MULTIPLE PREVIOUS CONCUSSIONS AND DUAL TASK PARADIGMS: REACTIVE POSTURAL PERTURBATION MANAGEMENT

by

Jillian Katrina Dierijck

B.Sc. (Hons), Wilfrid Laurier University, 2015

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE COLLEGE OF GRADUATE STUDIES

(Interdisciplinary Studies)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

October 2017

© Jillian Katrina Dierijck, 2017

The undersigned certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis entitled:

MULTIPLE PREVIOUS CONCUSSIONS AND DUAL TASK PARADIGMS: REACTIVE POSTURAL PERTURBATION MANAGEMENT

submitted by <u>Jillian Katrina Dierijck</u> in partial fulfilment of the requirements

of the degree of <u>Masters of Science</u>, Interdisciplinary Studies, Health and Exercise Science

Dr. Paul van Donkelaar, School of Health and Exercise Sciences

Supervisor, Professor

Dr. Brian Dalton, School of Health and Exercise Science

Supervisory Committee Member, Professor

Dr. Chris McNeil, School of Health and Exercise Sciences

Supervisory Committee Member, Professor

Dr. Harry Miller, Irving K Barber School of Arts and Sciences

University Examiner, Professor

Abstract

Sport-related concussion has received increasing concern and research in the last 20 years. Despite much research being done in the acute phase, chronic disturbances as a result of multiple concussions have received notably less attention. Moreover, these long-term difficulties as a result of multiple concussions have the capacity to influence the future of the athletes sporting career as well as their day-to-day functioning. Of particular interest is the impact of multiple concussions on balance. While studies of quiet stance balance are informative, they do not challenge the postural control system as contact sport game-play does. Therefore, the purpose of this study was to evaluate the influence of multiple previous concussions on the ability to manage external perturbations (analogous to pushes and tackles) under varying attentional demands. A group of contact-sport athletes who have never had a concussion (n=16) and a group of contact sport athletes who have been exposed to two or more concussions (n=16) were recruited. Participants completed a button press task, an arm reaching task with unexpected external perturbations, and both tasks simultaneously. A 2×2 mixed model ANOVA was used to assess for the main effects of task (single vs. dual) and concussion history (zero vs. two or more). Dependent variables included aspects of centre of pressure (COP; displacement and velocity), hand kinematics (displacement and velocity), and reaction time. Under dual-task conditions performance decreased on a number of variables including COP, hand kinematics, and reaction time. Moreover, the group with multiple previous concussions performed significantly worse, particularly in COP metrics compared to the group who have no concussion history. These findings indicate a history of concussion alters COP metrics (postural control). Furthermore, these findings highlight the potential use of this novel task (combining external perturbations and a secondary attention task) in concussion assessment and return-to-play decision making. Taken together, the current findings add crucial information to the impact of concussion on postural control. Given this information, interventions need to be designed and implemented to mitigate the chronic disturbances to balance (that could influence the future sporting career and day-today life) which may result from exposure to multiple concussions.

Preface

The research presented in this thesis was approved by the University of British Columbia's Clinical Research Ethics Board (H14-02996).

Table of Contents

Abstract	iii
Preface	iv
Table of Contents	v
List of Tables	viii
List of Figures	ix
List of Abbreviations	v
	*
Acknowledgements	XI
Dedication	xii
1 Chapter: Introduction	1
1.1 Concussion Considerations	1
1.2 Postural Stability	6
1.2.1 Postural Control Following Concussion	12
1.3 Attention	21
1.3.1 Attention Following Concussion	22
1.4 Dual Task Paradigms - Postural Stability and Attention	27
1.4.1 Dual Task Paradigms and Concussion	
1.5 Knowledge Gap	
1.6 Purpose	34
1.7 Hypothesis	
2 Chapter: Methods	35
2.1 Participants	35
2.2 Instruments	
2.2.1 KINARM End-Point Robot System	
2.2.2 True Impulse Force Plate	
2.2.3 Custom-built Reaction Time Button	
2.3 Task	
2.3.1 Single Task – Button Press	
2.3.2 Single Task – Reach with Perturbation	40
2.3.3 Dual Task	

