

Changes in Heart Rate Variability in Varsity Athletes from Baseline to Post-injury and
Return to Play

by

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Bachelor of Athletic and Exercise Therapy, Camosun College, 2013

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

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Supervisory Committee

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Abstract

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Objective: To determine the change in HRV in concussed varsity athletes from baseline to post-injury to return to play. **Design:** Quasi-experimental, repeated measures design. **Participants:** five male varsity athletes four rugby, one basketball (mean age 19.6 ± 1.52 years), number of previous concussion 1.6 ± 0.55 . **Measurements:** HR & HRV frequency domain (LF n.u., HF n.u., LF/HF ratio, Total Power) & Heart rate (bpm) during both seated rest and steady state exercise using a stationary cycle. **Results:** Repeated measures ANOVA revealed a significant difference between baseline (pre-injury) resting heart rate and first post-injury assessment resting heart rate ($p=0.037$). Resting Total Power was significantly different between baseline (pre-injury) and first post-injury assessment ($p=0.044$) and between first post-injury and second post-injury assessment ($p=0.010$). No statistical significant differences in any variables were found during exercise, however the trends in the changes of HRV were similar to other research studies and could be of clinical importance. **Conclusion:** Athletes display dysfunction in neuroautonomic cardiovascular regulation post-concussion as seen with changes in HRV. Findings of this study warrant further investigation into the use of HRV as a marker of concussion and concussion recovery.

Table of Contents

Supervisory Committee	ii
Abstract	iii
List of Tables	vi
List of Figures	vii
Acknowledgments	viii
Dedication	ix
Chapter 1: Introduction	1
1.1 Concussions and Heart Rate Variability	4
1.2 Problem Statement	7
1.3 Research Question	8
1.4 Hypothesis	8
1.5 Operational Definitions	8
1.6 Assumptions	8
1.7 Limitations	9
1.8 Delimitations	9
Chapter 2: Literature Review	10
2.1 Autonomic nervous system	10
2.2 Heart Rate Variability	10
2.3 Cardiac Cycle	12
2.4 Frequency Domain	12
2.5 Neuroautonomic cardiovascular regulation	15
2.6 HRV and Brain Injuries	16
2.7 HRV and Exercise	17
2.8 HRV and Concussion	18
Chapter 3: Methods	22
3.1 Experimental Design	22
3.2 Concussion Diagnosis	23
3.3 Inclusion / Exclusion Criteria	24
3.4 Sample Size	25
3.5 Procedure	25
3.6 Statistical Analyses	26
Chapter 4: Results	28
Chapter 5: Discussion	41
5.1 HRV during Rest	42
5.2 Exercise	45
5.3 Future Research	47
5.4 Conclusion	48
Bibliography	49
Appendix 1 – Informed Consent Form	53
Appendix 2 – Medical and Concussion History Form	57

Appendix 3– SCAT Form.....	59
Appendix 4 – HRV Instructions.....	63
Appendix 6– PAR-Q Form.....	64
Appendix 7– Post-concussion Injury Form.....	65
Appendix 8 – Participation Withdrawal Form.....	66
Appendix 9 – HR Monitor Log	67
Appendix 10 – Literature Review.....	68

List of Tables

Table 1. Summary of HRV measurements in the frequency domain (Heart Rate Variability Task Force, 1996).....	14
Table 2. Summary of HRV frequency range of HF and LF (Heart Rate Variability Task Force, 1996).....	14
Table 3. Spectral analysis of HRV in stationary supine (Heart Rate Variability Task Force, 1996).....	15
Table 4. Subject age (years) and number of previous concussions (n=5).....	25
Table 5. Timeline of assessments, baseline to injury, injury to first assessment, first assessment to RTP assessment.....	28
Table 6. RR intervals and heart rate variability (mean \pm SD) at rest from baseline, PI1 and RTP.....	28
Table 7. RR intervals and heart rate variability (mean \pm SD) during exercise from baseline, PI1 and RTP.....	29

List of Figures

Figure 1. Summary of RTP protocol (McCrory et al., 2013)	3
Figure 2. Break down of wave formation in the frequency domain (King et al., 1996)...	14
Figure 3. HF n.u. during seated rest at three assessment time points.	30
Figure 4. LF n.u. during seated rest at three assessment time points.....	31
Figure 5. Total Power during seated rest at three assessment time points.....	32
Figure 6. LF/HF ratio during seated rest at three assessment time points	34
Figure 7. HR (BPM) ratio during seated rest at three assessment time points	35
Figure 8. HF n.u. during steady state exercise at three assessment times.....	36
Figure 9.LF n.u. during steady state exercise at three assessment times	37
Figure 10. Total Power during steady state exercise at three assessment times	38
Figure 11. LF/HF ratio during steady state exercise at three assessment time points	39
Figure 12.HR (BPM) ratio during steady state exercise at three assessment time points	40

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Dedication

This project is dedicated to my supportive family, each member of my family helped play a role in getting me to completion of this project. I would like to extend a personal dedication to my auntie Lori, as she offered her unwavering support throughout the entire process.

Chapter 1: Introduction

In recent years awareness of concussions in sport has been on the rise. According to the Canadian Medical Association, concussions have become one of the most common forms of traumatic brain injuries. The Public Health Agency of Canada reports 64% of emergency room visits for children aged 10-18 was for an injury related to sport and 39% of those children were diagnosed with a concussion and another 24% with a suspected concussion (Concussions, 2017). For many athletes, in contact or collision sports, concussions are of concern. It has been estimated that sustaining one concussion puts the individual at four to six times greater risk to sustain another concussion (Wilberg, Orega, & Solbonov, 2006; Henry & Beaumont, 2011). Multiple concussions can lead to prolonged side effects and athletes are at a higher risk than the general population for sustaining multiple concussions (Wilberg et al., 2006).

According to the 4th International Conference on Concussion in Sport, the current definition of concussion is: *“a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces”* (McCrory, Meeuwisse, Aubry, Cantu, Dvorak, Echemendia, Schneider, & Tator, 2013).

In addition to this, McCrory et al., 2013 reported a concussive head injury may:

1. *be caused by a direct blow to the head, face, neck or elsewhere on the body with an “impulsive” force transmitted to the head,*
2. *typically result in the rapid onset of short-lived impairment of neurologic function that resolves spontaneously. However, in some cases symptoms and signs may evolve over a number of minutes to hours,*

3. *result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury, and as such, no abnormality is seen on standard structural neuroimaging studies,*
4. *result in a graded set of clinical symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically follows a sequential course. However, it is important to note that in some cases symptoms may be prolonged.*

Current concussion management guidelines put forth by McCrory et al., 2013 at the 4th International Conference on Concussion in Sport, suggest that athletes complete a period of physical and cognitive rest until acute symptoms resolve and then follow a stepwise graded exertion exercise protocol (Figure.1) before medical clearance to return to full sport participation. Typically, 80-90% of concussion symptoms resolve in 7-10 days (McCrory et al., 2013). However, concussion symptoms may resolve before the injury within the brain is fully healed (Bigler, 2012). At this time concussion recovery is still largely based on an athlete's subjective symptom reporting and this can lead to premature return to play (RTP). In addition to this, it has been found that athletes may under report symptoms in order to RTP faster (McCrea Hammeke, Olsen, Leo, & Guskiewicz, 2004; Nierengarten, 2011).

Symptoms often reported by athletes post concussion are variable. Using the Sport Concussion Assessment tool third edition (SCAT3), this tool uses a list of 22 commonly reported symptoms post concussion (McCrory et al., 2013). This tool will ask users to subjectively rank their symptoms on a severity scale of 0-6, where 0=none, 1-2=mild, 3-

4=moderate and 5-6=severe (McCroory et al., 2013). The subjectively reported symptoms can also fit into groups such as somatic (headache), cognitive (feeling like in a fog) and emotional (lability) (McCroory et al., 2013). The other clinical domains to evaluate are physical signs (loss of consciousness), behavioural changes (irritability), cognitive impairment (slow reaction times) and sleep disturbances (McCroory et al., 2013)

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
1. No activity	Symptom limited physical and cognitive rest	Recovery
2. Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity <70% maximum permitted heart rate No resistance training	Increase HR
3. Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
4. Non-contact training drills	Progression to more complex training drills, eg, passing drills in football and ice hockey May start progressive resistance training	Exercise, coordination and cognitive load
5. Full-contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6. Return to play	Normal game play	

Figure 1. Summary of RTP protocol (McCroory et al., 2013)

Concussions can be a difficult injury to diagnose as they are not visible, and recovery cannot be quantitatively tracked by health care professionals, coaches or team trainers (Hutchison, Mainwaring, Comper, Richards, & Bisschop, 2009; Covassin & Elbin, 2011). This is why ongoing research is needed to help in identifying objective measures to aid in concussion diagnosis, monitoring of recovery and safe RTP. The majority of concussion research and diagnosis has been focused on the

neuropsychological aspect of the injury where baseline testing, post-injury testing and a gradual RTP protocol (Figure. 1) are predominantly used (Len, Neary, Asmundson, Goodman, Bjornson, & Bhambhani, 2011). Often these measurements lack objectivity, however; recent research has indicated that physiological measures have promise for providing an objective measure of injury assessment and recovery (Gall et al., 2004; Len & Neary, 2011).

1.1 Concussions and Heart Rate Variability

Sport related concussions are a complicated pathophysiological process that results in systemic physiological effects involving altered heart rate variability (HRV), decreased baroreflex sensitivity, cellular metabolism and cerebral blood flow (Len et al., 2011; Giza & Hovda, 2014). A pathophysiological change that occurs post-concussion is a disruption in neuroautonomic cardiovascular regulation, which is the coupling of the autonomic nervous system (ANS) and the cardiovascular system (Len & Neary, 2011). The ANS is a branch of the peripheral nervous system that is responsible for unconscious processes that occur within the body and is broken down into two branches: the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). It is the balance between the PNS & SNS that becomes the critical component to understanding the disruption in neuroautonomic cardiovascular regulation after a concussion has occurred (Goldstein et al., 2002; Gall et al., 2004; Len & Neary, 2011; Conder & Conder, 2014). According to Thayer, Hansen, Saus-Rose, & Johnsen, (2009) “the heart and brain are connected bidirectionally” and “vagally mediated and thus HRV appears to provide valuable information about the functioning of this system” (Thayer et al., 2009,pg.142). Indeed, using HRV as a way of measuring the function of the autonomic nervous system

has been widely accepted, and has the added benefit of being minimally invasive (Len & Neary, 2011; Conder & Conder, 2014; Blake, McKay, Meeuwisse, & Emery, 2014).

Heart Rate Variability (HRV) is defined as “the oscillation in the interval between consecutive heart beats (R-R intervals) in addition to the oscillations between consecutive instantaneous heart rates” (Heart Rate Variability Task Force, 1996). A fluctuation in HRV is the result of the dynamic control of the cardiovascular system by the ANS (Moses, Luecken, & Eason, 2007). The interaction of these two branches controls the physiological response and capacity to meet the demands of both physical and mental stress (Moses et al., 2007).

HRV is composed of two domains: time domain and the frequency domain. Time domain is used to determine HRV at a given point in time and the “intervals between adjacent QRS complexes resulting from sinus node depolarization” (Heart Rate Variability Task Force, 1996). Using time domain to measure HRV requires the measurements to be of long duration, typically 24 hours. In the frequency domain, power spectral analysis is used to explain how “HRV distributes as a function of frequency” (Heart Rate Variability Task Force, 1996). In a short-term recording of 2-5 minutes three main spectral components are evident, very low frequency (VLF), low frequency (LF) and high frequency (HF) (Heart Rate Variability Task Force, 1996). LF and HF central frequency is not fixed and may vary in relation to change in autonomic modulations of the heart period (Heart Rate Variability Task Force, 1996). The function of VLF is not fully understood and often questioned (Heart Rate Variability Task Force, 1996). The HF domain is under parasympathetic regulation from vagal activity and represents heart beat oscillations that occur due to respiratory frequency (Goldstein et al., 1998). Whereas the LF domain is under joint control from the sympathetic and parasympathetic

regulations, with sympathetic control dominating during times of stress on the body (Goldstein et al., 1998). In short time-course recordings, LF and HF power components can be reported in absolute values of power (ms^2) or measured in normalized units (n.u.) (Heart Rate Variability Task Force, 1996). N.U. represents the relative value of each power component in proportion to the total power minus VLF (Heart Rate Variability Task Force, 1996). By displaying the LF and HF components in n.u. highlights the control and balance behaviour of the sympathetic and parasympathetic nervous system (Heart Rate Variability Task Force, 1996).

HRV can be adversely affected post-concussion, and the more severe the injury the more drastic the change in HRV (Goldstein et al., 1998; Gall et al., 2004 Len & Neary, 2011; Conder & Conder, 2014). It is thought that this change in HRV occurs due to the uncoupling of the neuroautonomic regulation system post-acute brain injury (Goldstein et al., 1998). Using HRV as a means to objectively evaluate the presence of a concussion within an athletic population has shown some promising results and warrants further investigation. In a case study by Senthinathan et al, (2014) a single female athlete was tested three times before injury and again 72 hours after injury and showed a significant increase in HR and LF(n.u.) and decrease in HF(n.u.) at rest. In another study by Senthinathan et al., (2014) 11 concussed athletes were compared to 11 matched controls and it was found that concussed athletes had increased LF(n.u.) and decreased HF(n.u.) in sitting vs. controls. Gall et al., (2004) showed that when hockey players five and ten days' post-concussion compared to matched controls had a significant decrease in HF (ms^2) and LF (ms^2). Before using HRV as a means of diagnosing a concussion, as well as recovery from concussion, a few major pitfalls from previous studies need to be addressed. Both Gall et al., (2004) and Senthinathan et al., (2014) used a matched control

method for the comparison to the concussed athletes. Few studies could be found where baseline data was gathered pre-concussion for comparison to post-concussion data.

Baseline HRV data on participants gives a better understanding of how the pathophysiological process of a concussion impacts each individual.

A second weakness in previous studies is the lack of data on HRV response during exercise post-concussion. In non-concussed individuals, HR increases with exercise whereas HRV decreases with exercise due to an increase in sympathetic nervous system activation and a decrease in parasympathetic nervous system activation. This action varies within an individual due to heredity (size of left ventricle), fitness level, exercise mode and skill (exercise economy) (Aubert et al, 2003). To date there is limited literature on the impact of aerobic exercise on HRV in concussed individuals. More research data reported the exercise component was the change in HRV from lying to sitting to standing or using isometric grip strength. Since the change in HRV is inversely related to exercise intensity this exercise perturbation may be too mild to cause significant changes in HRV. An exercise protocol that is more physiologically challenging is needed to see more profound changes in HRV.

