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# Evaluating the Effects of Cardiorespiratory Fitness Level and Gender on Outcomes of the Buffalo Concussion Bike Test

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# Evaluating the Effects of Cardiorespiratory Fitness Level and Gender on Outcomes of the Buffalo Concussion Bike Test

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Health, Sport, and Exercise Science

by

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# Abstract

**Background:** Accurate assessment of concussion is crucial for creating a treatment plan. The Buffalo Concussion Bike Test (BCBT) is a 30-minute graded exercise protocol for a stationary bicycle. Previously this assessment has been reportedly used to screen for exercise intolerance secondary to autonomic dysfunction; however, the original purpose of the assessment was to find a sub-symptom threshold for exercise rehabilitation during concussion recovery. Starting resistance for the BCBT protocol is based solely on body mass. Other factors such as cardiorespiratory fitness level and sex have been noted to effect outcomes on similar assessments and are not considered in the BCBT protocol or interpretation.

**Purpose:** The primary purpose of this study is to determine the effects of cardiorespiratory fitness levels (CRF) on the time-to-test completion of the Buffalo Concussion Bike Test among adults with high and low CRF. The secondary purpose of this study is to document sex differences on time-to-test completion and heart rate at test completion on the BCBT.

**Study design**: This study employed a cross-sectional, extreme groups approach study design.

**Methods:** Forty-two healthy adults between 20-29 years of age (M = 22.31 ± 2.25 years) completed a VO2 max bike test at their first appointment to screen for eligibility and for placement into high and low groups. To assess for the effects of CRF level, only people with "excellent" and "superior" VO2 max scores were included in the HIGH CRF group (n = 21) and participants with "poor" and "very poor" VO2 max scores according to the American College of Sports Medicine cutoffs were included in the LOW CRF group (n = 21). Participants with "good" and "fair" VO2 max scores were excluded from the study. After eligibility was confirmed and they were assigned to their groups, participants completed the BCBT protocol within 3-14 days. Participants were also administered the Post-Concussion Symptom Scale

(PCSS) and the Vestibular/Ocular Motor Screening (VOMS) immediately before and after the BCBT.

**Results:** Participants in the HIGH CRF group exhibited longer times-to-test completion ($U =$ 15.00, $p <.001$) and had lower heart rates across the first four stages of the BCBT ($F$ (1) = 40.20, $p < .001$, $\eta^2 = 0.30$) compared to participants in the LOW CRF group. Participants in the HIGH CRF group exhibited significantly lower heart rates at rest ($t$ (40) = -3.87, $p = 0.01$), stage 1 ($t$ (40) = -6.25, $p <.001$), stage 2 ($t$ (40) =-5.66, $p <.001$), stage 3 ($t$ (40) = -5.87, $p < .001$), and stage 4 ($t$ (40) = -6.35, $p < .001$) compared to those in the LOW CRF group. Males and females did not significantly differ on time-to-test completion ($U = 148.00$, $p = 0.06$), or for final heart rate ($U = 159$, $p = 0.12$).

**Conclusions:** Non-concussed individuals with high CRF levels exhibited a ceiling effect on the BCBT protocol. However, they did not exhibit significantly different scores on the PCSS before or after the BCBT compared to individuals in the low CRF group. Males and females did not differ on time-to-test completion or peak heart rate, additionally, they exhibited similar VOMS change scores before and after the BCBT protocol. The findings for the current study further support the literature on interpretation of exercise testing and highlight the need for CRF level considerations for the BCBT protocol.

# Dedication and Acknowledgements

This dissertation is dedicated to my parents, Mark and Cheryl Stephenson. Without your support and love, I would not have accomplished half of what I was able to do in this life. I love you a bushel and a peck. Thank you. I also want to acknowledge my sister and brother-in-law, Sara and Brian Smith, for all of the dinners and sister days. Thank you for being my relief and distraction when life was difficult. I love you. To my nieces and nephews- Trenton, Maddie, Malachi, Emmie, and Eva- you have made the last few years not only bearable, but fun. Thank you for always being excited to see me and giving the best hugs. I can’t wait to see what you accomplish someday. To my brother, Travis, thank you for all the long phone calls and advice. It meant more than you know. I love you.

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# Chapter 1: Introduction

## Overview of the Problem

Autonomic dysfunction (AD), or dysautonomia, leads to exercise intolerance, which has posed a problem for clinicians trying to prescribe active rehabilitation for concussion (Leddy, 2020; Leddy et al., 2007; Miranda et al., 2018). The autonomic nervous system is a complex network within the central nervous system (McCorry, 2007). Among other functions, the autonomic nervous system (ANS) controls heart rate, heart rate variability, and blood pressure (Conder & Conder, 2014; Esterov & Greenwald, 2017; Hilz et al., 2016; Thayer & Lane, 2009). With dysfunction of the ANS, these systems are no longer able to accommodate for exercise and orthostatic posture changes (Karas et al., 2000; Miranda et al., 2018; Smit et al., 2004). Therefore, dysautonomia often presents as exercise intolerance in concussed populations. The prevalence of this phenomenon in concussion alone is currently unknown, partially due to the lack of consistent measures for dysautonomia.

To date, the Buffalo Concussion Test is only assessment for exercise intolerance specific to concussed patients that has a treadmill and bike version. The Buffalo Concussion Treadmill Test (BCTT) is a graded treadmill test that aims to find a sub-symptom threshold for heart rate (Haider, Leddy, et al., 2019; Leddy et al., 2011; Leddy & Willer, 2013). The heart rate at symptom exacerbation, or time of test completion, is then used to prescribe exercise intensity within concussion rehabilitation.  Throughout the protocol, workload increases as the patient progresses through the stages of the test. Starting speed on the treadmill test is determined by height (3.2 miles per hour and 3.6 miles per hour for those < and > 5’ 10” respectively). A major criticism of this test is that it does not consider fitness level or sex, only height, when determining workload and pace. This assessment was adapted for the stationary bike and dubbed the Buffalo Concussion Bike Test (BCBT) (Haider, Johnson, et al., 2019). Similar to the treadmill test, the bike test is a graded exercise test; however, starting workload is determined by weight of the patient. There is also a lack of consideration for sex or fitness level when determining the protocol for the BCBT. The outcomes of the BCBT include heart rate at symptom exacerbation or test completion, time-to-test completion, concussion symptoms reported on a Visual Analog Scale (VAS: rated 0 to 10), and rate of perceived exertion (RPE). Justifications for ending the test include inability to keep up with the 60 ± 5 repetitions per minute (RPM), an increase of 3 or more on the VAS, an RPE score of > 17, participant requests to quit for any reason, or reaching 90% of age predicted maximum heart rate.

It is currently unknown if the BCBT and BCTT protocols affect presentation on other concussion assessments, including symptom scales and vestibular and ocular motor screening. Exercise protocols are often used to decide medical clearance for athletes from concussion; however, little is known about how exercise bouts exacerbate concussions-like symptoms in healthy (i.e., non-concussed) individuals. Covassin and colleagues (2007) assessed symptoms in concussed patients and noted that they had an increase in self-reported fatigue (Covassin et al., 2007). Additionally, the Vestibular/Ocular Motor Screening (VOMS) is a screener for dysfunction of the vestibular and ocular motor systems and relies on self-reported symptom exacerbation. Moran and colleagues (2020) recently evaluated the effects of a graded maximal exercise bout on VOMS and symptoms immediately following exercise, at 20-minutes, and 40-minutes post injury. Symptoms were significantly elevated following maximal exercise; however, there were no differences in VOMS scores from pre-exercise to immediately following exercise. Symptom scores improved from baseline at the 20-minute time point (Moran et al., 2020). The BCBT and BCBT are submaximal exercise protocols that are often given at the clearance visit with a battery of concussion assessments (i.e., the Post-Concussion Symptom Scale: PCSS, and the VOMS). It is still unknown if the submaximal exercise protocol would negatively affect symptom scores similarly to the maximal protocol that Moran and colleagues (2020) explored.

The few studies that utilize the BCBT and BCTT have reported on risk factors for protracted concussion recovery, similarities between the bike and treadmill versions of the test, and sex differences on the treadmill version. Haider and colleagues (2019) recently reported that change in heart rate from rest to symptom threshold of $\leq$50 BPM on the BCTT was predictive of a protracted recovery in adolescents that were prescribed cognitive and physical rest; however, this relationship did not occur in individuals that were prescribed active rehabilitation (Haider, Leddy, et al., 2019). Heart rate at symptom exacerbation in concussed adolescents and at voluntary exhaustion in controls are statistically equivalent for both the BCTT and BCBT versions of the test (Haider, Johnson, et al., 2019). Additionally, sex differences on the BCTT reported that females had a higher resting HR and higher heart rate symptom threshold; however, males and females did not differ on change from resting heart rate to heart rate symptom threshold, total treadmill time, maximum VAS score, or change in symptom exacerbation on the VAS (Chizuk et al., 2021). However, these same differences have yet to be examined on the BCBT. Despite these findings, the administration of these tests does not account for cardiorespiratory fitness levels or sex differences, which are two factors that are established in the exercise testing literature to influence outcomes (Bakker et al., 2021; Dimkpa et al., 2015; Fomin et al., 2012; Weller et al., 1992).

## Significance of the Problem

An individual's current level of cardiorespiratory fitness (CRF) is an important consideration for determining workload for an exercise test; exclusion of this consideration leads to higher risk of floor and ceiling effects. A ceiling effect occurs when the measure is not difficult enough, and as a result, scores are skewed towards the upper limit of the instrument (Cramer & Howitt, 2004). In contrast, floor effects occur when the evaluation is too difficult and scores are skewed towards the lower limit of the scale (Cramer & Howitt, 2004). In both cases, there is very little variance in the scores, and the measure potentially misses the true representation of the data as scores were limited by the scale. Due to this, meaningful analysis of the results would therefore be impossible. These effects have been noted previously in exercise testing. Bakker and colleagues (2021) concluded in a recent review that CRF testing for deconditioned individuals may not be possible and results are subject to floor effects; in contrast, CRF testing in highly fit and functional individuals are subject to ceiling effects. Similarly, ceiling effects have been noted on the Canadian Aerobic Fitness Test (CAFT) and modified CAFT submaximal tests (Weller et al., 1992) and researchers concluded it was because there were too few stages to meet the target heart rate. Weller and colleagues (1992) developed additional stages for the test to address this issue. Floor effects on cardiorespiratory fitness testing have been noted in untrained populations with chronic illnesses (Campos et al., 2018; Granger et al., 2015; Maddocks et al., 2017; Parry et al., 2015). These findings in the literature support the need for CRF considerations for exercise testing protocols and would also apply to the BCBT. Therefore, physical fitness level should be a consideration for the protocol and/or interpretation of the BCBT.

There is a clear relationship between cardiorespiratory fitness level and cardiac variables such as heart rate that further support the need to consider CRF in exercise testing. High cardiorespiratory fitness levels have been shown to mediate the effect of age on peak heart rate during exercise (Ozemek et al., 2016). Tulppo and colleagues (1998) investigated the influence of age and fitness level on maximum oxygen consumption, vagal modulation of heart rate, and the instantaneous R-R interval during cycle exercise testing. Age was not a significant predictor for cardiac outcomes; however, they reported that poor physical fitness resulted in impaired vagal function during exercise. Vagal modulation of the heart is a dynamic relationship between the sympathetic and parasympathetic nervous systems; both of which are controlled by the ANS (Tulppo et al., 1998). However, poor physical fitness is not equivalent to dysautonomia. In individuals without dysautonomia, is widely accepted that the autonomic nervous system will adapt to exercise training relatively quickly, and these differences would likely decrease or disappear over time with training (Amano et al., 2001; Besnier et al., 2017; Oya et al., 1999). Based on the aforementioned findings in the literature, concussed patients that score poorly on the BCBT may not have dysautonomia, but in fact have differing heart rate due to their poor cardiorespiratory fitness.

In addition to considering the influence of CRF on the BCBT, sex has also played a role in mitigating ceiling and floor effects for exercise testing. Numerous studies show that females exhibit different cardiac performance on exercise tests compared to their male counterparts (Fomin et al., 2012). In a study by Fomin and colleagues (2012) females had lower cardiac output at maximum exercise, and lower peak VO2 (Fomin et al., 2012). Similarly, females' heart rate responds differently during and after a bout of submaximal exercise on the cycle ergometer compared to male counterparts (Dimkpa et al., 2015); specifically, males exhibited larger change from rest to peak heart rate recorded during the trial. Males also exhibited higher percent heart rate max and percent heart rate reserve during exercise compared to females (Dimkpa et al., 2015). Additionally, sex differences have been reported in concussion symptom reporting at baseline and following injury (Covassin et al., 2006; Frommer et al., 2011; Wallace et al., 2017). These findings support the inclusion of considerations for factors such as sex and physical fitness level in addition to weight on the Buffalo Concussion Bike Test. Due to the influence of these factors on testing outcomes, several cycling tests make considerations for these factors in their protocol.

Other exercise testing protocols make considerations in their test design and/or interpretation to accommodate cardiorespiratory fitness and sex. The Astrand bicycle test is a similar aerobic cycling test to the BCBT in that heart rate is a main outcome; however, it accounts for the participants biological sex, fitness level, and body weight when deciding the initial power for the start of the assessment (Åstrand, 1965; Beam & Adams, 2011). Additionally, outcome scores are interpreted based on sex (Åstrand, 1965; Beam & Adams, 2011). Similarly, other graded exercise tests such as the Wingate bike test (Maud & Shultz, 1989) have differing interpretations of outcome scores based on the participant’s sex and CRF (Shvartz & Reibold, 1990). Despite the well-documented influences and considerations of CRF and sex on application of exercise testing and the interpretation of results, the BCBT does not account for these confounding variables which may lead to inaccurate outcome scores.

The target population for the BCBT includes athletes that vary in their CRF as well as RPE and symptom reports on exercise testing. Several studies have reported that athletes, even within the same sport and team, can differ significantly on CRF (Lynch et al., 2016). Factors such as diet (Lynch et al., 2016; Wang et al., 2010), genetic profile (Varillas-Delgado et al., 2021), age (Mota et al., 2002; Wang et al., 2010), and sex (Mota et al., 2002; Wang et al., 2010) have been reported to influence cardiorespiratory fitness levels. Additionally, untrained participants are not consistent at reporting perceived exertion compared to actual exertion (Eng et al., 2002), and report higher rates of perceived exertions earlier in testing protocols compared to trained participants (C. Kaufman et al., 2006). Further, there are mixed reports on the effect of sex on perceived exertion during exercise, with some reports supporting that females endorse higher RPE scores compared to their male counterparts (Pincivero et al., 2004) and other studies noting no differences between the groups (Pincivero et al., 2000). Given this variability in CRF and symptom reporting among these individuals it should be expected that the effect of these variables will also influence outcomes on the BCBT.

## Purpose of the Study

The primary purpose of this study is to determine the effects of cardiorespiratory fitness levels (CRF) on heart rate and time-to-test completion of the Buffalo Concussion Bike Test among adults with high and low CRF. The secondary purpose of this study is to document sex differences on time-to-test completion and heart rate at test completion on the BCBT.

### Exploratory Analyses

EQ1: Females will report higher symptoms on the Post-Concussion Symptom Scale at both pre- and post- test time points compared to their male counterparts.

EQ2: Males and females will exhibit similar change scores on the items of the VOMS at pre- and post- test time points.

EQ3: Males and females will exhibit similar change scores on near point of convergence distance (NPC) distance of the VOMS at pre- and post- test time points.

EQ4: Participants in the LOW CRF group will report higher post-test symptoms on the PCSS compared to participants in the HIGH CRF group.

### Hypotheses

H1: Participants in the high CRF group will exhibit a longer time-to-test completion on the BCBT than the participants in the low CRF group.

H2: Participants in the high CRF group will have lower peak heart rate for the first four stages of the BCBT protocol than the participants in the low CRF group.

H3: Males and females will not differ significantly on time-to-test completion on the BCBT.

H4: Females will have a significantly higher heart rate at test completion during exercise on the BCBT compared to their male counterparts.

### Operational Definitions

1. Cardiorespiratory fitness- this is defined as the ability to perform dynamic, moderate to vigorous exercise for prolonged periods of time. This is quantified by evaluating maximal oxygen uptake, which can be estimated using submaximal testing (American College of Sports Medicine, 2013; Medicine, 2013).

2. High cardiorespiratory fitness- this was defined as VO2 max scores that fall under the Superior or Excellent groups with a VO2 max of 51 ml/kg/min or greater for men, or 38 ml/kg/min or greater in females per ACSM guidelines for VO2 max categorization (American College of Sports Medicine, 2013; Liguori & Medicine, 2020) (See Appendix 6).
3. Low cardiorespiratory fitness- this was defined as VO2 max scores that fall under the Very Poor and Poor groups with a VO2 max of 37 ml/kg/min or lower in men, or 27 ml/kg/min or lower in women per ACSM guidelines for VO2 max categorization (American College of Sports Medicine, 2013; Liguori & Medicine, 2020) (See Appendix 6).
4. Sub-maximal testing- in comparison to maximal testing, submaximal exercise testing does not require an individual to exercise to the point of volitional fatigue (American College of Sports Medicine, 2013; Liguori & Medicine, 2020).
5. Rating of Perceived Exertion- this is defined as a quantifiable way to measure exertion. The Borg RPE scale ranges from 6 (zero exertion) to 20 (maximal exertion) (Borg, 1982). The participant self-reports their exertion rating.
6. Visual Analog Scale- this is a quantification of symptoms on a scale. Possible scores range from 0 (no symptoms) to 10 (worst I have ever felt) and the participant verbally endorses a rating at the end of every stage of the BCBT. Individual symptoms are not identified on this scale, it is a global rating.
7. Time-to-test completion on the BCBT- this is a measurement of test duration on the BCBT. Time begins when the test protocol starts and ends when at least one of the stopping criteria are met.

8. Stopping criteria for the BCBT- criteria for ending the test include an increase of symptom reports by 3 or more points on the VAS, an RPE score of >17, inability to keep cycling at 60 ± 5 RPM, participant requests to quit for any reason, or reaching 90% of age predicted maximum heart rate.

# Chapter 2: Literature Review

## The Definition of Concussion

A current, accurate, and uniform definition of concussion is a necessary endeavor to ensure that research and medicine are consistent when addressing this injury. Sport centered entities such as the National Athletic Training Association (NATA), the American Medical Society for Sports Medicine (AMSSM), American College of Sports Medicine (ACSM), and the Concussion in Sport Group (CISG) have published similar definitions of concussion. Overlapping similarities of these definitions include that a concussion is defined as a complex pathophysiologic process induced by biomechanical forces, which typically results in the rapid onset of transient neurologic dysfunction (rather than a structural injury), that resolves spontaneously over a variable period of time, and may or may not involve loss of consciousness (Broglio et al., 2014; Harmon et al., 2019; Herring et al., 2011; McCrory et al., 2017a). The only inconsistencies lie in the level of detail afforded to these definitions. The CISG definition encompassed previous definitions and added additional criteria, such as the description of whiplash injuries (versus direct blows to the head) and the description of clinical signs (e.g., loss of consciousness or vomiting), symptoms (e.g., dizziness, fatigue, nausea, and visual disturbances), and impairments (e.g., neurocognitive or motor) which cannot be attributed to drug use (prescribed or not), alcohol use, or other pre-existing or co-existing medical conditions (McCrory et al., 2017). These overlapping definitions provide a clearer criterion for the recognition of concussion by medical professionals; however, there are still some controversies in terminology when referring to concussion.

Throughout the literature, the term mild traumatic brain injury (mTBI) is used synonymously with concussion; however, some researchers have criticized that this maybe confusing and misleading (Head, 1993; Slobounov et al., 2009; Yeates, 2010). For example, the definition of mTBI differs from that of concussion. There is a wide variety in the diagnosis criteria for mTBI; however, criteria typically center around length of time the patient is unconscious (< 30 minutes), Glasgow Coma Scale scores of $\geq$ 13, and length of post-traumatic amnesia (< 24 hours) (Head, 1993; von Holst & Cassidy, 2004), where with concussion, neither length of time for unconsciousness or post-traumatic amnesia are required for diagnosis (McCrory et al., 2017b). Due to these discrepancies, researchers have criticized the use of these terms as interchangeable, stating that it is confusing and hampers the ability to compare findings across studies (Yeates, 2010). In addition, it may hinder the accurate identification and diagnosis of mTBI (J. M. Powell et al., 2008). Commenting on this controversy, researchers Slobounov and colleagues (2014) have stated that "there is nothing *mild* about mild traumatic brain injury" [referring to concussion] (p. 75, Slobounov, Cao, & Sebastianelli, 2009). They believe that the term mild maybe misleading, and further support this claim by pointing out that there are some studies that show long-lasting functional brain alterations (Barkhoudarian et al., 2011; Slobounov et al., 2012). In contrast to researchers' use of these terms, a study by Gordon and colleagues (2010) asked parents of youth athletes their opinions of concussion versus mTBI diagnoses. Their study revealed that the majority of parents thought that "concussion" and "mild/minor traumatic brain injury" were equivalent diagnoses; however, those who did not rate them as equivalent rated concussion as significantly better or "less worse" than mild or minor traumatic brain injury (Gordon et al., 2010). Although these opinions appear to be on differing sides as to which term is worse or more severe than the other, it is clear that the terms (concussion and mTBI) are not synonymous to either researchers, clinicians, or parents.

## Prevalence and incidence of sport- and recreation-related concussion

The overall reported estimates of concussion prevalence and incidence in sports and recreation vary widely; however, there is consensus that reports have increased in recent years. Langlois and colleagues (2006) estimated that between 1.8 and 3.8 million sport and recreation related concussions occur each year; whereas Bryan and colleagues (2016) reported estimate 1.1 to 1.9 million sport and recreation related concussions occur in a narrower age group (e.g., youth and adolescents). In an older, multi-site study by Powell and colleagues (1999) including 246 high school athletic trainers over a 3-year period, there were 1219 concussions over 4.4 million athletic exposures (AEs) (or 0.27/1000 AEs). This is low compared to more recent estimates that range from 0.4-9.1 concussions per 1000 AEs (Gonzalez et al., 2020; Kerr et al., 2019). Some discrepancies in the overall prevalence and incidence of concussion could be due to an increase of reported injuries over time.

In the past couple of decades, reports of the prevalence of concussion have increased by 7-15% and incidence of concussion has increased from 0.12 to 0.49 per 1000 AEs in the high school and college age groups (Hootman et al., 2007; Kerr et al., 2017; Lincoln et al., 2011; Rosenthal et al., 2014). More specifically, concussion prevalence in high school athletes has increased by 15.5% annually over an 11-year period from 0.12 per 1000 AEs in 1998 to 0.49 per 1000 in 2008 (Lincoln et al., 2011). Similarly, concussion prevalence in National Collegiate Athletic Association (NCAA) athletes has increased by 7% annually between 1988 to 2004 (Hootman et al., 2007). A more recent study by Kerr et al. (2017) revealed some conflicting evidence and reported 274 concussions occurred in the NCAA each year for the 2011-2015 academic school years (Kerr et al., 2017), compared to the previous report of 563 per year for the years 1988-2014 (Hootman et al., 2007). This conflicting report of concussion prevalence and incidence trends over time could be due a multitude of things including an increase in concussion education, reporting, and media coverage in recent years (Bramley et al., 2012). In addition, surveillance systems have more recently become electronic, streamlining the injury reporting procedures and making it easier to track injury incidence (Kerr et al., 2017). Factors such as sex, competition level, sport, and sport-setting (i.e., practice versus games) influence in in concussion prevalence and incidence rates.

#### ***Prevalence and incidence of concussion by sex.***

Female athletes report higher prevalence and incidences of concussions compared to their male counterparts, even when comparing similar sports (Bretzin et al., 2018; Covassin et al., 2003a, 2003a; Hootman et al., 2007; Kerr et al., 2017; Lincoln et al., 2011). An athlete's sex may play a role in risk of concussion. Women exhibit/are reported to have higher incidence rates of concussion at 0.36 concussions per 1000 AEs, compared to men at 0.22 concussions per 1000 AEs in men (Gessel et al., 2007a) and were 1.9 times more likely to sustain a SRC during their season compared to their male counterparts (Bretzin et al., 2018). Another way of examining sex differences, rather than looking at overall incidents, in concussion prevalence is by comparing concussion rates per athletic exposures in comparable sports (i.e., baseball and softball, girls' and boys' soccer, and boys' and girls' basketball). A recent study by Kerr et al. (2017) follows this trend and the authors reported that in every comparable sport (e.g., softball: 0.26/1000 AE's and baseball: 0.09/1000 AE's) females reported significantly higher incidence of concussion compared to their male counterparts.