	2.4	Data Analysis	44
	2.5	Dependent Variables	45
	2.5.1	1 SCAT3	45
	2.5.2	2 Centre of Pressure	46
	2.5.3	3 Hand Kinematics	46
	2.5.4	4 Reaction Time	47
	2.6	Statistical Analysis	47
3	Chap	pter: Results	49
	3.1	Centre of Pressure	49
	3.1.1	l Main Effects – Task	49
	3.1.2	2 Main Effects – Concussion History	53
	3.1.3	3 Interaction Effects	57
	3.2	Hand Kinematics	57
	3.2.1	1 Main Effects – Task	57
	3.2.2	2 Main Effects – Concussion History	61
	3.2.3	3 Interaction Effects	61
	3.3	Reaction Time	63
	3.3.1	1 Reach Task Reaction Time	63
	3.	.3.1.1 Main Effects – Task	63
	3.	.3.1.2 Main Effects – Concussion History	63
	3.	.3.1.3 Interaction Effects	64
	3.3.2	2 Secondary Task Reaction Time	65
	3.	.3.2.1 Main Effects – Task	65
	3.	.3.2.2 Main Effects – Concussion History	65
	3.	.3.2.3 Interaction Effects	65
	3.4	SCAT3 Metrics	66
4	Chap	oter: Discussion	68
	4.1	Dual Task Effect	68
	4.2	The Influence of Multiple Previous Concussions	73
	4.3	The Interaction of Dual Task and Previous Concussions	76
	4.4	Relating to the SCAT	77
	4.5	Limitations and Future Directions	78
5	Chap	oter: Conclusion	81

REFERENCES	84
APPENDIX	96
Appendix A - Sport Concussion Assessment Tool 3 (SCAT3)	96

List of Tables

Table 1.1	Balance Error Scoring System (BESS) Errors	14
Table 2.1	Participant Demographics	36
Table 2.2	Dependent Variables	45
Table 3.1	COP ANOVA, Main Effect - Task	52
Table 3.2	COP ANOVA, Main Effect - Concussion History	56
Table 3.3	Hand Kinematics, ANOVA, Main Effect - Task	60
Table 3.4	Hand RT, Main Effect - Task	63
Table 3.5	Secondary Task RT, Main Effect - Task	65
Table 3.6	Independent Samples T-Test, SCAT3 Metrics - Concussion History	66
Table 3.7	SCAT3 Correlations	67

List of Figures

Figure 1.1	BOS, COP, COM, COG7
Figure 1.2	Balance Error Scoring System
Figure 1.3	Attentional Network Task
Figure 2.1	KINARM Set Up
Figure 2.2	Force Plate
Figure 2.3	Custom-made Button
Figure 2.4	Trial Protocol
Figure 3.1	Representative participant data of the AP displacement and velocity of COP
	during no perturbation trials over time by task
Figure 3.2	Average time of maximum COP AP displacement and velocity under no
	perturbation conditions
Figure 3.3	Representative participant data of COP AP displacement and velocity during
	no perturbation conditions by concussion history group
Figure 3.4	Average maximum AP displacement and velocity of COP during no
	perturbation conditions by concussion history group
Figure 3.5	Representative maximum ML hand displacement during left perturbations 58
Figure 3.6	Maximum ML hand displacement and velocity during left perturbation
	by task
Figure 3.7	Maximum AP hand velocity during right perturbation
Figure 3.8	Interaction effect of hand RT during right perturbation

List of Abbreviations

- ANT Attentional Network Test
- AP Anterior/Posterior
- BESS Balance Error Scoring System
- BMI Body Mass Index
- BOS Base of Support
- COG Centre of Gravity
- COM Centre of Mass
- COP Centre of Pressure
- EC-Eyes-Closed
- EO-Eyes-Open
- mBESS modified Balance Error Scoring System
- ML Medial/Lateral
- mTBI mild Traumatic Brain Injury
- RMS Root Mean Square
- RT Reaction Time
- RTP-Return-to-Play
- SOT Sensory Organization Test

Acknowledgements

First, I would like to thank my supervisor, Paul van Donkelaar, for never getting annoyed no matter how many emails or texts he received from me. Moreover, I would like to thank my lab mates (Jon S., Mike, Colin, and Sandy), for editing, always providing support and guidance, and participating in throw-back-Thursdays (despite never participating in lipstick-Fridays). As well, Chris McNeil for always providing an interesting perspective.

A special thank you is due to Brian Dalton, who essentially became a second supervisor, taught me how to code, and dealt with my insane ramblings about Matlab when no one else could understand what I was saying. Thank you, thank you, thank you...

Without the financial assistance of the Canadian Traumatic Brain Injury Research Consortium (CTRC) a significantly larger amount of my time would have been spent grading labs and assignments. I thank you for awarding me the first ever MSc Trainee Grant.