1.2 Problem Statement

The purpose of this research was to determine if there are changes in the physiological marker, HRV, in athletes post-concussion. Specifically changes in the frequency domains were assessed. In addition, this research investigated if changes in HRV did occur and whether they were still present once the athlete has been returned to play (RTP).

1.3 Research Question

- Is HRV affected post-concussion at rest and during exercise?

1.4 Hypothesis

It is hypothesized that a within person difference in HRV during submaximal exercise and rest will be seen at baseline to post-concussion and in post-concussion to RTP comparisons.

1.5 Operational Definitions

- Concussion: a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces.
- Heart Rate Variability: the measurement between R intervals of QRS complex (time between heart beats).
- Neuroautonomic cardiovascular regulation: the coupling of the autonomic and cardiovascular system.
- Autonomic nervous system: a component of the efferent division of peripheral nervous system that consists of sympathetic and parasympathetic subdivisions; innervates cardiac muscle, smooth muscle and glands.
 - Parasympathetic Nervous System is an inhibitory pathway.
 - Sympathetic Nervous System is an excitatory pathway.
- Return to play: the stepwise progression of a graded program of exertion that is started once an athlete is asymptomatic.

1.6 Assumptions

- Athletes will report injury and be honest when reporting symptoms post-injury.
- Athletes will put forth full effort at baseline testing and be motivated.
- Athletes will not be concussed at baseline measures.

1.7 Limitations

- Athletes reporting the injury.
- Communication between athletes, student athletic therapist, varsity athletic therapists, varsity sports doctor.
- Selection bias due to convenience sampling.
- Different levels of concussive injury between subjects.

1.8 Delimitations

- Participants living within the Victoria area.
- Athletes playing on a varsity sports team at the University of Victoria limited to rugby, basketball, soccer and field hockey.
- Athletes playing hockey in the Vancouver Island Junior Hockey League (VIJHL).
- All participants were able to speak English.

Chapter 2: Literature Review

2.1 Autonomic nervous system

The autonomic nervous system (ANS) is responsible for regulating numerous bodily functions without conscious input. The ANS is divided into two branches: the sympathetic and parasympathetic nervous systems, SNS and PNS respectively. The organs innervated by the ANS receive innervation from both the SNS and the PNS allowing for both sympathetic and parasympathetic input/influence. The SNS causes the ‘fight or flight’ reaction in the body whereas the PNS is responsible for the ‘rest and digest’ functions within the body. Essentially, the two branches of the ANS work in a reciprocal fashion (Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004). This project only looked at the ANS control of the heart, and the effect of this control post-concussion. However, it is evident that more organs that are under ANS control could be impacted post-concussion. As the ANS has control over other bodily functions such as respirations, digestion and kidney functions.

2.2 Heart Rate Variability

In a healthy individual, normal sinus rhythm of the heart varies from beat to beat, which is termed heart rate variability (HRV) (Bilchick & Berger, 2006). These variations occur as a result of a dynamic interplay between multiple physiological mechanisms that regulate the instantaneous heart rate (Bilchick & Berger, 2006). In healthy individuals the sinoatrial node (SA node), which is located in the posterior wall of the right atrium of the heart, sets the pace of each heartbeat (Stauss, 2003). The instability in membrane potentials of the myocytes leads to the generation of action potentials at a fairly constant frequency however the autorhythmicity established by the SA node is modulated by

many factors (Stauss, 2003). These factors cause variability to the heart rate signal at different frequencies (Bilchick & Berger, 2006). Regulation of heart rate in the short term is by sympathetic and parasympathetic neural activity (Bilchick & Berger, 2006). When the sympathetic nervous system is active norepinephrine is released which binds to β_1 adrenergic receptors on the SA nodal cells. Norepinephrine- β_1 adrenergic receptor binding leads to the activation of the cAMP secondary messenger system, which causes the opening of both funny channels and T-type calcium channels in cardiomyocytes. This results in an increase in the slope of the spontaneous depolarization of cardiomyocytes and a decrease in the level of repolarization. Consequently, the threshold for action potentials (AP's) is achieved more rapidly. The frequency of action potentials is increased, leading to an increase in heart rate and cardiac output. Conversely, an increase in the parasympathetic neural output to the SA node will decrease the frequency of action potentials due to the release of acetylcholine (ACH). ACH binds to muscarinic cholinergic receptors on the SA nodal cells. The binding of ACH to muscarinic cholinergic receptors leads to the opening of potassium channels, as well as suppresses the opening of funny channels and T-type calcium channels. This causes a decrease in the slope of spontaneous depolarization and hyper-repolarization of membrane potentials, thus the threshold for an AP is reached at a slower rate. A noted decrease occurs in the frequency of AP's resulting in a reduction in heart rate and a decrease in cardiac output. Examining the fluctuation in heart rate allows for the state and integrity of the autonomic nervous system to be understood (Bilchick & Berger, 2006).

2.3 Cardiac Cycle

Each cardiac cycle of the heart is shown through three distinct waveforms, P wave, QRS complex and T wave (Tortora & Derrickson, 2013). It is the QRS complex of the cardiac cycle that HRV is concerned with, specifically the time between each RR interval. As an action potential is propagated through cardiac tissue the first event is atrial depolarization shown as the P wave, second the QRS complex represents ventricular depolarization and last is the T wave where ventricular repolarization is occurring (Tortora & Derrickson, 2013). The resting membrane potential of cardiac muscle is around -90mv, when an action potential brings the membrane to threshold voltage-gated Na⁺ channels open rapidly leading to depolarization (Tortora & Derrickson, 2013). Repolarization occurs to restore resting membrane potential. During this phase the K⁺ channels open and an outflow of K⁺ will restore the negative resting membrane (Tortora & Derrickson, 2013).

2.4 Frequency Domain

Monitoring of HRV can be displayed as either time domain or frequency domain. This research used the frequency domain only as the time domain requires long sample times. The frequency domain uses a power spectrum density (PSD) estimate to calculate the RR interval series. The PSD estimation is calculated using either the fast fourier transform (FFT) based method or parametric autoregressive (AR) modeling based methods. For this project the FFT methods was used, as it was simple to implement. The FFT works by causing the waveform to decompose into a sum of the sinusoids of different frequencies, if the sinusoids sum to the original waveform then determination of the Fourier transformation of the waveform can be understood. The Kubois software used

in this research to analyze HRV calculates the FFT using Welch's periodogram method. Welch's periodogram method measures the HRV sample by dividing it into overlapping segments then averaging the spectra of the segment.

The frequency domain is broken down into three frequencies: high, low and very low frequency. High frequency (HF), designated as frequencies between 0.15-0.4Hz, is thought to represent the parasympathetic activity of the ANS and respiratory rhythm (Stauss, 2003; Gall et al., 2004). Low Frequency (LF), designated as frequencies between 0.04-0.15Hz, is sensitive to changes in cardiac sympathetic nerve activity, and presumably sensitive to parasympathetic nerve activity as well (Heart Rate Variability Task Force, 1996; Stauss, 2003; Gall et al., 2004). Very Low Frequency (VLF) (0-0.04Hz) is still not fully understood as the exact function has yet to be elucidated, but it is thought to be affected by temperature regulation and humoral system (Heart Rate Variability Task Force, 1996; Stauss, 2003).

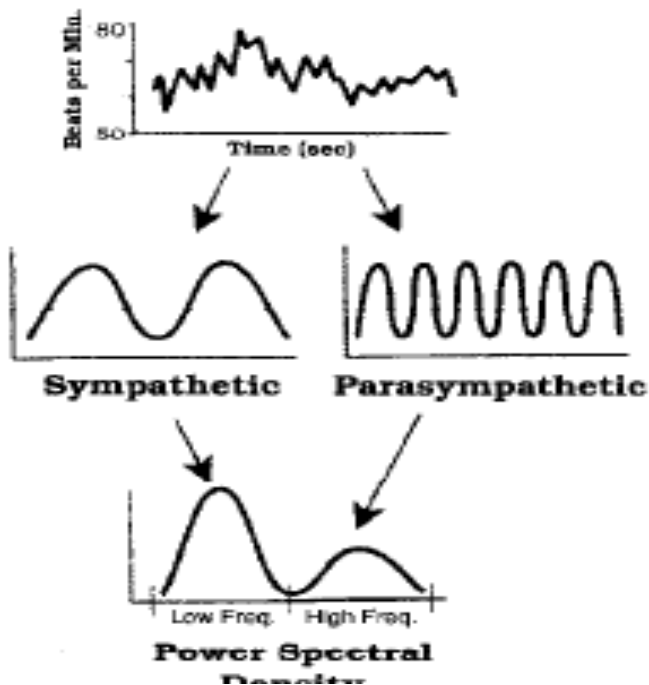


Figure 2. Break down of wave formation in the frequency domain (King et al., 1996).

Table 1. Summary of HRV measurements in the frequency domain (Heart Rate Variability Task Force, 1996)

Measurement	Units	Description
Frequency domain		
LF & HF powers	[ms ²]	Absolute power of LF & HF bands
LF & HF powers	[n.u.]	Powers of LF & HF bands in normalized units. Calculated by LF/(TP-VLF) HF/ (TP-VLF)
LF/HF	[ms ²]	Ratio between LF and HF band powers

Table 2. Summary of HRV frequency range of HF and LF (Heart Rate Variability Task Force, 1996)

Measurement	Units	Frequency Range
HF	[ms ²]	0.15-0.4 Hz
LF	[ms ²]	0.04-0.15 Hz

Table 3. Spectral analysis of HRV in stationary supine (Heart Rate Variability Task Force, 1996)

Measures	Units	Normal Values
Total power	ms ²	3466 ±1018
LF	n.u.	54 ±4
HF	n.u.	29 ±3
LF/HF ratio		1.5 ±2

2.5 Neuroautonomic cardiovascular regulation

The bodies cardiovascular system is under autonomic control. When the ANS and cardiovascular system are coupled, neuroautonomic cardiovascular regulation is established (Goldstein et al., 1998; Len & Neary, 2011; Conder & Conder, 2014). Using HRV as a way to monitor neuroautonomic cardiovascular regulation is a noninvasive measure of autonomic regulation of cardiovascular function during various pathophysiological states in the body and shows the activity of the sympathetic and parasympathetic nervous systems (Goldstein et al., 1998; Gall et al., 2004; Len & Neary, 2011; Conder & Conder, 2014). Research has demonstrated that an uncoupling of the neuroautonomic cardiovascular system can occur following a concussion injury (Gall et al., 2004 & Len, & Neary, 2011 & Conder, & Conder, 2014, & Goldstein et al., 1998). However, it seems that the degree of uncoupling is related to the severity of the concussion, the more catastrophic the injury the more uncoupling is evident (Goldstein et al., 1993, 1998).

2.6 HRV and Brain Injuries

It has been established that the degree of uncoupling is dependent upon the severity of injury and since most sport related concussions are typically classified as mild in severity, the degree of uncoupling may not be as profound (Goldstein et al., 1993, 1998). However research by both Gall et al., (2004) and Senthinathan et al., (2014) have shown that this uncoupling may be occurring after a sports related concussion.

Goldstein et al., (1998) performed a study using 24 participants with varying degrees of brain injuries. This research demonstrated significant correlations between Glasgow Coma Scale (GCS) and mean heart rate ($P=0.006$), heart rate SD ($P=0.015$), and low frequency heart rate power ($P<0.001$). Glasgow Outcome Score (GOS) correlated with mean heart rate ($P=0.02$), heart rate SD ($P=0.03$), low frequency heart rate power ($P=0.003$) and low frequency mean blood pressure power ($P=0.05$). Results of this study show that HRV, especially at low frequency, diminished in proportion to the degree of neurological injury, and correlated with neurological outcome, which approaches zero during brain death. The demonstrated levels of uncoupling occur within the brain, SA node, peripheral vasculature and arterial baroreceptors. Other studies by Goldstein et al., (1993) and Goldstein et al., (1996) found similar results to support that the autonomic and cardiovascular system are completely uncoupled at all levels during brain death. Su et al., (2005) had a population sample of 90 participants with varying levels of head injury. Participants were placed into one of five groups according to their GCS. Group one GCS of 14, group two GCS 9-14, group three GCS 4-8, no pupil dilations, group four-eight with pupil dilation and group five GCS 3. Findings of this study showed

that alterations in sympathetic and parasympathetic drive can be correlated to the severity of head injury. More severe injuries had an increase in sympathetic drive and decrease in parasympathetic drive at rest. HRV can also be used to in a hospital setting to help predict outcomes of a severe head injury. King et al., (1997) concluded that the severity of neurological injury, outcome and survivals are inversely associated with the degree of cardiovascular variability.

2.7 HRV and Exercise

The initiation of exercise leads to adjustments in the cardiovascular system (Aubert, Seps, & Beckers, 2003). The adjustments that occur are a combination and integration of both neural and local chemical factors (Aubert et al., 2003). Prompt changes in sympathovagal balance occur and the overall result will be an increase in the SNS, increased HR & myocardial contractile force and peripheral vasoconstriction (Maceel, Gallo, Neto, Lima Filho, & Martins, 1986; Aubert et al., 2003; Ng, Sundaram, Kadish, & Goldberger, 2009). During recovery from exercise an abrupt reduction in HR and cardiac output occur, and thus an increase in parasympathetic tone (Maceel et al., 1986; Aubert., et al 2003; Ng et al., 2009). The degree of change in activation of the two nervous systems is dependent on exercise intensity (Aubert et al., 2003). During a bout of exercise there is a marked reduction in HRV (Sandercock, Bromley, & Brodie, 2005).

Arai, Saul, Albrecht, Hartley, Lilly, Cohen, & Colucci, (1989), were among the first to show parasympathetic withdrawal and sympathetic activation during exercise using a group of 43 healthy individuals who exercised to peak levels. Brenner, Thomas, & Shephard, (1998) also showed a similar response at the onset of exercise. During a

bout of steady state exercise, Kamath et al., (1991) observed that LF percentage (LF%) was greater than when compared to supine lying, but unchanged when compared to standing. The LF/HF ratio is a marker of sympathovagal balance (Heart Rate Variability Task Force, 1996). As such one would expect that during a bout of exercise the LF/HF ratio would decrease. Most often with incremental exercise LF/HF will be increased at lower exercise intensities and decrease as exercise intensity increases (Sandercock et al., 2006). It was noted by Sandercock et al., (2006) that using power spectral analysis to assess HRV during a rest state is useful, but the usefulness of power spectral analysis during an exercise state is limited. However, this is opposed by McNarry & Lewis., (2012), who were able to display good reproducibility of HRV parameters during exercise.

