (i.e., casual reading, screen time) that were performed over the duration of the study.

Conclusion

Despite previous research identifying structured post-concussion physical activity as improving concussion recovery, the current study found no such relationship with physical activity in a free-living condition. These results insinuate that physical activity intensity may be a modulating factor for concussion recovery. Research is needed directly comparing different post-concussion physical activity intensities and their effects on recovery. One feasible suggestion is to utilize heart rate to assist in quantifying physical activity intensity. When determining the clinical utility of physical activity as a concussion treatment, clinicians may need to provide

patients with specific instructions rather than telling patients to simply increase their activity levels. For example, this may mean providing patients with a specific treadmill or stationary bike protocol as this has been shown to be beneficial in previous research. Future research using accelerometers after concussion, should aim to identify if meeting a movement threshold (i.e., 10,000 steps per day) improves concussion recovery. Although more research is needed in this area, clinicians should encourage patients to gradually increase their post-concussion physical activity levels after the initial 24-48 hours after injury.

APPENDICES

APPENDIX A

Post-Concussion Symptom Evaluation

1. Please check the box for each symptom based on how you are CURRENTLY FEELING:
0= Not experiencing symptom, 6= Severely experiencing symptom

	0	1	2	3	4	5	6
Headache	☐	☐	☐	☐	☐	☐	☐
Pressure in Head	☐	☐	☐	☐	☐	☐	☐
Neck Pain	☐	☐	☐	☐	☐	☐	☐
Nausea or Vomiting	☐	☐	☐	☐	☐	☐	☐
Dizziness	☐	☐	☐	☐	☐	☐	☐
Blurred Vision	☐	☐	☐	☐	☐	☐	☐
Balance Problems	☐	☐	☐	☐	☐	☐	☐
Sensitivity to Light	☐	☐	☐	☐	☐	☐	☐
Sensitivity to Noise	☐	☐	☐	☐	☐	☐	☐
Feeling Slowed Down	☐	☐	☐	☐	☐	☐	☐
Feeling like “in a fog”	☐	☐	☐	☐	☐	☐	☐
“Don’t Feel Right”	☐	☐	☐	☐	☐	☐	☐
Difficulty Concentrating	☐	☐	☐	☐	☐	☐	☐
Difficulty Remembering	☐	☐	☐	☐	☐	☐	☐
Fatigue or Low Energy	☐	☐	☐	☐	☐	☐	☐
Confusion	☐	☐	☐	☐	☐	☐	☐
Drowsiness	☐	☐	☐	☐	☐	☐	☐
More Emotional	☐	☐	☐	☐	☐	☐	☐
Irritability	☐	☐	☐	☐	☐	☐	☐
Sadness	☐	☐	☐	☐	☐	☐	☐
Nervous or Anxious	☐	☐	☐	☐	☐	☐	☐
Trouble Falling Asleep	☐	☐	☐	☐	☐	☐	☐

APPENDIX B

ActiGraph GT9X Link Physical Activity Monitor

Figure 2: Flyer for ActiGraph GT9X Link Physical Activity Monitor

Activity Monitor

ActiGraph GT9X Link

U.S. federal law restricts this device to sale by or on the order of a physician.





ActiGraph GT9X Link

The new ActiGraph GT9X Link is the most sophisticated activity monitor available from the global leader in actigraphy measurement. The redesigned ActiGraph GT9X Link combines our validated 3-axis accelerometer and data filtering technology with a sleek, low profile case, and a variety of advanced new features, including:



Programmable display

The ActiGraph Link features a programmable LCD window that can be configured to display date and time, provide optional real-time feedback, or can be completely disabled.



Inertial Measurement Unit (IMU)

An integrated IMU contains a secondary accelerometer, gyroscope, and magnetometer sensors, providing raw position and rotational data for a variety of advanced applications, including inclination, gait analysis, and fall detection.*



Bluetooth® LE

The Bluetooth® Smart enabled ActiGraph Link supports a variety of wireless features, including heart rate monitoring, proximity detection, and communication with ActiGraph's suite of mobile applications for iOS and Android devices.



Wear time sensor

A wear time sensor uses capacitive touch technology to automatically detect when a wrist worn device has been removed for simplified compliance monitoring and data cleaning.