Lastly, my family and friends spread across the country. Thank you to my Dad, for always making me feel like the smartest and most accomplished person on the planet, it's the pride you have for me that keeps me going. Thank you to my Mom, you always know how to put things in perspective and rebuild my world when its falling apart. To my long-distance friends Jade, and Jessica, the letters, texts, video chats, and snap chats reminded me I always have someone in my corner. Finally, to all the new friends that I have met in Kelowna (Kevin, Nicole, Rebecca, Jon M., and Gill), it took a while, but you made this town home.

For my sanity,

Was it worth it?

1 Chapter: Introduction

1.1 Concussion Considerations

Sport-related concussion is a prominent public health issue with an estimated 1.6 - 3.4 million head injuries occurring annually in the United States.¹ Considering the difference in population, this estimate corresponds to approximately $176\ 000 - 418\ 000$ injuries in Canada. While many epidemiological studies of concussion incidence exist in the United States (both in collegiate and high school athletes), significantly less literature has been published on Canadian populations. Recently, concussion incidence rates of up to 20% in some Canadian varsity sports have been reported with an average rate across all collegiate sports of 6.7%.²

Concussion is a type of mild traumatic brain injury (mTBI) induced by biomechanical forces resulting in complex pathophysiological alterations within the brain.³ Some common features of concussion include rapid onset of impaired neurological functioning resolving spontaneously, functional (rather than structural) disturbances, and an assortment of clinical symptoms (Reviewed in: McCrory, *et. al.*³). These associated symptoms generally include somatic (e.g., headache, balance difficulties, dizziness), cognitive (e.g., difficulty concentrating, feeling in a fog), and emotional (e.g., more emotional, depression, anxiety) disturbances. Concussion symptoms vary across individuals resulting in injuries with markedly different clinical presentations for impacts of similar profiles.^{3–6} Moreover, symptoms as a result of a concussive event are not correlated to the apparent severity of the precipitating impact.⁷ Therefore, although the mechanism of injury for two concussions may appear similar, the injured individuals will likely present very differently clinically.

Since symptomatology of this injury is extremely varied, an accurate diagnosis of concussion may prove difficult. Currently, concussions are diagnosed based on presence of self-report symptoms, and mechanism of injury as there is no definitive, objective test available.³

This method of diagnosis poses two major problems. First, using self-reported symptoms relies on the assumption that individuals who have recently suffered a brain injury have the capacity to provide accurate information to clinicians. Additionally, this approach relies heavily on the concussed individual to be honest about the symptoms (severity of said symptoms) when they are reported. In a study by Kerr and colleagues⁸, 214 former collegiate athletes (age 35.3 ± 7.5) retrospectively self-identified sports-related concussions, and reported the number of times these concussions were not disclosed to the appropriate staff. It was found as many as 68.3% of football players did not report their concussion to medical personnel. While 70% is an alarming statistic, of equal concern are the many individuals who purposefully under-reported either i) the number or severity of symptoms either due to desire/pressure to return to sport; or ii) the changes to cognitive functioning as a result of the head injury. Secondly, diagnosing in this manner (based on symptoms and mechanisms) relies on the ability of the clinician to recognize an array of non-specific symptoms (e.g., headache, nausea, drowsiness) which present following concussion. To further complicate this issue, it is likely the diagnosing clinicians did not witness the concussive event and instead must rely on second-hand information regarding the potential mechanism of injury. Donaworth and colleagues⁹, surveyed medical students regarding their own knowledge and understanding of concussions. This study revealed deficits in knowledge, appropriate management, and exposure to concussion across all four years of clinical training during medical school. Unsurprisingly, the limited knowledge regarding concussion during their formal training period can impact the accuracy of clinical diagnoses. Taken together, the combined difficulties from both the patient and clinician perspectives in diagnosis likely results in concussion incidence rates being significantly larger than estimated.¹

In an effort to provide a consistent message internationally regarding detection and return-to-play (RTP) management, the International Conference of Concussion in Sport produced the Sport Concussion Assessment Tool (SCAT). The SCAT3 is the most widely used assessment tool in the literature and was released in 2013. Its main components include: a symptom evaluation, Standardized Assessment of Concussion (SAC), and a balance assessment (modified Balance Error Scoring System; mBESS). The symptom evaluation consists of 22 symptoms which are rated on a 7-point Likert scale (none (0) – severe (6)) and provide total symptom number (up to 22 points) and total symptom severity (up to 132 points). The SAC includes measures of orientation, immediate memory, concentration, and delayed recall, providing a total score out of a maximum 30 points. The final main component of the SCAT is mBESS. This balance assessment uses three different foot positions to challenge balance while the eyes are closed. Number of errors are recorded (with a maximum of 10 errors for each position) with a perfect score being zero.