2.8 HRV and Concussion

Concussions are the result of biomechanical forces to the brain that causes either a functional or microstructural injury to neural tissue (Giza & Hovda, 2014). The functional injury that results from a concussion can refer to perturbations of cellular or physiological function that can include ionic shifts, metabolic changes or impaired neurotransmission (Giza & Hovda, 2014). The uncoupling of the neuroautonomic cardiovascular regulation during an acute brain injury has been detailed by Goldstien et al., 1993,1996 & 1998 and they concluded that “the neuroanatomic pathways are adversely affected during acute brain injury, thus resulting in decreased efferent signals to the SA node, peripheral vasculature and baroreceptors. This disruption that occurs within the neuroanatomic pathways will leave the body in a state of stress and this stress will cause an alteration in the bodies ability to maintain homeostasis. Through the use of

HRV monitoring this adverse affect on the bodies neuroautonomic pathways and homeostasis can be seen in real time”. As this tool has the potential to have profound benefits to the sporting community in assisting health care professionals make informed decisions based on science about concussion diagnosis and RTP.

Research by Gall et al., (2004) on ice hockey players was the first of its kind to look at changes in HRV with concussed athletes comparing them to 14 match controls. The concussed athletes demonstrated significantly lower mean RR intervals than matched controls five and ten days following injury during low to moderate steady state exercise. The concussed athletes also had significantly lower LF values and significantly lower HF values then matched controls five and ten days post-injury during low to moderate steady state exercise.

Katz-Leurer et al., (2010) performed a comparative study with 12 boys’ post-concussion and 18 age-matched boys typically developed (TD). They found that boys post-concussion had significantly higher resting and walking mean HR ($p < 0.01$, $p = 0.03$) even at a lower walking velocity for the post-concussion group. It was concluded that post-severe concussion the bodies’ cardiac autonomic mechanism is less efficient at rest and had a decreased ability to adapt to exercise.

Hilz et al., (2011) had a group of 20 participants that sustained a concussion 5 – 43 months prior to examination. They compared concussed participants to non-concussed participants during different body positions of supine lying and standing and found a dysfunction in cardiovascular autonomic regulation post-concussion. During body positions of supine lying, mean RR ($p = 0.006$), SDNN ($p = 0.043$) and HF (n.u.) ($p = 0.000$) were significantly lower whereas LF(n.u.) ($p = 0.001$) and the LF: HF ratio ($p = 0.001$) were significantly higher in the concussed participants. During assessment of participants

standing, SDNN ($p=0.013$) and LF ($p=0.013$) were significantly lower in participants who sustained concussions when compared to controls.

Senthinathan et al., (2014) completed a study using one concussed varsity female athlete. Three separate testing sessions were completed within 1-month before injury, 72 hours post-concussion, at the beginning of RTP once asymptomatic and one week follow full RTP. A significant elevation in HR, LF (n.u.) and a significant decrease in HF (n.u.) were noted 72 hours post-injury at rest. A significant elevation in HR occurred at the start of exercise progression. Participants were measured at three-time points post-concussion diagnosis, in both seating and standing position. Time points included 1) 72-96 hours post-injury, 2) when participant were asymptomatic and started a graded exercise RTP program, and 3) one week after they were medically cleared to RTP. During the acute phase (72-96 hours post-concussion), concussed athletes showed an increase in LF (n.u) and a decrease in HF (n.u) while sitting and displayed a smaller change in HF (n.u) and LF (n.u) between sitting and standing. These results provide support of the dysfunction that occurs post-concussion with neuroautonomic cardiovascular regulation.

The apparent disruption in neuroautonomic cardiovascular regulation provides evidence that post-concussion the body is able to maintain neurocardiovascular regulation at rest but not during moderate intensity exercise. This disruption in neuroautonomic cardiovascular regulation can be seen in athletes up to ten days' post-injury during submaximal exercise (Gall et al., 2004). The results of the above studies suggest that using HRV as a marker of concussion recovery as well as a determinate in RTP of an athlete could be viable however more research is needed to ensure that this measure is a valid and reliable tool. Previous research has used a between methodology to compare concussed participants to matched controls. To help increase the robustness of the

research, a within subject design is needed using participants as their own controls and having baseline measures for each participant.

Chapter 3: Methods

3.1 Experimental Design

The University of Victoria Human Research Ethics Board (Appendix 1) granted approval for all procedures used in this study. This research used a repeated measures time series quasi-experimental design. Because it was not known which athletes would get concussed, the athletes could not be randomized into experimental and control groups. For this study, concussion was the independent variable with the various parameters of HRV being the dependent variables. Data was collected from participants at three-time periods: 1) baseline, 2) post-injury (PI1), and 3) once the participant returned to play (PI2).

This study ran over the course of nine months and followed competitive athletes that competed in varsity status sports (rugby, soccer, field hockey and basketball) at the University of Victoria and Junior B hockey players who played in the Vancouver Island Junior Hockey League (VIJHL). Baseline data collection was completed during pre-season training camps, between August 2015 and November 2015. Post-concussive HRV data was collected once the athlete was deemed concussed in accordance with the SCAT 3 guidelines (McCrory et al., 2013). Exercise testing post-concussion was not completed until the athlete reported that they were free of concussion symptoms according to the list of 22 symptoms on the SCAT 3, the cognitive and balance aspects of the SCAT 3 were back to baseline.

3.2 Concussion Diagnosis

Participants in this study were deemed concussed by having (1) a mechanism of injury, (2) positive responses on the SCAT 3 and (3) deviations from their baseline SCAT 3 assessments. A certified Athletic Therapist completed the post-injury assessments. All baseline measures and post-injury reassessments were conducted under the supervision of a certified Athletic Therapist and a CASM physician completed final diagnosis of concussion and return to play clearance. The first post-injury assessment occurred within 24-48 hours and athletes were monitored and followed up with every 2-3 days. Once the athlete reported they were asymptomatic according to the symptomology on the SCAT3 and the cognitive portion of the SCAT3 was back to baseline they would complete the exercise testing at two separate times. First once asymptomatic and second once full RTP had occurred.



Figure 3. Testing timeline

3.2 Participants

Recruitment

Recruiting of participants was completed using convenience sampling through the University of Victoria Sports Injury clinic, as well as reaching out to teams of the VIJHL. Athletes between the ages of 16- 30 years old who were playing varsity sport at the University of Victoria and Junior B hockey players in the VIJHL were recruited for baseline testing

3.3 Inclusion / Exclusion Criteria.

Participants that met the following criteria were eligible to be included in this study:

- 1) Apparently healthy
- 2) A varsity athlete at the University of Victoria or play in the VIJHL in Victoria
- 3) English speaking
- 4) Located in the Victoria area
- 5) Ages 16-30
- 6) “No” responses on the PAR-Q and self-report
- 7) Injury free from concussion for a minimum of 30 days.

Participants were excluded from the study if they met one or more of the following exclusion criteria: had sustained a concussion in the past 30 days before baseline assessment and if they had sustained any injury that resulted in them being unable to perform the constant load cycle test, had positive responses on the PAR-Q or were outside the set age range.

3.4 Sample Size

Because this research project was looking at the effects of concussion on HRV parameters a large initial sample size was needed. A sample size of 177 participants was achieved (67 female, 110 male, age 19.4 ± 2.2). Of the 177 baseline measurements, only five participants reported sustaining a concussion during the timeline duration of the study and thus fit into the inclusion criteria for the experimental group. The concussed participants were all male, and participated in rugby ($n= 4$) and basketball ($n=1$).

Table 4. Subject age (years) and number of previous concussions (n=5)

Age	Number of concussions
19.6 ± 1.52	1.6 ± 0.55

3.5 Procedure

As this research used varsity athletes from the University of Victoria, preseason meetings were held with the head Athletic Therapist to review the study protocols and objectives. Baseline testing was completed with the contact and collision sports at the University of Victoria. If an athlete was deemed concussed the head Athletic Therapist would email the PI to set up reassessments with the concussed athlete. The other group of participants in this study were hockey players in the VIJHL. Each of the nine teams in the VIJHL received an email outlining the protocol and objectives of this research. They were to contact the PI if they were interested in participating. Three teams were interesting in participating but giving the location of the PI only one team was assessed in baseline measures. The hockey

team also had a student Athletic Therapist that contacted the PI if an athlete was deemed concussed in order to set up a reassessment with the concussed athlete.

All measurements took place in the concussion lab at the University of Victoria. At the initial testing all participants were required to complete an informed consent, a physical activity readiness questionnaire (PAR-Q) and a medical history form and received a review of the study procedures. Once this was completed, the PI fastened the Polar Team 2 heart rate monitor around their mid chest and then the participant proceeded to rest for 10 minutes in a comfortable seated position. Once resting was complete, the participant completed a 14-minute low-moderate intensity steady state bike test on a Monark cycle ergometer. The exercise performed by athletes in this study was modeled after Gall et al., (2004). The protocol completed was as followed:

- 2-minute warm-up pedaling at 50-60 rpm @ 40W
- Pedal @ 80-90 rpm with a load of 1.5Wxkg of body weight for 10 minutes
 - The resistance stayed the same at each assessment period
- 2-minute active cool down @ 50 rpm.

At the second and third assessments, the same data collection protocol was used and each time verbal consent was given to the PI.

3.6 Statistical Analyses

A one group x 3 measurement repeated measure ANOVA was performed using My Stat. The analysis was run using HR and the values of HRV in the frequency domain (LF (nu), HF (nu) and HF/LF ratio). Both the raw values and percent change values previously detailed were analyzed. If significance was found an independent t-test was

used to detect group difference at each assessment point. A p-value of <0.05 was considered statistically significant.

Chapter 4: Results

Baseline measures of athletes occurred at the beginning of their competitive seasons from August 2015 to November 2015. Time from baseline measurement to reported concussion injury varied with a range of 31 days to 185 days an average of 84.2 days \pm 70.4. Participants involved in this study on average reported to be asymptomatic within 10.8 days \pm 4.97 post-concussion (range of 6 -19 days). From first post-injury assessment to RTP ranged from 21-50 days with an average of 32 days \pm 11.6. The FFT (mean \pm SD) results of frequency domain at rest and during exercise are detailed in Tables six and seven.

Table 5. Timeline of assessments, baseline to injury, injury to first assessment, first assessment to RTP assessment.

Baseline assessment to injury	Injury to PI1 assessment	PI1 to PI2
84.2 days \pm 70.4.	10.8 days \pm 4.97	32 days \pm 11.6.

Table 6. RR intervals and heart rate variability (mean \pm SD) at rest from baseline, PI1 and RTP.

Rest	Baseline	Post-injury 1	Post-injury 2
HR (bpm)	66.6 \pm 7.89*	71.26 \pm 5.76*	67.2 \pm 8.64
HF N.U.	58.15 \pm 30.16	49.53 \pm 17.64	52.44 \pm 26.61
LF N.U.	41.63 \pm 30.26	50.27 \pm 17.57	47.38 \pm 26.63
Ratios	1.18 \pm 1.16	1.24 \pm 0.82	1.37 \pm 1.27
Total Power	9088.0 \pm 6045.35*	3633.18 \pm 2418.49*	10943.48 \pm 6120.38*

- * denotes a significant difference ($p > 0.05$)

Table 7. RR intervals and heart rate variability (mean \pm SD) during exercise from baseline, PI1 and RTP.

Exercise	Baseline	Post-injury 1	Post-injury 2
HR (bpm)	148.20 \pm 4.15	150.40 \pm 9.07	143.60 \pm 7.70
HF N.U.	12.05 \pm 8.37	18.96 \pm 16.55	14.26 \pm 8.42
LF N.U.	87.83 \pm 8.58	80.94 \pm 16.61	85.64 \pm 8.50
Ratios	9.67 \pm 4.50	9.07 \pm 9.84	9.94 \pm 8.92
Total Power	76.63 \pm 62.56	92.12 \pm 100.10	108.97 \pm 80.24

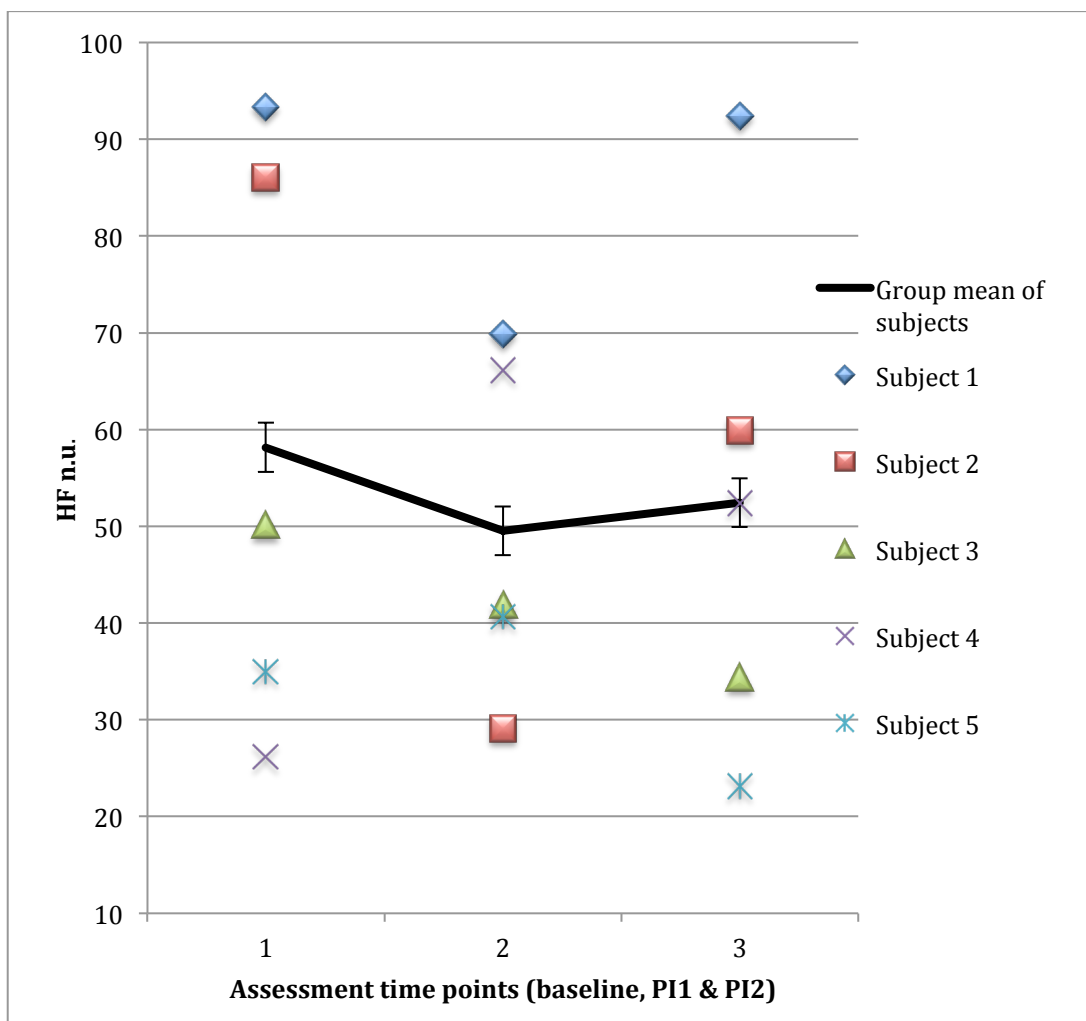


Figure 3. HF n.u. during seated rest at three assessment time points.