Objective Measures

The ActiGraph Link, in conjunction with our innovative software platform delivers a variety of physical activity and sleep/wake measures including:

- Raw acceleration
- Energy expenditure
- MET rates
- Steps taken

- Physical activity intensity
- Activity Bouts
- Sedentary Bouts
- Heart rate R-R intervals*

- Body position
- Sleep latency
- Total sleep time
- Sleep efficiency

* Requires compatible Bluetooth® heart rate monitor

Specifications

Dimensions	3.5 x 3.5 x 1 cm	Dynamic range (primary accelerometer)	+/- 8G	IMU Sample Rate	100 Hertz
Weight	14 grams	Dynamic range (secondary accelerometer)	+/- 16G	Water resistance	1 meter, 30 min.
Sample rate	30-100 Hertz	Gyroscope dynamic range	+/- 2000 deg/sec	Wear location	Wrist, waist
Battery life	14 days*	Magnetometer dynamic range	+/- 4800 micro-Tesla	Warranty	1 year
Data storage	180 days/4 GB	Communication	USB, Bluetooth® LE		

* Rechargeable Lithium ion, wireless and gyro disabled, 50 Hz sample rate

actigraphcorp.com

APPENDIX C

Daily Questionnaire

1. What is your first name and the first letter of your last name?
2. What time did you go to bed last night?
3. What time did you wake up today?
4. Did you take the black wrist monitor off today?
 - a. If so, approximately what time(s) did you take it off?
5. Did you take any naps today?
 - a. Approximately what time(s) was your nap(s)?
6. Did you work out today?
 - a. If so, which of the following workouts did you do?
 - i. Conditioning with team
 - ii. Conditioning on your own
 - iii. Weight room with team
 - iv. Weight room on your own
7. Approximately how many hours did you spend in class today?
8. Approximately how many hours did you spend on homework today?

APPENDIX D

Vestibular and Ocular Motor Screening

Subject Identification: _____

Does athlete wear glasses/contacts: ☐ Yes ☐ No

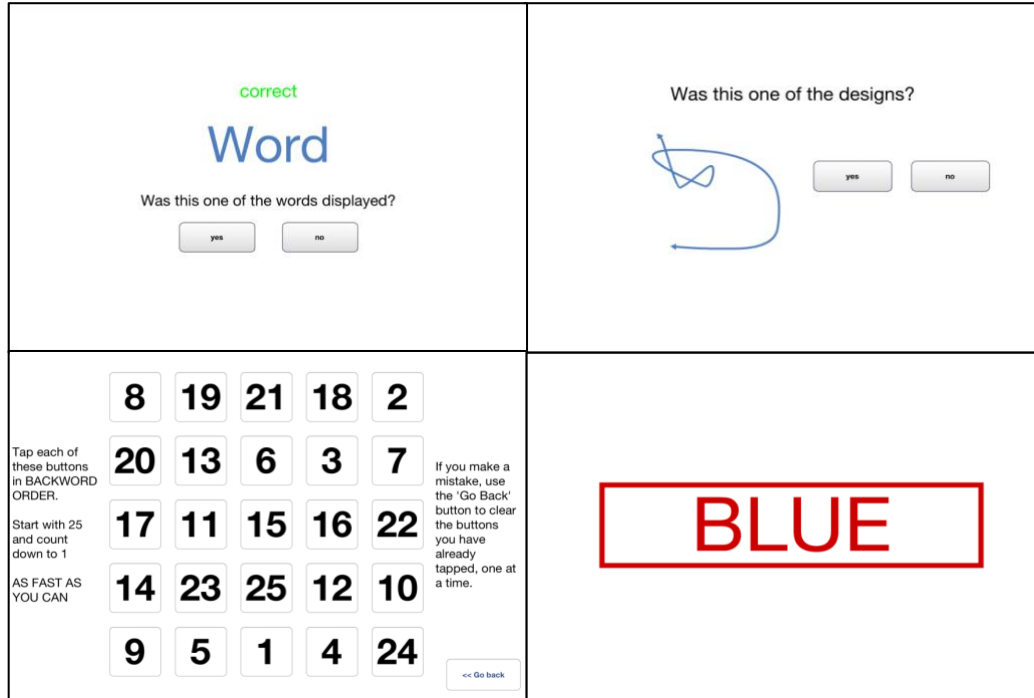
Are they wearing them: ☐ Yes ☐ No

VOMS Test:	Headache 0-10	Dizziness 0-10	Nausea 0-10	Fogginess 0-10	Comments
Baseline Symptoms					
Smooth Pursuits					
Saccades - Horizontal					
Saccades - Vertical					
Convergence					(Near point in cm): Measure 1: _____ Measure 2: _____ Measure 3: _____
VOR - Horizontal					
VOR - Vertical					
Visual Motion Sensitivity Test					

APPENDIX E

Immediate Post-Concussion Assessment and Cognitive Test

Figure 3: Screenshots from The Immediate Post-Concussion Assessment and Cognitive Test



APPENDIX F

Modified Balance Error Scoring System

Figure 4: Scoring Section for The Modified Balance Error Scoring System

BALANCE EXAMINATION	
Modified Balance Error Scoring System (mBESS) testing⁵	
Which foot was tested (i.e. which is the non-dominant foot)	☐ Left ☐ Right
Testing surface (hard floor, field, etc.) _____	
Footwear (shoes, barefoot, braces, tape, etc.) _____	
Condition	Errors
Double leg stance	of 10
Single leg stance (non-dominant foot)	of 10
Tandem stance (non-dominant foot at the back)	of 10
Total Errors	of 30

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