The exception to this pattern was with ice hockey and lacrosse (Gessel et al., 2007a; Kerr et al., 2017); however, this is most likely due to variations in game rules and protective equipment between boys' and girls' leagues that make these two sports incomparable. More specifically in boys' lacrosse, body contact is allowed, whereas with girls' lacrosse it is not (*Player Equipment*, 2016). Further, boys' and girls' lacrosse differ in protective equipment. Required equipment for boys' lacrosse includes a helmet, mouthpiece, gloves, shoulder pads, and arm pads; and girls are required to wear a mouthpiece, and eyewear (*Player Equipment*, 2016). There is a psychological theory, called the *Peltzman Effect,* which states that people tend to take more risks when more protective measures are in place (Peltzman, 1975). If applied to sport, it could provide some support as to why athletes may be at higher risk of injury when wearing more protective equipment.

Factors such as injury reporting differences and anatomical differences (e.g., females have weaker neck strength) may play a key role in explaining the higher prevalence and incidence of sport-related concussion in female compared to male athletes. Previous researchers have reported that these aforementioned sex differences may be partially due to a higher likelihood for female athletes to disclose their concussion compared to males (Kerr et al., 2016; Wallace et al., 2017). Where males may be more likely to "play through the pain" and hide injuries from authoritative figures to avoid losing playing time or letting teammates or coaches down compared with female student-athletes (Wallace et al., 2017). In addition, it has been proposed that weaker neck strength reduces the ability to brace for impact (Eckner et al., 2014; Tierney et al., 2005), and therefore increases risk of injury. Collins and colleagues (2014) reported that neck strength was a significant predictor of concussion, even after adjusting for sex and sport. Similarly, other literature supports that athletes with smaller, weaker necks are more likely to exhibit greater linear and angular head displacements, velocities, and accelerations after impact (Broglio, Sosnoff, et al., 2009; Brolinson et al., 2006; Mihalik et al., 2007; Tierney et al., 2005; Viano et al., 2007); therefore, these athletes would be more likely to sustain a concussion.

In contrast, other researchers have reported no correlation between neck strength and reducing the severity of head impact (Mansell et al., 2005; Mihalik et al., 2011). Overall, the literature on neck strength and its contributions to concussion risk is contradictory and inconclusive. In addition to sex, researchers have also documented differences for the prevalence and incidence of SRC across competition level of sport.

### ***Prevalence and incidence of concussion by competition level.***

The prevalence and incidence of sport-related concussion increases as competition level increases from youth through professional. Literature on youth sports is scant; however, with the little evidence that is available, they appear agree with the overall trend. Incidence rates per 1000 AE have been reported at 0.23-1.57 for youth sports (Dompier et al., 2015; Pfister et al., 2016), 0.23-1.86 for high school (Dompier et al., 2015; Gessel et al., 2007a; Kerr et al., 2018; Marar et al., 2012), and 0.38-6.94 for college sports (Covassin et al., 2003b; Dompier et al., 2015; Kerr et al., 2018). Similarly, Daneshvar and colleagues (2011) reported that concussions prevalence was significantly higher for collegiate sports than in high school for football, soccer, volleyball, boys', and girls' basketball, wrestling, and softball. College baseball rates did not differ from high school baseball (Daneshvar et al., 2011). In contrast to these findings, an older study by Guskiewicz and colleagues (2000) reported an inverse relationship between competition level and concussion risk. Specifically, high school football had a higher incidence of concussion at 5.6%, followed by division III college football at 5.5%, division II at 4.5% and division I at 4.4% (Guskiewicz et al., 2000). The difference in these findings could be due to differences in methodologies of collecting the data. Daneshvar and colleagues (2011) compiled data from various studies for a literature review on the prevalence and incidence by sport, where Guskiewicz and colleagues (2011) reported the results from a survey of collegiate and high school athletic trainers. The majority of research supports that concussion rates are higher in collegiate level sports, compared to high school level. These data suggest that as competition level increases, so does the risk of sport-related concussion, regardless of sport; however, when considering actual risk these trends should be interpreted with caution. Because collegiate athletes have greater access to medical professionals, the higher rate of concussion in collegiate sports may be due to accessibility to diagnosis and care, rather than differences in actual risk of concussion (Pryor et al., 2015).

### ***Prevalence and incidence of concussion by sport.***

Sports, such as football and soccer, have a higher prevalence of concussion compared to other sports (e.g., track). The majority of studies agree that American football has the highest prevalence of concussion compared to other sports (Gessel et al., 2007a; Kerr et al., 2017, 2018; Lincoln et al., 2011; Marar et al., 2012; J. W. Powell & Barber-Foss, 1999; Rosenthal et al., 2014); however, many reports differ which sports hold the second and third highest prevalence. In an earlier study by Powell and colleagues (1999), reported that football accounted for 63% of the concussion cases, followed by wrestling (10.5%, 128/1219), girls' soccer and boys' soccer (5.7%). A more recent study supported that football concussion rates were followed by girls' soccer (21.5%), boys' soccer (15.4%), and girls' basketball (9.5%) (Gessel et al., 2007a). In contrast, Prien and colleagues (2018) reviewed 70 articles on the prevalence of concussion by sport between 2000 and 2018. Results of this review revealed that rugby game-play had the highest prevalence of concussion with 3.89 concussions per 1000 hours of exposure, or 3.00 per 1000 AEs (Prien et al., 2018). These data reveal a consensus that contact sports (i.e., football and soccer) consistently have a higher concussion risk compared to non-contact sports (i.e., track or swimming). Although there appears to be a clear relationship between sport type and concussion prevalence, there is also an established relationship between sport setting (i.e., game versus practice) and concussion prevalence within these sports.

### ***Prevalence and incidence of concussion by sports setting.***

Further, prevalence and incidence of concussion differs by sports setting (i.e., game versus practice). The literature is consistent that there are higher incidence rates for games compared to practices. More specifically, football practice had lower incidence rates at 0.25 per 1000 practice exposures (PE), compared to 2.85 per 1000 game exposures (GE) (J. W. Powell & Barber-Foss, 1999). Gessel and colleagues (2007) extended these results and reported approximately 35% of concussions occurred during practice and 65% occurred during games (Gessel, Fields, Collins, Dick, & Comstock, 2007). Kontos and colleagues (2013) also noted this pattern in a sample of youth athletes (8-12 yrs.) football players, where concussion incidence was 0.24/1000 AEs in practices and 6.16/1000 AEs in games. This pattern of higher rates during games was also noted for boys' baseball (0.03 PE versus 0.12 GE), boys' basketball (0.06 PE versus 0.28 GE), boys' soccer (0.04 PE versus 0.57 GE), wrestling (0.17 PE versus 0.51 GE), girls' basketball (0.07 PE versus 0.42 GE), girls' field hockey (0.02 PE versus 0.29 GE), softball (0.08 PE versus 0.13 GE), and girls' soccer (0.05 PE versus 0.71 GE) (Rechel et al., 2008). These data support that athletes are at a higher risk of concussion during game play compared to practice; however, there are several limitations to the study of concussion prevalence and incidence.

### ***Limitations to concussion prevalence and incidence studies.***

The prevalence and incidence of concussion is difficult to estimate for a multitude of reasons. For example, it is difficult to measure a phenomena that is not reported, and previous research reveals that an estimated 30.5-52.7% of suspected concussions go unreported (McCrea et al., 2004; Meehan, Mannix, O'Brien, et al., 2013). Register-Mihalik and colleagues (2013) noted several factors (e.g., direct attitudes, subjective norms, and direct perceived behavioral control) that influence reporting intentions. Concussion-related education (Bramley et al., 2012), as well as pressure from teammates, coaches, fans, and parents (Kroshus et al., 2015) has also been noted to influence reporting intentions. More specifically, over a third of athletes report experiencing pressure from at least one of the aforementioned sources to keep playing after sustaining a head impact. And athletes that experienced pressure to play through a head injury from all four aforementioned sources were significantly more likely to continue playing compared to those who experienced pressure from 3 or fewer of these sources (Kroshus et al., 2015). Limitations for prevalence and incidence studies also include reliance on self-report and honesty of the athletes, as well as the assumption that all are using the same definition and diagnosis criteria for concussion.

## Biomechanical Forces of Concussion

The human brain is suspended in cerebrospinal fluid within the skull, and a concussion occurs when biomechanical forces cause the brain to make contact with the inside of the skull (Gurdjian & Volis, 1966). Early work by Denny-Brown and Russell (1940, 1941) acted as a keystone for future research on the biomechanical forces that contributed to concussion. These researchers attempted to induce concussion to animals' using varying forces of different magnitudes and noted that they were only able to successfully induce a concussion if the head was allowed to move freely upon impact (as compared to being fixed to a stable point) (Denny-Brown & Russell, 1940, 1941). The forces that Denny-Brown and Russell studied have been further delineated into categories that make them easier to study. For example, forces could be described as contact or inertial forces. Contact forces are associated with the head directly hitting an object, and inertial forces are associated with the lack of the head striking an object, and causing an impulsive motion (i.e., whiplash) (Meaney & Smith, 2011). This could result in coup and/or contrecoup injury. Coup injuries occur at the site of impact, and contrecoup injuries occur when the injury to the brain occurs on the opposite side of where the head was hit, such as in whiplash injuries (Zhang, Yang & King, 2004). Forces may also be further classified as linear or rotational.

Recent literature has noted that rotational forces may be necessary to result in a concussion. Linear forces act in a straight line, where rotational forces may act in a spiral motion. Researchers have theorized that rotational forces would lead to the greatest neurobehavioral impairments (Barth et al., 2001) due to the rotational forces being associated with shear-inducing tissue damage (Adams et al., 1982; Gennarelli et al., 1982; Holbourn, 1943; Unterharnscheidt & Higgins, 1969). This may be due to the anatomical arrangement of the rostro-caudal axis and the brainstem cross at almost perfect 90 degree angles (Ommaya, Rockoff, Baldwin, & Friauf, 1964). Other studies more explicitly conclude that rotational forces are required to induce a concussion (Holbourn, 1943, 1945; Ommaya & Gennarelli, 1974) and that linear forces are more likely to induce injuries such as cortical contusions and subdermal hematomas (Ommaya & Gennarelli, 1974). More recent studies have also noted that linear and rotational forces are not tied to any pattern of symptom presentation (Rowson et al., 2017). In contrast, more recent studies have reported that linear forces also induce concussion (Broglio et al., 2010; Rowson et al., 2019; Rowson & Duma, 2013). Similarly, the magnitude of the force may also play a role in the injury occurrence and presentation as well.

To date there is no empirical consensus on a biomechanical threshold that is associated with concussion. Proposed thresholds ranging from 200 to 7,500 rad/sec2 have been reported from various sources (Ommaya, Hirsch, Yarnell, & Harris, 1967; Unterharnscheidt & Higgins, 1969). The varying reports could be a result of varying definitions of thresholds and methodology of measuring force on what medium (animal versus human brains). In one of the first studies to investigate this question, Ommaya and colleagues extrapolated results from rhesus monkeys and reported that a force exceeding 7,500 rads/s2 had a >99% chance of produce a concussion (Ommaya, Hirsch, & Harris, 1967.). In contrast, Unterhanscheidt & Higgins (1969) reported that rotational forces of 200 rad/sec2 resulted in concussion in the majority of their animal sample. In a small sample of concussed high school football players with helmet accelerometers, Broglio and colleagues (2010) reported that a concussion was more likely to occur when a linear force that is 96.1g or greater when paired with rotational acceleration that exceeded 5,582 rad/s2, and the impact occurred on the front, side or top of the helmet (Broglio et al., 2010). In a more recent study by Rowson and colleagues (2019) researchers controlled for more individual differences by comparing physically matched controls and concussed football players on biomechanical measures quantifying impact frequency and acceleration magnitude, and reported that concussed subjects experienced more head impacts, more high magnitude impacts, and 1.9 × greater risk-weighted exposure than their physically matched non-concussed controls (Rowson et al., 2019). In addition, O’Connor and colleagues (2017) compared the threshold for individual impact magnitude and cumulative impact magnitude (e.g., a simplistic measure of the total exposure sustained by a player over a given period) and reported that no cumulative count measure was significant for either linear nor rotational forces (O’Connor et al., 2017). However, no absolute threshold has been identified and this finding is only useful in identifying those who are at a risk of concussion due to a high magnitude impact (Broglio et al., 2017; Eckner et al., 2011; Romeu-Mejia et al., 2019).

Studies have failed to agree upon one threshold of force for concussion, and this may be in part due to the continuously changing design of helmets. Many studies have evaluated the efficacy of current helmets in preventing concussion. Research with the NFL and Biokinetics (www.biokinetics.com) began in 1997 to investigate the biomechanics of concussion in professional football players (Pellman, 2003). In an important development, Biokinetics created the pendulum test, a machine designed to imitate helmet-to-helmet contact with 9 accelerometers placed on the test helmet for the purpose of testing a helmet's ability to absorb forces. Pellman and colleagues published a series of studies utilizing the pendulum test to asses different helmet designs on their ability to absorb force and reported that the helmets were successful in reducing the risk of concussion at the 7.4-9.3 m/s impacts; however the location and direction of the impact influenced these outcomes (Pellman, 2003; Pellman et al., 2006, 2006; Pellman, Viano, Tucker, & Casson, 2003; Pellman, Viano, Tucker, Casson, et al., 2003). In addition to this series of studies, other researchers have investigated the efficacy of helmets in reducing the risk of concussion and reported mixed results. Specifically, football helmets only reduced the risk of concussion by 20% and are ineffective against rotational acceleration impacts (Lloyd & Conidi, 2014). Another study noted that leather football helmets were comparable or better in head-impact doses and TBI risk compared to modern helmets (Bartsch et al., 2012). These controversial findings are likely due to athletes adapting their risk-taking behaviors based on the perceptions of their safety. In short, athletes feel safer when wearing a helmet and are more likely to take more risks that result in injury (e.g., concussion) compared to when they are not wearing protective equipment (Gamble & Walker, 2016). In addition to helmets, other companies have marketed other equipment with the concept of reducing concussion risk, including mouth guards and headbands. The previous literature on mouth guards for reducing concussion risk seemed to be in agreement that they were ineffective (Labella et al., 2002), with the exception of two key papers: The first had insufficient data for statistical analysis of protective effect (Stenger et al., 1964), and the second only that mouthguards showed a decrease of linear acceleration and changes in intercranial pressure in cadaver models (Hickey et al., 1967) where we now know that these (linear acceleration and intercranial pressure) are not the cause of diffuse brain injuries such as concussion (McCrory, 2001) . In contrast, newer studies show mouthguards may have a modest impact on decreasing risk (Chisholm et al., 2020; Green, 2017; Knapik et al., 2019; Ono et al., 2020). Chisolm and colleagues (2020) executed a nested case-control study with youth ice hockey players and reported that off-the-shelf mouthguards were associated with a 69% lower odds of concussion, noting that the proposed mechanism of the mouthguard is by positioning the jaw to absorb the impact forces that would otherwise be transmitted to the skull and brain (Green, 2017). Similarly, there are conflicting reports about headbands, most often used in soccer. Some studies show that headbands significantly reduce forces (Broglio et al., 2003; Naunheim et al., 2003), where others show no significant differences for headband wearers (R. J. Elbin et al., 2015; Naunheim et al., 2003). Elbin et al. (2015) reported compared changes in neurocognitive performance and symptoms following heading drills between headband wearers and non-wearers and reported no significant improvement for headband wearers compared to non-wearers. To date there have been no equipment developed that completely eliminate the risk of SRC; however, the literature supports that some equipment (e.g., some types of helmets) are able to absorb higher forces compared to others.

There are currently a multitude of devices and methods available for measuring the forces associated with concussion; however, they are not without limitation, and researchers and clinicians warn against their utility for clinical use in their current form. Researchers have developed devices such as the Head Impact Telemetry System (HITs) (Greenwald et al., 2008), Sideline Response System (*Riddell IQ – Helmet and Head-Impact Monitoring Systems*, n.d.), Insight (*Riddell InSite - Smart Football Helmets*, n.d.), Shockbox (*I1 Biometrics Acquires Shockbox For Its Impact Sensing Technology*, n.d.), and the X-Patch ("The X-Patch | X2 Solutions," n.d.). The HITs system calculates rotational acceleration, impact duration and location, Gadd Severity Index (a scale for measuring internal head injury hazard based on forces), Head Injury Criterion (a measure of the acceleration and likelihood of head injury), and Head Impact Telemetry severity profile (a composite score derived from linear and rotational accelerations and impact location and duration) (Williams et al., 2016). There are noted limitations to each device. Helmet devices such as the HITs system, are the most commonly used in head-impact research (Williams et al., 2016); however, it assumes that the helmet and the skull move together as a unit which is a major limitation, and can be a fatal flaw if the helmets are ill-fitting (Broglio et al., 2012). In response to this limitation, other devices (e.g., skin patches like the X-Patch and mouthguard sensors like the X-Guard) have sought to overcome this limitation; however, they have limitations of their own. With skin sensors, skin motion is often not directly related to skull motion, and saliva build up have been shown to be problematic for mouthguards (Williams et al., 2016). Researchers agree that, of the devices that are currently available, and because of what is known about the threshold for concussion (or lack thereof), there is currently little room for clinical utility of head impact monitoring systems in the clinical setting (Broglio et al., 2012; Eckner et al., 2011; Williams et al., 2016).

## Pathophysiology of Concussion

The understanding of the pathophysiology of concussion has increased in the past decade. In 2001, Giza and Hovda published a seminal review on pathophysiological effects of mTBI and later published an update in 2014. Many of the theories and known mechanisms following concussion presented in the 2001 review gained further support in the newer models proposed in the 2014 review. For example, contributions of the imbalance between free radicals and antioxidants (e.g., oxidative stress), impairments in the process by which substances synthesized in the neurosome (e.g., proteins) are transported through the cytoskeleton to the nerve endings (e.g., impaired axonal transport), and altered neurotransmission are now clearly linked to the initial ionic fluxes of potassium and calcium, glutamate release, and the energy crisis (Giza & Hovda, 2014). These reviews have provided an overview of the neuronal processes that follow a concussion.

First, the impact from the biomechanical forces initiates an ionic flux and glutamate release in the neurons. Simultaneously, in the neuron there is an efflux of potassium ions and influx of sodium and calcium ions due to mechanoporation of lipid membranes (Katayama et al., 1990; Takahashi et al., 1981), which leads to the depolarization of the neurons. This neuronal depolarization causes the sodium potassium pumps to work harder than normal and use more energy (adenosine triphosphate: ATP) to restore homeostasis after the initial ionic flux (Yoshino et al., 1991). Calcium influx may persist longer (>3 days) than the sodium and potassium efflux (<1 day), which leads to a buildup of calcium in the cells. High levels of calcium surround the mitochondria and lead to mitochondrial dysfunction and a decline of ATP production; therefore, the demand for energy is high, while supply is low. During this time cerebral blood flow (CBF) may be decreased (See Figure 1) (McGoron et al., 2008; Pasco et al., 2007). There are several theories on why CBF may be affected in some cases following mTBI.

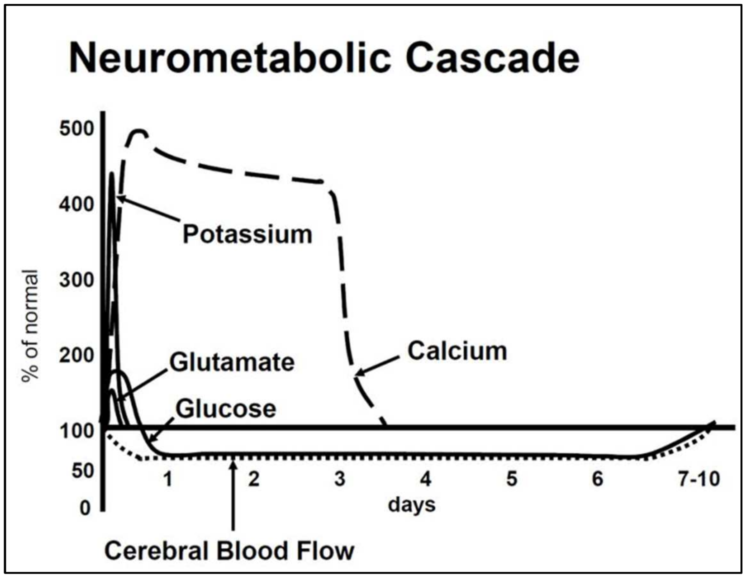


Figure 1. *Time course of the neurometabolic cascade of events following concussion.* Reprinted from The New Neurometabolic Cascade of Concussion by C. C. Giza and D. A. Hovda, 2014, *Neruosurgery, 75*(4).

It is unclear if the decrease in CBF is due to the primary injury (e.g., trauma to the capillaries) or secondary factors (e.g., protective measures to reduce inflammation and swelling). Following mTBI, there is both a semi-acute reduction in the number and diameter of capillaries both centrally (at the site of the injury) and distally (Park et al., 2009). This finding has been interpreted as a fault in the structural integrity of the microvasculature that may directly contribute to the decrease in CBF (Meier et al., 2015). While CBF is decreased, active transport pumps utilize ATP to move the ions, further exacerbating the aforementioned energy crisis (See Figure 2).

The biomechanical forces imparted to the head and resulting ionic fluctuations have negative effects on the microstructural components of the neuron (e.g., dendritic arbors, axons, and astrocytic processes). The influx of calcium leads to the phosphorylation of side arms and loss of structural integrity of the axon (Pettus & Povlishock, 1996), as well as proteolytic damage to the subaxolemmal spectrin and other cytoskeletal components (Büki & Povlishock, 2006). Microtubule disruption due to the axonal stretching may lead to decreased bidirectional axon transportation and even disconnection (Büki & Povlishock, 2006).

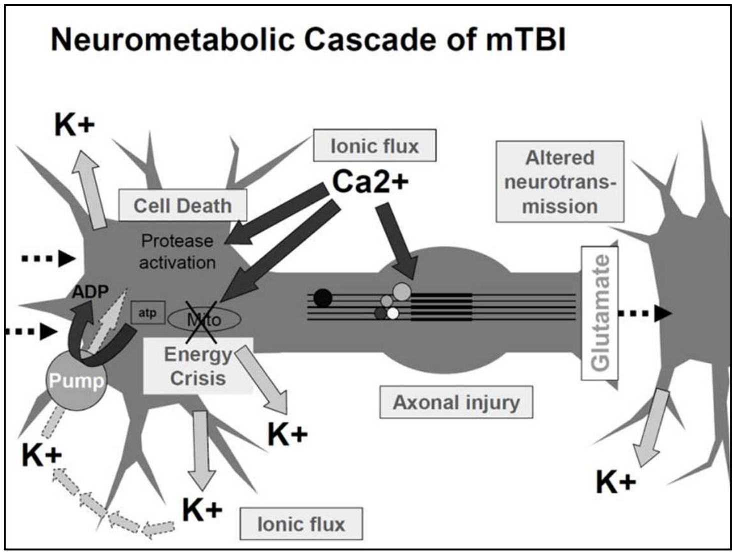


Figure 2. *A diagram of the acute processes within the neuron after concussion.* Reprinted from The New Neurometabolic Cascade of Concussion by C. C. Giza and D. A. Hovda, 2014, *Neruosurgery, 75*(4).

Axons are vulnerable to biomechanical stretching, which leads to an increase in permeability of the axon (Pettus et al., 1994). Disconnection can follow damage to the neurofilaments and microtubules; however, disconnection does not always cause death of the cell. Atrophy is typical, leading to a loss of functionality of the cell (Singleton et al., 2002). Unmyelinated axons are particularly vulnerable to these forces. Myelination is an ongoing maturational process in developing brains (Reeves et al., 2005). This may be a possible mechanism for why youth are more susceptible to concussions; however, this is only conjecture and further evidence is needed to attribute lack of myelination to the source of susceptibility.

Concussion is also known to alter neurotransmission. Changes in the glutamate receptors (N-Methyl- d-aspartic acid: NMDAR) lead to changes in activation of calmodulin-dependent protein kinase II (CaMKII), extracellular receptor kinase (ERK), cAMP response element-binding protein (CREB), and brain-derived neurotrophic factor (BDNF) (Atkins et al., 2009; Griesbach et al., 2007). More importantly to the current study, the excitatory/inhibitory balance of GABA is disrupted post-injury (Lowenstein et al., 1992; Zanier et al., 2003).