Subject 1-5 Individual participant values of HF n.u. at rest over three assessment time points. Group mean of subject's HF n.u. at rest over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.773$). In order to normalize the data, percent change was calculated using the formula $((y_2-y_1)/y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p= 0.955$).

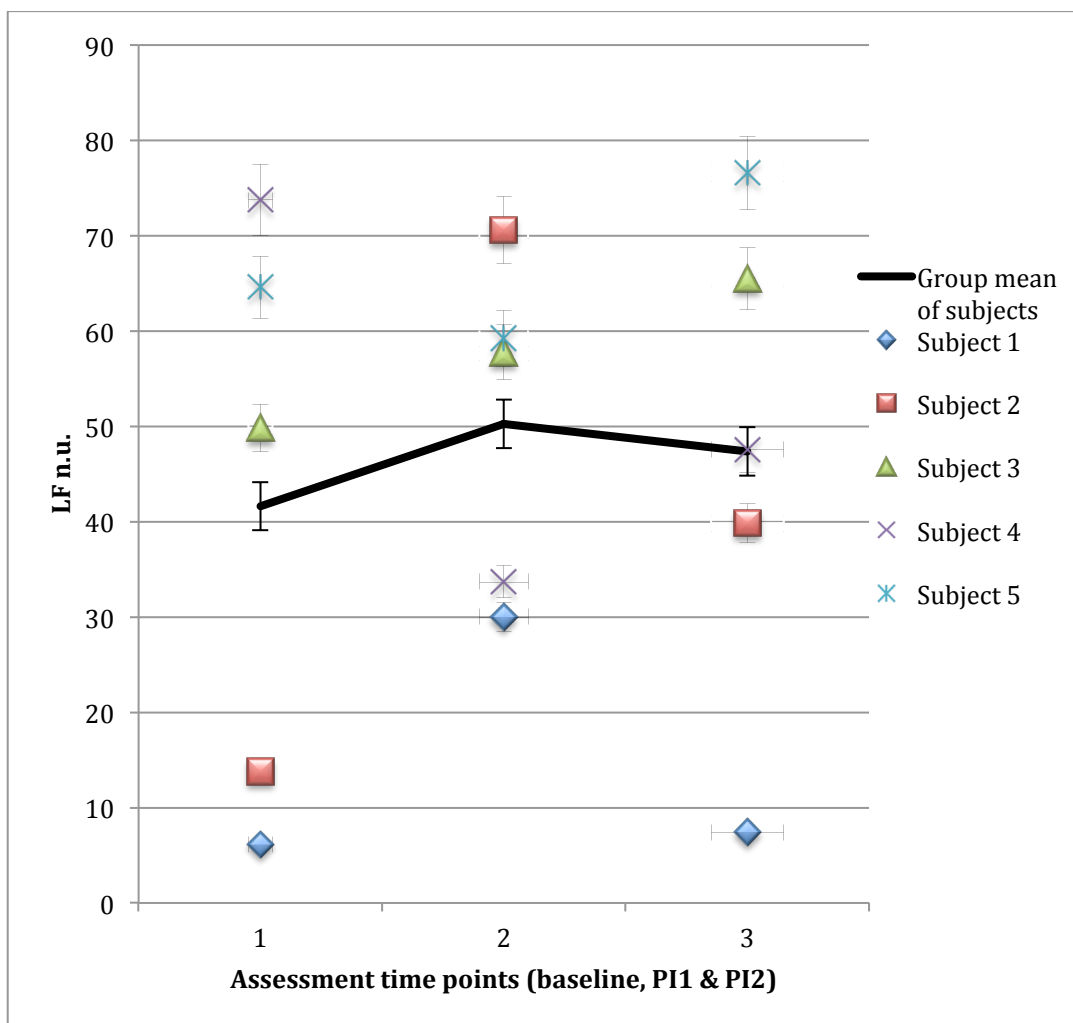


Figure 4. LF n.u. during seated rest at three assessment time points

Subject 1-5 individual participant values of LF n.u. at rest over three assessment time points. Group mean of subject's LF n.u. at rest over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.772$). In order to normalize the data, percent change was calculated using the formula $((y_2-y_1)/y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p= 0.266$).

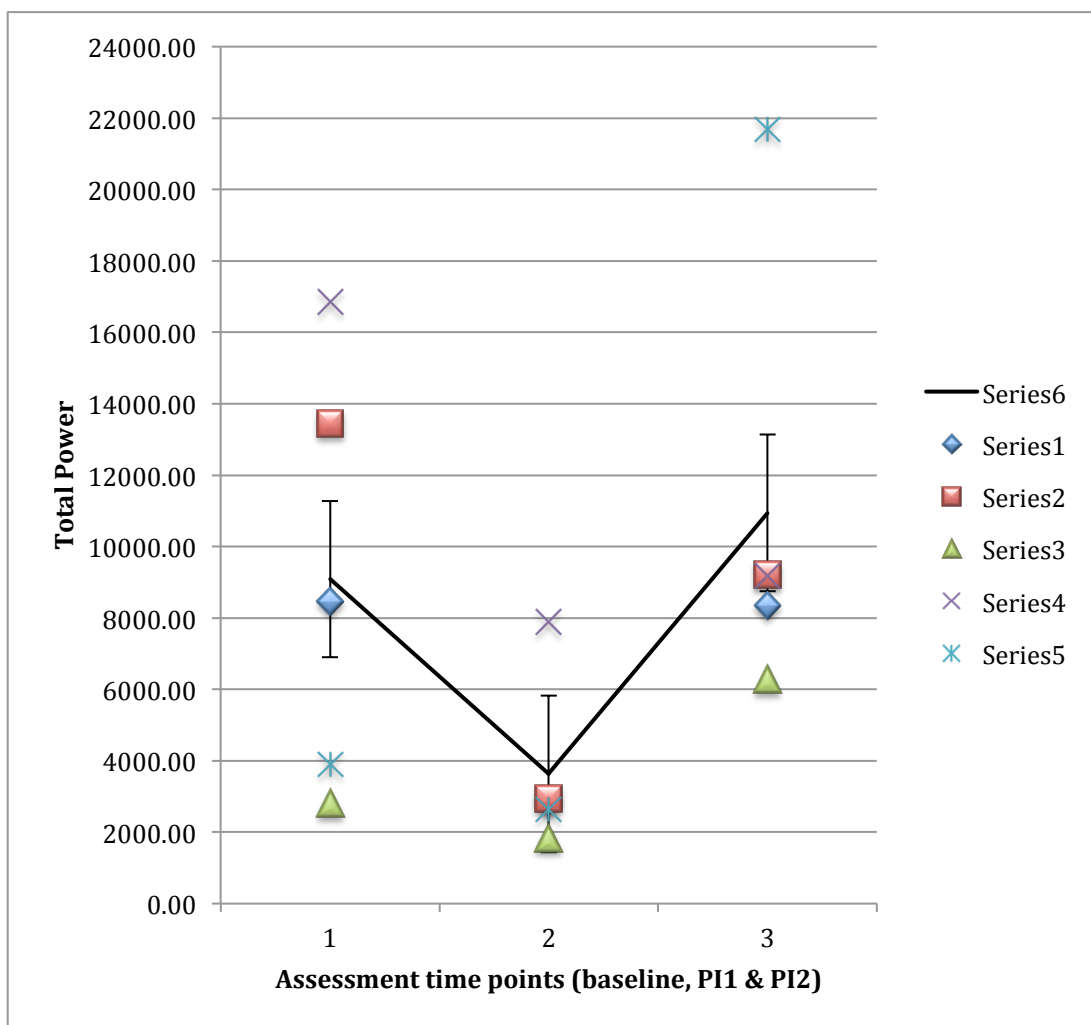


Figure 5. Total Power during seated rest at three assessment time points

Subject 1-5 individual participant values of Total Power at rest over three assessment time points. Group mean of subject's Total Power at rest over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.130$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1) / y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. A

significant difference was found ($p= 0.015$). T-test performed on percent change values revealed that a significant difference was found between baseline and PI1 ($p=0.044$) and PI1 and PI2 ($p=0.010$).

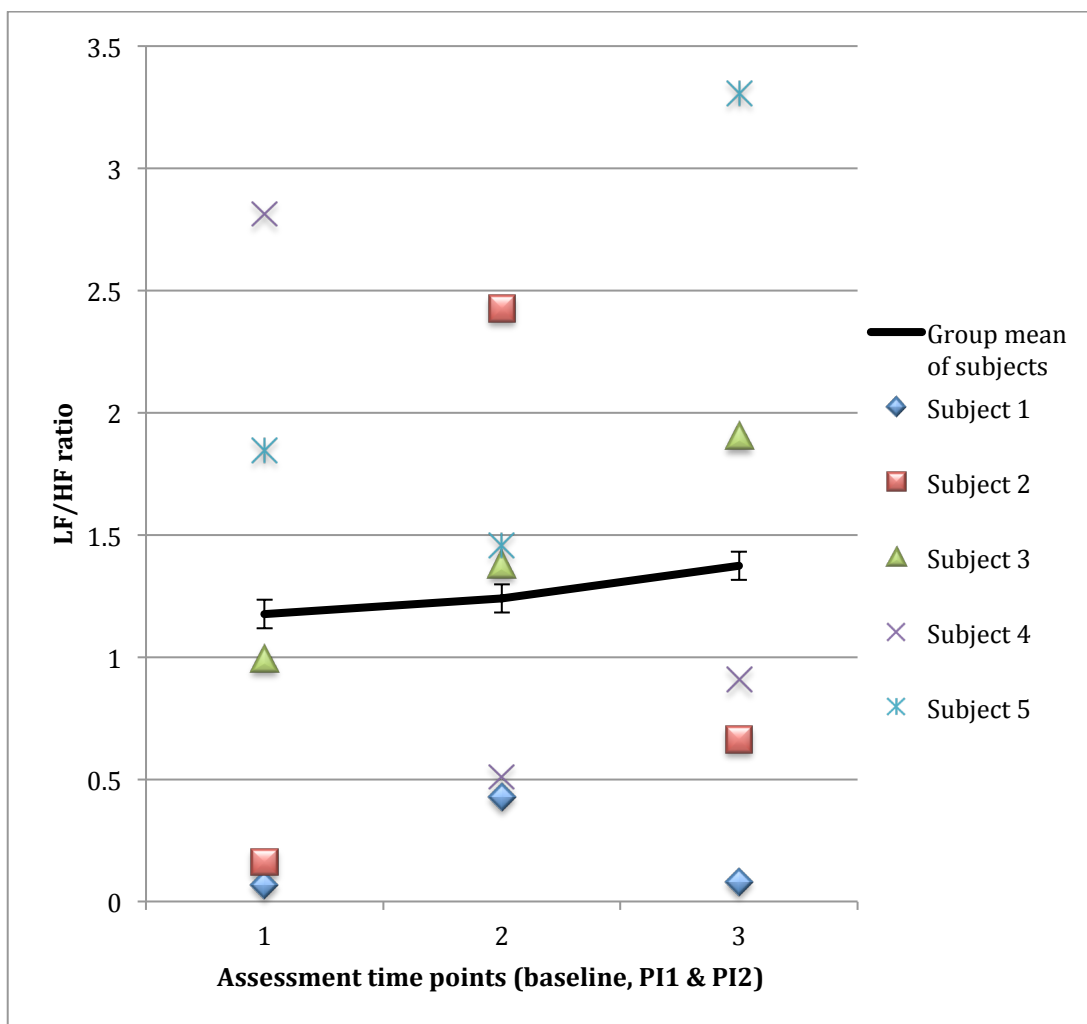


Figure 6. LF/HF ratio during seated rest at three assessment time points

Subject 1-5 individual participant values of LF/HF ratio at rest over three assessment time points. Group mean of subject's LF/HF ratio at rest at rest over three assessment time points. A one (group) x three (phase)) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.952$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1)/y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p=0.308$).

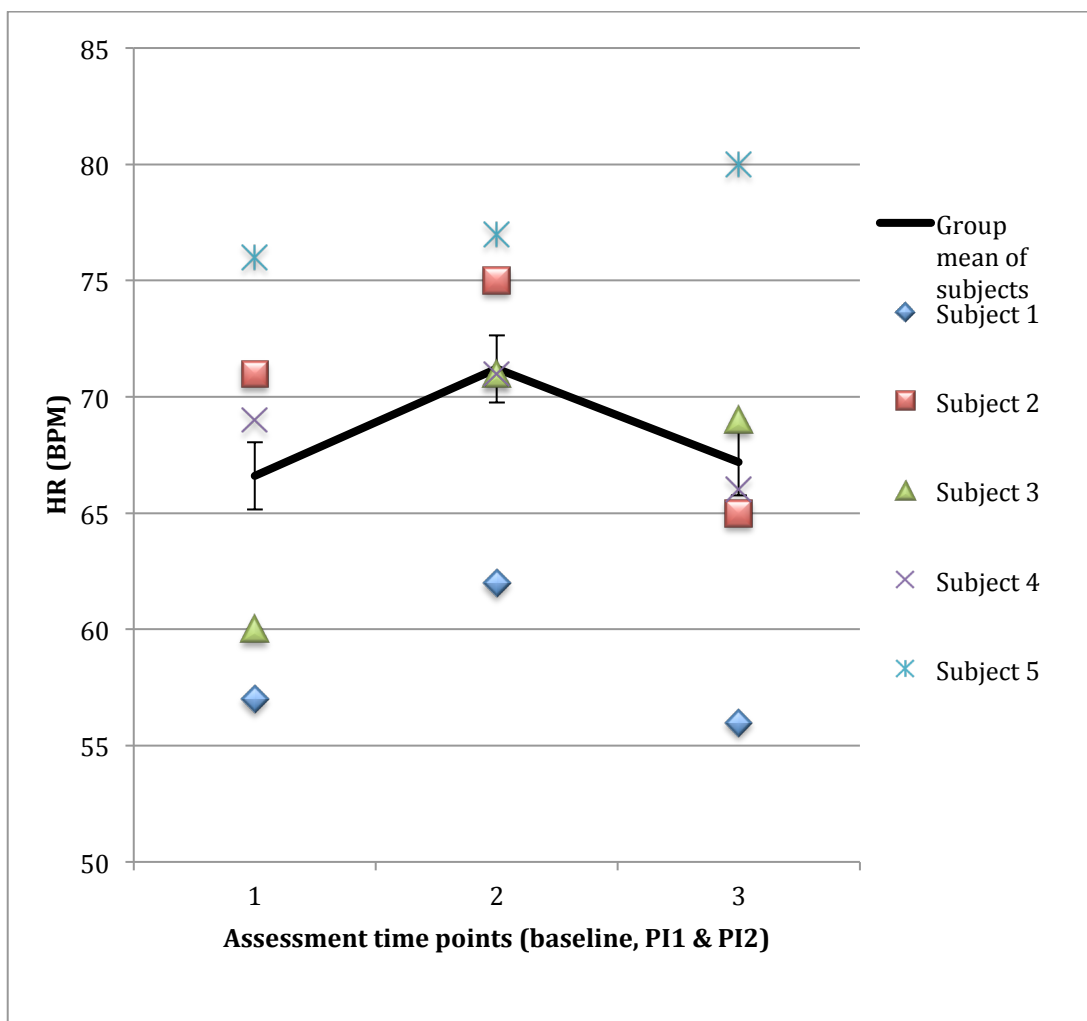


Figure 7. HR (BPM) ratio during seated rest at three assessment time points

Subject 1-5 individual participant values of heart rate (bpm) at rest over three assessment time points. Series 6 group mean of heart rate (bpm) at rest over three assessment time points. A one (group) x 3 (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.141$). In order to normalize the data, percent change was calculated using the formula $((y_2-y_1)/y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. A significant difference was found ($p= 0.016$). T-test performed on percent change values revealed that a significant difference was found between baseline and PI1 ($p=0.037$).