While the SCAT3 has been widely adopted it remains an imperfect measure of concussion. Specifically, issues regarding validity, applicability, reliability, and subjectivity have been raised and explored. Literature on the ability of the SCAT to detect concussion is mixed (Reviewed in: Yengo-Kahn¹⁰). Immediately following concussion, the SCAT components appear able to discriminate a clinical alteration in functioning associated with the concussion.¹⁰ Although detection using the SCAT, particularly detection more than one day after the injury, may be limited.¹⁰ Furthermore, it should be noted the vast majority of these studies exploring validity and reliability of the SCAT used male collegiate football players.¹⁰ Therefore, if used on a different population or a mixed population the SCAT may not be sensitive enough to detect changes between groups.¹⁰ One final drawback to be aware of when using the SCAT is

"sandbagging". This occurs when athletes perform at a sub-optimal level on purpose during their pre-injury baseline testing session. Should a concussion occur, their injured performance is less likely to appear different from their pre-injury baseline. This effect has been noted with neuropsychological testing (Reviewed in: Alsalaheen, *et. al.*¹¹) but has yet to be explored with the SCAT. Alternatively, athletes could sandbag/underreport symptoms when concussed. As the SCAT is a subjective measure, the trainer or physician administering the SCAT can alone speculate whether or not athletes are being truthful based on previous encounters with the athlete. Therefore, although the SCAT is useful in providing an assessment of subject clinical symptoms, it is limited as it does not provide a definitive objective measure of concussion. With a large amount of evidence showing the concern over the SCAT being sensitive enough to quantify when a concussion has occurred¹⁰, caution must be taken when using and interpreting this tool.

While an objective diagnostic marker of concussion has yet to be developed, fortunately for most concussed individuals, the associated symptoms of concussion are usually short-lived, persisting 7-10 days in 80 – 90% of cases.³ Acutely following concussion, a symptom-limited graded RTP protocol is introduced.⁶ Although in the vast majority of cases athletes make a full recovery³, concern has been growing about the cumulative effects of multiple concussions.¹² In a large National Collegiate Athletic Association (NCAA) study, it was found that when concussed, those athletes with a history of multiple concussions displayed a longer time to symptom recovery and with each incident concussion, risk of future concussion increased (one previous concussion = $1.4 \times$ risk; two previous concussion = $2.5 \times$ risk; 3 previous concussions = $3.0 \times$ risk).¹³ Moreover, significantly larger symptom burden has been noted following recurrent concussions when compared to the first concussive event.¹⁴ However, these aforementioned

effects are noted during the acutely concussed phase of an injured athlete with previous concussion history. The potential chronic disturbances as a result of compounding concussions are less clear.¹² As with the majority of the concussion literature, controversy remains regarding the extent of functional changes present following multiple concussions. Results from multiple studies using various measurements such as the SCAT, neurocognitive tests, and fMRI have produced conflicting evidence (Reviewed in Yengo et. al.¹⁰ and Elbin et. al.¹⁵). Furthermore, one of the most worrisome potential long-term consequence of multiple concussions is chronic traumatic encephalopathy (CTE). Although a definite cause and effect relationship has not been established¹², this disease typically presents decades following exposure to multiple head injuries.¹⁶ CTE involves a variety of severe symptoms including mood, behaviour, cognitive and motor issues.¹⁷ Currently, CTE can only be diagnosed post-mortem.¹⁷ These chronic effects need to be better understood *in vivo*, so athletes are aware of the potential risks of playing contact sports, and are able to make informed decisions regarding how it may influence their life years later. Once we have a better understanding of these long-term deficits associated with concussions, recovery programs can be established to help cope or reverse them.¹²

Concussion awareness has exponentially increased globally over the past few decades through increased media attention as well as policy changes at both the national and international sporting league levels. In general, concussions have been demonstrated to induce a wide variety of non-specific symptoms which typically resolve spontaneously within the first 1-2 weeks following the injury. The SCAT was developed to aid in concussion identification,^{3,6} however, as stated previously, it may not be overly effective when used more than a day after injury. There is much still to be learned about this complex injury, specifically more work needs to be done to address the possible long-term outcomes of concussion.¹² These effects have the potential to

influence not only the remainder of the athlete's sporting career, but also the day-to-day functioning of life following the conclusion of sport participation. Moreover, should long-term deficits as a result of concussion persist, potential rehabilitation options need to be identified and researched. ¹³