In both more severe and mild cases of traumatic brain, the injury has been found to upregulate cytokines and inflammatory genes in some studies (Giza & Prins, 2006; Li et al., 2004). Researches coined the term “immunoexcitotoxicity” after theorizing that glutamate release was related to the activation of immune receptors to oxidative stress and hypothetical later cell injury (Blaylock & Maroon, 2011). Models show that cellular death after concussion is rare (Gurkoff et al., 2006; Lyeth et al., 1990; Prins et al., 2010); however, it is theoretically possible that there is a higher risk for cell death after subsequent concussions (Giza & Hovda, 2014). Functional impairment has been well documented to be more significant after subsequent injuries (DeFord et al., 2002; Longhi et al., 2005; Prins et al., 2010).

It should be noted that these findings are not without limitation. The majority if studies investigating the pathophysiology of concussion have been done in animal models; although they provide a likely comparison, it is a limitation of this research. Future research should investigate causal links between the acute injury of concussion and more chronic effects, and how they relate to progressive neurodegenerative diseases.

## Autonomic Dysfunction and Concussion

These aforementioned pathophysiological events of concussion can also manifest in autonomic dysfunction, or dysautonomia. The autonomic nervous system (ANS) is a complex network in the central nervous system. Within the ANS, there are the sympathetic and parasympathetic nervous systems. The ANS includes the cerebral cortex, amygdala, stria, terminalis, hypothalamus, and brainstem centers (McCorry, 2007). The amygdala controls the autonomic, endocrine and cardiovascular responses (Conder & Conder, 2014; Esterov & Greenwald, 2017; Hilz et al., 2016; Thayer & Lane, 2009) by innervating cardiac muscle, smooth muscle, and glands within the body system to respond to environmental and internal ques. Specific functions the ANS controls include heart rate (beats per minute: BPM), heart rate variability, blood pressure, cerebral blood flow, gastrointestinal movement, glucose metabolism, and sexual response amongst other functions (Pertab et al., 2018). Dysregulation in the ANS may be the result of a biomechanical force and leads to many subsequent issues (e.g., dysregulation of heart rate and blood pressure). The response of these systems are no longer able to accommodate for exercise and orthostatic posture changes (Karas et al., 2000; Miranda et al., 2018; Smit et al., 2004). Dysfunction of the autonomic nervous system has been linked to many co-morbid conditions found in concussed patients, including poor sleep (Basta et al., 2007; Farina et al., 2014; Huang et al., 2011), deconditioning (Convertino et al., 1990; Farina et al., 2014), depression (Bassett, 2016; Perlmuter et al., 2012), anxiety (Brudey et al., 2015; Thayer et al., 1996; Tulen et al., 1996), and cervical strain or whiplash injuries (Nijs & Brussel, 2013; Sterling, 2011). Concussed patients have been noted in the literature to develop abnormal blood pressure responses to exercise (Kozlowski et al., 2013; Leddy et al., 2011) and postural orthostatic tachycardic syndrome (POTS) (Heyer, Fischer, et al., 2016; Kanjwal et al., 2010), which are both forms of autonomic dysfunction. However, the prevalence of dysautonomia in concussed patients is currently unknown; this could be due to the lack of concussion-specific assessments for autonomic dysfunction, and the barriers to accessing gold-standard assessment tools for autonomic dysfunction. There is more on the assessment of dysautonomia in the assessments section below.

## Signs, Symptoms, and Impairments of Concussion

The signs, symptoms, and impairments of concussion are important for characterizing the injury and deciding an appropriate management and treatment approach. Concussions present differently and uniquely in every case, further supporting the necessity of measuring each domain. The purpose of this section is to review the signs, symptoms, and impairments that are often reported with concussion.

### ***Signs of Concussion.***

There are a variety of signs of concussion, and signs may have implications for symptoms and recovery. On-field signs of concussion include confusion, disorientation, loss of consciousness, balance disturbances, tonic posturing, vomiting, amnesia, and slower pupillary response metrics. Often these physical signs are mistaken as diagnostic criterion (i.e., required for diagnosis) for concussion but are frequently absent in the injury (McCrory et al., 2017a). In fact, in a study by Gessel and colleagues (2007) only 8.6% reported confusion, 6.4% reported amnesia, and 3.9% of high school athletes who sustained a concussion reported loss of consciousness. Pupillary light reflex metrics have also been noted to differ significantly between concussed athletes and controls (e.g., maximum pupillary diameter, minimum pupillary diameter, average constriction velocity, peak constriction velocity, average dilation velocity, and peak dilation velocity); however, these measurements are not quantifiable without specialized equipment that is not currently used in the clinic (Master et al., 2020). Although signs are often absent from the injury, they are relevant for assessment by clinicians. In fact, the presence of retrograde and post-traumatic amnesia has been shown to be predictive of symptom scores and neurological deficits at two days post injury (Collins et al., 2003). In contrast, a study by Lau and colleagues, (2011) found that on-field signs were not a significant predictor of protracted recovery in a sample of 107 high school football players. Previous literature noted that loss of consciousness is a sign of a worse/more severe injury (Kelly, 2001); however, newer literature has refuted this and reported that there was no association with protracted recovery (Kontos, Elbin, et al., 2019). In addition to loss of consciousness, post-traumatic amnesia has previously been thought to be associated with a protracted recovery (Halstead & Walter, 2010; Lovell et al., 2003). This was reinforced by grading scales such as the Cantu Grading System and the Colorado Medical Society classification guidelines, where concussion grade was largely dependent on the presence of on-field signs such as loss of consciousness and amnesia (Bazarian et al., 2001; Cantu, 2001). However, newer studies have found contradictory results, and note that amnesia was not associated with protracted recovery (Meehan, Mannix, Stracciolini, et al., 2013). Other entities have recently noted the utility of signs for identifying players that may have sustained a concussion. Elbin and colleagues (2020) reported that on-field signs were a poor measure for discriminating between concussed and non-concussed (AUC = 0.66). These findings support that many of the indicators of concussion are not outwardly visible; therefore, clinicians must also rely on a comprehensive exam for concussion diagnosis, including athletes’ report of subjective symptoms.

### ***Post-concussion symptoms.***

Symptoms of concussion can vary widely and typically first appear over a matter of seconds to hours and persist over days to months (McCrory et al., 2017). Although each injury presents differently, it is helpful for clinicians to be able to recognize the common symptoms of concussion. Lovell and colleagues (2006) studied a sample of concussed high school and collegiate athletes using the Post-Concussion Scale (PCS) and reported the most highly endorsed symptoms as headaches, fatigue, feeling slowed down, drowsiness, difficulty concentrating, feeling mentally foggy, and dizziness. More recently, Frommer and colleagues (2011) reported data from a surveillance study (n=421) and noted headache was present in 95% of the cases, followed by dizziness (77%), difficulty concentrating (50%), and confusion (49%). Differences in reported prevalence of symptoms could be due to the differences in assessments utilized by researchers.

Researchers and clinicians have published factor analyses that encompass the different clusters of symptom presentations. Piland and colleagues (2003) evaluated factor structures of the HIS and reported a 3-factor model (e.g., somatic, cognitive, and neuropsychological). Piland et al., (2006) also conducted a similar study on the GSC and reported a similar 3-factor model for this assessment (somatic, cognitive, and neurobehavioral); however, this study only included non-concussed participants, and symptoms may cluster differently after a concussion. Kontos and colleagues (2012) addressed this limitation in a similar study including both non-concussed and concussed samples for the Post-Concussion Symptom Scale (PCSS), and the data from the concussed sample revealed four main group factors (e.g., cognitive-migraine-fatigue, affective, somatic, and sleep). The data from the healthy, non-concussed sample revealed a four-factor solution that included cognitive-sensory, sleep-arousal, vestibular-somatic, and affective factors

(Kontos, Elbin, et al., 2012). The differences in clusters is in part due to the differences in the scales themselves, but differences may also be due to assessing the symptoms at different time points (i.e., baseline, acute post-concussion, and sub-acute post-concussion). Similarly, Barker-Collo and colleagues (2018) examined the factor structure of the RPQ at baseline and post-injury. Baseline data revealed a 3-factor structure including 1) cognitive and physiologic disturbances; 2) mood, sleep, and nausea/vomiting; and 3) visual/auditory disturbances, dizziness and headaches. Data from 1-month post-concussion revealed three new factors: 1) cognitive/mood; 2) headache, nausea and dizziness; and 3) visual disturbances. Researchers re-evaluated the concussed individuals at 6 and 12 months and reported two factors: 1) cognitive/mood; and 2) physiological symptoms (Barker-Collo et al., 2018). Discrepancies between factors reported in these studies is in part due to the variation in assessments used between them. In addition, symptoms are reported to evolve over time, as supported by the findings by Barker-Collo and colleagues (2018); therefore, the variation in time points at baseline and following concussion could account for some of the variety in factors reported by researchers. Further, there are several other considerations to be made when assessing symptoms.

#### ***Difficulties and considerations for assessing concussion symptoms.***

As previously noted in this review, there are several factors that may influence the reporting of concussions, therefore influencing the reporting of symptoms. Due to the subjective nature of symptoms, athletes may downplay the injury for a multitude of reasons. For example, factors such as direct attitudes, subjective norms, and direct perceived behavioral control, concussion-related education, as well as pressure from teammates, coaches, fans, and parents influence reporting intentions (Bramley et al., 2012; Kroshus et al., 2015; Register-Mihalik et al., 2013).

Moreover, some number of symptoms may be considered normal in non-concussed individuals. Covassin and colleagues (2006) reported a mean symptom score of 7.34 (±11.01) for males and 10.16 (± 12.47) for females at baseline. Similarly, Iverson et al., (2015) noted that in a sample of over 30,000 non-concussed high school students, the mean PCSS score was 4.5 (± 7.9) for males and 6.5 (± 9.9) for females. Moreover, 23.6% of males and 36.2% of females met criteria for mild to moderate post-concussion syndrome (G. L. Iverson et al., 2015). Further, there is a subset of the population that reports symptoms that cannot be explained by a known cause, which is referred to as somatization (Campo & Fritsch, 1994; Postilnik et al., 2006). Somatization is associated with other psychiatric symptoms and may also be prevalent in concussed patients (Campo & Fritsch, 1994; Ernst et al., 1984; Root et al., 2016; Walker et al., 1991). A recent study by Root and colleagues (2016) reported that in a sample of concussed 10-18 year-olds, a subsample who scored >12 on the Children's Somatization Inventory (CSI) had persistent post-concussion symptoms, lasting longer than the other subjects. In addition to measuring signs and symptoms, concussion impairments should be quantified and measured.

### ***Post-concussion impairments.***

In addition to the signs and symptoms of concussion, patients might present with impairments of function. An impairment is a diminishment or loss of function and can be found in a variety of domains. Impairments often noted with concussion include neurocognitive, vestibular, and ocular motor impairment (Ellemberg et al., 2007; M. J. Ellis et al., 2015).

Neurocognitive impairments are measured with neurocognitive assessments, including paper and pencil as well as computerized versions that assess various components of cognitive function (e.g., memory, reaction time, and concentration). Neurocognitive testing offers a more objective measure of the injury progression outside of symptom reporting. In a study by Broglio and colleagues (2007) 38% of asymptomatic, recently concussed collegiate athletes demonstrated neurocognitive impairments on a computerized neurocognitive test (CNT). Similarly, Covassin and colleagues (2010) found that concussed athletes reported resolution of symptoms at 7 days post-concussion; however, neurocognitive outcomes (e.g., reaction times) did not return to baseline until 21 days after sustaining their injury.

Concussed athletes may present with elevated mood impairments following SRC. Mood impairments may present with ruminating thoughts, hypervigilance, anxiety, panic, depressive mood, apathy, sleep disruption, and symptom endorsement on psychological inventories (Collins et al., 2014; Henry et al., 2016; Reynolds et al., 2014; Sandel et al., 2017). The anxiety/mood clinical profile is often associated with persistent, or chronic post-concussion symptoms (Carroll et al., 2004; Corwin et al., 2014; Mittenberg et al., 2001; Ponsford et al., 2012). The exact prevalence of mood impairments following SRC is arduous to measure; however, research suggests that up to 20% of collegiate athletes endorse increased depressive symptoms following SRC compared to 5% of control groups (Vargas et al., 2015). Mood impairments (e.g., anxiety) have also been reported to be correlated with other impairments, specifically vestibular impairments.

In addition, vestibular and ocular-motor impairments are prevalent in approximately 60% of athletes following SRC (Mucha et al., 2014), and may require treatments for resolution. Vestibular dysfunction has been documented in 51-81% of concussion cases (Corwin et al., 2015; R. Elbin et al., 2018; M. J. Ellis et al., 2015; Lau et al., 2011; Mucha et al., 2014). Similarly, ocular dysfunction has been reported in approximately 42-69% of concussion cases (Master et al., 2016; Mucha et al., 2014; Pearce et al., 2015) and may include eye positioning in a “down and out” position, eyelid drooping, or unreactive pupils, crossed eyes, double vision, diplopia, nystagmus, twisting of images or separation of images, dizziness, visual gaze instability, postural instability, nausea, sensitivity in busy environments, and fogginess (C. Graham & Mohseni, 2020; Kapoor & Ciuffreda, 2002; Kim et al., 2020; Modi & Arsiwalla, 2020). Often times following concussion, these signs and symptoms are verbalized as eyestrain, visual fatigue, headaches, dizziness, and difficulty with near visual work (Storey et al., 2017; Ventura et al., 2014).

## Assessments for Concussion

There are a myriad of assessments available for concussion, and current consensus statements support the necessity for a multimodal approach to assessing concussion (McCrory et al., 2017a). The multimodal approach includes employing multiple assessments that capture multiple facets of the injury (e.g., vestibular/oculomotor, balance, neurocognitive, signs and symptoms). An important, and often overlooked, component of a multimodal assessment of concussion is the vestibular and ocular-motor assessment.

### *Vestibular and Ocular-motor Assessment.*

Assessment of the vestibular and ocular-motor systems are relatively new to concussion. There are several concussion-specific assessments for vestibular and ocular function (e.g., the Balance Error Scoring System (BESS) (Guskiewicz, 2011), the Vestibular/Ocular-Motor Screening (VOMS) (Mucha et al., 2014), and King Devick test (KD) (Galetta et al., 2011)). In addition, there are several vestibular and ocular assessments that are not concussion-specific; however, these often require specialized training to administer and interpret (e.g., the Clinical Test of Sensory Organization and Balance (CTSIB) (Shumway-Cook & Horak, 1986), Sensory Organization Test (SOT) (Nashner et al., 1982), the Romberg Scale (Lanska & Goetz, 2000), the head thrust test/VOR test (Schubert et al., 2006), the gaze stability test (GST) (D. R. Kaufman et al., 2014)).

### *The Balance Error Scoring System (BESS).*

The Balance Error Scoring System (BESS) is widely used to assess balance and vestibular dysfunction in concussed athletes. The BESS assessment includes 3 stances (e.g., double-leg, single-leg, and tandem stances) that are performed two times (once on a foam surface and once on a firm surface) with eyes closed for 20 seconds each. Errors during each task are recorded and tallied for a max of 10 points per stance. There is also a modified version (mBESS) available that is essentially the same 3 stances on the firm surface (excludes the repeated stances on a foam surface) (McCrory et al., 2017a). Scores on the the mBESS typically range from 2-8 in healthy populations and increase by 2-3 errors from baseline following concussion (King et al., 2014; Luoto et al., 2014). These stances assess static balance, which involves feedback from visual, vestibular, and somatosensory systems (Goldie et al., 1989; Nashner et al., 1982).

Specificity of the BESS for concussion diagnosis is high (0.91), while sensitivity is low to moderate (0.34 to 0.64) (Giza et al., 2013); however, increases in sensitivity have been reported when the BESS is used in conjunction with the Standardized Assessment of Concussion (SAC) and a graded symptom checklist (Giza et al., 2013). The BESS has only been found to be useful within the first 2 days following injury (Giza et al., 2013; McCrea et al., 2003). Although the BESS has relatively high established reliability (intrarater reliability 0.60-0.98; Interrater reliability 0.78-0.96; test-retest reliability 0.70) (Broglio, Zhu, et al., 2009; Erkmen et al., 2009; Finnoff et al., 2009; Hunt et al., 2009; McLeod et al., 2004, 2006; Riemann et al., 1999), there is some controversy over whether this assessment is useful in screening for vestibular dysfunction. Several studies have compared the BESS and mBESS to other measures of vestibular function and balance. King et al., (2014) reported that the mBESS and BESS scores were similar in a sample of concussed and matched controls; however, the scores from a wearable inertial sensor with an accelerometer and gyroscope to quantify bidirectional body sway were significantly different than the mBESS and BESS scores. The inertial sensor was significantly better at discerning the concussed from matched controls compared to the BESS and mBESS (King et al., 2014). There have been several other issues reported of the BESS throughout the literature.

Specifically, previous researchers have noted that the BESS scores are influenced by fatigue (Wilkins et al., 2004), and has learning and ceiling effects (Mulligan et al., 2013; Valovich et al., 2003). Postural stability has been noted to decrease following fatigue (Seliga et al., 1991; Skinner et al., 1986; J. R. Thomas et al., 1975). In healthy controls, balance ability on the BESS is significantly diminished following an exertion protocol (Erkmen et al., 2009; Wilkins et al., 2004). This is important to note, as the mBESS is a component of the SCAT5 and is meant to be administered on the sideline, potentially following physical exertion. In addition, conflicting reports of learning effects have been noted. Broglio and colleagues (2009) reported that serial administration of the BESS may result in improved balance (i.e., lower scores on the BESS), which has been attributed to learning effects (Broglio, Zhu, et al., 2009); however, Volovich and colleagues (2004) reported a lack of learning effects in a similar study, to which they attributed to a ceiling effect and their method of counterbalancing the assessments for all subjects. Ceiling and floor effects occur when the assessment is unable to assess the true ability of a patient on a given domain. Ceiling effects have also been noted for the mBESS (Kleffelgaard et al., 2018).

### *The Vestibular/Ocular Motor Screening (VOMS).*

Although there is a myriad of vestibular and ocular-motor assessments available, the majority of them require expensive equipment and specialized training; however, the VOMS was developed and first published in 2014 by clinicians and researchers to address these shortcomings in clinical vestibular assessments. The VOMS is a brief vestibular and ocular-motor screening tool with seven components: smooth pursuits, horizontal and vertical saccades, horizontal and vertical vestibular ocular reflex, visual motion sensitivity, and near point of convergence distance. Following each component, participants rate symptoms of headache, dizziness, nausea, and mental fogginess on a scale from 1 (none) to 10 (severe). Multiple studies have reported VOMS items to have high internal consistency (Cronbach a = 0.92-0.97) (Kontos, Sufrinko, et al., 2016; Moran et al., 2018; Mucha et al., 2014) and established validity and reliability (Mucha et al., 2014; Yorke et al., 2017). However, there is some controversy on the methods of scoring the VOMS (e.g., total scoring vs change scoring) (Elbin et al., in review).

The originally intended method of scoring included in the paper by Mucha et al., (2014) was to total each line of symptoms and has been used in the majority of VOMS literature (R. Elbin et al., 2018, 2019; Kontos, Sufrinko, et al., 2016; Moran et al., 2018; Sinnott et al., 2019; Sufrinko, Mucha, et al., 2017, 2017; Worts et al., 2018); however, a newer method of using change scores to calculate provocation has appeared in the literature as well (R. Elbin et al., 2018; Sinnott et al., 2019; Yorke et al., 2017). Clinical cutoff values for identifying SRC using the total score approach suggest that any total symptom score $\geq 2$ on any VOMS symptom resulted in an increased probability in correctly identifying concussed subjects, and the vestibular ocular reflex and visual motion sensitivity components yielded the highest predictive capabilities (sensitivity of 89%) when using the total scoring method (Mucha et al., 2014). In addition to the total scoring method, researchers and clinicians have reported using change scoring methods, where scores are calculated by subtracting pre-test symptom scores to reveal a provocation score. Elbin and colleagues (in review) recently reported cutoffs for the change scoring method and reported alternative cutoffs as a change of > 1 on any one symptom, or a near point of convergence distance of > 3 cm (Elbin et al., in review). When using the change scoring method, sensitivity of the measure decreases to 63% (Elbin et al., in review), which is consistent with the expected rate of vestibular and ocular-motor impairment in concussed populations (60-74%) (Corwin et al., 2014; Mucha et al., 2014).

Previous studies have added to the growing body of literature on the VOMS and its utility in the clinic in comparison to, and in conjunction with, other measures. The VOMS is correlated with another ocular assessment (the KD) (Russell-Giller et al., 2018); however, the VOMS has a low false positive rate (2%) comparatively (KD false positive rate: 36%) (Worts et al., 2018), suggesting that it may be a more specific measure. In addition, the VOMS is correlated with a common symptom scale (the Post-Concussion Symptom Scale: PCSS) (Mucha et al., 2014). Similarly to symptom reports, females report higher symptom provocation on the vestibular ocular reflex component of the VOMS (Sufrinko, Mucha, et al., 2017). In contrast to the noted sex differences on the VOMS, no sex differences have been noted with the BESS (Sufrinko, Mucha, et al., 2017), which could be interpreted to mean that the VOMS is more sensitive to vestibular and ocular-motor provocation. Although the VOMS may provide a more sensitive measure to changes and differences in vestibular function, there are mixed reports on whether the VOMS is a good predictor of protracted recovery (Anzalone et al., 2017; Sufrinko, Marchetti, et al., 2017). Anzalone and colleagues (2017) reported that symptom provocation for all VOMS components except near point of convergence distance was associated with delayed recovery. In contrast, Surfinko and colleagues (2017) reported that vestibular and ocular-motor scores were not significant predictors of recovery time. Overall, the literature supports the utility of the VOMS as a tool to screen for concussion and assess for vestibular and ocular dysfunction in adolescents.

### ***Clinical Vestibular and Ocular-Motor Assessments.***

There are a multitude of other vestibular and ocular-motor assessments that were not intended to be used as concussion assessments (e.g., King Devick, CTSIB, SOT, and Romberg tests). The King Devick (KD) test is another ocular-motor assessment that was originally created to assess for reading and learning disabilities but has been used in concussed populations. The KD test requires the patient to perform visual saccades as well as multitask (e.g., language function and attention) as patients read a series of numbers off of a card or screen. Concussed athletes perform significantly slower (worse) on this task compared to their baseline scores The KD test has high test-retest reliability (ICC= 0.95), but participants also exhibit a learning effect (significantly faster/improved scores) (Leong et al., 2015). Validity and reliability of the other assessments (e.g., CTSIB, SOT, and Romberg test) have not been established in concussed populations (Murray et al., 2014). Assessments such as the head thrust test, and gaze stability test require some extensive training to administer and interpret and typically fall outside of the expertise of athletic trainers that often manage concussed athletes. Each assessment may offer varying strengths and weaknesses; however, which assessment clinicians should use would depend on their training and access to equipment. Rehabilitation therapies have increasingly been designed to target these dysfunctions to ameliorate the aforementioned symptoms, including vestibular therapy (Aligene & Lin, 2013; B. A. Alsalaheen et al., 2010; Gagnon et al., 2016) and visual rehabilitation (Thiagarajan & Ciuffreda, 2014). Future research should compare the overlap between common clinical assessments that are not concussion-specific with the VOMS.

### *The Assessment of Signs and Symptoms of Concussion*

There are several symptom assessments available, including the PCS, the Post-Concussion Symptom Scale (PCSS), the Graded Symptom Checklist (GSC), the Rivermead Post-Concussion Questionnaire (RPQ), and the Head Injury Scale (HIS). Each scale is made up of a list of symptoms and requires the patient/subject to rate their endorsement of each symptom on a Likert-type scale. There is a large portion of overlap between scales, with the main differences being different ways of grouping symptoms together (e.g., vomiting and/or nausea) or wording differences (e.g., easily distracted versus difficulty concentrating, and sleep disturbances versus trouble falling asleep and trouble staying asleep). By grouping these symptoms differently and changing the wording, concussed patients may endorse significantly different scores across different scales at the same time point. These scales are more thoroughly discussed further in this review. These discrepancies effect the generalizability of symptom scale findings across scales.

### *The Assessment of Mood in Concussion*

Often times after sustaining a concussion, patients will exhibit a change in mood. Approximately 19-33% of concussed samples report increased depressive symptoms following concussion (Casson et al., 2014; Strain et al., 2013; Vargas et al., 2015). Other researchers have reported a dose response for head impacts and depressive symptoms later in life (Didehbani et al., 2013; Montenigro et al., 2017). In addition, anxiety symptoms have been reported to be significantly elevated in concussed samples within 2 weeks of injury compared to healthy controls (Meier et al., 2015). Anxiety and depression do appear to be related following injury.

Athletes with depression at baseline were 3.4 times more likely to experience state anxiety symptoms following concussions compared to those without baseline depression (Yang et al., 2015). Several assessments are available to quantify these changes in mood. Although none are concussion-specific measures several have reportedly high reliability and validity.