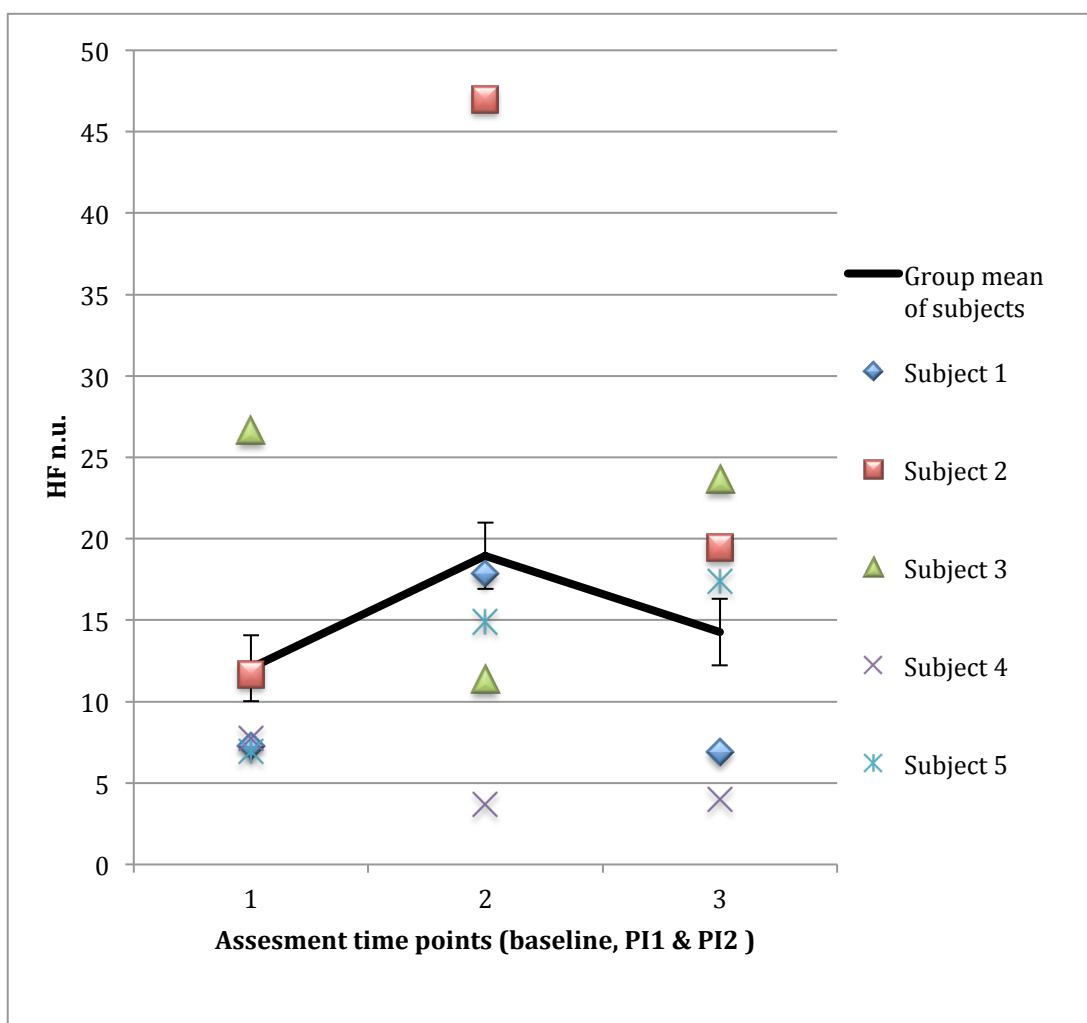


Figure 8. HF n.u. during steady state exercise at three assessment times

Subject 1-5 Individual participant values of HF n.u. during steady state exercise over three assessment time points. Group mean of subject's HF n.u. during steady state exercise over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.576$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1) / y_1 * 100)$. The percent change was analyzed using a one (group) X three (phase) repeated measure ANOVA. No significant difference was found ($p=0.465$).

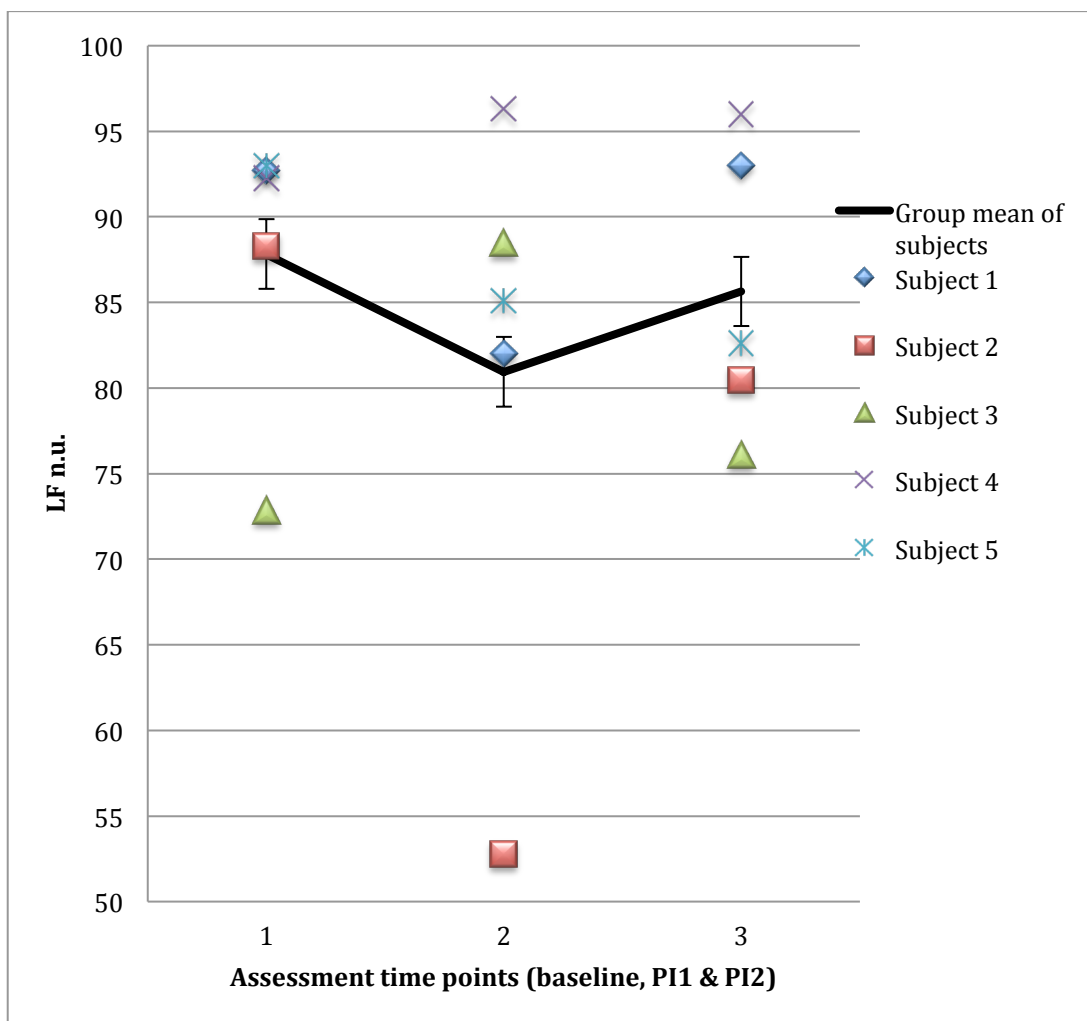


Figure 9. LF n.u. during steady state exercise at three assessment times

Subject 1-5 individual participant values of LF n.u. during steady state exercise over three assessment time points. Group mean of subject's LF n.u. during steady state exercise over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.582$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1) / y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p=0.559$).

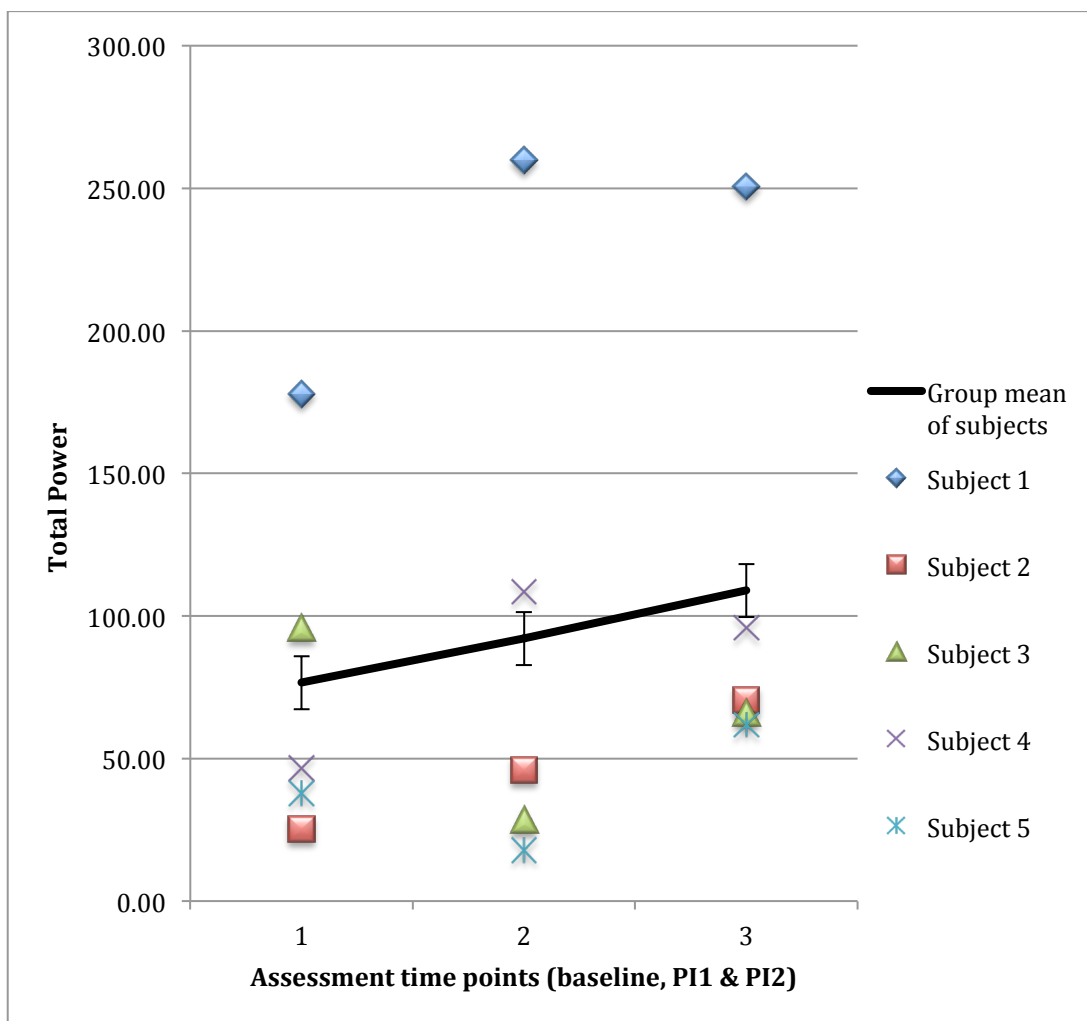


Figure 10. Total Power during steady state exercise at three assessment times

Subject 1-5 individual participant values of Total Power during steady state exercise over three assessment time points. Group mean of subject's Total Power during steady state exercise at rest over three assessment time points. A one (group) x three (phase) measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.315$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1) / y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p= 0.669$).