1.2 Postural Stability

Postural control is vital to daily functioning and sport performance as it allow us to complete tasks and move through our environment without falling over. Specifically, postural control encompasses stability and orientation of the body's position in space. Two main systems are necessary for the control of posture, neural and musculoskeletal systems.¹⁸ The neural system plans movements and integrates sensory feedback to then update the movement plan.¹⁸ The musculoskeletal system is responsible for producing the movement set out by the neural system.¹⁸ One large component of postural control is the maintenance of balance or postural stability. Balance requires the centre of mass (COM) be controlled in relation to the base of support (BOS).¹⁸ The COM is the point location of the total body mass or the weighted average of the COM of each body segment, while the BOS is the area in which the body is in contact with the support surface (Figure 1.1). Other variables of interest in postural stability include the centre of gravity (COG) and the centre of pressure (COP). The COG is the vertical projection of the COM onto the support surface.¹⁹ Finally, COP is a controlling variable of the COM. The COP is the average point of the total force applied to the support surface or the vertical ground reaction force vector.^{18,19} The COP continually moves outside of the COM such that the COM is pushed inward and maintained within the BOS. Therefore, although the COP and COM are independent components, the two variables are highly correlated with COP being larger in magnitude. As such, the movement of the COP can be used as a surrogate for COM movements.



Figure 1.1. Representation of the base of support (BOS), centre of pressure (COP), centre of mass (COM), and centre of gravity (COG)

A common method of assessing postural stability is the collection of COP via underfoot force plates. Force plates measure the ground reaction forces and moments that occur as a person stands or walks across them. From this data, the position of the COP over time can be derived providing displacement and velocity in anterior-posterior (AP) and medial-lateral (ML) directions. Increases in COP movement have been noted when the eyes are closed compared to open and in more challenging postures (i.e. one footed stance compared to two footed).¹⁹ Therefore, an increase in COP displacement or velocity is typically interpreted as the subject having increased difficulty controlling balance or a decreased postural control ability. Postural data obtained from force plates remains one of the best methods of assessing balance control.¹⁹

Postural stability depends on information provided by the senses. Specifically, balance is highly dependent on vision, somatosensation (proprioception, cutaneous and joint receptors), and the vestibular system.¹⁸ Vision provides information regarding the movement of the head with respect to external objects.¹⁸ Two pieces of information are gained from somatosensation. The first is from cutaneous receptors in the skin which generate signals proportional to the pressure at the point of contact with the skin and skin stretch around the joints.¹⁸ The second aspect of somatosensation is proprioception. Proprioception uses signals generated in muscle and joint receptors (e.g. muscle spindles, golgi tendon organs) to provide information about where the different body segments are located in space, and where the segments are in relation to one another and the rest of the body.¹⁸ Finally, the vestibular system provides information regarding linear and rotational acceleration of the head with respect to gravity.¹⁸ Because of the redundancy in sensory information available, balance can be maintained despite a lack of, or incorrect information from one system.¹⁸ In fact, the sensory weighting model²⁰ describes this phenomenon of increasing the gain or importance of certain sensory information when another is known to be unreliable or unavailable. Therefore, instead of each of the three sensory systems being equally valued in terms of importance across all situations, the relative weight of dependence on each system is flexible. If, for example, vision was removed, somatosensation and vestibular information would carry more weight when providing feedback to maintain postural stability.²⁰

Indeed, postural control is vastly more complex than it may look while observing an individual during static balance situations. When standing quietly (or statically) the body continuously sways small amounts, primarily in the AP direction. Therefore, although commonly referred to as static, quiet stance is in fact dynamic in nature. Not only are many processes and

systems at work to maintain quiet postural stability, but numerous changes occur in the postural control system to static stance before a voluntary movement is undertaken. These small preparatory changes prior to the actual postural control task are called anticipatory postural adjustments (APAs). Specifically, APAs can be defined as adjustments to posture whose onsets occur prior (~50-100 ms) to the onset of a voluntary postural task.^{21,22} These adjustments occur to prevent the disturbances to balance that would otherwise arise as a result of the movement taking place and are known to be specific to the task (type and complexity) being undertaken.^{18,21} One such case would be during an arm movement. Prior to the start of the arm movement, muscles in the legs and trunk are activated, in a distal to proximal fashion.²³ This muscle activity counteracts the dynamic forces required to move the arm to the new position and ensures stability in the new posture.