Depression and anxiety measures that are commonly reported in the concussion literature include the Generalized Anxiety Disorder-7 (GAD-7), State-Trait Anxiety Inventory (STAI), Screening for Child Anxiety Related Disorders- Child Reports (SCARED-C), Patient Health Questionnaire-9 (PHQ-9), Depression and Anxiety Stress Scale- 42 (DASS-42). The GAD-7 is a 7 item questionnaire designed to assess anxiety status retrospectively over a 2 week period (Spitzer et al., 2006), and has a sensitivity and specificity of 0.89 and 0.82 respectively (Kroenke et al., 2007). The STAI offers both a trait and state anxiety form, and a sensitivity 0.82 and specificity of 0.88 (Kvaal et al., 2005). Similarly, the PHQ-9 is a 9-item questionnaire that offers a sensitivity of 0.88 and specificity of 0.85 (Levis et al., 2019). These assessments are useful tools in identifying patients that are at risk for developing mood disorders following concussion. However, although these norm-referenced measures have high validity and reliability, they do not substitute the necessity for fulfilling the three other pillars of psychological assessment (e.g., clinical interview, observations, and informal assessment procedures) (Sattler, 2001). In sum, further evaluation is necessary before a formal diagnosis is warranted, especially in concussed samples.

### ***The Assessment of Neurocognitive Deficits in Concussion***

Multiple consensus statements have supported the necessity for including a neurocognitive assessment component in the multimodal approach to assessing concussion (Broglio et al., 2014; McCrory et al., 2017a). Neurocognitive assessments (e.g., Stroop Color

Word Test, Trails A and B, Controlled Oral Word Association, Wechsler Letter Number Sequencing, Wechsler Digit Span: digits forward and digits backwards, Symbol Digit Modalities Test, Paced Auditory Serial Addition Test) were created to offer a more objective measure of cognitive impairments in healthy (i.e., non-concussed) populations, and some were adapted specifically for concussed populations (e.g., Standardized Assessment of Concussion: SAC, and Immediate Post-Concussion Assessment and Cognitive Testing: ImPACT).

Clinicians have gradually transitioned from paper and pencil cognitive assessments to CNT (Webbe & Zimmer, 2015); however, there are noted strengths and weaknesses to either assessment method. Traditionally, paper and pencil assessments offer more flexible, task-specific approach, and rely on the tester to document behavioral observations (effort, attention, affect). There are currently a myriad of different paper and pencil assessments available to measure different domains of cognition (e.g., intelligence, neurocognitive batteries, learning and memory, literacy, attention/concentration, processing speed, language, executive functioning, effort, mood, and self-reported behavior) (Kontos, Alicia, et al., 2016). However, paper and pencil assessments are time consuming, require administration by a clinician trained in psychology or neuropsychology, and subject to inter- and intrarater variability (G. L. Iverson & Schatz, 2015). In recent years, clinicians and researchers have developed computerized neurocognitive tests (CNT) to address these shortcomings. Computerized neurocognitive tests aim to offer a more time efficient option compared to paper and pencil neurocognitive assessments (Schatz & Zillmer, 2003) and eliminate inter-rater and intra-rater reliability concerns (Aubry et al., 2002). Traditional paper and pencil assessments measure different constructs (i.g., free recall memory assessment), where computerized neurocognitive assessments assess forced choice recognition, which is objectively an easier cognitive task (Bruce & Echemendia, 2009).

Several researchers have compared these assessment methods. Broglio and colleagues (2007) compared computerized neurocognitive assessments (e.g., Immediate Post-Concussion Assessment) and a brief paper and pencil and reported that CNT had higher sensitivity at detecting concussion compared to the paper and pencil test (Broglio et al., 2007). One study compared several assessments, including a symptom scale (PCSS), a paper and pencil assessment (SAC) as part of the Sport Concussion Assessment Tool-3 (SCAT3), King Devick, CogSport, and Concussion Resolution Index, and reported that ImPACT was the most sensitive and specific for concussion (Dessy et al., 2017). In sum, neuropsychological tests are one important tool in the multimodal assessment battery. There are a wide variety of neuropsychological assessments available, with different strengths and weaknesses.

### ***The Assessment of Autonomic Dysfunction and Concussion***

The autonomic nervous system (ANS) controls many domains and functions within the body, and autonomic dysfunction (i.e., dysautonomia) can occur outside of the concussion mechanism; therefore, other specialties assess specific domains or use testing batteries for ANS dysfunction. Additionally, not all individuals who sustain a concussion exhibit autonomic dysfunction. Domains that are commonly assessed include heart rate variability (HRV), the Valsalva maneuver, head tilt testing, cerebral perfusion with blood pressure changes, sympathetic response to stress, oculo-cardiac reflex, arterial pulse wave, and pupillary response to light. Heart rate variability is a measurement of the variability between beats, and is the most commonly used assessment for ANS dysfunction and works by assuming that the heart rate is regulated by input from the sympathetic and parasympathetic nervous systems (which are housed in the ANS) (Rajendra Acharya et al., 2006). The sympathetic nervous system increases heart rate and decreases HRV, and the parasympathetic nervous system decreases heart rate and increases HRV (Camm et al., 1996). In cases of TBI, HRV does not respond appropriately to external stimuli such as postural changes (Hilz et al., 2011; Keren et al., 2005). The Valsalva maneuver is a measurement of the ANS response to changes in intrathoracic pressure. This is done by having patients blow into a mouthpiece for a matter of seconds, and outcome scores include changes in blood pressure, heart rate and HRV (Low et al., 2013). The head tilt test is done by measuring heart rate and blood pressure after changes in head tilting positions. With this measure, clinicians expect both heart rate and blood pressure to increase as a response to changes in posture to maintain orthostatic pressure (Low et al., 2013). Another measure includes changes in cerebral profusion in response to manipulation of blood pressure. To measure this, clinicians or researchers would need a transcranial doppler ultrasonography machine, or access to an arterial spin labeling MRI. After manipulating systemic blood pressure with either medication or by releasing pressurized leg cuffs, which should activate an ANS response of the baroreceptors (the baroreflex) to maintain perfusion to the brain (Pertab et al., 2018). The sympathetic response to stress can be induced with a physical stressor such as exercise or pain, or environmental stress such as temperature or loud noises. A researcher or clinician would expect changes in heart rate and sweat rate in response to these stimuli, and these responses can be objectively measured (Pertab et al., 2018). Due to the multifaceted job description of the ANS, a battery is often used, compared to a single test; however, within the concussed samples, there is only one concussion-specific autonomic assessment.

Exercise intolerance is one diagnostic option for identifying dysautonomia (i.e., autonomic dyfunction); however, there is a large overlap between cardiorespiratory fitness level and cardiac variables measured on exercise intolerance testing, such as heart rate and heart rate variability. High cardiorespiratory fitness levels have been shown to preserve peak heart rate during exercise, even with age (Ozemek et al., 2016). Additionally, poor physical fitness results in impaired vagal function during exercise. Vagal modulation of the heart is a dynamic relationship between the sympathetic and parasympathetic nervous systems; both of which are controlled by the ANS (Tulppo et al., 1998). However, poor physical fitness is not equivalent to dysautonomia. In individuals without dysautonomia, is widely accepted that the autonomic nervous system will adapt to exercise training relatively quickly, and these differences would likely decrease or disappear over time with training, even in individuals with a history of myocardial infarction (Amano et al., 2001; Besnier et al., 2017; Oya et al., 1999). Clinicians should consider this overlap when evaluating patients for dysautonomia.

The Buffalo Concussion Treadmill Test (BCTT) is an example of a measure of the sympathetic response to stress (e.g., exercise) and was created specifically for concussed individuals. The BCTT is an exercise assessment developed by Leddy and colleagues (Leddy et al., 2010a; Leddy & Willer, 2013), intended to be used to prescribe a tolerable amount of cardiovascular exercise for concussed, exercise intolerant athletes. The graded exercise is based on the Balke treadmill protocol with increasing grade (Leddy et al., 2010b, 2011; Leddy & Willer, 2013), and heart rate is followed throughout the protocol. At the point the symptom threshold is met, the exercise is discontinued and that becomes their new peak heart rate max for exercise prescription. Patients are then give exercise prescriptions based on their new sub-symptom heart rate. This is suggested to be updated weekly throughout recovery. Despite the intended purpose of this assessment, it has been reported as a diagnosis tool in the literature (Leddy & Willer, 2013). Researchers note "…the Buffalo Concussion Treadmill Test (BCTT), that is the only functional test thus far shown to diagnose safely and reliably physiologic dysfunction in concussion…" (Leddy & Willer, 2013, p. 372). The papers that he cites as support for this statement included a study where the Balke treadmill exercise protocol (of which the BCTT was based) was a safe tool for prescribing exercise for concussed samples (Leddy et al., 2010b), and a study about the interrater reliability of the Balke exercise treadmill protocol (Leddy et al., 2011). Neither of these studies established the utility of the BCTT as a diagnosis tool nor include suggested cutoffs for the BCTT for autonomic dysfunction. Additionally, it has been investigated as a tool for identifying those at risk for protracted recovery (Haider, Leddy, et al., 2019). Haider and colleagues reported that change in heart rate values ($\leq$50 BPM) were significantly lower in sedentary participants with protracted recovery (> 30 days); however, this finding did not exist in participants who were prescribed active rehabilitation. Additionally, Chizuk and colleagues (2019) investigated sex differences on outcomes of the BCTT and reported that females have higher resting heart rate and higher heart rate symptom thresholds; however, Males and females did not differ on change from resting to heart rate symptom threshold, time-to-test completion, maximum symptom score, and change in symptom exacerbation. More recently, a bicycle version of the BCTT has been developed (the Buffalo Concussion Bicycle Test: BCBT). The BCBT has been compared to the original treadmill test version and median peak heart rate for the bike test did not significantly differ from the treadmill test and researchers concluded that the bike test was a suitable alternative to the treadmill test (R. F. Graham et al., 2021).

## Management and Treatment of Concussion

The management and treatment of sport-related concussion has recently evolved and vastly improved as our knowledge of concussion advances. Previously clinicians took a more passive, rest-based approach to the management of concussion; however, following a series of studies (Collins et al., 2016; Eastman & Chang, 2015; Schneider et al., 2017; Silverberg & Iverson, 2013; Danny G. Thomas, 2013; Thomas, Apps, Hoffmann, McCrea, & Hammeke, 2015) a brief (24-28 hour) rest period followed by active treatment has been found to be the most advantageous approach. Thomas and colleagues (2013) conducted a randomized control trial comparing strict rest (no physical or cognitive activity for 5 days) to standard of care (1-2 days of rest followed by a stepwise return to play) and reported that the rest group had significantly higher total symptom scores for days two through five. These findings support the active rehabilitation approach to concussion treatment.

In recent years, laws have also been enacted to address gaps in identifying concussion and return to play decisions. Between 2009 and 2014 all 50 states and the District of Columbia have enacted legislation addressing return to play rules with suspected injuries with the aim of reducing and preventing traumatic brain injuries (*Traumatic Brain Injury Legislation*, n.d.). These recent legislation changes, and position statements have set new standards for holding athletes out of play if an injury is suspected. Arkansas' law titled 'An Act to Create the Arkansas Concussion Protocol Act" was passed in 2013 and requires that persons operating and participating in youth athletic activities will be sent concussion education information, and that youth athletes who are suspected of sustaining a concussion or who has a confirmed concussion will be removed from game, activity, or practice and cannot return until evaluated by a licensed healthcare provider (THE ARKANSAS CONCUSSION PROTOCOL ACT., 2013). This delay in action provides clinicians the time and resources to better assess and diagnose potential concussions. Once a concussion is diagnosed, clinicians often want to be able to label the injury to understand the prognosis; and previous researchers and clinicians have developed scales to grade the injuries.

A multitude of grading scales for concussion are available; however, clinicians and researchers have questioned their utility for understanding the injury and predicting recovery. Several grading scales are available in the literature, including Cantu's scale (Cantu, 1986, 2001), American Academy of Neurology (American Academy of Neurology, 1997), and Colorado Scale (Kelly, 2001). However, these scales place weight on specific signs of loss of consciousness and post-traumatic amnesia in deciding the severity of the injury (Leclerc et al., 2001); which has been not been consistently associated with severity in other studies (Halstead & Walter, 2010; Kontos, Elbin, et al., 2019; Lau et al., 2011; Lovell et al., 2003). The purpose of these scales was originally to offer clinicians a framework to base their management and treatment decisions on; however, researchers and clinicians have questioned their applicability towards injury management. Specifically, these scales do not offer unique management and treatment descriptions.

Clinical profiles are classifications that afford clinicians the ability to identify predominant clinical trajectories that can be targeted with active treatment plans (Collins et al., 2014). A couple recent reviews (Collins et al., 2014; Kontos, Sufrinko, et al., 2019) outline five clinical profiles (e.g., vestibular, ocular, cognitive/fatigue, migraine, and anxiety/mood) and two modifiers (e.g., cervical and sleep) that are identified through a comprehensive clinical assessment, and help characterize the injury and inform treatment. Treatments and therapies for each profile are matched to the underlying deficits, which range from therapies, rehabilitation programs, to pharmacological interventions. However, some profiles (e.g., cognitive/fatigue, migraine, and anxiety/ mood) have overlapping treatment approaches. For instance, vestibular therapy is an advantageous treatment approach for concussed adolescents with vestibular impairments (B. Alsalaheen et al., 2020). In addition, migraine interventions have been adapted as treatment for post-traumatic migraine (Larsen et al., 2019). Many of the treatments are adapted from comorbid and overlapping disorders and health issues. One common treatment approach that fits more than one clinical profile is behavioral regulation, which is often a conservative, low cost approach to treating concussion (Collins et al., 2014). Behavioral regulation is described as the maintenance of healthy and consistent sleep, diet, hydration, physical activity, and stress with a schedule (Womble & Collins, 2016). There is still research to be done on this topic and that some of these treatments are borrowed from other injuries/diseases/disorders (e.g., migraine). The clinical profiles approach to treating concussion is unique in that it requires a team of specialists from a variety of backgrounds.

Several consensus statements and clinical recommendation papers mention and support the utility of an interdisciplinary team of specialists to address each injury (Broglio et al., 2014; Collins et al., 2014; Kontos, Sufrinko, et al., 2019; McCrory et al., 2017a). A randomized control trial study by McCarty and colleagues (2016) noted that concussed adolescents that received collaborative care (e.g., cognitive behavioral therapy, care management, and psychopharmacological consultation) fared significantly better than those who were assigned to controls assigned to usual care (e.g., monitoring throughout recovery). Specifically, athletes in the collaborative care group reported significant improvements in symptoms and functional gains on neuropsychological testing compared to controls at 6 months from their initial assessment (McCarty et al., 2016). Consensus statements often recommend a myriad of different specialists to collaborate to best treat concussion. Specifically, a combination of a physician or neuropsychologist, physical therapist, vestibular therapist, athletic trainer, optometrist or ophthalmologist, speech or language pathologist, clinical or sport psychology professional, and occupational therapist may be warranted depending on the case (Kontos, Sufrinko, et al., 2019).

These specialties relate to the aforementioned clinical profiles and their targeted treatments. Concussion is a heterogeneous injury and warrants a targeted and personalized approach to treatment. Such approaches should be informed by a comprehensive approach to assessment that includes clinical interview, examination, medical history, injury characteristics, sign and symptom evaluation, and impairment evaluations (Collins et al., 2014; Kontos, Sufrinko, et al., 2019; Reynolds et al., 2014).

### Recovery time

The definition of concussion recovery varies widely in the literature, and these variations account for some of the conflicting reports of time frames for recovery. The current Concussion in Sport Group consensus statement defines concussion as return to normal activities, including school, work, and sport after injury, with resolution of post-concussion-related symptoms and return to clinically normal balance and cognitive functioning (McCrory et al., 2017a); however, this does not cover all of the aforementioned domains of interest with concussion impairment. Further, different domains of may recover at different rates, and different assessments of the same domains may show recovery at different rates. For example, neurocognitive performance, as measured by ImPACT, appears to resolve at approximately 10 days following injury in most (G. Iverson et al., 2006); in contrast, neurocognitive scores, as measured by SAC, appear to return to baseline within 72 hours of injury (McCrea et al., 2005; Teel et al., 2017). McCrea and colleagues (2005) reported that average balance scores (BESS) in a concussed sample were better than controls by day 5 following concussion. Due to these discrepancies, current consensus recommendations state that a multimodal approach to deciding recovery is most accurate (Broglio et al., 2014; Echemendia et al., 2015; McCrory et al., 2017a).

The average reported recovery time ranges from 7-10 days for most studies that measured recovery according to a multimodal toolbox (Buckley et al., 2016; G. Iverson et al., 2006; McCrea et al., 2003; Williams et al., 2015); although, there are some outliers when looking for recovery time. Corwin and colleagues reported that the median time for full medical clearance (completed exertional return to play protocol, symptom free at rest, full cognitive workload, and normal vestibular/ocular exams) was 76 days in a sample of 7-18-year olds. This could be due to conservative care decisions secondary to it being such a young sample. Alternatively, it could be due to the requirement for participants to be symptom free. As previously noted in this review, some number of symptoms (scores of 7-10 on the PCSS) are expected at baseline (Covassin et al., 2006). In addition, some discrepancies for reported recovery time could be due to treatment approaches. Rest based treatment approaches have been reported to lead to longer recovery times compared to active approaches (Buckley et al., 2016). Regardless, approximately 80-90 percent of cases will recover within 3 weeks of injury (Makdissi et al., 2010; McClincy et al., 2006; McCrea et al., 2009; McCrory et al., 2017b); however, recent studies have focused on identifying risk factors for falling into the remaining 20%.

## Risk Factors for Protracted Recovery

Risk factors for concussion can be broken down into two major categories: primary and secondary risk factors. Primary risk factors are factors that increase the risk of the injury itself, and secondary risk factors influence recovery outcomes and are associated with protracted recovery. Protracted recovery is defined as recovery times greater than or equal to 21 days (Covassin et al., 2010; R. J. Elbin et al., 2016; Kontos et al., 2013; Lau et al., 2011). Primary risk factors for concussion were discussed in the prevalence section of this review. This section will focus on secondary risk factors for concussion.

Reports of potential secondary risk factors for concussion are plenty and conflicting; however, some are generally supported. Potential risk factors with some support include sex (female) (M. Ellis et al., 2018; Kontos, Elbin, et al., 2019; Neidecker et al., 2017; S. Stone et al., 2017), age (younger) (Kontos, Elbin, et al., 2019; Neidecker et al., 2017), history of learning disorder (Harmon et al., 2013; Zemek et al., 2016), history of attention deficit hyperactivity disorder (Harmon et al., 2013; Mautner et al., 2015; Miller et al., 2016), mood disorders (anxiety and depression) (Kontos, Covassin, et al., 2012; Meares et al., 2011; Solomon et al., 2016), history of concussion (Covassin et al., 2008; G. L. Iverson et al., 2004), and history of migraines (Harmon et al., 2013). Following the injury, on field signs (e.g., loss of consciousness, and amnesia) have had conflicting reports for being predictors of recovery (G. L. Iverson et al., 2004; Kelly, 2001; Kontos, Elbin, et al., 2019; Lau et al., 2011). One study noted retrograde amnesia, general cognitive problems, fatigue, and a high symptom burden at initial presentation as markers for protracted recovery in professional football athletes (Pellman, Viano, Tucker, Casson, et al., 2003). Although initial symptom burden as a risk factor for protracted recovery from concussion is generally well supported in the literature (Erlanger et al., 2003; Kowalczyk et al., 2019; Lovell et al., 2003; Meehan III et al., 2016; Meehan et al., 2014; Schilling et al., 2020), there are conflicting reports on ADHD, loss of consciousness, and amnesia. In contrast the aforementioned literature, Kontos and colleagues (2019) reported that ADHD, loss of consciousness and post-traumatic amnesia were not associated with protracted recovery. Also, acute presentation following the injury (i.e., number, duration and severity of symptoms, post-traumatic headache or migraine, and post-concussion mood) have been noted to predict concussion recovery (Kontos, Elbin, et al., 2019).

In addition to past medical history and acute presentation, modifiable choices following the concussion can influence recovery rate. For instance, removal from play status and/or exposure to additional head trauma is also significantly associated with recovery time (Asken et al., 2016; R. J. Elbin et al., 2016; Heyer, Schaffer, et al., 2016; Terwilliger et al., 2016). Elbin and colleagues (2016) compared athletes who were immediately removed from play to those who finished their game on recovery time and reported that athletes that continued to play were over 8 times more likely to demonstrate a protracted recovery ($\geq$ 21 days). Athletes that do not recover in the normal time frame fall into chronic recovery status and may suffer from post-concussion syndrome.

Post-concussion syndrome is defined as three or more persistent concussion-related symptoms (i.e., physical, cognitive, and emotional/behavioral symptoms) and cognitive deficits in attention or memory that linger beyond the expected recovery period (Boake et al., 2005; Broshek et al., 2015; Ryan & Warden, 2003). These lasting impairments may affect patients' work and academic life drastically. However, some controversial reports say that post-concussion syndrome symptoms overlap heavily with other etiologies and therefore, are often misdiagnosed (Broshek et al., 2015; Meares et al., 2008; Willer & Leddy, 2006). One study compared the prevalence of persistent post-concussion syndrome symptoms in a sample of previously concussed individuals with matched controls, and reported that approximately 31-34% of both groups qualified for post-concussion syndrome (Dean et al., 2012), further supporting previous claims that post-concussion syndrome may easily be misdiagnosed. In addition, the recent push towards a more active treatment approach, as opposed to a rest-based management approach (Collins et al., 2016; Kontos, Sufrinko, et al., 2019; McCrory et al., 2017b) may influence this prevalence moving forward. As new, emerging treatment options for concussion are becoming more popularly prescribed, we may see a shift in the prevalence of post-concussion syndrome cases.

### Cardiorespiratory Fitness Testing

Physical fitness has been defined as a set of attributes that relates to the ability to perform physical activity (American College of Sports Medicine, 2013). The domains of physical fitness include aerobic, anaerobic, muscular strength, flexibility, and body composition (American College of Sports Medicine, 2013; Liguori & Medicine, 2020). For the purpose of this review, aerobic capacity will be the main focus. Aerobic capacity or cardiorespiratory fitness is defined as the ability of the body (including the cardiac and pulmonary systems) to deliver oxygen to the muscle tissues during exercise. Aerobic capacity can be improved with training (Kaynak et al., 2017). Additionally, cardiorespiratory fitness is measured using the units of ml of oxygen per kg of body mass per minute (VO2 max) (Liguori & Medicine, 2020). There are many submaximal assessments that are commonly used to estimate aerobic capacity, such as step tests (e.g., Canadian Step Test and Queen's College Step Test), and submaximal cycle ergometer tests (e.g., the Astrand Test). Assumptions of these assessments are that a steady state heart rate is achieved, there is a linear relationship between heart rate and work rate, the difference between actual and predicted maximal heart rate is minimal, mechanical efficiency is the same for everyone, the individual is not on any heart rate altering medications, and the individual is not ill with a high fever which could alter heart rate response (Liguori & Medicine, 2020). Additionally, the VO2 max assessment directly measures inspired and expired air contents (CO2 and O2) during exercise to measure how much oxygen was delivered to the muscles using a metabolic cart. Norms for VO2 are available in Appendix 6.

# Chapter 3: Methods

## Study Design

The current study employed an extreme groups approach, cross-sectional design.

## Participants

Participants included adults ages 20-29 years. Female participants were excluded if they were not on hormonal birth control to control for the confounding effects of hormone fluctuation throughout the menstrual cycle. Participants were excluded if they had a history of concussion in the past year, autonomic dysfunction, vestibular disorder, migraine history, or if they reported a past medical history of contraindications for exercise testing as listed on the BCBT (See Appendix 1). An extreme groups approach was be used for this study. Participants were placed in either the 1) HIGH CRF group with a VO2 max of 51 ml/kg/min or greater for men, or 38 ml/kg/min or greater in females (Superior or Excellent groups based on ACSM norms) or 2) the LOW CRF group with a VO2 max of 38 ml/kg/min or lower in men, or 28 ml/kg/min or lower in women- the Very Poor and Poor groups per ACSM norms for VO2 max categorization for the 20-29 age group on cycle ergometer-based cardiorespiratory fitness (American College of Sports Medicine, 2013) (See Appendix 6).

## Measures

### *Demographics and Exercise Contraindications Form.*

The demographics form was used to collect demographic information including, age, biological sex, weight, hormonal birth control use (for females), and their eligibility according to the inclusion and exclusion criteria (e.g., past medical history of history of concussion in the past year, autonomic dysfunction, vestibular disorder, and migraine history). See Appendix 7.