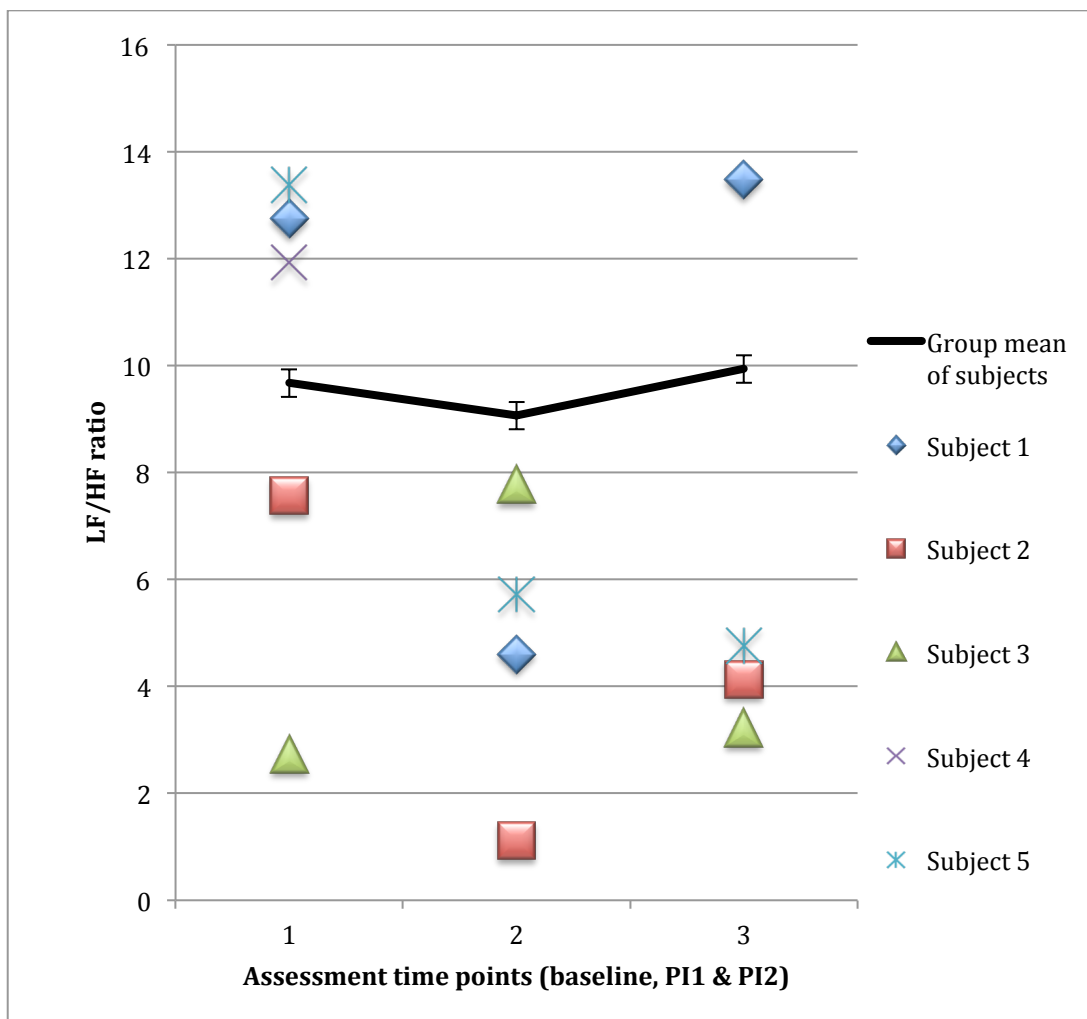


Figure 11. LF/HF ratio during steady state exercise at three assessment time points

Subject 1-5 individual participant values of LF/HF ratio during steady state exercise over three assessment time points. Group mean of subject's LF/HF ratio during steady state exercise over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.968$). In order to normalize the data, percent change was calculated using the formula $((y_2-y_1)/y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p= 0.669$).

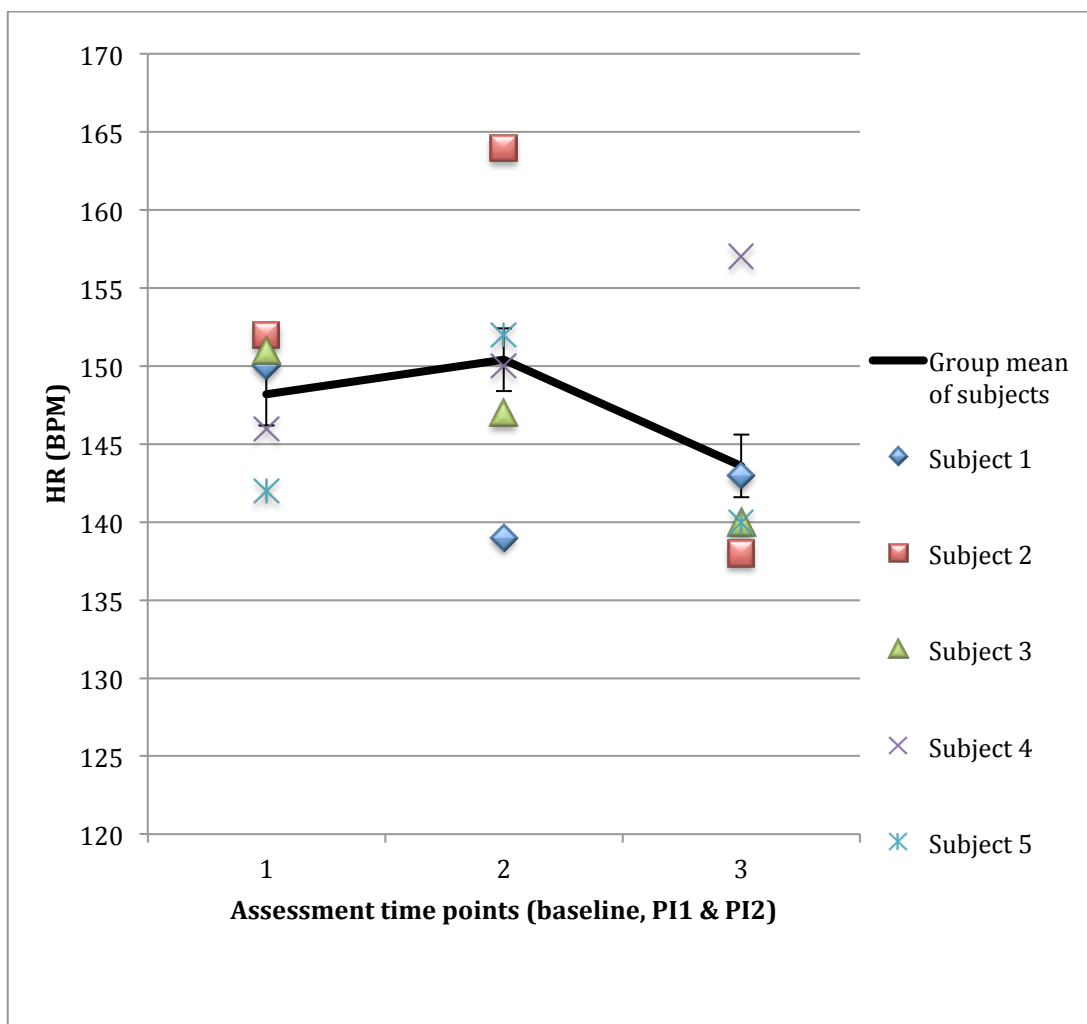


Figure 12. HR (BPM) ratio during steady state exercise at three assessment time points
 Subject 1-5 individual participant values of Heart Rate (bpm) during steady state exercise over three assessment time points. Group mean of subject's Heart Rate (bpm) during steady state exercise over three assessment time points. A one (group) x three (phase) repeated measure ANOVA revealed no significant difference between any of the three assessment times ($p=0.413$). In order to normalize the data, percent change was calculated using the formula $((y_2 - y_1) / y_1 * 100)$. The percent change was analyzed using a one (group) x three (phase) repeated measure ANOVA. No significant difference was found ($p= 0.438$).

Chapter 5: Discussion

The objective of this research was to determine if changes in HRV occurred in concussed athletes from baseline to post-concussion and return to play. The results of this study showed two significant differences at rest, HR ($p=0.016$) and total power ($p=0.015$). Due to low subject numbers (n) this study was not able to confirm that a concussion resulted in statistically significant changes in HRV during exercise. This research was conducted to answer the follow research question:

1. Is HRV affected post-concussion, both at rest and during exercise?

Research specifically investigating HRV in athletes post-concussion has been limited, and prior to this current study there has been a paucity of research where athletes have served as their own controls. Senthinathan et al., (2014) was the only study found where a single athlete was tested prior to a concussion. The research design of this study has limitations, most predominantly the low subject numbers (n) due to the ‘naturally occurring’ intervention. The low n resulted in non-significant p values but the results did show similar trends to other research in the area, which may be of clinical significance. It has been stated by Goldstein et al., (1998), that the degree of autonomic uncoupling in cardiovascular control (as reflected by changes in HRV at rest and during exercise) is related to the severity of the concussive injury and currently concussion that occur in sport are not graded on a severity scale. Further complicating results was the fact that exercise testing could not be completed until participants subjectively reported that they were asymptomatic, which could have resulted in some re-coupling of the neuroautonomic cardiovascular system. The majority of concussions resolve spontaneously within seven to ten days (McCroory et al., 2013) and this study was only

able to test participants once they reported that they were symptom free. In the 2012 Consensus statement on concussions in sport it was stated “the cornerstone of concussion management is physical and cognitive rest until the acute symptoms resolve and then a graded programme of exertion prior to medical clearance and RTP”. This statement complicated the ability of the PI to be granted ethical approval for early exercise intervention and monitoring of HRV during a more acute phase of concussion.

This resulted in first post-injury assessment of resting and exercise HRV occurring on average of 10.8 ± 4.97 days post-injury. This delay in testing could have resulted in diminished results in regards to the changes in HRV. As the research and evidence in the benefit of sub-symptom threshold exercise post-concussion is growing, completing research monitoring HRV during the acute phase using sub-symptom threshold exercise could be of benefit and may provide a better view of the impact of concussion on HRV. Although low subject numbers impaired statistical significance, it should be noted that consistent trends in HRV changes that concurred with previous literature were seen and warrant further investigation.

5.1 HRV during Rest

During the rest period, measures of total power calculated in % change, which is a measure of the variance of all RR intervals, reached a level of significance ($p=0.015$). These significant changes were seen from baseline to first post-injury assessment ($p=0.04$), and from first post-injury assessment to RTP ($p=0.01$). The change seen here were a significant decrease in total power from baseline assessment to PI1 assessment and a significant increase in total power from PI1 to PI2.

HR from baseline to P11 assessment during a period of rest in this study showed a significant increase ($p=0.016$). A study done by Katz-Leurer et al., (2009) also showed a similar increase ($p= <0.01$) in resting HR's in boys' who were post-concussion compared to matched controls. Other studies by King et al., (1997) and a case study by Senthinathan et al., (2014) also showed an increase in HR at rest post-concussion. It is well known that HR is under the control of the autonomic nervous system. When the body is in a resting state HR will be controlled by both branches of the ANS, however HR control is dominated by the parasympathetic nervous system at rest (Heart Rate Variability Task Force, 1996). However, post-concussion HRV results show an increase in sympathetic activation acting on the heart at rest. The imposed stress to the body from a concussion may be enough to cause an increase in circulating epinephrine, in turn leading to an increase in HR.

Gall et al., (2004) examined changes in the frequency domain in HRV of concussed junior B hockey players at rest and during a bout of exercise. They did not find a significant difference between the concussed and control group at rest, 1.8 days and 5.6 days post-injury however, they did find the concussed group displayed a non-significant increase in LF (n.u.) and a decrease in HF (n.u.) compared to the control group at both assessment times. Senthinathan et al., (2014) also found concussed athletes showed an increase in LF (n.u.) and a decrease in HF (n.u.) while sitting when compared to controls, however this was not significant. Senthinathan et al., (2014) also completed a case study of one varsity athlete and found a significant elevation in LF (n.u.) and decrease in HF (n.u.) ($p=<0.05$) 72 hours post-concussion. The findings of the current study, although not significant, also found that the group mean of LF (n.u.) increased from baseline to the first post-injury assessment while the mean HF (n.u.) decreased. In the study by

Senthinathan et al., (2014), it was also observed in the results that this change in HF (n.u.) and LF (n.u.) seem to improve towards expected resting values of a high parasympathetic activation represented in HF (n.u.) and lower sympathetic activation LF (n.u.) in sitting for the concussed group. This result was also observed in the current study, although not significant. From a physiological stand point both of these studies are demonstrating that by having an increase in LF (n.u.) and decrease in HF (n.u.) at rest suggests an increase in sympathetic activation while in a resting state post-concussion.

LF/HF ratio, an important component of HRV, represents the sympathovagal balance of the ANS (Heart Rate Variability Task Force, 1996). At rest, LF/HF ratio increased during the three assessment periods in this current study. From baseline to first post-injury assessment this would be the expected result as an increase in LF/HF ratio is the result of an increase in sympathetic activation. This increase could be a response to the concussion as LF/HF ratio represents the sympathovagal balance and an increase in sympathetic activation results in an increase in this ratio. Research by Gall et al., (2004) and Senthinathan et al., (2014) also showed a similar result. In both studies at first post-concussion assessment LF/HF ratios was higher than that of the matched controls, although not significant. However; both of these studies showed a decreasing trend from first post-injury assessment to the final assessment. This was not the case for this study in which an increasing trend was seen over the three trials.

From the results of this study at rest it appears that the increase in markers of sympathetic activation and decrease in parasympathetic activation at rest can be attributed to the body being in a state of stress as a result of a concussion in sport (Aubert et al., 2003). This also supports the idea that post-concussion and uncoupling of the

neuroautonomic cardiovascular regulation occurs and may be related to the severity of injury.

Further limitations noted were that it would have been of benefit to this study to have a rest assessment of concussed athletes 24-72 hours post-injury. This could have resulted in an improved understanding of autonomic regulation during the acute phase after a concussion and an improved understanding on what is occurring to their neuroautonomic cardiovascular regulation.

5.2 Exercise

With the initiation of exercise there is an increase in HR due to a withdrawal of parasympathetic activation and an increase in sympathetic activation (Aubert et al., 2003). This switch to a sympathetic dominance results in a decrease in HRV as reflected by an increase in LF/HF ratio when compared to resting. The extent to which HRV decreases will depend on many factors, such as age, gender, sport played, fitness level and exercise intensity (Aubert et al., 2003). The results of this study showed the anticipated outcome with participants having an increase in sympathetic activation and HR, and a reduction in parasympathetic activation during exercise across all three trials when compared to resting state (Table 7). Although not significant, the extent of change in sympathetic activation and parasympathetic decrease was diminished post-concussion.

During exercise, participants in this study showed changes across all three trials consistent with other research. The stress exercise imposed to the body can be seen through the elevation in HR and sympathetic activation with a decrease in parasympathetic activation (Table 7). During this study participants showed a non-significant increase in exercising steady state HR from baseline to post-injury and a

decrease from post-injury to return play assessment (Table 4). This trend was similar to results of Katz-Leurer et al., (2016) who found that post severe concussion participants had significantly higher HR ($p=0.03$) than matched controls during treadmill testing. Gall et al., (2004) also found higher HR 5 and 10 days post-injury in a group of hockey players ($n=9$) that missed playing time due to concussion, when compared to match controls during exercise. This increase in HR during exercise post-concussion was also found to be significant in a case study by Senthinathan et al., (2014) with one female varsity athlete testing before and after concussion injuries.