An arm movement or any other potentially destabilizing movement produced voluntarily is considered an internal perturbation. In contrast, a perturbation can also be applied externally without the knowledge of the individual necessitating a reactive response.¹⁹ External perturbations may challenge balance in a variety of different ways. First, the perturbation may cause the COM to be relocated outside of the BOS. This would be analogous to a push or in the sporting context a tackle from an opposing player. Alternatively, the BOS may be moved out from under the COM. This scenario would be equivalent to slipping on ice in the winter. Finally, perturbations may be sensory in nature thereby creating the illusion of a loss of balance when no such situation exists or inaccurate sensory information may be used (misjudging the location of a curb) resulting in a loss of balance.

When coping with postural perturbations which result in a change in the movement of the COM, an individual will generally adopt one of two potential strategies: fixed support or change

in support. Fixed support strategies include movement about the ankle, or hip, or a combination of the two, while the change in support strategy involves a step or reach. The fixed support ankle strategy is typically employed when the perturbation to balance is small and the supporting surface is firm.¹⁸ This strategy re-establishes postural stability by torques created primarily at the ankle. Depending on the direction of the perturbation, lower leg muscles will produce plantar- or dorsiflexion torques ~90–100ms after the perturbation to slow and reverse the movement of the COM.¹⁸ This muscle activity is followed by muscle activation in the upper leg and trunk to maintain an upright, extended posture.¹⁸ The second fixed support strategy is the hip strategy. This involves large quick hip flexions or extensions (depending on the direction of the perturbation) in which the core muscles are once again activated first, ~90–100ms after the perturbation followed by the upper leg muscles.¹⁸ The hip strategy is typically used when the perturbation is larger in magnitude or velocity, or when the support surface is small or compliant. In contrast, the change in support strategy involves an adjustment to the BOS by way of a step or reach to capture and maintain the COM within the BOS. Originally, it was thought changes in support strategies were used exclusively when the COM was shifted outside of the BOS.¹⁸ This idea has been refuted however, as stepping strategies have been noted for small perturbations in which the COM remained within the BOS (after performing experiments in which the participants were not given explicit constraining instructions regarding avoiding stepping).^{18,24} Since postural control situations are rarely as simple as a small perturbation which pushes our COM perfectly forwards or backwards, these movement strategies are generally considered to occur along a continuum and therefore overlap in real world situations.

To understand and quantify postural control following perturbations we must be able to produce perturbations in a controlled laboratory setting such that responses can be collected and

analysed scientifically. For the purposes of this thesis, one method of perturbing postural stability is via an arm perturbation. The participant is asked to grasp a movable handle or manipulandum which then exerts a destabilizing force while the participant performs a focal movement. Whereas it is common to assess the muscular response of such a perturbation using electromyography (EMG), to date only one study has attempted to characterize the movements of the COP and therefore postural control following an arm perturbation.²⁵ Lowrey, Nashed, and Scott, created a reaching task using a flexible robot platform with graspable manipulanda (KINARM end-point robotic device, BKIN Technologies, Kingston, Ontario) which subjects used to perform focal arm movements as quickly and accurately as possible to a target.²⁵ On 20% of trials, an unexpected external perturbing force was generated by the robot, altering the trajectory of the arm, thereby creating a COP shift. The authors observed deviations in COP in the opposite direction of the arm movement prior to the focal movement indicative of an APA. During perturbation trials, despite an immediate change in the arm, COP alterations did not occur for ~100ms after the disturbance.²⁵ Moreover, muscle activity in the lower limbs was observed ~70ms after the disturbance (i.e. before COP deviations).²⁵ Taken together these findings suggest that feedback from the perturbed arm is responsible for the postural responses occurring in the lower limbs and that this response is actively generated.

Although postural control is complex in nature, humans are generally able to maintain balance with little to no conscious thought. However, postural stability is greatly challenged when the task or situation becomes more complex, as when coping with perturbations. If perturbations cannot be managed successfully, individuals will experience a loss of balance and fall, increasing the likelihood of injury. Investigation into postural stability following external perturbations to balance induced during upper limb movements has only just begun. Developing

a greater understanding of how the COM and COP move (in terms of displacement and velocity) following perturbations to balance will allow characterization of responses. This in turn will allow training and strategies to be developed to more effectively cope with perturbations and reduce falls and their associated injuries.