### *Medical Screening Form.*

The Medical Screening Form was used to screen for medical contraindications to exercising that are not specific to the Buffalo Concussion Bike Test protocol, including heart conditions, chest pain or pressure with physical activity, etc. See Appendix 8.

### *Cycle Ergometer VO2 Max.*

To establish cardiorespiratory fitness group, the cycle $VO_2$ max test was used to determine maximum oxygen consumption. Prior to the $VO_2$ max trial, the metabolic cart was calibrated using a 3-liter syringe. The test procedures were explained to the participant. A graded exercise test was performed on the cycle ergometer (Lode bike). Starting stage began at 100 watts on the cycle ergometer and increased by 25 watts every 2 minutes until the participant could no longer maintain cadence over 60 RPM. Male participants who were anticipated to be in the HIGH CRF group (i.e., cyclists) started at 150 watts to shorten the time it would take to get to max exertion. Throughout this protocol, the exercise workload was gradually increased in increments from moderate to maximal intensity. Perceived exertion was assessed at the end of every 2-minute stage. Heart rate was measured continuously by a Timex heartrate monitor. Oxygen uptake was calculated from measures of ventilation and the oxygen and carbon dioxide in the expired air. Participants were required to meet at least 2 criteria for reaching max: pedal speed below the required 60 RPM, RPE of 20, plateu of the $VO_2$ max score, reaching age-predicted heart rate max, and RER of >1.10. Results of the VO2 max test was presented in milliliters of oxygen per kilograms of body mass per minute (ml/kg/min). This maximal exertion bike protocol was adapted by Stone and colleagues (T. Stone et al., 2021).

### ***Post-Concussion Symptom Scale.***

Symptoms were assessed prior to and following the BCBT protocol using the Post-Concussion Symptom Scale (PCSS). The PCSS is a 22-item concussion-specific symptom scale (Pardini et al., 2004). Items on the PCSS are rated on a Likert scale from 0 (not at all) to 6 (severe), and the items included on the scale consist of headache, nausea, vomiting, balance problems, dizziness, fatigue, trouble falling asleep, sleeping more than usual, sleeping less than usual, drowsiness, sensitivity to light, sensitivity to noise, irritability, sadness, nervousness, feeling more emotional, numbness or tingling, feeling slowed down, feeling mentally ''foggy,'' difficulty concentrating, difficulty remembering, and visual problems. A total symptom score was calculated by summing all symptom item scores. The reliability and validity of the PCSS are well documented; internal consistency reliability of the PCSS ranged from .88 to .94 (Lovell et al., 2006). The items on the scale were summed to calculate a total scores.

### ***Vestibular/Ocular Motor Screening.***

Vestibular and ocular provocation was also assessed prior to and following the BCBT protocol. The Vestibular/Ocular Motor Screening (VOMS) is a brief clinical assessment for vestibular and ocular motor impairments. It consists of vestibular (horizontal and vertical vestibular ocular reflex, and visual motion sensitivity) and ocular (smooth pursuits, horizontal saccades, vertical saccades, convergence, and near point of convergence distance) components. Participants rated four symptoms (headache, dizziness, nausea, and fogginess) on a scale from 0 to 10 at pre-test and following each exercise to measure symptom provocation (Mucha et al., 2014). A change score was calculated for each item by subtracting the pre-test VOMS symptom scores to the symptom scores for each VOMS item. An overall change score was calculated by summing the change scores for each item. Near point of convergence was measured in centimeters and the average of three consecutive measurements was taken. The VOMS has a high overall internal consistency among college athletes, with a Cronbach α of .97 (Kontos, Sufrinko, et al., 2016).

### *The Buffalo Concussion Bike Test (BCBT).*

The BCBT is a 30-minute cycle ergometer test. Protocol for this assessment requires a continuous heartrate monitor. Power/resistance for each stage were based on the participant's weight (See Appendix 1 for resistance tables). The VAS and RPE scales were placed in front of the bike for easy visual access every two minutes during the test. At the beginning of the BCBT protocol, the participant was instructed to begin pedaling at 60 ± 5 RPM. After speed was met, the resistance was increased to their Stage 1 power. The participants reported their RPE, symptoms on the VAS, and the tester recorded HR every 2 minutes. This was repeated where RPE, symptoms, and HR were recorded, and resistance is increased at the end of each 2-minute stage. If symptom reports do increase, the tester clarified if it was a new symptom or an increase in the severity of previously reported symptoms, and this information was documented qualitatively. Stopping criteria for the test include symptom exacerbation (e.g., an increase of 3 or more on the VAS scale from their pre-test score), voluntary exhaustion (an RPE score >17), patient reached 90% of age predicted heart rate max without reaching >17 on the RPE scale, dropping in speed below 55 RPM, or if the participant requests to stop for any reason (reasons were documented qualitatively) (Haider, Johnson, et al., 2019).

## **Procedures**

This sample was a convenience sample of university undergraduate and graduate students, faculty, and community members. Recruitment efforts were stratified by sex in each group to achieve an even distribution of males and females. Participants provided informed consent upon arrival for their screening appointment. Prior to enrollment into the study, participants completed the demographics form, medical screening form, and the $VO_2$ max test protocol. The $VO_2$ max value were used as a screener to ensure that they met inclusion and exclusion criteria, and to assign groups. If criteria were met, participants were enrolled and complete the BCBT protocol within 3 days to 2 weeks of their original $VO_2$ appointment. During their second (and final appointment) researchers reviewed the consent form for the full study. Following informed consent, the researcher administered the PCSS and VOMS. Following this, the researcher explained the protocol for the BCBT, the VAS symptom scale, RPE scale, and took a resting heart rate prior to beginning the BCBT protocol. Participants were administered the BCBT protocol and immediately repeated the PCSS and VOMS following the BCBT.

## Data analysis

### *Power analysis*

To power the primary purpose of this study, assuming a large effect size for the extreme groups, an N of 42 was needed, including 21 in both groups to reach power of 80%. Additionally, a lower anticipated power was conceded for Aim 2 due to feasibility and equipment constraints. A sample size of 42, with a small to medium effect size (0.4) and alpha of 0.05, would give a power of 60%. It is understood that we were only sufficiently powered to find a trend.

### *Describing the Sample*

Sample demographics were described using means, standard deviations, and percentile scores. Participant age (years), sex (female to male ratios), and body mass (kg) were described using means, standard deviations, and frequencies. Participants with risk factors such as migraine history, autonomic dysfunction, concussion history, vestibular disorder, or any history of cardiac or pulmonary diseases were excluded from our final sample; therefore, frequencies of these risk factors were zero and not mentioned in the results. The frequency of stopping criteria for each group was reported using frequencies.

### ***Statistical Assumptions***

All variables and data were inspected for accuracy with frequencies, means, standard deviations prior to analysis. Assumptions for each analysis were investigated using Shapiro-Wilks ($p < 0.05$), skewness (>-2 and <2), and kurtosis (>-7 and <7) (Byrne, 2013; Hair et al., 2010) tests for normality and Levene's test (cutoff is $p < 0.05$) for homogeneity of variance with corresponding cutoffs. In cases where the data violated assumptions of normality and/or homogeneity of variance, non-parametric alternatives were used in place of the originally proposed parametric analyses. Additionally, a Mauchley's test for sphericity was used for multivariate analyses and a Greenhouse-Geisser correction was used if this statistical test for sphericity was significant.

### ***H1: Participants in the high CRF group will exhibit a longer time-to-test completion on the BCBT than the participants in the low CRF group.***

The first hypothesis was assessed using a Mann-Whitney *U* test. The independent variable was the CRF group (HIGH and LOW), and time-to-test completion in minutes was the dependent variable. Significance was set at $p \leq 0.05$.

### ***H2: Participants in the high CRF group will have lower peak heart rate for the first four stages of the BCBT protocol than the participants in the low CRF group.***

The second hypothesis was assessed using a repeated measures analysis of variance (ANOVA). The categorical independent variable was CRF group, and the continuous dependent variable was heart rate across rest and the first four stages of the BCBT. A Tukey correction was used for post-hoc analyses of multiple time points.

***H3: Males and females will not differ significantly on time-to-test completion on the BCBT.***

The third hypothesis was evaluated using a Mann-Whitney U test. The independent variable was sex, and dependent variable was time-to-test completion in minutes on the BCBT. Significance was set at $p \leq 0.05$.

***H4: Females will have a significantly higher heart rate at test completion during exercise on the BCBT compared to their male counterparts.***

The fourth hypothesis was evaluated using a Mann-Whitney U test. The independent variable was sex (male and female), and dependent variable was final heart rate (BPM) on the BCBT. Significance was set at $p \leq 0.05$.

## Exploratory Analyses

***EQ1: Females will report higher symptoms on the Post-Concussion Symptom Scale at both pre- and post- test time points compared to their male counterparts.***

Exploratory question one was assessed using a two-way ANOVA comparing males and female PCSS test scores at both pre and post-test timepoints. The independent variables were sex (male, female) and time (pre, post) and the continuous dependent variable was PCSS score. Significance was set at $p \leq 0.05$.

***EQ2: Males and females will exhibit similar change scores on the items of the VOMS at pre- and post- test time points.***

Exploratory question two was assessed using a repeated measures ANOVA to compare males and female VOMS test change scores at both pre and post-test timepoints. The categorical independent variables were sex (male and female) and time (pre-test and post-test), and the continuous dependent variables included change scores for smooth pursuits, horizontal saccades, vertical saccades, near point of convergence symptoms, horizontal vestibular ocular reflex, vertical vestibular ocular reflex, and visual motion sensitivity, at each time point. In addition, an overall change score was used as an outcome (Elbin et al., 2021). Significance was set at $p \leq 0.05$.

***EQ3: Males and females will exhibit similar change scores on NPC distance of the VOMS at pre- and post- test time points.***

A 2x2 ANOVA was used to compare males and female VOMS NPC scores at both pre and post-test timepoints. The categorical independent variables were sex (male and female) and time (pre-test and post-test), and the continuous dependent variables included NPC distance at each time point. Significance was set at $p \leq 0.05$.

***EQ4: Participants in the LOW CRF group will report higher post-test symptoms on the PCSS compared to participants in the HIGH CRF group.***

A Mann-Whitney U test was used to compare the independent variable of CRF group on the dependent variable of post-BCBT symptom severity on the PCSS. Significance was set at $p \leq 0.05$.

# Chapter 4: Results

## Demographics of the sample

Participants were recruited via fliers, social media posts, emails, and in-person. Of the numerous recruitment efforts, a total of 64 participants agreed to complete the screening test ($VO_2$ max). There were 22 individuals who completed a $VO_2$ max appointment that were not included in the final sample; one individual withdrew due to scheduling conflicts, and 21 failed to meet the required peak $VO_2$ max cutoff for a group assignment. Of these, 42 (21/42; 50% female) met inclusion criteria. Approximately 52% (11/21) of the LOW CRF group were female, and 48% (10/21) of the HIGH CRF group were female. The final sample (N = 42) included in the study (M = 22.31 ± 2.25 years) was assigned to HIGH (n = 21) or LOW (n=21) CRF groups based on peak VO2 max scores. The HIGH CRF group (22.05 ±1.60 years old), and the LOW CRF group (22.57±2.77 years) did not differ on age ($t(40)=-0.75$, $p= 0.46$). Additionally, they did not differ on sex ($x$ (1) =0.10, $p = 0.76$), or body mass ($t(40)=-1.83$, $p= 0.08$). The LOW CRF group (74.86 ± 18.51 kg) was not statistically significantly heavier than the HIGH CRF group (66.48 ± 9.88 kg). Groups were defined by peak $VO_2$ max scores, but there was some variance in the sample. Peak $VO_2$ max for males in the HIGH CRF group ranged from 50.4 to 78.3 ml/kg/min, and females in the HIGH CRF group ranged from 38.8 to 49.9 ml/kg/min. Males in the LOW CRF group ranged from 24.4 to 36.3 ml/kg/min, and females in the low CRF group ranged from 21.6 to 27.9 ml/kg/min (see group means in Table 1).

**Table 1.**

**Means, standard deviations, and frequencies for age, body mass (kg), peak $VO_2$ max (ml/kg/min), time-to-test completion, and sex.**

| | **High (n = 21)** | | | **Low (n = 21)** | | |
|---|---|---|---|---|---|---|
| | **Total HIGH group** | ***Males (n=11)*** | ***Females (n=10)*** | **Total LOW group** | **Males *(n=10)*** | **Females *(n=11)*** |
| | ***M*(SD)** | ***M*(SD)** | ***M*(SD)** | ***M*(SD)** | ***M*(SD)** | ***M*(SD)** |
| **Age (years)** | 22.05 (1.60) | 22.36 (1.57) | 21.70 (1.64) | 22.57 (2.77) | 22.00 (2.79) | 23.09 (2.77) |
| **$VO_2$ max Peak** | 50.40 (11.15) | 58.74 (8.56) | 41.22 (4.06) | 28.34 (4.35) | 31.38 (4.02) | 25.58 (2.40) |
| **Body mass** | 66.48 (9.88) | 69.33 (8.80) | 63.35 (10.49) | 74.86 (18.51) | 77.84 (11.89) | 72.15 (23.26) |

### Frequency of Stopping Criteria for the Buffalo Concussion Bike Test.

Sixty-four percent (27/42) of the sample met stopping criteria on the BCBT protocol. Approximately 72% (15/21) of the HIGH CRF group completed the full BCBT protocol; however, zero (0/21) participants in the LOW CRF group completed the BCBT protocol. The most frequent reason for stopping the BCBT among the low group was meeting 90% of HR maximum (19/21; 90%), followed by inability to keep the pedal speed > 55 RPMs (10%; 2/21). All (11/11) of the males and 40% (4/10) of the females in the HIGH CRF group completed the full BCBT protocol without meeting any stopping criteria. See Table 2 for a description of stopping criteria stratified by group and sex on the BCBT.

**Table 2.**

**Frequencies of the stopping criteria met for the groups on the BCBT.**

| | **Groups** | | | |
|---|---|---|---|---|
| | **High** | | **Low** | |
| **Stopping Criteria** | **Males (n = 11)** | **Females (n = 10)** | **Males (n = 10)** | **Females (n = 11)** |
| **Met 90% of HR max** | 0 (0%) | 5 (50%) | 9 (90%) | 10 (91%) |
| **VAS symptoms** | 0 (0%) | 1 (10%) | 0 (0%) | 0 (0%) |
| **Speed** | 0 (0%) | 0 (0%) | 1 (10%) | 1 (9%) |
| **RPE >17** | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |

### H1: Participants in the high CRF group will exhibit a longer time-to-test completion on the BCBT than the participants in the low CRF group.

Data for the time-to-test completion (minutes) was non-normal (Shapiro Wilks = 0.87, $p < .001$; skewness = -0.40; kurtosis = -1.17). The results of a Mann-Whitney U test revealed that the HIGH CRF group had significantly longer test times compared to the LOW CRF group ($U$ = 15.00, $p <.001$). Means, standard deviations, medians, and ranges for time to test completion are presented in Table 3.

**Table 3.**

**Average time-to-test completion (mins) by group.**

| | **High (n = 21)** | | **Low (n = 21)** | |
|---|---|---|---|---|
| | ***M*** | **SD** | ***M*** | **SD** |
| **Time-to-test Completion (min)** | 28.37 | 3.27 | 17.19 | 4.57 |

**H2: Participants in the high CRF group will have lower peak heart rate for the first four stages of the BCBT protocol than the participants in the low CRF group.**

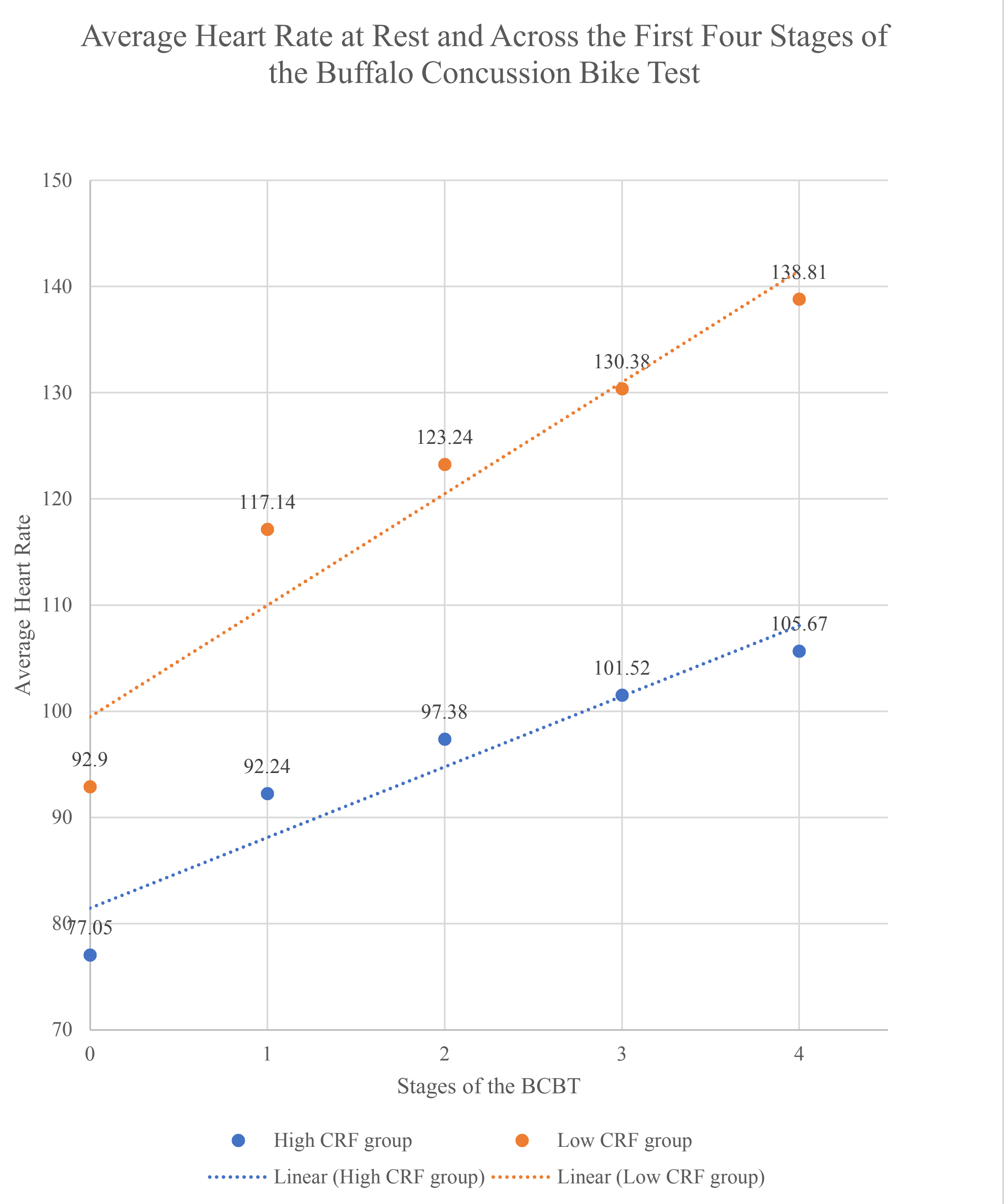
Participants in the low group did not complete the full BCBT protocol; therefore, the original hypothesis was rewritten to better specify the time frame that we had complete data- rest and the first four stages of the BCBT. The original hypothesis stated "early stages" in place of a number. See Table 4 for the distribution of heart rate data across the stages by group. The results of the assumption checks for hypothesis two revealed that the heart rate data at rest and across the first four stages of the BCBT are normally distributed. Additionally, there was equal variance of heart rate data at rest (Levene's test = 0.017, $p = 0.90$), stage 1 (Levene's test = 0.13, $p = 0.72$), stage 2 (Levene's test = 0.91, $p = 0.35$), stage 3 (Levene's test = 0.88, $p = 0.35$), and stage 4 (Levene's test = 0.89, $p = 0.35$). A Greenhouse-Geisser correction was used to correct for the violation of sphericity (Mauchly's W = 0.03, $p < 0.001$).

**Table 4. Heart rate across the stages of the BCBT**

| | **HIGH CRF group** | | | | **LOW CRF group** | | | |
|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***Md*** | ***M*** | **SD** | ***n*** | ***Md*** | ***M*** | **SD** |
| **Rest** | 21 | 77 | 77.05 | 7.90 | 21 | 91 | 92.90 | 17.02 |
| **Stage 1** | 21 | 90 | 92.24 | 12.99 | 21 | 116 | 117.14 | 12.85 |
| **Stage 2** | 21 | 96 | 97.38 | 14.62 | 21 | 121 | 123.24 | 14.99 |
| **Stage 3** | 21 | 98 | 101.52 | 15.31 | 21 | 128 | 130.38 | 16.52 |
| **Stage 4** | 21 | 103 | 105.67 | 16.14 | 21 | 138 | 138.81 | 17.66 |
| **Stage 5** | 21 | 109 | 110.24 | 16.39 | 20 | 141 | 143.30 | 18.39 |
| **Stage 6** | 21 | 113 | 115.00 | 17.24 | 19 | 149 | 150.00 | 18.80 |
| **Stage 7** | 21 | 119 | 120.10 | 19.87 | 15 | 150 | 150.93 | 14.33 |
| **Stage 8** | 21 | 118 | 124.05 | 19.96 | 13 | 159 | 155.00 | 12.91 |
| **Stage 9** | 21 | 124 | 128.76 | 20.16 | 11 | 164 | 161.36 | 9.27 |
| **Stage 10** | 20 | 127.5 | 131.55 | 18.11 | 9 | 169 | 167.89 | 9.12 |
| **Stage 11** | 20 | 134.5 | 136.90 | 18.95 | 6 | 169.5 | 170.17 | 6.11 |
| **Stage 12** | 19 | 141 | 140.89 | 19.46 | 1 | 170 | 170 | -- |
| **Stage 13** | 18 | 145.5 | 144.06 | 18.28 | 1 | 177 | 177 | -- |
| **Stage 14** | 17 | 148 | 147.53 | 15.76 | 0 | -- | -- | -- |
| **Stage 15** | 15 | 155 | 149.80 | 13.84 | 0 | -- | -- | -- |

There were several significant findings from the 2x5 ANOVA investigating CRF group, on heart rate data across 5 time points. There was a small, but significant main effect for CRF group (*F* (1) = 40.20, $p < .001$, $\eta^2 = 0.30$). Additionally, the within-subjects' effect for time (e.g., pre- and post-test time points) was significant, but small (*F* (1.40) = 143.33, $p < .001$, $\eta^2 = 0.30$). There was also a group by time interaction for heart rate (*F*(1.40) = 7.19, $p < .001$, $\eta^2 = 0.02$). A post-hoc pairwise comparison using a Tukey correction compared mean differences in scores between the two groups for each time point, and the results revealed that there were group differences at rest (*t* (40) = -3.87, $p = 0.01$), stage 1 (*t* (40) = -6.25, $p <.001$), stage 2 (*t* (40) =-5.66 , $p <.001$), stage 3 (*t* (40) = -5.87, $p < .001$), and stage 4 (*t* (40) = -6.35, $p < .001$), with the LOW CRF group recording higher heart rate at each timepoint compared to the HIGH CRF group. See Graph 3 for a heart rate data across rest and the first 4 stages of the BCBT by group.

**Figure 1.**



**Average heart rate at rest, and across the first four stages of the Buffalo Concussion Bike Test protocol for HIGH and LOW CRF groups.**

### H3: Males and females will not differ significantly on time-to-test completion on the BCBT.

The time-to-test completion variable was assessed for normality using a Shapiro Wilks test, and was normal ($W = 3.49, p < .06$). However, Levene's test showed that the variances for time-to-test completion were not equal, F (3,38) = 9.27, p < .001. Multiple log transformations, a square root transformation, and a 1/(x) transformation were used, and none were able to correct this violation; in result, a Mann Whitney U test was used. The results of the Mann-Whitney U test revealed no statistical significance between males ($Md$=30.00, $M$ =24.64 ± 6.49) and females ($Md$ = 20.83, $M$ = 20.93 ± 6.93) on time-to-test completion, $U$ = 148.00, $p$ = 0.06. (See time-to-test completion by sex in Table 5).

### H4: Females will have a significantly higher heart rate at test completion during exercise on the BCBT compared to their male counterparts.