During exercise the increase in HR is required to meet the physiological demand of exercise and increased need for oxygen. Normally as HR increases, LF also increases reflecting the increased sympathetic modulation and HF decreases as vagal withdrawal occurs. Results showed a trend for an increase in HR with exercise, however this was not accompanied by an expected change in HRV. LF (n.u.) values showed an 8.5% reduction from baseline to first post-injury and in turn HF (n.u.) values showed a 36% increase of HF. This can be interpreted as a blunted sympathetic response to exercise post-concussion. This blunted result seems to adjust more towards baseline measurements at the second post-injury assessment. The changes that occurred in LF/HF ratio between each assessment phase did not reach a level of significance, most likely due to the very low subject numbers. Despite the lack of statistical significance what is encouraging is the similar trends as were seen in other concussion literature. This suggests that this blunted response may be of clinical significance and should be investigated further.

These alterations in HRV suggest that concussion may cause an autonomic disruption resulting in a reduction in sympathetic activation in response to exercise stress. Further investigation is warranted into the other body systems that the ANS interacts with

to determine if this reduction in sympathetic activation occurs post-concussion injury. Body systems such as the adrenal medulla or kidneys would be important targets as they have a function in helping to maintain blood pressure (BP); therefore, disruption to the ANS may cause disruption in the kidneys ability to maintain BP. Neuroautonomic cardiovascular regulation is said to become 'uncoupled' post-concussion and has been shown to be dependent on the severity of the injury (King et al., 1997). Results of this study are consistent with other research in this area and suggest that this uncoupling is occurring even in the mildest concussions such as those experienced by the participants of this study.

5.3 Future Research

Future research should continue to investigate the use of HRV as a measure of concussion recovery. Using a larger population sample of concussed athletes would increase the statistical power in the studies and would help make the trends that were seeing in this study reach statistical significance. Future research should also focus on obtaining resting HRV data immediately after concussive injury and in the 24-72 hours following concussive injury. This could provide insight into the extent and duration of autonomic uncoupling during the acute phase of injury. Lastly research looking into the impact of multiple concussions on HRV response at rest and during exercise.

5.4 Conclusion

The purpose of this research was to investigate the change in HRV in athletes post-concussion. Athletes display dysfunction in neuroautonomic cardiovascular regulation post-concussion as seen with changes in HRV. A significant difference was found between baseline (pre-injury) resting heart rate and first post-injury assessment resting heart rate ($p=0.037$). Resting Total Power was significantly different between baseline (pre-injury) and first post-injury assessment ($p=0.044$) and between first post-injury and second post-injury assessment ($p=0.010$). No statistical significant differences in any variables were found during exercise, however the trends in the changes of HRV were similar to other research studies and could be of clinical importance. There seems to be a practical use for monitoring HRV as a tool to help guide RTP and ensure safe RTP occurs for athletes. However more research is needed to fully understand how HRV is altered post-concussion.

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Appendix 1 – Informed Consent Form



**University
of Victoria**

Participant Consent Form

Analysis of alternative assessment tools for post-concussion cognitive and balance deficits

You are invited to participate in a study entitled Analysis of alternative assessment tools for post-concussion cognitive and balance deficits that is being conducted by Hilary Cullen, Allison Rodway, Dr. Brian Christie and Dr. Paul Zehr.

Hilary Cullen and Allison Rodway are both Graduate Student in the department of Exercise Physical and Health Education at the University of Victoria and you may contact them if you have further questions by email at hcullen@uvic.ca OR allisonr@uvic.ca.

As Graduate students we are required to conduct research as part of the requirements for a degree in Master of Science (Kinesiology). It is being conducted under the co-supervision of Dr. Brian Christie and Dr. Paul Zehr. You may contact the co-supervisors by telephone or email (DR. Christie - 250-472-4244 OR BRAIN64@UVIC.CA) or (DR. Zehr - 250-721-8379 OR PZEHR@UVIC.CA)

This research is being funded by THE CANADIA INSTITUTE OF HEALTH RESEARCH (CIHR). CIHR PROVIDES FUNDS FOR HEALTH RELATED RESEARCH IN CANADA.

Purpose and Objectives

The purpose of this research project is to provide more information about concussion assessment tools. While concussions have garnered much attention as a growing public health concern, researchers have yet to reach consensus about what is the “best” way to assess people with concussions. The current study will focus on concussion assessment tools that evaluate balance and brain function. People with concussions usually take longer to recover in these areas, so concentrating assessment tools on them may give clinicians a better indication of how well an individual is recovering and when it is safe for them to return to play. This study focuses on the Wii Balance Board to assess balance and the NeuroTracker computer program to assess cognitive function. There are two research questions for this project, 1) Are the NeuroTracker and Wii Balance Board tools sensitive indicators of post-concussion cognitive and balance deficits? and 2) Does baseline performance on the NeuroTracker and Wii Balance Board tools correlate to other concussion assessment tools?

Importance of this Research

The main contribution of this project is to develop and validate a concussion assessment tool that coaches, parents, training staff and health professionals can use. Developing evidence-based assessment tools to help determine return to play/school/work is an important area of research given the high incidence of concussion and current controversy about how to best diagnose and manage concussions.

Participants Selection

You are being asked to participate in this study because you are a member of the target population. We are looking to involve varsity athletes in this research project and you meet this description.

What is involved?

If you consent to voluntarily participate in this research, your participation will include a baseline and post-season assessment of your cognitive function, balance, and heart rate variability. Should you sustain a concussion over the course of your season you SHOULD FIRST SEEK MEDICAL ATTENTION FROM YOUR MEDICAL DOCTOR. AFTER CONSULTING WITH YOUR MEDICAL DOCTOR, WE ASK THAT YOU CONTACT A MEMBER OF THE RESEARCH TEAM IN ORDER TO complete three post-injury assessments of the same factors. All assessments will take approximately 60 minutes to complete.

Inconvenience

Participation in this study may cause some inconvenience to you, because of the time commitment required. We will book all data collection appointments at times that are convenient for you.

Risks

WITH THIS RESEARCH THERE ARE KNOWN RISK WITH PARTICIPATION HOWEVER, THESE RISKS HAVE BEEN DEEMED AS MINIMAL. PARTICIPANTS MAY EXPERIENCE PHYSICAL AND MENTAL FATIGUE FOLLOWING THE COGNITIVE, BALANCE OR SUB-MAXIMAL EXERCISE TESTS. PARTICIPANTS MAY SUSTAIN A PHYSICAL INJURY (E.G. MUSCLE STRAIN OR SIMILAR) DURING THE BALANCE AND SUB-MAXIMAL TESTS.

Benefits

Participants will be given the opportunity to participate in more advanced concussion assessment protocol, which could be beneficial to their overall injury management. This will decrease the risk of premature Return to Play, which is associated with higher risk of subsequent injury. Participants will also gain a greater understanding and knowledge of concussion.

Voluntary Participation

Your participation in this research must be completely voluntary and you will not receive any compensation for participation. If you do decide to participate, you may withdraw at any time without any consequences or any explanation. If you choose to withdraw from the study your data will be used only if you agree to its use.

Researcher's Relationship with Participants

Researcher Allison Rodway may have a relationship to potential participants as a Varsity Athletic Therapist. To help prevent this relationship from influencing your decision to participate, the following steps to prevent coercion have been taken:

- Participants will not be recruited during treatment sessions
- No information about individuals testing results will be shared during treatment sessions
- All participants will be free to withdrawal from the study at anytime

YOUR PARTICIPATION IN THIS RESEARCH PROJECT IS COMPLETELY SEPARATE FROM YOUR ROLE AS A VARSITY ATHLETE AT THE UNIVERSITY OF VICTORIA. THE RESEARCH TEAM DOES NOT MAKE DECISIONS REGARDING RETURN TO PLAY TIMELINES OR ELIGIBILITY.

On-going Consent

To make sure that you continue to consent to participate in this research, I will have you initial your consent on an Appointment History and Ongoing Consent Form.

Anonymity

In terms of protecting your anonymity you will be assigned a unique participant number and all data will be completely anonymized following data collection. When presenting our findings, only participant number will identify case studies.

Confidentiality

There are limits to confidentiality due to the methods of this project. Only participants who sustain a head injury will be re-tested in Phase Two of data collection (i.e. post-concussion). Participant numbers will be assigned to each participant to provide a certain level of anonymity; however, due to the decreased number to be re-tested versus the number of participants in Phase One (i.e. baseline), some individuals may be able to deduce subject results. When presenting our findings, case studies will be presented using participant numbers, not names. When data collection is completed, data will be completely anonymized as all identifying factors will be removed from participants' data. Anonymized data will be kept indefinitely by researchers at the University of Victoria and CogniSens Athletics Inc.

Please be advised that this research study includes data storage in the U.S.A. **THROUGH RESEARCHERS' USE OF GOOGLE APPLICATIONS FOR DATA ORGANIZATION PURPOSES.** As such, there is a possibility that information about you that is gathered for this research study may be accessed without your knowledge or consent by the U.S. government in compliance with the U.S. Patriot Act.

Dissemination of Results

It is anticipated that the results of this study will be shared with others in the following ways: thesis, dissertations, class presentations, presentations at scholarly meetings, published article, chapter or book, internet, online library collections, media, directly to participants and/or groups involved.

Commercial Use of Results

This research may lead to a commercial product or service. The nature of this commercial use is to evaluate the effectiveness of the NeuroTracker computer program as a "return to play" indicator for concussions.

COGNISENS ATHLETICS INC. IS THE DEVELOPER OF THE NEUROTRACKER COMPUTER PROGRAM THAT IS INCLUDED IN THIS RESEARCH. THE COMPANY HAS NO INFLUENCE OR DIRECTION IN THE WAY IN WHICH WE ARE CONDUCTING THIS STUDY.

MEMBERS OF THE RESEARCH TEAM DO NOT HOLD SHARES IN THE COGNISENS ATHLETICS INC. COMPANY.

Disposal of Data

Data from this study will be disposed of by shredding paper copies and deleting electronic files. DE-IDENTIFIED DATA WILL BE KEPT INDEFINITELY FOR FUTURE USE. These files will be anonymized, encrypted; password protected, and only be accessible by the Researcher and stakeholders at CogniSens Athletics Inc.

Contacts

Individuals that may be contacted regarding this study include Principle Investigators and MSc Students Hilary Cullen (hcullen@uvic.ca), Allison Rodway (allisonr@uvic.ca) or their supervisors (as referred above).

In addition, you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Human Research Ethics Office at the University of Victoria (250-472-4545 or ethics@uvic.ca).

Your signature below indicates that you understand the above conditions of participation in this study, that you have had the opportunity to have your questions answered by the researchers, and that you consent to participate in this research project.

Name of Participant

Signature

Date

Future Use of Data

I consent to the use of my data in future research BY UVIC: _____ (Participant to provide initials)

I **do not** consent to the use of my data in future research BY UVIC: _____ (Participant to provide initials)

I CONSENT TO THE USE OF MY DATA IN FUTURE RESEARCH BY COGNISENS ATHLETICS INC: _____ (PARTICIPANT TO PROVIDE INITIALS)

I **DO NOT** CONSENT TO THE USE OF MY DATA IN FUTURE RESEARCH BY COGNISENS ATHLETICS INC: _____ (PARTICIPANT TO PROVIDE INITIALS)

Appendix 2 – Medical and Concussion History Form

PARTICIPANT CONTACT INFORMATION			
First Name		Last Name	
Phone (home)		Phone (cell)	
Email			

EMERGENCY CONTACT INFORMATION			
First Name		Last Name	
Phone (home)		Phone (cell)	
Email			
Relationship to You			

GENERAL PARTICIPANT INFORMATION			
Height (ft)		Weight (lbs)	
Age		DOB (yyyy/mm/dd)	
Gender		Highest Education Level	
What hand do you write with?			
What hand do you shoot a hockey puck with?			
What hand do you use to throw a ball?			

MEDICAL INFORMATION			
Do you have ADHD?		Are you dislexic?	
Do you have ADD?		Are you colourblind?	
List any current medications you are on.			

CURRENT SPORT PARTICIPATION			
SPORT	POSITION	LEVEL	YEARS

PREVIOUS SPORT PARTICIPATION			
SPORT	POSITION	CURRENT LEVEL	YEARS TOTAL

Appendix 3– SCAT Form

Downloaded from bjsm.bmj.com on September 24, 2014 - Published by group.bmj.com

SCAT3™



FIFA®



FEI

Sport Concussion Assessment Tool – 3rd Edition

For use by medical professionals only

Name

Date/Time of Injury:
Date of Assessment:

Examiner:

What is the SCAT3?¹

The SCAT3 is a standardized tool for evaluating injured athletes for concussion and can be used in athletes aged from 13 years and older. It supersedes the original SCAT and the SCAT2 published in 2005 and 2009, respectively². For younger persons, ages 12 and under, please use the Child SCAT3. The SCAT3 is designed for use by medical professionals. If you are not qualified, please use the Sport Concussion Recognition Tool³. Preseason baseline testing with the SCAT3 can be helpful for interpreting post-injury test scores.

Specific instructions for use of the SCAT3 are provided on page 3. If you are not familiar with the SCAT3, please read through these instructions carefully. This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. Any revision or any reproduction in a digital form requires approval by the Concussion in Sport Group.

NOTE: The diagnosis of a concussion is a clinical judgment, ideally made by a medical professional. The SCAT3 should not be used solely to make, or exclude, the diagnosis of concussion in the absence of clinical judgement. An athlete may have a concussion even if their SCAT3 is "normal".

What is a concussion?

A concussion is a disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific signs and/or symptoms (some examples listed below) and most often does not involve loss of consciousness. Concussion should be suspected in the presence of **any one or more** of the following:

- Symptoms (e.g., headache), or
- Physical signs (e.g., unsteadiness), or
- Impaired brain function (e.g. confusion) or
- Abnormal behaviour (e.g., change in personality).

SIDELINE ASSESSMENT

Indications for Emergency Management

NOTE: A hit to the head can sometimes be associated with a more serious brain injury. Any of the following warrants consideration of activating emergency procedures and urgent transportation to the nearest hospital:

- Glasgow Coma score less than 15
- Deteriorating mental status
- Potential spinal injury
- Progressive, worsening symptoms or new neurologic signs

Potential signs of concussion?

If any of the following signs are observed after a direct or indirect blow to the head, the athlete should stop participation, be evaluated by a medical professional and **should not be permitted to return to sport the same day** if a concussion is suspected.