1.2.1 Postural Control Following Concussion

As briefly mentioned earlier, balance deficits are a very common symptom associated with concussion with ~77% of concussed athletes reporting this issue.¹³ The previous literature has suggested these postural stability deficits are short lived; only persisting 3-5 days following the concussive event.^{26,27} As such, many studies have been done following concussion in an attempt to characterize these disturbances.^{13,26–75} Although metrics of postural stability obtained via force plates are highly valuable in understanding postural control, it is not always feasible for investigators to collect and analyze data on a force plate following a concussion. As such, two of the most common methods of assessing postural stability following concussion are the BESS^{26,50,63,64} and the sensory organization test (SOT).^{26,27,50,52,65,75}

The BESS was created as a cost effective and easy to administer tool for clinical concussion assessment.⁷⁶ In total, it consists of six conditions, three performed on firm ground which are then repeated on a compliant surface (foam). The three conditions are hip-width two footed standing, one footed standing (non-dominant leg), and tandem Romberg stance (dominant foot directly behind non-dominant). Each condition is held with the eyes-closed and the hands placed on the hips (Figure 1.2). The BESS is scored based on the total number of errors. Therefore, a higher score indicates worse balance. Potential errors that participants may make during the BESS are described in Table 1.1. Each error made during the 20 second condition is added to give a total score. The maximum score for any given posture is 10 and should multiple

errors occur at once, only one error point is added (i.e. hands come off hips while taking a step). A shorter iteration of the BESS exists and is termed the modified Balance Error Scoring System (mBESS). The mBESS which is a component of the SCAT3, only includes the three conditions on firm ground (Figure 1.2a-c). The mBESS follows the same scoring as the full BESS (Table 1.1). Riemann and Guskiewicz⁵⁰, Guskiewicz, Ross, and Marshall,²⁶ McCrea *et. al.* (2003),⁶³ and McCrea *et. al.* (2013)⁶⁴ all used the BESS as one method of testing acutely concussed athletes. All studies recruited collegiate athletes with McCrea *et. al.* (2013)⁶⁴ using a mixed sample of college and high school athletes. Across studies, either a control group of matched athletes⁵⁰ or a combination of matched athletes and prospective baseline scores^{26,63,64} were used for comparison. Despite differences in study design, all groups reported increased BESS scores immediately following the injury (within a few hours) or one-day post-concussion with scores normalizing by the subsequent assessment (max three days post-injury).^{26,50,63,64}



Figure 1.2. Balance error scoring system conditions. (A-C = firm support surface; D-F = compliant support surface; A&D = hip width two footed stance; B&E single leg stance; C&F tandem Romberg stance.

Table 1.1. Datable entry system possible entry.	Table 1.1.	Balance error	scoring system	possible errors.
--	------------	---------------	----------------	------------------

Possible BESS Errors
Hand lifted off hips
Eyes Open
Taking a step, stumbling, falling
Hip abduction of >30 degrees
Forefoot or heel lift
Staying out of testing position for more than 5 seconds

While the BESS (or mBESS) has proven useful at detecting balance problems immediately following concussion there are a number of limitations associated with this measure. The BESS has been criticized for its reliability, learning effects, subjectivity, and susceptibility to sandbagging.^{76–78} Finnoff and colleagues⁷⁷ assessed the intra-rater and interrater reliability of the BESS and determined an overall intra-class correlation coefficient across all conditions were just 0.74 and 0.57, respectively. The particularly low inter-rater reliability (0.57 ICC) results underline the subjectivity of this measure. The BESS requires raters to make decisions about small changes in posture which can be easily missed. For example, one of the potential errors is hip abduction of more than 30 degrees (Table 1.1). Determining exactly a movement of more than 30 degrees while simultaneously watching for all other possible errors can be difficult to the untrained rater. Moreover, Hunt et. al.⁷⁶ determined the intra-class reliability of the BESS to be 0.60. These reliability values are below conventionally accepted levels of clinical assessments.⁷⁹ Not only is the reliability of this tool low the BESS is also susceptible to learning effects.⁷⁸ A study by Mulligan, Boland, and McIlhenny⁷⁸ used three different group of participants, all of which performed the BESS at baseline then followed different timelines of repeat assessments over the course of 28 days. While comparable at baseline, the groups who completed the BESS again at 1-week and 2-weeks post-baseline demonstrated a decreased score (increase in performance) indicating a learning effect. Some groups also showed this effect to persist 28 days following the initial BESS assessment. The last factor to be aware of with the BESS for the assessment and management of concussions is sandbagging. Essentially sandbagging occurs when athletes intentionally underperform on baseline measures such that should a concussion occur, their acutely concussed BESS error score appears comparable to the pre-injury baseline. Although (to the authors' knowledge) no literature

has been published on sandbagging during the BESS, this type of behaviour has been observed on neuropsychological measures.¹¹ Collectively, given the low reliability, learning effects, subjectivity, and susceptibility to sandbagging this measure may not be the most suitable for clinical concussion assessment.