The final heart rate data were decidedly non-normal ($W = 0.91, p = 0.002$); additionally, the data violates the assumption of homogeneity of variance (Levene's Test = 11.19, $p$ = 0.002). Therefore, a Mann-Whitney U test was run in place of the originally planned t-test. A Mann-Whitney U test revealed that males ($Md$ = 165, $M$ =161 ± 19.4) and females ($Md$ = 176, $M$ = 172 ± 11.0) had similar heart rates at test completion ($U$ = 159, $p$ = 0.12) (See final heart rate by sex in Table 5).

**Table 5**

**Time-to-test completion, final heart rate and pre-test/post-test PCSS scores on the Buffalo Concussion Bike Test by sex.**

| | **Males** | | **Females** | |
|---|---|---|---|---|
| | ***M*** | **SD** | ***M*** | **SD** |
| **Time-to-test completion** | 24.60 | 6.49 | 20.90 | 6.93 |
| **Final heart rate** | 161.00 | 19.40 | 172.00 | 11.0 |
| **Pre-test PCSS symptoms** | 0.86 | 1.65 | 1.00 | 1.18 |
| **Post-test PCSS symptoms** | 0.76 | 1.48 | 0.24 | 0.44 |

## Exploratory Analyses

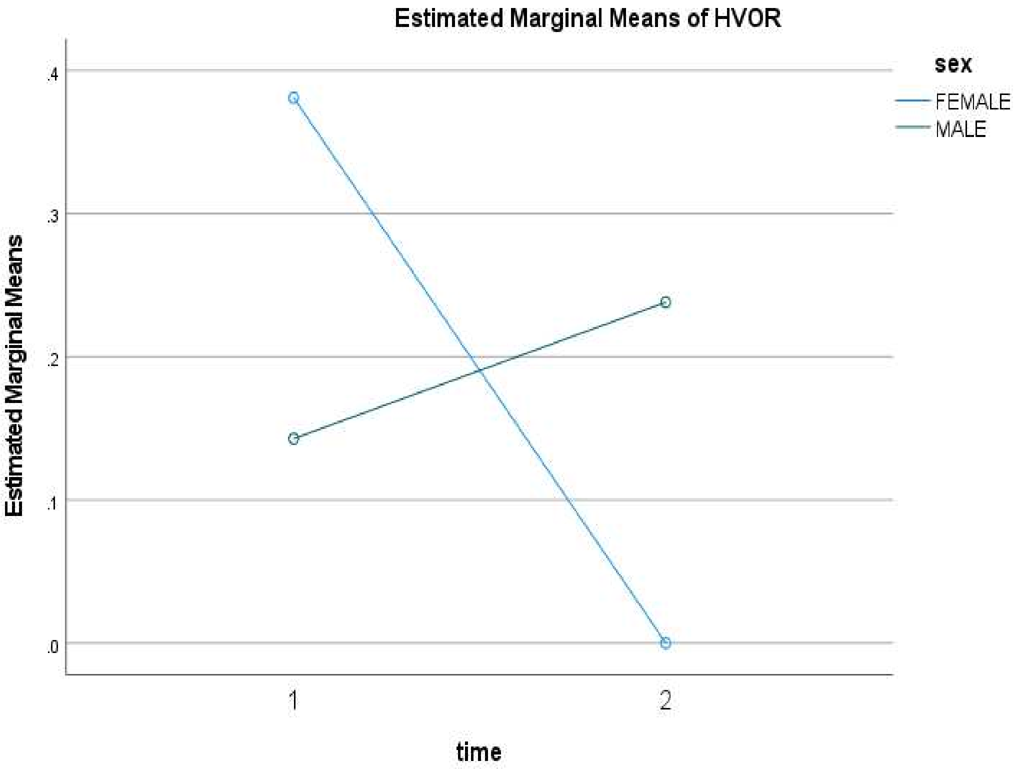
### *EQ1: Females will report higher symptoms on the Post-Concussion Symptom Scale at both pre- and post- test time points compared to their male counterparts.*

The pre- ($W = 0.76, p < .001$) and post-test ($W = 0.79, p = .001$) total symptom scores were assessed for normality and were both decidedly non-normal; however, there is no non-parametric alternative to a 2x2 ANOVA, and the two-way ANOVA is considered "robust" to violations of normality (Blanca Mena et al., 2017). A two-way between-groups ANOVA revealed a main effect of time ($F\ (1) = 4.28, p = 0.045$), but no main effect for sex, ($F\ (1{,}40) = 0.004, p = 0.95$) on PCSS scores. Both males (pre = 3.81 ± 5.57 and post = 5.90 ± 5.83) females (pre = 4.19± 4.61 and post = 5.33± 6.89) showed an increase in PCSS scores from the pre-test to the post-test BCBT timepoints. The interaction was not significant ($F\ (1, 40) = 0.37, p = 0.55$). See Table 5.

### *EQ2: Males and females will exhibit similar scores on the VOMS items at pre- and post- test time points.*

The pre- ($W$ (42) = 0.69, $p < .001$; skewness = 2.22; kurtosis = 6.88) and post-test ($W$ (42) = 0.51, $p < .001$; skewness = 3.48; kurtosis = 14.8) VOMS change scores were assessed for normality and were both decidedly non-normal; however, the repeated measures ANOVA is robust to non-normal data (Blanca Mena et al., 2017). The results of a repeated measures ANOVA comparing males and females on VOMS change scores at both pre-test and post-test time points revealed that there were significant differences for males and females on change scores for individual items on the VOMS or the overall change score at pre- and post-test timepoints, ($F(34)= 2.78$, $p = 0.02$; $\eta^2_p=$ 0.36). However, there was no significant main effect for sex ($F(34)= 0.52$, $p = 0.81$), or time ($F(34)= 2.01$, $p= 0.08$). Univariate post-hoc analyses for the time by sex interaction revealed that the interaction for time and sex on smooth pursuits ($F(1) = 1.00$, $p = 0.32$), horizontal saccades ($F(1) = 0.65$, $p = 0.43$), vertical saccades ($F(1) =-0.00$ , $p = 1.00$), NPC symptoms ($F(1) = 0.32$, $p = 0.57$), vertical VOR (F(1) = 0.69, $p = 0.41$), or VMST (F(1) = 0.00, $p = 1.00$), and overall change ($F(1) = 1.99$, $p = 0.17$) were not significantly different. The interaction for sex and time on horizontal VOR was significant ($F(1) = 10.87$, $p = 0.002$). See Figure 2. This finding in isolation, although statistically significant, is not clinically relevant.

**Figure 2.**



**Estimated marginal means for horizontal vestibular ocular reflex between males and females before and after completing the Buffalo Concussion Bike Test.**

***EQ3: Males and females will exhibit similar scores on NPC distance of the VOMS at pre- and post- test time points.***

The pre-test (Shapiro Wilk's = 0.06, *p*= .80; skewness = 1.19; kurtosis = 2.18) and post-test (Shapiro Wilk's = 1.57, *p*=0.22;skewness = 2.51; kurtosis =10.20) NPC distance scores were assessed for normality and were both decidedly non-normal; however, the ANOVA is robust to non-normal data (Blanca Mena et al., 2017). The results of a 2x2 ANOVA revealed there were no significant differences for males and females on NPC distances on the VOMS at pre-and post-test time points, (*F* (1)= 0.56, *p* = 0.46). Additionally, there was no significant main effect for sex (*F* (1)= 0.15, *p* = 0.70) or time (*F*(1)= 3.98, *p* = 0.05). See Table 6.

**Table 6**

**VOMS item change scores before and following the BCBT protocol.**

**BCBT VOMS Change Scores**

| | **Males** | | **Females** | |
|---|---|---|---|---|
| | ***PRE*** | **POST** | ***PRE*** | **POST** |
| | ***M (SD)*** | ***M (SD)*** | ***M (SD)*** | ***M (SD)*** |
| **Smooth pursuits** | 0.05 (0.22) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) |
| **H-saccades** | 0.05 (0.22) | 0.10 (0.30) | 0.19 (0.30) | 0.05 (0.22) |
| **V-saccades** | 0.05 (0.22) | 0.10 (0.30) | 0.10 (0.00) | 0.05 (0.22) |
| **NPC symptoms** | 0.10 (0.30) | 0.10 (0.30) | 0.48 (0.22) | 0.00 (0.00) |
| **HVOR** | 0.14 (0.36) | 0.38 (0.50) | 0.38 (0.50) | 0.14 (0.36) |
| **VVOR** | 0.19 (0.40) | 0.14 (0.36) | 0.24 (0.44) | 0.10 (0.30) |
| **VMS** | 0.29 (0.46) | 0.10 (0.30) | 0.24 (0.44) | 0.05 (0.22) |
| **NPC distance (cm)** | 3.48 (3.26) | 4.79 (5.78) | 4.28 (3.08) | 4.87 (2.04) |
| **Overall change score** | 0.86 (1.65) | 0.76 (1.48) | 1.00 (1.18) | 0.24 (0.44) |

***EQ4: Participants in the LOW CRF group will report higher post-test symptoms on the PCSS compared to participants in the HIGH CRF group.***

The post-test PCSS symptom scores were assessed for normality and were decidedly non-normal ($W = 0.79$, $p < .001$); therefore, a Mann-Whitney U test was run in place of an independent samples t-test. The results revealed that the LOW ($Md = 3.00$, $M = 4.95 \pm 6.30$) and HIGH ($Md = 2.00$, $M = 2.90 \pm 3.32$) CRF groups did not differ significantly on pre-test PCSS scores ($U = 187.00$, $p = 0.39$). Similarly, the LOW CRF group ($Md = 6.00$, $M = 7.67 \pm 8.19$) and HIGH CRF group ($Md = 4.00$, $M = 3.57 \pm 2.42$) scored similarly on post-test PCSS scores ($U$ (21) = 180.00, $p = 0.30$).

# Chapter 5: Discussion

To date, this was the first study that aimed to determine the effects of cardiorespiratory fitness levels (CRF) on outcomes (e.g., time-to-test completion and heart rate) of the Buffalo Concussion Bike Test among healthy adults with high and low CRF, and to document sex differences on the BCBT. Primary findings of this study were that individuals in the highly fit group had lower heart rates across the BCBT stages, and longer time-to-test completion compared to individuals in the low CRF group. However, they did not exhibit significantly different scores on the PCSS before or after the BCBT. Males and females did not differ on time-to-test completion or peak heart rate, additionally, they exhibited similar VOMS change scores before and following the BCBT protocol (i.e., the protocol did not provoke the vestibular and/or ocular motor system).

Hypothesis one stated that participants in the high CRF group will exhibit a longer time-to-test completion on the BCBT than the participants in the low CRF group and was supported. In the current study, 100% (11/11) of males in the HIGH CRF group completed the entire 30-minute protocol without reaching 90% of their age-predicted heart rate maximum (stopping criteria for the test), indicating a ceiling effect in healthy individuals. This could be due to several factors, including differing starting resistances; both men and women in the LOW CRF group had objectively higher starting resistance on the BCBT protocol than the males in the HIGH CRF group because the protocol relies on body mass alone. About 71% (15/21) of people in the HIGH CRF group completed the full protocol. Similar measures such as the Canadian Aerobic Fitness Test (CAFT) and modified CAFT submaximal tests (Weller et al., 1992) exhibited similar ceiling effects. These effects were corrected by adding additional stages for the test to address this issue (Weller et al., 1992). Additionally, floor effects on cardiorespiratory fitness testing have been noted in untrained populations with chronic illnesses (Campos et al., 2018; Granger et al., 2015; Maddocks et al., 2017; Parry et al., 2015). Although none of our sample had chronic illness, no one in the LOW CRF group completed the last two stages (e.g., stage 14 and 15) of the BCBT, and it should be noted that only one person in the study met the VAS stopping criteria (a female in the HIGH CRF group). This alone is not indicative of a floor effect, as times of test completion did vary in the LOW CRF group, and no one in the LOW CRF group failed due to symptom exacerbation in our non-concussed sample. Overall, the majority of the sample (24/42) stopped due to meeting 90% of their age predicted heartrate max. Compared to a previous study using the BCBT in healthy individuals, 50% (10/20) of the sample completed the BCBT and reported zero concussion-related symptoms on the VAS. In our study VAS scores ranged from 0 to 3 (which met stopping criteria for one individual), and is more in line with previous literature that showed that healthy individuals are rarely asymptomatic at baseline (Alla et al., 2012).

Hypothesis two stated that participants in the high CRF group will have lower peak heart rate for the first four stages of the BCBT protocol than the participants in the low CRF group and was supported. Many previous studies have shown an effect of training on lowering heart rate at rest (Cornelissen et al., 2010) and during exercise (Borresen & Lambert, 2008; Levy et al., 1998). Many studies have noted several reasons for this decrease in heart rate with training. This could be due to the heart muscles increased strength and ability to pump more blood per beat; therefore, the heart become more efficient and needs fewer beats to deliver the same amount of oxygen (Borresen & Lambert, 2008; Smith et al., 1989). Additionally, the sympathetic and parasympathetic systems can affect heart rate and are influenced by training. Smith and colleagues (Smith et al., 1989) suggested that the decrease in heart rate following training was due to a decrease in the intrinsic rhythmicity of the heart and an increase in the predominance of a parasympathetic control.

The third hypothesis that stated males and females would not differ significantly on time-to-test completion on the BCBT was supported. A previous study on the treadmill version of the Buffalo test reported that males and females did not differ on total treadmill time (Chizuk et al., 2021). Similar to the treadmill version, males and females did not differ on time-to-test completion in our non-concussed sample. The fourth hypothesis stated that females will have a significantly higher heart rate at test completion during exercise on the BCBT compared to their male counterparts and was not supported; however, it was not sufficiently powered and, although not significant, females did have higher median and average heart rates compared to their male counter parts. A previous study on the BCTT noted females had a higher resting HR and higher heart rate symptom threshold; however, males and females did not differ on change from resting heart rate to heart rate symptom threshold, and time-to-test completion (Chizuk et al., 2021). Several factors could contribute to this difference in previous literature and the current study. Firstly, the current study included only non-concussed individuals that met CRF requirements to participate. Of the current sample, and only one participant met symptom exacerbation on the VAS, where in the Chizuk et al., (2021) study, they had concussed and symptomatic participants that met symptom thresholds for stopping the Buffalo Concussion Treadmill test. Additionally, the current study was underpowered and therefore could be missing true differences. Lastly, Chizuk and colleagues had younger sample (13-18 years) compared to those in the current sample and likely had lighter body mass due to this, therefore an easier starting resistance. These differences likely account for the discrepancies between the literature and the findings in the current study.

## Strengths and Limitations

This study is limited by the following: the ability of participants to report symptoms accurately and honestly. False or inaccurate symptoms may threaten validity and reliability of the symptom threshold timing; therefore, the time to end of the BCBT. There may have been a tendency to under or over report symptoms based on differing motivations for ending the test early or pushing through the stopping criteria. Additionally, the outcomes on the BCBT are subject to the participants' ability to put forth maximum effort. Participants will not be screened using a gold standard test battery to rule out autonomic dysfunction, and the researchers will rely on self-reported health history for deciding if inclusion and exclusion criteria are met. Additionally, the study was underpowered to identify sex differences in outcomes of the BCBT. Secondly, males and females did have different VO2max cutoffs for groups according to the ACSM guidelines. This did create differences in CRF level between high and LOW CRF groups where high females that were close to the lower end of the cutoff might be more similar to males that are on the upper limit of the LOW CRF group. This potential limitation was combatted with fact that there were still significant group difference findings for the high and LOW CRF groups. Strengths of the current study include the extreme groups approach for finding differences. Additionally, the sample was well-controlled for confounding factors such as menstrual cycle. Females were required to be on a form of hormonal birth control to qualify for the study to control for fluctuations in hormones that affected symptom reporting on concussion scales. A previous study by Malleck and colleagues (2019) revealed that eumenorrheic females had systematic changes in individual symptoms across their menstrual cycle, whereas females taking hormonal contraceptives showed no differences over time (Malleck et al., 2019). Other potentially confounding factors that were controlled for were history of concussion, migraine treatment, and cardiac irregularities including those associated with autonomic dysfunction or exercise intolerance.

### Future research

Future research should determine how many additional stages of the BCBT are needed to fix the ceiling effects noted in the current study. Secondly, future research should investigate sex differences on the BCBT in healthy and concussed samples to determine if further revisions of the protocol are called for. Additionally, future research should repeat the current findings in high and low CRF groups following concussion. CRF level can be estimated by step-tests, athlete type, and physical activity participation (Buttar et al., 2019; George et al., 1993; Zwiren et al., 1991). Lastly, further studies are needed to establish a gold standard for identifying exercise intolerance secondary to autonomic dysfunction in concussed athletes.

### Conclusion

Non-concussed individuals in the low group were unable to complete the 30-minute BCBT protocol, and individuals in the high CRF group exhibited a ceiling effect on the BCBT. However, they did not exhibit significantly different scores on the PCSS before or after the BCBT compared to individuals in the low CRF group. The implications of these findings are that the BCBT did not allow participants with high CRF to meet 90% of their HR max, post-injury participants may be falsely given clearance to exercise without restriction because the BCBT was not adequately challenging. Males and females did not differ on time-to-test completion or peak heart rate, additionally, they exhibited similar VOMS change scores before and after the BCBT protocol. The findings for the current study further support the literature and highlight the need for CRF level considerations for the BCBT protocol. Clinicians should adapt the protocol (e.g., add additional stages or increase starting resistance) for individuals with high CRF level to make sure patients are reaching the required 90% of their age predicted max heart rate to determine true symptom exacerbation in concussed induvial.

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# Appendices

## Appendix 1: Buffalo Concussion Bike Test Manual

### BUFFALO CONCUSSION BIKE TEST (BCBT) – INSTRUCTION MANUAL

John J Leddy, Mohammad N Haider, Barry S Willer

**Purpose**

To assess the degree of exercise tolerance in patients with concussion.
To identify the heart rate (HR) at which concussion-specific symptom exacerbation occurs (i.e. the Heart Rate Threshold [HRt]).
To help establish a safe level of exercise for treatment of concussion.
To help differentiate between concussion and other possible diagnoses for concussive symptoms (e.g. cervicogenic post-traumatic disorder).
To identify physiological variables associated with exacerbation of symptoms, and the patient's level of recovery.

**Caution**

**The BCBT alone should never been used to make a diagnosis of concussion or clearance to begin the return-to-play protocol. The BCBT is a supplementary test and should be interpreted alongside a complete history and physical examination.**

**Eligibility**

The BCBT is designed for patients who have significant vestibular/balance problems which prevents them from walking safely on a treadmill.
Before beginning the BCBT, participants should be evaluated for any contraindications to exercise testing. The AHA Guidelines contraindications to exercise testing are as follows:

**Absolute Contraindications**

Acute myocardial infarction (within 2 days)
High-risk unstable angina
Uncontrolled cardiac arrhythmias causing symptoms or hemodynamic compromise
Symptomatic severe aortic stenosis
Uncontrolled symptomatic heart failure
Acute pulmonary embolus or infarction
Acute myocarditis or pericarditis
Acute aortic dissection

**Relative Contraindications**

Left main coronary stenosis
Moderate stenotic valvular heart disease
Electrolyte imbalance
Severe arterial hypertension (>200 mmHg systolic or >110 mmHg diastolic)
Tachyarrhythmia or bradyarrhythmia
Hypertrophic cardiomyopathy and other forms of outflow tract obstruction
Mental or physical impairment leading to inability to exercise adequately
High-degree atrioventricular block

The BCBT is not recommended within 24 hours of concussive brain injury or if the patient is too symptomatic (symptom severity 7/10 or more).

**Safety Considerations**

While testing, participants must be dressed for exercise (comfortable clothing, running shoes), wearing any vision or hearing aids (glasses, etc.), and should be hydrated.
It is suggested that at least 1 person trained in CPR be present at the time the test is being performed.

- It is important to engage in casual conversation with the patient during the exercise test to assess his/her confidence level as well as any changes in cognitive and communicative functioning. As exercise intensifies, note if patient seems to have difficulty communicating, looks suddenly pale or withdrawn, or otherwise appears to be masking serious discomfort.
- Be aware of postural and structural changes (slouching, rounding the back, leaning head) since noting the patient's thoracic and cervical posture can offer clues on the etiology of the injury.

### Equipment Requirements

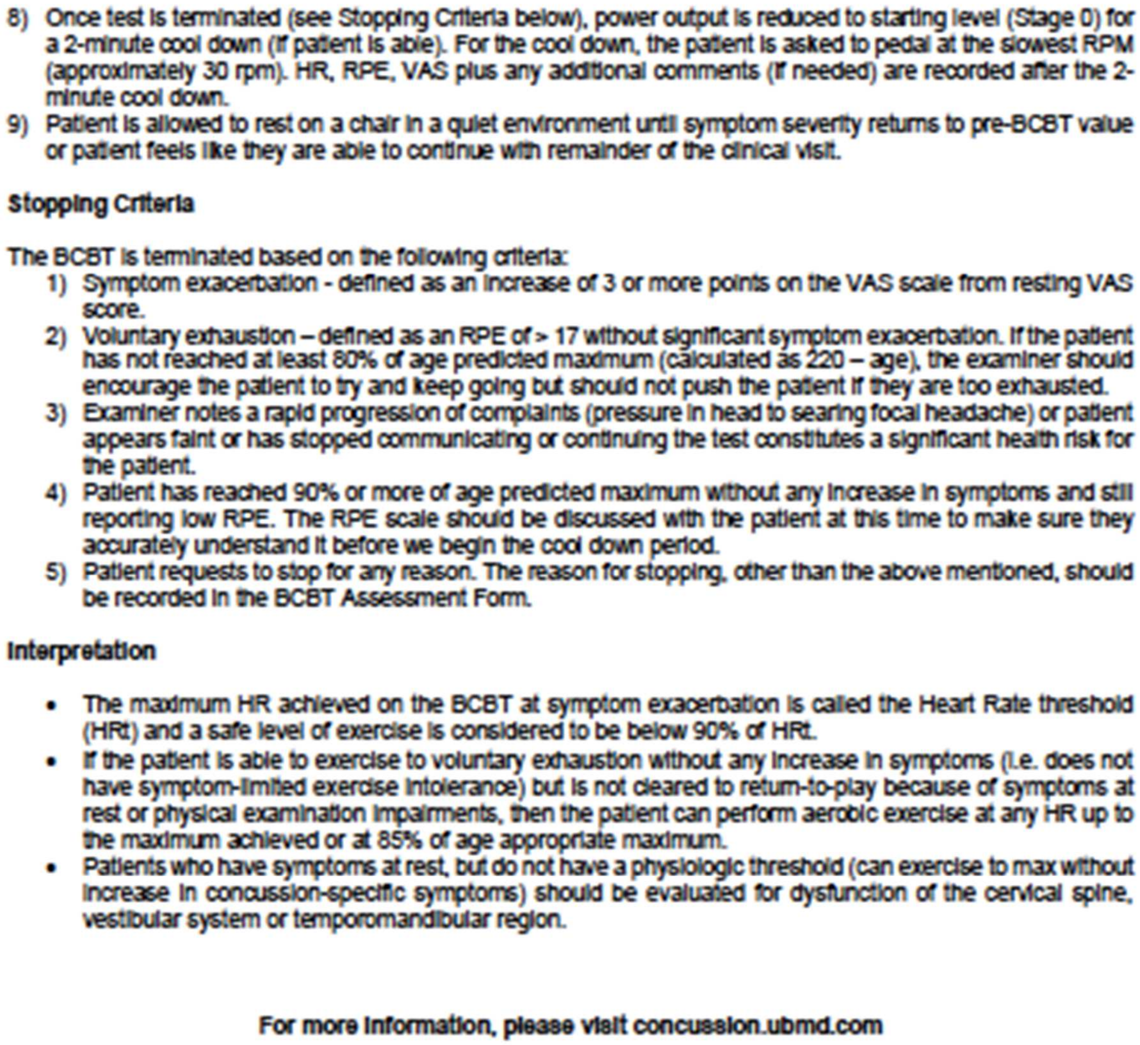
- Recumbent or upright stationary bike capable of maintaining a constant power output or "workload" (measured in Watts) that can be controlled by the test administrator.
- HR monitor (Polar OH arm band or chest band is recommended).
- BCBT Assessment Form for monitoring HR, power output, symptom severity, RPE and relevant observations – *See form attached*
- BCBT Weight to Power/Watt Conversion Table. - *See fprm attached*
- Visual Analogue Scale (VAS): Can be explained to patients as a measure of "how bad their concussion-specific symptoms are". It should be clarified that getting tired from cycling on a cycle ergometer is not a concussion-specific symptom and should be reported in the next scale - *See form attached*
- Borg Rating of Perceived Exertion (RPE): Can be explained to patients as a measure of "how hard you feel like you're working out". The scale ranges from 6 – 20, 6 being no exertion and 20 being the maximum they can ever do. Descriptors of each exercise intensity level should be pointed out and patient should be allowed to read through it before the test begins.- *See form attached*
- Chair, water and towel for patient recovery after exercise.