Any loss of consciousness? Y N
 "If so, how long?" _____
 Balance or motor incoordination (stumbles, slow/laboured movements, etc.)? Y N
 Disorientation or confusion (inability to respond appropriately to questions)? Y N
 Loss of memory:
 "If so, how long?" _____
 "Before or after the injury?" _____
 Blank or vacant look: Y N
 Visible facial injury in combination with any of the above: Y N

1 Glasgow coma scale (GCS)

Best eye response (E)

No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	3
Eyes opening spontaneously	4

Best verbal response (V)

No verbal response	1
Incomprehensible sounds	2
Inappropriate words	3
Confused	4
Oriented	5

Best motor response (M)

No motor response	1
Extension to pain	2
Abnormal flexion to pain	3
Flexion/Withdrawal to pain	4
Localizes to pain	5
Obeys commands	6

Glasgow Coma score (E + V + M) _____ of 15

GCS should be recorded for all athletes in case of subsequent deterioration.

2 Maddocks Score³

"I am going to ask you a few questions, please listen carefully and give your best effort."

Modified Maddocks questions (1 point for each correct answer)

What venue are we at today?	0	1
Which half is it now?	0	1
Who scored last in this match?	0	1
What team did you play last week/game?	0	1
Did your team win the last game?	0	1
Maddocks score	_____ of 5	

Maddocks score is validated for sideline diagnosis of concussion only and is not used for serial testing.

Notes: Mechanism of Injury ("tell me what happened?"):

Any athlete with a suspected concussion should be REMOVED FROM PLAY, medically assessed, monitored for deterioration (i.e., should not be left alone) and should not drive a motor vehicle until cleared to do so by a medical professional. No athlete diagnosed with concussion should be returned to sports participation on the day of injury.

BACKGROUND

Name: _____ Date: _____
 Examiner: _____
 Sport/team/school: _____ Date/time of injury: _____
 Age: _____ Gender: M F
 Years of education completed: _____
 Dominant hand: right left neither
 How many concussions do you think you have had in the past? _____
 When was the most recent concussion? _____
 How long was your recovery from the most recent concussion? _____
 Have you ever been hospitalized or had medical imaging done for a head injury? Y N
 Have you ever been diagnosed with headaches or migraines? Y N
 Do you have a learning disability, dyslexia, ADD/ADHD? Y N
 Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? Y N
 Has anyone in your family ever been diagnosed with any of these problems? Y N
 Are you on any medications? If yes, please list: Y N

SCAT3 to be done in resting state. Best done 10 or more minutes post exercise.

SYMPTOM EVALUATION

3 How do you feel?

"You should score yourself on the following symptoms, based on how you feel now".

	none	mild	moderate	severe			
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

Total number of symptoms (Maximum possible 22) _____

Symptom severity score (Maximum possible 132) _____

Do the symptoms get worse with physical activity? Y N

Do the symptoms get worse with mental activity? Y N

self rated self rated and clinician monitored

clinician interview self rated with parent input

Overall rating: If you know the athlete well prior to the injury, how different is the athlete acting compared to his/her usual self?

Please circle one response:

no different very different unsure N/A

Scoring on the SCAT3 should not be used as a stand-alone method to diagnose concussion, measure recovery or make decisions about an athlete's readiness to return to competition after concussion. Since signs and symptoms may evolve over time, it is important to consider repeat evaluation in the acute assessment of concussion.

COGNITIVE & PHYSICAL EVALUATION

4 Cognitive assessment

Standardized Assessment of Concussion (SAC)⁴

Orientation (1 point for each correct answer)

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1

Orientation score _____ of 5

Immediate memory

List	Trial 1	Trial 2	Trial 3	Alternative word list					
elbow	0	1	0	1	0	1	candle	baby	finger
apple	0	1	0	1	0	1	paper	monkey	penny
carpet	0	1	0	1	0	1	sugar	perfume	blanket
saddle	0	1	0	1	0	1	sandwich	sunset	lemon
bubble	0	1	0	1	0	1	wagon	iron	insect

Total _____

Immediate memory score total _____ of 15

Concentration: Digits Backward

List	Trial 1	Alternative digit list			
4-9-3	0	1	6-2-9	5-2-6	4-1-5
3-8-1-4	0	1	3-2-7-9	1-7-9-5	4-9-6-8
6-2-9-7-1	0	1	1-5-2-8-6	3-8-5-2-7	6-1-8-4-3
7-1-8-4-6-2	0	1	5-3-9-1-4-8	8-3-1-9-6-4	7-2-4-8-5-6

Total of 4 _____

Concentration: Month in Reverse Order (1 pt. for entire sequence correct)

Dec-Nov-Oct-Sept-Aug-Jul-Jun-May-Apr-Mar-Feb-Jan	0	1
--	---	---

Concentration score _____ of 5

5 Neck Examination:

Range of motion _____ Tenderness _____ Upper and lower limb sensation & strength _____

Findings: _____

6 Balance examination

Do one or both of the following tests.

Footwear (shoes, barefoot, braces, tape, etc.) _____

Modified Balance Error Scoring System (BESS) testing⁵

Which foot was tested (i.e. which is the non-dominant foot) Left Right

Testing surface (hard floor, field, etc.) _____

Condition

Double leg stance: _____ Errors

Single leg stance (non-dominant foot): _____ Errors

Tandem stance (non-dominant foot at back): _____ Errors

And / Or

Tandem gait^{6,7}

Time (best of 4 trials): _____ seconds

7 Coordination examination

Upper limb coordination

Which arm was tested: Left Right

Coordination score _____ of 1

8 SAC Delayed Recall⁴

Delayed recall score _____ of 5

INSTRUCTIONS

Words in *Italics* throughout the SCAT3 are the instructions given to the athlete by the tester.

Symptom Scale

"You should score yourself on the following symptoms, based on how you feel now".

To be completed by the athlete. In situations where the symptom scale is being completed after exercise, it should still be done in a resting state, at least 10 minutes post exercise.

For total number of symptoms, maximum possible is 22.

For Symptom severity score, add all scores in table, maximum possible is 22x6=132.

SAC⁴

Immediate Memory

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Complete all 3 trials regardless of score on trial 1 & 2. Read the words at a rate of one per second. **Score 1 pt. for each correct response.** Total score equals sum across all 3 trials. Do not inform the athlete that delayed recall will be tested.

Concentration

Digits backward

"I am going to read you a string of numbers and when I am done, you repeat them back to me backwards, in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."

If correct, go to next string length. If incorrect, read trial 2. **One point possible for each string length.** Stop after incorrect on both trials. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after completion of the Balance and Coordination Examination.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing⁵

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)⁵. A stopwatch or watch with a second hand is required for this testing.

"I am now going to test your balance. Please take your shoes off, roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty-second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

Each of the 20-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the athlete. The examiner will begin counting errors only after the individual has assumed the proper start position. **The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum total number of errors for any single condition is 10.** If an athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once subject is set. Subjects that are unable to maintain the testing procedure for a minimum of **five seconds** at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50cmx40cmx6cm).

Tandem Gait^{6,7}

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 meter line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. A total of 4 trials are done and the best time is retained. Athletes should complete the test in 14 seconds. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object. In this case, the time is not recorded and the trial repeated, if appropriate.

Coordination Examination

Upper limb coordination

Finger-to-nose (FTN) task:

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

Scoring: 5 correct repetitions in < 4 seconds = 1

Note for testers: Athletes fail the test if they do not touch their nose, do not fully extend their elbow or do not perform five repetitions. **Failure should be scored as 0.**

References & Footnotes

1. This tool has been developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport held in Zurich, Switzerland in November 2012. The full details of the conference outcomes and the authors of the tool are published in The BJSM Injury Prevention and Health Protection, 2013, Volume 47, Issue 5. The outcome paper will also be simultaneously co-published in other leading biomedical journals with the copyright held by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made.
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3. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine. 1995; 5(1): 32-3.
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6. Schneiders, A.G., Sullivan, S.J., Gray, A., Hammond-Tooke, G. & McCrory, P. Normative values for 16-37 year old subjects for three clinical measures of motor performance used in the assessment of sports concussions. Journal of Science and Medicine in Sport. 2010; 13(2): 196-201.
7. Schneiders, A.G., Sullivan, S.J., Kvarnstrom, J.K., Olsson, M., Yden, T. & Marshall, S.W. The effect of footwear and sports-surface on dynamic neurological screening in sport-related concussion. Journal of Science and Medicine in Sport. 2010; 13(4): 382-386

Appendix 4 – HRV Instructions

1. Place the heart rate monitor around the midline of the chest.
2. Ensure heart rate monitor is transmitting.
3. Have the participant relax for 5 minutes in a comfortable position.
4. The heart rate monitor will stay on through out the duration of each testing component.

Appendix 5 – Submaximal Cycling Exercise Instructions

1. Set the bike seat to the appropriate height, legs should be not be in full extension at the end of the pedal stroke.
2. Set the handlebars in a comfortable position.
3. Ensure the heart rate monitor is in the proper spot and transmitting data correctly.
4. Calculate the appropriate resistance using $1.5W \times kg$ of body weight.
5. 2 minute warm-up pedaling at 50-60 rpm @ 40W.
6. 10 minute pedal @ 80-90 rpm with calculated workload.
7. 2 minute active cool down @ 50 rpm.

Appendix 6– PAR-Q Form

Physical Activity Readiness
Questionnaire – PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
<input type="checkbox"/>	<input type="checkbox"/>	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?
<input type="checkbox"/>	<input type="checkbox"/>	2. Do you feel pain in your chest when you do physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	3. In the past month, have you had chest pain when you were not doing physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
<input type="checkbox"/>	<input type="checkbox"/>	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
<input type="checkbox"/>	<input type="checkbox"/>	7. Do you know of <u>any other reason</u> why you should not do physical activity?

**If
you
answered**

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT
or GUARDIAN (for participants under the age of majority) _____

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



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Appendix 7– Post-concussion Injury Form

DOB (yyyy/mm/dd)		Participant Number	
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Did you experience a head injury (a direct or indirect blow to the head) resulting in concussion-like symptoms (eg. headache, nausea, balance problems, tiredness, visual problems, etc.)?

YES

NO

Current Date (yyyy/mm/dd)	
Date of Injury (yyyy/mm/dd)	
Did you lose consciousness?	
Duration of loss of consciousness (min)	
Describe how the injury happened	
How many concussions have you had in the past? When was your most recent concussion, other than this one?	

Other Information (ex. list of symptoms, activities that worsen/alleviate symptoms, etc.)

Appendix 8 – Participation Withdrawal Form

DOB (yyyy/mm/dd)		Participant Number	
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I have decided to withdraw from this study. I acknowledge that I am withdrawing from the study at my own free will and will not face any consequence for withdrawing my participation.

I consent to the use of data collected prior to the withdrawal date noted below.

Data collected prior to the withdrawal will be used for analysis and publication purposes

I do not consent to the use of data collected prior to the withdrawal date noted below.

Data collected prior to the withdrawal will be used for analysis and publication purposes

Withdrawal Date:

Participant Name:

Participant Signature:

Appendix 9 – HR Monitor Log

HR MONITOR LOG

Monitor #	
Date (mm/dd/yyyy)	

Test	Time on	Time off	Participant #	Team
ON				
SCAT 3				
KD				
NT				
Wii				
Bike				
OFF				
Test	Time on	Time off	Participant #	Team
ON				
SCAT 3				
KD				
NT				
Wii				
Bike				
OFF				

Appendix 10 – Literature Review

Reference	Study Design	Measures	Population	Key Findings
Gall, B., Parkhouse, W., & Goodman, D. (2004). Heart rate variability of recently concussed athletes at rest and exercise. <i>Medicine and Science in Sports and Exercise</i> , 36(8), 1269-1274	Prospective Cohort	HRV – Mean RR, SDRR, LF, HF, HF/LF, LF (n.u.), HF (n.u.), total power	14 concussion junior hockey players, 14 matched controls	No significant difference between concussed and match controls in measures of HRV at rest 2-3 days or 7 days following concussion. Concussed athletes had significantly lower LF (ms ²) than match controls 5 and 10 days post-concussion than matched controls during low to moderate steady state exercise. Concussed athletes has significantly lower HF (ms ²) than matched controls 5 and 10 days post-concussion. No significant difference on LF (n.u.) or HF (n.u.) between concussed and match controls.
Gall, B., Parkhouse, W., & Goodman, D. (2004). Exercise following a sport induced concussion. <i>British Journal of sports medicine</i> 2004; 38:773-777	Prospective Cohort	HR	9 concussed male junior hockey players with time loss, 5 concussed male hockey players no time lost and 4 matched controls	Concussed athletes that missed time had significantly higher HR during steady state exercise than matched controls, 5 and 10 days post-injury.
Senthinathan, A., Mainwaring, L., & Hutchinson, M.,	Case study, pre / post-injury measures	HR Parameters of HRV (mean RR,	18 year old female, tested 3 times in 1	Significant increase in HR and LF (n.u.) and significant decrease in

(2014).Physiological and psychologic markers of concussion recovery: A female varsity athlete case study		SDNN<, NN50, pNN50, LF (n.u.), HF (n.u.)	month prior to injury, re-tested 72 hours post-concussion, at start of exercise progression & 1 week following medical clearance to RTP	HF (n.u.) 72 hours post-concussion. Significant increase on HR at start of exercise progression.
Senthinathan, A., Mainwaring, I., (2014). Heart rate variability in concussed varsity athletes: From injury to return-to-play. Brain Injury	Prospective cohort	HRV – LF, HF, HF/LF, LF (n.u.), HF (n.u.),	11 varsity concussed athletes and 11 matched controls	Concussed athletes has increased LF (n.u.) and decreased HF (n.u.) in sitting vs controls 72 hours post-concussion
Katz-Leurer, M., Rotem, H., Keren, O., & Meyer, S. (2010). Heart rate and heart rate variability at rest and during exercise in boys who suffered a severe traumatic brain injury and typically-developed controls. Brain Injury, 24(2), 110-114. doi:10.3109/02699050903508234	Comparative	HR Time domain parameters of HRV	12 boys post severe brain injury and 18 typically developed boys age matched	Post brain injury boy had higher mean HR at rest and during exercise
Hilz, M. J., DeFina, P. A., Anders, S., Koehn, J., Lang, C. J., Pauli, E., & Marthol, H. (2011). Frequency analysis unveils cardiac autonomic dysfunction after mild traumatic brain injury. Journal of Neurotrauma, 28(9), 1727-1738. doi:10.1089/neu.2010.1497	Cross-sectional	HR HRV (time domain RR, SDRR) (frequency domain LF, HF, LF (n.u.), HF (n.u.), LF/HF	20 participant 17 male, 3 female who sustain mTBI 5-43 months prior, 20 age and sex matched controls, 15 male and 5 female	Supine resting mean HF & HF (n.u.) were significantly lower in participants who sustained a concussion vs. controls. Supine resting mean LF & LF (n.u.) were significantly higher in participants who sustained a concussion vs. controls.