### Setup

- Attach HR monitoring device according to manufacturer's instructions.
- Determine power out required for each stage according to patient's weight.
- Place RPE and VAS scales within comfortable viewing distance of participant while on cycle ergometer (it is suggested that participants should not have to turn head to view scales).

### Test Protocol

1) Inform participant about test procedures and what to expect during the BCBT. Review in detail that the purpose is not to "push through" symptoms but to honestly report them.
2) Explain and demonstrate the RPE and VAS and obtain resting scores. Remind participant that he/she will be asked to rate RPE and symptom severity every 2 minutes during exercise.
3) Obtain resting HR after 2-minute seated position before getting the patient on cycle ergometer.
4) Care should be taken to ensure the cycle ergometer settings, such as seat and handle bar heights, are appropriate to the participant. The participant should not assume a standing position at any time during the protocol.
5) The HR at Stage 0 is the HR when the patient is sitting on the cycle ergometer immediately after starting the BCBT and not after the 2-minute seated rest.
6) Tell the participant to start pedaling at 60 ± 5 RPM. Participant must maintain a relatively consistent pace throughout the test.
7) After 2 minutes at this power output, adjust power output for Stage 1. Ask participant to rate exertion on RPE and symptom severity on VAS at the beginning of each stage. Record HR at the beginning of each stage. Examiner should also record general observations as the test progresses if needed. This procedure is repeated every 2 minutes with the power output at the subsequent stage.
   Changes to VAS rating should be specifically clarified/noted, for example, if the rating moves from 2 to 3, it should be clarified if this reflects the addition of a new symptom and/or increased severity of an existing symptom. 1-point is given for any worsening of a symptom and 1-point for the addition of a new symptom, for example, if the patient reports symptom severity change from 2/10 to 3/10 and reports slight increase of headache and onset of light sensitivity, then this should be considered a 2-point increase to 4/10.



8) Once test is terminated (see Stopping Criteria below), power output is reduced to starting level (Stage 0) for a 2-minute cool down (if patient is able). For the cool down, the patient is asked to pedal at the slowest RPM (approximately 30 rpm). HR, RPE, VAS plus any additional comments (if needed) are recorded after the 2-minute cool down.
9) Patient is allowed to rest on a chair in a quiet environment until symptom severity returns to pre-BCBT value or patient feels like they are able to continue with remainder of the clinical visit.

**Stopping Criteria**

The BCBT is terminated based on the following criteria:

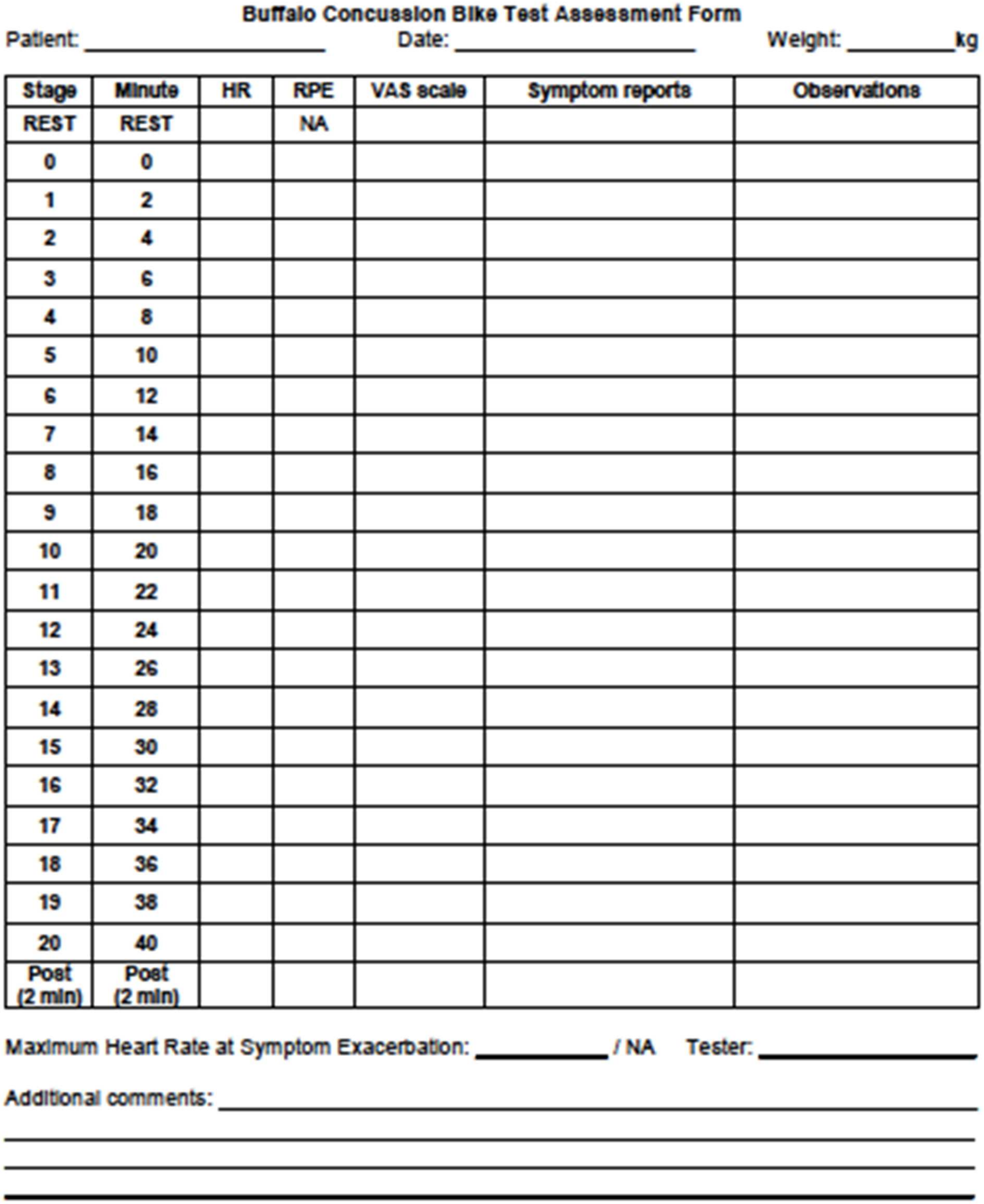
1) Symptom exacerbation - defined as an increase of 3 or more points on the VAS scale from resting VAS score.
2) Voluntary exhaustion – defined as an RPE of > 17 without significant symptom exacerbation. If the patient has not reached at least 80% of age predicted maximum (calculated as 220 – age), the examiner should encourage the patient to try and keep going but should not push the patient if they are too exhausted.
3) Examiner notes a rapid progression of complaints (pressure in head to searing focal headache) or patient appears faint or has stopped communicating or continuing the test constitutes a significant health risk for the patient.
4) Patient has reached 90% or more of age predicted maximum without any increase in symptoms and still reporting low RPE. The RPE scale should be discussed with the patient at this time to make sure they accurately understand it before we begin the cool down period.
5) Patient requests to stop for any reason. The reason for stopping, other than the above mentioned, should be recorded in the BCBT Assessment Form.

**Interpretation**

- The maximum HR achieved on the BCBT at symptom exacerbation is called the Heart Rate threshold (HRt) and a safe level of exercise is considered to be below 90% of HRt.
- If the patient is able to exercise to voluntary exhaustion without any increase in symptoms (i.e. does not have symptom-limited exercise intolerance) but is not cleared to return-to-play because of symptoms at rest or physical examination impairments, then the patient can perform aerobic exercise at any HR up to the maximum achieved or at 85% of age appropriate maximum.
- Patients who have symptoms at rest, but do not have a physiologic threshold (can exercise to max without increase in concussion-specific symptoms) should be evaluated for dysfunction of the cervical spine, vestibular system or temporomandibular region.

**For more information, please visit concussion.ubmd.com**

## Appendix 2: Buffalo Concussion Bike Test Data Collection Form



**Buffalo Concussion Bike Test Assessment Form**

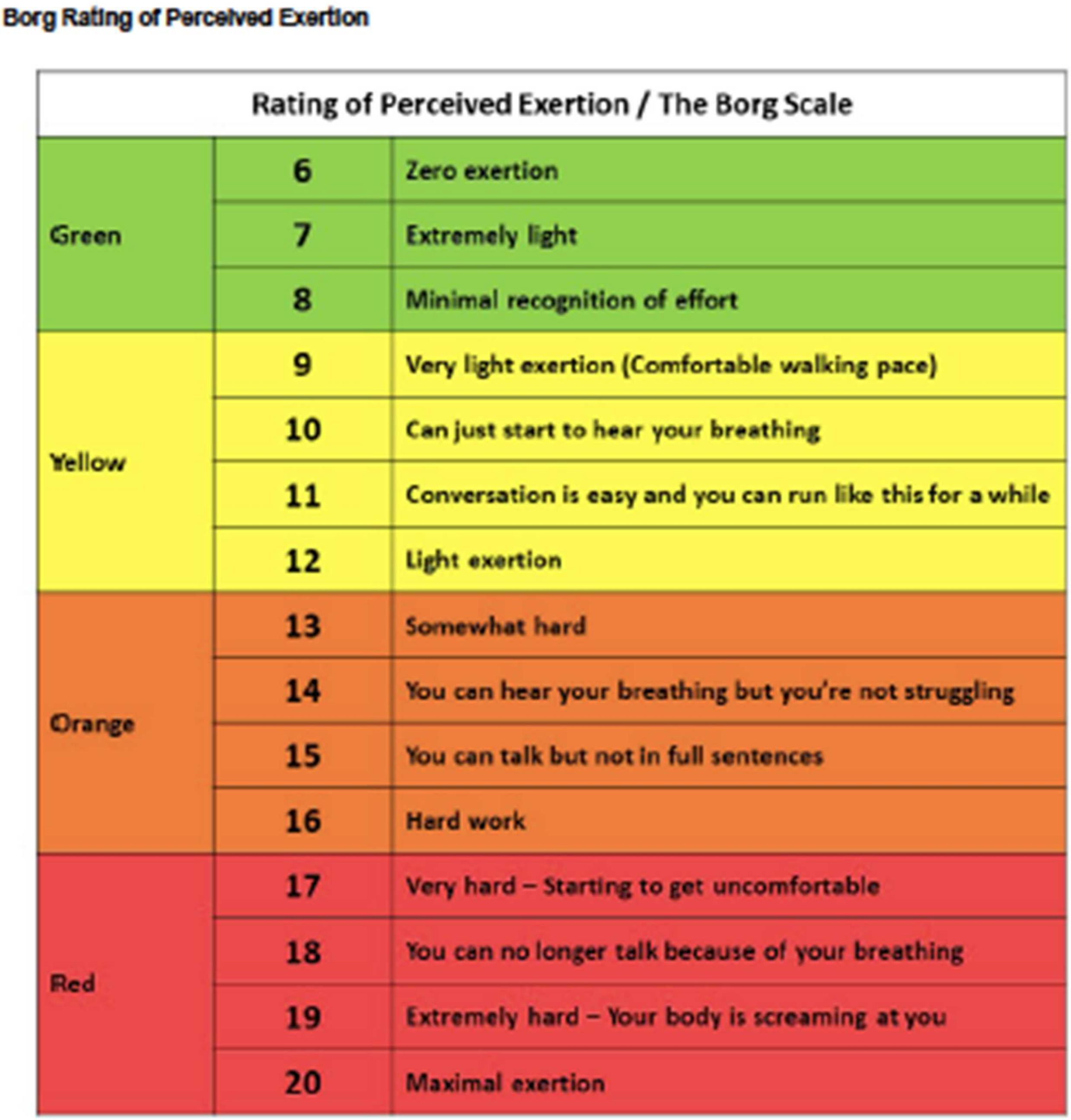
Patient: ____________________ Date: ____________________ Weight: _________kg

| Stage | Minute | HR | RPE | VAS scale | Symptom reports | Observations |
|---|---|---|---|---|---|---|
| REST | REST | | NA | | | |
| 0 | 0 | | | | | |
| 1 | 2 | | | | | |
| 2 | 4 | | | | | |
| 3 | 6 | | | | | |
| 4 | 8 | | | | | |
| 5 | 10 | | | | | |
| 6 | 12 | | | | | |
| 7 | 14 | | | | | |
| 8 | 16 | | | | | |
| 9 | 18 | | | | | |
| 10 | 20 | | | | | |
| 11 | 22 | | | | | |
| 12 | 24 | | | | | |
| 13 | 26 | | | | | |
| 14 | 28 | | | | | |
| 15 | 30 | | | | | |
| 16 | 32 | | | | | |
| 17 | 34 | | | | | |
| 18 | 36 | | | | | |
| 19 | 38 | | | | | |
| 20 | 40 | | | | | |
| Post (2 min) | Post (2 min) | | | | | |

Maximum Heart Rate at Symptom Exacerbation: __________ / NA Tester: ________________

Additional comments: ______________________________________________

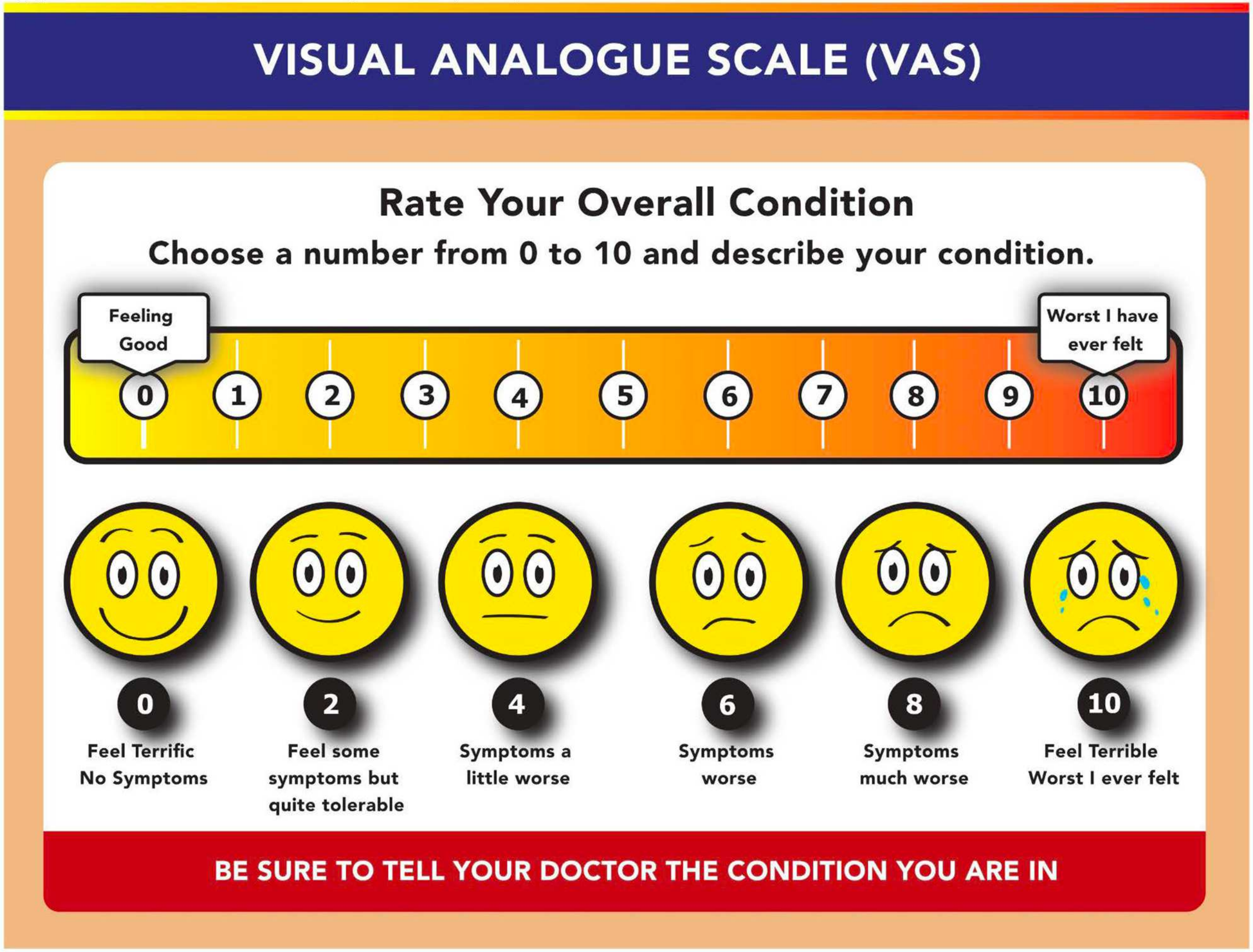
## Appendix 3: Borg Rating of Perceived Exertion (RPE Scale)



Borg Rating of Perceived Exertion

| Rating of Perceived Exertion / The Borg Scale | | |
|---|---|---|
| Green | 6 | Zero exertion |
| | 7 | Extremely light |
| | 8 | Minimal recognition of effort |
| Yellow | 9 | Very light exertion (Comfortable walking pace) |
| | 10 | Can just start to hear your breathing |
| | 11 | Conversation is easy and you can run like this for a while |
| | 12 | Light exertion |
| Orange | 13 | Somewhat hard |
| | 14 | You can hear your breathing but you're not struggling |
| | 15 | You can talk but not in full sentences |
| | 16 | Hard work |
| Red | 17 | Very hard – Starting to get uncomfortable |
| | 18 | You can no longer talk because of your breathing |
| | 19 | Extremely hard – Your body is screaming at you |
| | 20 | Maximal exertion |

## Appendix 4: Visual Analog Scale (VAS)



VISUAL ANALOGUE SCALE (VAS)

Rate Your Overall Condition

Choose a number from 0 to 10 and describe your condition.

0 Feel Terrific No Symptoms

2 Feel some symptoms but quite tolerable

4 Symptoms a little worse

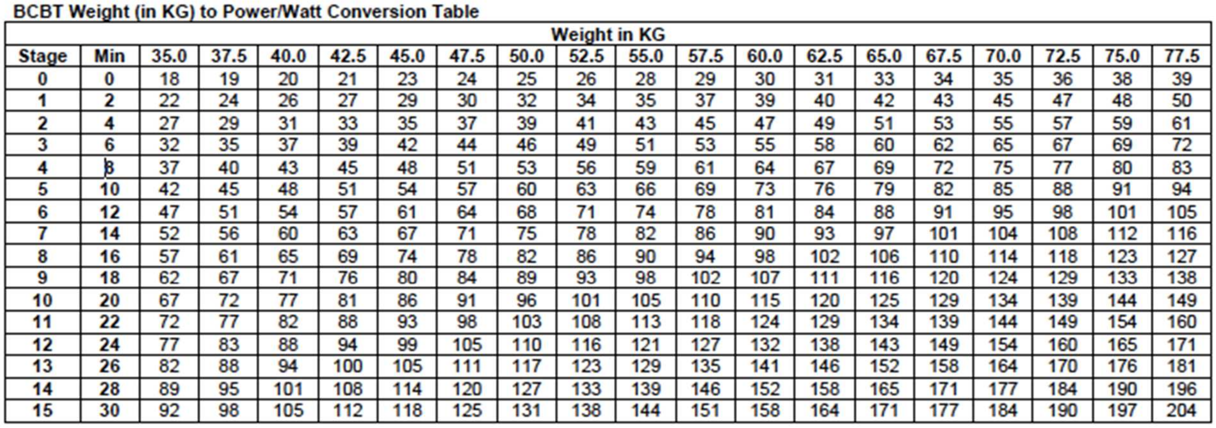
6 Symptoms worse

8 Symptoms much worse

10 Feel Terrible Worst I ever felt

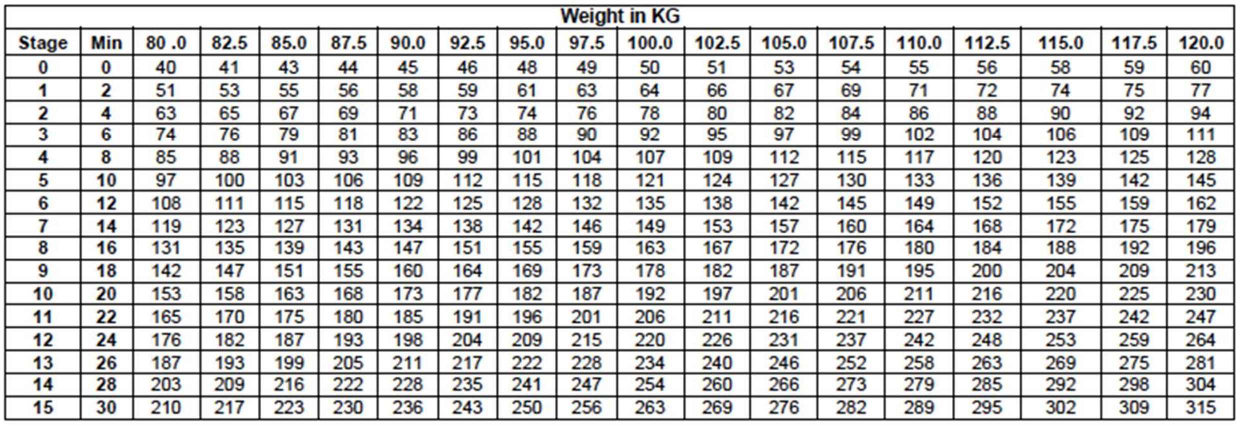
BE SURE TO TELL YOUR DOCTOR THE CONDITION YOU ARE IN

## Appendix 5: Buffalo Concussion Bike Test Resistance Stages by Mass



BCBT Weight (in KG) to Power/Watt Conversion Table

| | | Weight in KG | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Stage** | **Min** | **35.0** | **37.5** | **40.0** | **42.5** | **45.0** | **47.5** | **50.0** | **52.5** | **55.0** | **57.5** | **60.0** | **62.5** | **65.0** | **67.5** | **70.0** | **72.5** | **75.0** | **77.5** |
| **0** | **0** | 18 | 19 | 20 | 21 | 23 | 24 | 25 | 26 | 28 | 29 | 30 | 31 | 33 | 34 | 35 | 36 | 38 | 39 |
| **1** | **2** | 22 | 24 | 26 | 27 | 29 | 30 | 32 | 34 | 35 | 37 | 39 | 40 | 42 | 43 | 45 | 47 | 48 | 50 |
| **2** | **4** | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 |
| **3** | **6** | 32 | 35 | 37 | 39 | 42 | 44 | 46 | 49 | 51 | 53 | 55 | 58 | 60 | 62 | 65 | 67 | 69 | 72 |
| **4** | **8** | 37 | 40 | 43 | 45 | 48 | 51 | 53 | 56 | 59 | 61 | 64 | 67 | 69 | 72 | 75 | 77 | 80 | 83 |
| **5** | **10** | 42 | 45 | 48 | 51 | 54 | 57 | 60 | 63 | 66 | 69 | 73 | 76 | 79 | 82 | 85 | 88 | 91 | 94 |
| **6** | **12** | 47 | 51 | 54 | 57 | 61 | 64 | 68 | 71 | 74 | 78 | 81 | 84 | 88 | 91 | 95 | 98 | 101 | 105 |
| **7** | **14** | 52 | 56 | 60 | 63 | 67 | 71 | 75 | 78 | 82 | 86 | 90 | 93 | 97 | 101 | 104 | 108 | 112 | 116 |
| **8** | **16** | 57 | 61 | 65 | 69 | 74 | 78 | 82 | 86 | 90 | 94 | 98 | 102 | 106 | 110 | 114 | 118 | 123 | 127 |
| **9** | **18** | 62 | 67 | 71 | 76 | 80 | 84 | 89 | 93 | 98 | 102 | 107 | 111 | 116 | 120 | 124 | 129 | 133 | 138 |
| **10** | **20** | 67 | 72 | 77 | 81 | 86 | 91 | 96 | 101 | 105 | 110 | 115 | 120 | 125 | 129 | 134 | 139 | 144 | 149 |
| **11** | **22** | 72 | 77 | 82 | 88 | 93 | 98 | 103 | 108 | 113 | 118 | 124 | 129 | 134 | 139 | 144 | 149 | 154 | 160 |
| **12** | **24** | 77 | 83 | 88 | 94 | 99 | 105 | 110 | 116 | 121 | 127 | 132 | 138 | 143 | 149 | 154 | 160 | 165 | 171 |
| **13** | **26** | 82 | 88 | 94 | 100 | 105 | 111 | 117 | 123 | 129 | 135 | 141 | 146 | 152 | 158 | 164 | 170 | 176 | 181 |
| **14** | **28** | 89 | 95 | 101 | 108 | 114 | 120 | 127 | 133 | 139 | 146 | 152 | 158 | 165 | 171 | 177 | 184 | 190 | 196 |
| **15** | **30** | 92 | 98 | 105 | 112 | 118 | 125 | 131 | 138 | 144 | 151 | 158 | 164 | 171 | 177 | 184 | 190 | 197 | 204 |



| | | Weight in KG | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Stage** | **Min** | **80 .0** | **82.5** | **85.0** | **87.5** | **90.0** | **92.5** | **95.0** | **97.5** | **100.0** | **102.5** | **105.0** | **107.5** | **110.0** | **112.5** | **115.0** | **117.5** | **120.0** |
| **0** | **0** | 40 | 41 | 43 | 44 | 45 | 46 | 48 | 49 | 50 | 51 | 53 | 54 | 55 | 56 | 58 | 59 | 60 |
| **1** | **2** | 51 | 53 | 55 | 56 | 58 | 59 | 61 | 63 | 64 | 66 | 67 | 69 | 71 | 72 | 74 | 75 | 77 |
| **2** | **4** | 63 | 65 | 67 | 69 | 71 | 73 | 74 | 76 | 78 | 80 | 82 | 84 | 86 | 88 | 90 | 92 | 94 |
| **3** | **6** | 74 | 76 | 79 | 81 | 83 | 86 | 88 | 90 | 92 | 95 | 97 | 99 | 102 | 104 | 106 | 109 | 111 |
| **4** | **8** | 85 | 88 | 91 | 93 | 96 | 99 | 101 | 104 | 107 | 109 | 112 | 115 | 117 | 120 | 123 | 125 | 128 |
| **5** | **10** | 97 | 100 | 103 | 106 | 109 | 112 | 115 | 118 | 121 | 124 | 127 | 130 | 133 | 136 | 139 | 142 | 145 |
| **6** | **12** | 108 | 111 | 115 | 118 | 122 | 125 | 128 | 132 | 135 | 138 | 142 | 145 | 149 | 152 | 155 | 159 | 162 |
| **7** | **14** | 119 | 123 | 127 | 131 | 134 | 138 | 142 | 146 | 149 | 153 | 157 | 160 | 164 | 168 | 172 | 175 | 179 |
| **8** | **16** | 131 | 135 | 139 | 143 | 147 | 151 | 155 | 159 | 163 | 167 | 172 | 176 | 180 | 184 | 188 | 192 | 196 |
| **9** | **18** | 142 | 147 | 151 | 155 | 160 | 164 | 169 | 173 | 178 | 182 | 187 | 191 | 195 | 200 | 204 | 209 | 213 |
| **10** | **20** | 153 | 158 | 163 | 168 | 173 | 177 | 182 | 187 | 192 | 197 | 201 | 206 | 211 | 216 | 220 | 225 | 230 |
| **11** | **22** | 165 | 170 | 175 | 180 | 185 | 191 | 196 | 201 | 206 | 211 | 216 | 221 | 227 | 232 | 237 | 242 | 247 |
| **12** | **24** | 176 | 182 | 187 | 193 | 198 | 204 | 209 | 215 | 220 | 226 | 231 | 237 | 242 | 248 | 253 | 259 | 264 |
| **13** | **26** | 187 | 193 | 199 | 205 | 211 | 217 | 222 | 228 | 234 | 240 | 246 | 252 | 258 | 263 | 269 | 275 | 281 |
| **14** | **28** | 203 | 209 | 216 | 222 | 228 | 235 | 241 | 247 | 254 | 260 | 266 | 273 | 279 | 285 | 292 | 298 | 304 |
| **15** | **30** | 210 | 217 | 223 | 230 | 236 | 243 | 250 | 256 | 263 | 269 | 276 | 282 | 289 | 295 | 302 | 309 | 315 |

# Appendix 6: American College of Sports Medicine VO2 max Categories

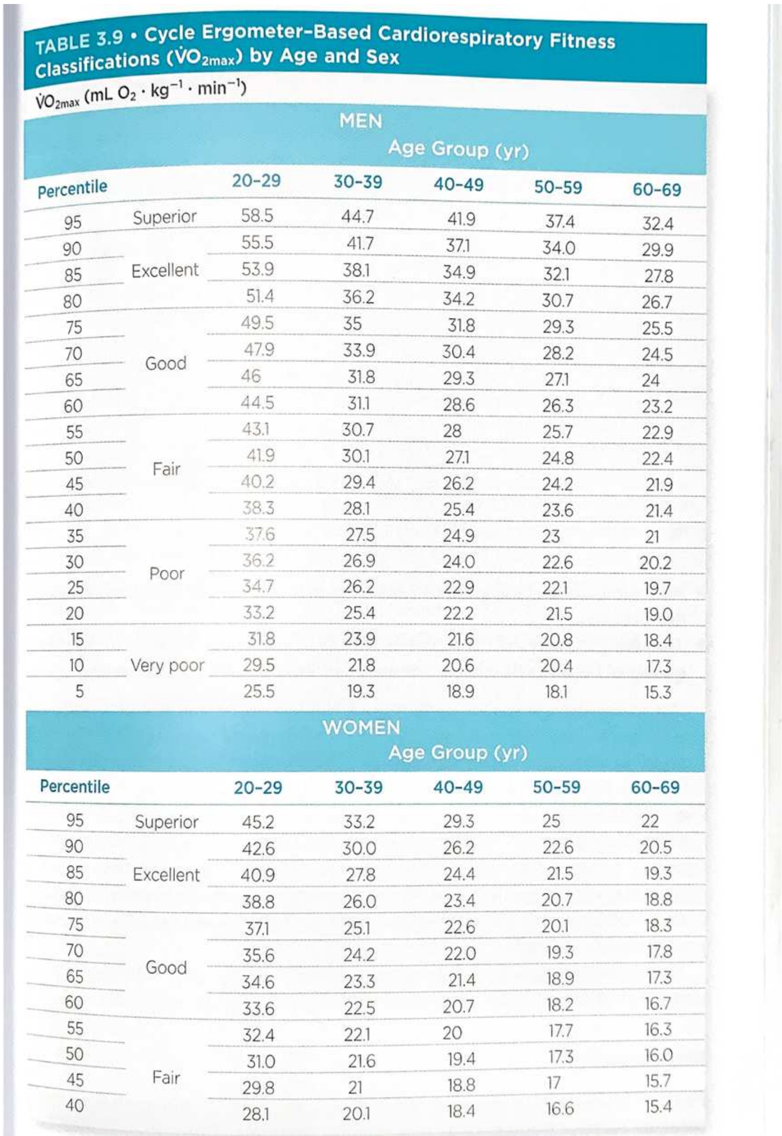


**TABLE 3.9 • Cycle Ergometer-Based Cardiorespiratory Fitness Classifications ($\dot{V}O_{2max}$) by Age and Sex**

$\dot{V}O_{2max}$ (mL $O_2 \cdot kg^{-1} \cdot min^{-1}$)

**MEN**

| Percentile | | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 |
|---|---|---|---|---|---|---|
| 95 | Superior | 58.5 | 44.7 | 41.9 | 37.4 | 32.4 |
| 90 | Excellent | 55.5 | 41.7 | 37.1 | 34.0 | 29.9 |
| 85 | | 53.9 | 38.1 | 34.9 | 32.1 | 27.8 |
| 80 | | 51.4 | 36.2 | 34.2 | 30.7 | 26.7 |
| 75 | Good | 49.5 | 35 | 31.8 | 29.3 | 25.5 |
| 70 | | 47.9 | 33.9 | 30.4 | 28.2 | 24.5 |
| 65 | | 46 | 31.8 | 29.3 | 27.1 | 24 |
| 60 | | 44.5 | 31.1 | 28.6 | 26.3 | 23.2 |
| 55 | Fair | 43.1 | 30.7 | 28 | 25.7 | 22.9 |
| 50 | | 41.9 | 30.1 | 27.1 | 24.8 | 22.4 |
| 45 | | 40.2 | 29.4 | 26.2 | 24.2 | 21.9 |
| 40 | | 38.3 | 28.1 | 25.4 | 23.6 | 21.4 |
| 35 | Poor | 37.6 | 27.5 | 24.9 | 23 | 21 |
| 30 | | 36.2 | 26.9 | 24.0 | 22.6 | 20.2 |
| 25 | | 34.7 | 26.2 | 22.9 | 22.1 | 19.7 |
| 20 | | 33.2 | 25.4 | 22.2 | 21.5 | 19.0 |
| 15 | Very poor | 31.8 | 23.9 | 21.6 | 20.8 | 18.4 |
| 10 | | 29.5 | 21.8 | 20.6 | 20.4 | 17.3 |
| 5 | | 25.5 | 19.3 | 18.9 | 18.1 | 15.3 |

**WOMEN**

| Percentile | | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 |
|---|---|---|---|---|---|---|
| 95 | Superior | 45.2 | 33.2 | 29.3 | 25 | 22 |
| 90 | Excellent | 42.6 | 30.0 | 26.2 | 22.6 | 20.5 |
| 85 | | 40.9 | 27.8 | 24.4 | 21.5 | 19.3 |
| 80 | | 38.8 | 26.0 | 23.4 | 20.7 | 18.8 |
| 75 | Good | 37.1 | 25.1 | 22.6 | 20.1 | 18.3 |
| 70 | | 35.6 | 24.2 | 22.0 | 19.3 | 17.8 |
| 65 | | 34.6 | 23.3 | 21.4 | 18.9 | 17.3 |
| 60 | | 33.6 | 22.5 | 20.7 | 18.2 | 16.7 |
| 55 | Fair | 32.4 | 22.1 | 20 | 17.7 | 16.3 |
| 50 | | 31.0 | 21.6 | 19.4 | 17.3 | 16.0 |
| 45 | | 29.8 | 21 | 18.8 | 17 | 15.7 |
| 40 | | 28.1 | 20.1 | 18.4 | 16.6 | 15.4 |

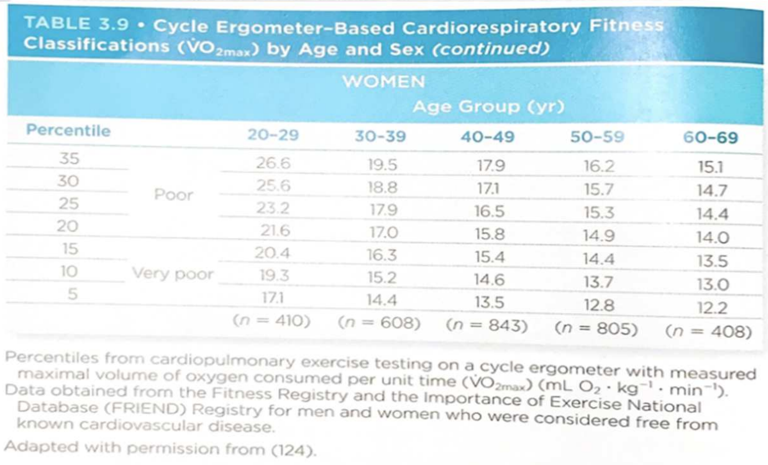


**TABLE 3.9 • Cycle Ergometer-Based Cardiorespiratory Fitness Classifications ($\dot{V}O_{2max}$) by Age and Sex *(continued)***

**WOMEN**

| Percentile | | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 |
|---|---|---|---|---|---|---|
| 35 | Poor | 26.6 | 19.5 | 17.9 | 16.2 | 15.1 |
| 30 | | 25.6 | 18.8 | 17.1 | 15.7 | 14.7 |
| 25 | | 23.2 | 17.9 | 16.5 | 15.3 | 14.4 |
| 20 | | 21.6 | 17.0 | 15.8 | 14.9 | 14.0 |
| 15 | Very poor | 20.4 | 16.3 | 15.4 | 14.4 | 13.5 |
| 10 | | 19.3 | 15.2 | 14.6 | 13.7 | 13.0 |
| 5 | | 17.1 | 14.4 | 13.5 | 12.8 | 12.2 |
| | | (*n* = 410) | (*n* = 608) | (*n* = 843) | (*n* = 805) | (*n* = 408) |

Percentiles from cardiopulmonary exercise testing on a cycle ergometer with measured maximal volume of oxygen consumed per unit time ($\dot{V}O_{2max}$) (mL $O_2 \cdot kg^{-1} \cdot min^{-1}$).

Data obtained from the Fitness Registry and the Importance of Exercise National Database (FRIEND) Registry for men and women who were considered free from known cardiovascular disease.

Adapted with permission from (124).

## Appendix 7: Demographics and Exercise Contraindications Form

### Demographics and Exercise Contraindications

**Participant number: _______**
**Age: ______**
**Sex: ______**
**Weight: ______**
**For females:**
    **Oral contraceptive use (must be yes): ______**
    **Date of beginning of last menstrual cycle: ______**
    **Length of menstrual cycle: ______**

**Do they have a past medical history of contraindications to (ALL MUST BE NO TO ENROLL IN THE STUDY):**

| Past medical history item: | Y/N |
|---|---|
| Acute myocardial infarction | |
| high-risk unstable angina | |
| uncontrolled cardiac arrhythmias | |
| symptomatic angina | |
| uncontrolled symptomatic heart failure | |
| acute pulmonary embolus or infarction | |
| pericarditis or myocarditis | |
| acute aortic dissection | |
| heart disease | |
| pneumonia | |
| syncope | |
| coronary stenosis | |
| electrolyte imbalance | |
| severe hypertension > 200 systolic or >110 diastolic | |
| tachy- or brady-arrhythmia | |
| hypertrophic cardiomyopathy | |
| mental or physical impairment leading to an inability to exercise | |
| high-degree atrioventricular block | |
| Autonomic nervous system dysfunction or dysautonomia | |
| Concussion in the past year | |
| Vestibular disorder | |
| Migraine history | |

## Appendix 8: Medical Screening Form

### EXERCISE SCIENCE RESEARCH CENTER MEDICAL HISTORY QUESTIONNAIRE

**PLEASE ANSWER ALL OF THE FOLLOWING QUESTIONS AND PROVIDE DETAILS FOR ALL "YES" ANSWERS IN THE SPACES AT THE BOTTOM OF THE FORM.**

| YES | NO | | |
|---|---|---|---|
| yes | no | 1. | Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor? |
| yes | no | 2. | Has your doctor ever denied or restricted your participation in sports or exercise for any reason? |
| yes | no | 3. | Do you ever feel discomfort, pressure, or pain in your chest when you do physical activity? |
| yes | no | 4. | In the past month, have you had chest pain when you were not doing physical activity? |
| yes | no | 5. | Do you lose your balance because of dizziness or do you ever lose consciousness? |
| yes | no | 6. | Does your heart race or skip beats during exercise? |
| yes | no | 7. | Has a doctor ever ordered a test for you heart? (i.e. EKG, echocardiogram) |
| yes | no | 8. | Has anyone in your family died for no apparent reason or died from heart problems or sudden death before the age of 50? |
| yes | no | 9. | Have you ever had to spend the night in a hospital? |
| yes | no | 10. | Have you ever had surgery? Or do you have an implanted electromedical device? |
| yes | no | 11. | Have you been diagnosed with inflammatory bowel disease, gag reflex disorder or hypomotility of the gastrointestinal tract? |
| yes | no | 12. | Please check the box next to any of the following illnesses with which you have ever been diagnosed or for which you have been treated. |

- ☐ High blood pressure
- ☐ Asthma
- ☐ Bladder Problems
- ☐ Coronary artery disease
- ☐ Elevated cholesterol
- ☐ Epilepsy (seizures)
- ☐ Anemia
- ☐ Lung problems
- ☐ Diabetes
- ☐ Kidney problems
- ☐ Heart problems
- ☐ Chronic headaches

| YES | NO | | |
|---|---|---|---|
| yes | no | 13. | Have you ever gotten sick because of exercising in the heat? (i.e. cramps, heat exhaustion, heat stroke) |
| yes | no | 14. | Have you had any other significant illnesses not listed above? |
| yes | no | 15. | Do you currently have any illness? |
| yes | no | 16. | Do you know of <u>any other reason</u> why you should not do physical activity? |
| yes | no | 17. | Have you ever been diagnosed with diverticulitis, abdominal adhesions or have a history of abdominal obstructions? |
| yes | no | 18. | Please list all medications you are currently taking. Make sure to include over-the-counter medications and birth control pills. |

| Drugs/Supplements/Vitamins | Dose | Frequency (i.e. daily, 2x/day, etc.) |
|---|---|---|
| | | |
| | | |
| | | |

____________________ ____________ ______________

**DETAILS:** ______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

19. Please list all allergies you have.

| Substance | Reaction |
|---|---|
| | |
| | |
| | |
| | |

| YES | NO | 20. Have you smoked? | If yes, #/day | Age Started | If you've quit, what age? |
|---|---|---|---|---|---|
| yes | no | Cigarettes | | | |
| yes | no | Cigars | | | |
| yes | no | Pipes | | | |

| | | | | |
|---|---|---|---|---|
| yes | no | 21. Do you drink alcoholic beverages? | If yes, how much? | How often? |
| | | | | |

yes no 22. Do you have a family history of any of the following problems? If yes, note who in the space provided.

| | | | |
|---|---|---|---|
| ☐ High blood pressure | | ☐ Heart disease | |
| ☐ High cholesterol | | ☐ Kidney disease | |
| ☐ Diabetes | | ☐ Thyroid disease | |

yes no 23. Please check the box next to any of the following body parts you have injured in the past and provide details.

| | | | | | |
|---|---|---|---|---|---|
| ☐ Head | | ☐ Hip | | ☐ Calf/shin | |
| ☐ Neck | | ☐ Thigh | | ☐ Shoulder | |
| ☐ Upper back | | ☐ Knee | | ☐ Upper arm | |
| ☐ Lower back | | ☐ Ankle | | ☐ Elbow | |
| ☐ Chest | | ☐ Foot | | ☐ Hand/fingers | |

| YES | NO | |
|---|---|---|
| yes | no | 24. Have you ever had a stress fracture? |
| yes | no | 25. Have you ever had a disc injury in your back? |
| yes | no | 26. Has a doctor ever restricted your exercise because of an injury? |
| yes | no | 27. Do you currently have any injuries that are bothering you? |

28. Do you consider your occupation as?

☐ Sedentary (no exercise)
☐ Inactive-occasional light activity (walking)
☐ Active-regular light activity and/or occasional vigorous activity (heavy lifting, running, etc.)
☐ Heavy Work-regular vigorous activity

29. List your regular physical activities

| Activity | How often do you do it? | How long do you do it? | How long ago did you start? |
|---|---|---|---|
| ________ | ________ | ________ | ________ |
| ________ | ________ | ________ | ________ |
| ________ | ________ | ________ | ________ |
| ________ | ________ | ________ | ________ |

**ADDITIONAL DETAILS:** ____________________________________________
____________________________________________

## Appendix 9: Stopping Criteria for the BCBT

**Subject Number: ________**
**Subject Age: ______**
**Subject Age Predicted Max HR: _______**

**Justifications for stopping the BCBT:** criteria for ending the test include an increase of symptom reports by 3 or more points on the VAS, an RPE score of >17, inability to keep cycling at 60 ± 5 RPM, participant requests to quit for any reason, or reaching 90% of age predicted maximum heart rate.

**Time of test completion: _______**

**Reasoning for stopping the test: _________________________________________________**

**______________________________________________________________________________**

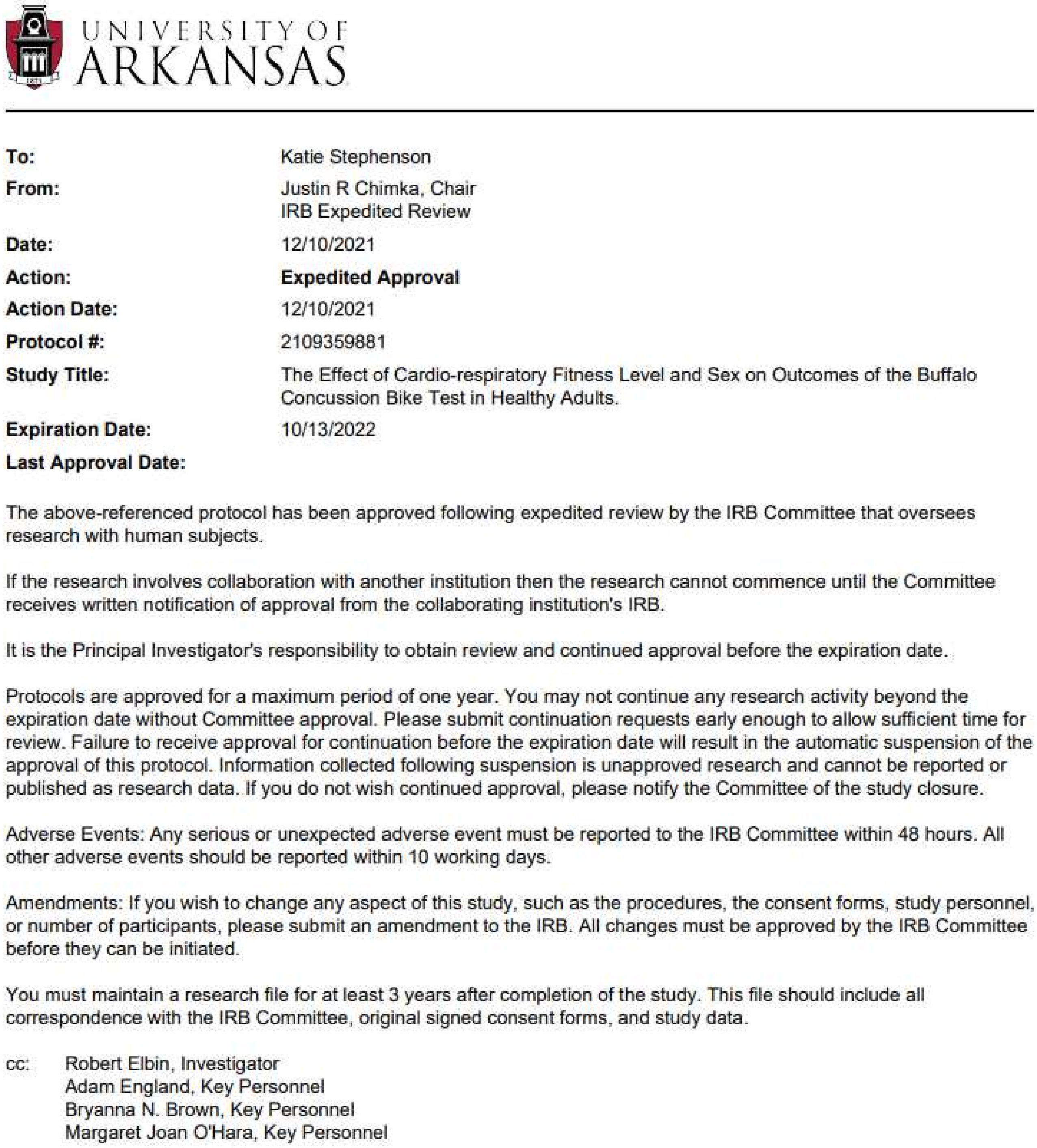
**Final RPE Score: _______**

**Final VAS Score: _______**

**Qualitatively describe symptoms: ________________________________________________**

**______________________________________________________________________________**

## Appendix 10: IRB Approval Letter



UNIVERSITY OF ARKANSAS

|  |  |
|---|---|
| **To:** | Katie Stephenson |
| **From:** | Justin R Chimka, Chair<br>IRB Expedited Review |
| **Date:** | 12/10/2021 |
| **Action:** | **Expedited Approval** |
| **Action Date:** | 12/10/2021 |
| **Protocol #:** | 2109359881 |
| **Study Title:** | The Effect of Cardio-respiratory Fitness Level and Sex on Outcomes of the Buffalo Concussion Bike Test in Healthy Adults. |
| **Expiration Date:** | 10/13/2022 |
| **Last Approval Date:** |  |

The above-referenced protocol has been approved following expedited review by the IRB Committee that oversees research with human subjects.

If the research involves collaboration with another institution then the research cannot commence until the Committee receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date.

Protocols are approved for a maximum period of one year. You may not continue any research activity beyond the expiration date without Committee approval. Please submit continuation requests early enough to allow sufficient time for review. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study closure.

Adverse Events: Any serious or unexpected adverse event must be reported to the IRB Committee within 48 hours. All other adverse events should be reported within 10 working days.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, study personnel, or number of participants, please submit an amendment to the IRB. All changes must be approved by the IRB Committee before they can be initiated.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with the IRB Committee, original signed consent forms, and study data.

cc: Robert Elbin, Investigator
Adam England, Key Personnel
Bryanna N. Brown, Key Personnel
Margaret Joan O'Hara, Key Personnel