The second commonly used balance assessment in concussed populations is the Sensory Organization Test (SOT). The SOT is designed to assess postural stability while systematically disrupting the sensory systems responsible for maintaining balance. This test requires participants to stand on a force platform with a visual surround under six different conditions. The conditions involved are two different support conditions; fixed and sway-referenced support, as well as three visual conditions; eyes-open, eyes-closed, and sway-referenced vision. In the fixed condition, the support surface is static. Alternatively, in the sway-referenced support condition the platform tilts directly in proportion to the COG, maintaining ankle joint position and thereby removing somatosensory information usually obtained from the ankle joint. The sway referenced visual condition is similar to the sway referenced support condition as the visual surround moves as the participant sways. Therefore, although sway may be generated in this condition, no signals associated with this occur within the visual system. Overall, the conditions include, 1) fixed support, eyes-open; 2) fixed support, eyes-closed; 3) fixed support, sway referenced vision; 4) sway referenced support, eyes-open; 5) sway referenced support, eyesclosed; 6) sway referenced support, sway referenced vision. The SOT provides an overall equilibrium score and sensory ratio scores in which a high score indicates better postural stability.

A number of studies have investigated postural stability acutely following concussion using the SOT.^{26,27,50,52,65,75} The majority of these studies found significantly decreased postural

control (decreased composite equilibrium score) on the first day after the concussion when compared to control groups.^{26,27,50,75} As well, most studies found a significant difference between acutely concussed individuals scores at one-day and the same acutely concussed athletes at threedays post-concussion (scores increased from day one to day three) showing improvement.^{27,50} While the majority of studies observed no difference in postural stability persisting longer than one-day post-concussion^{26,27,50,52}, Peterson and coworkers⁷⁵ reported significant decreases in the composite balance score 10-days post-concussion as well as a decreased vestibular ratio up to 2days post-concussion. Similarly, Guskiewicz and colleagues²⁷ observed a decreased visual ratio, one-day following concussion compared to matched controls. Most of these studies tested subjects at 1, 3, 5, and 10 days post-concussion. Therefore, with this number of repeat tests in a short period of time, learning effects need to be considered. In a study by Wrisley and colleagues⁸⁰ it was discovered that significant increases in SOT composite scores take place across multiple follow-up tests in healthy controls, a finding consistent with of learning effects. This is troublesome as the improvements noted in SOT scores in the days following concussion are likely influenced by learning and may not be entirely attributable to recovery. Moreover, in the study by Wrisley et. al.⁸⁰ test-retest reliability of the composite score yielded only a fair to moderate ICC of 0.67. As such, the SOT is not without limitations and should be interpreted with caution.

As mentioned previously, force plates obtain COP data which are highly correlated to COM. These metrics of postural stability provide precise information regarding the magnitude and velocity of body sway occurring in the AP and ML directions on a millisecond to millisecond basis. Although assessing balance in this way is incredibly informative, relatively few studies have assessed postural stability following concussion using these force plate

outcomes. Slobounov and colleagues⁶⁷ measured COP area and velocity at baseline and 30-days post-concussion under eyes-open (EO) and eyes-closed (EC) conditions. These authors found no significant differences in COP area or velocity in either direction (AP or ML) at 30-days postconcussion compared to baseline performance. However, these findings are contrasted by Powers, Kalmar, and Cinelli⁵⁶ who assessed acutely concussed individuals and matched controls (average 5-days post-concussion, and at RTP) using COP root-mean-square (RMS) displacement and velocity during EO and EC quiet standing. These authors observed greater COP RMS displacement and velocity in the AP direction acutely following concussion compared to control athletes. More importantly, Powers, Kalmar, and Cinelli⁵⁶ found an increased ML and AP RMS velocity at RTP (average 26 days post-concussion). These results seem to align with the general belief that balance control is impaired following a concussion. The literature demonstrates control of balance worsens with larger and faster movements of the COM and by extension the COP metrics.⁵⁶ However, in another study, Hides et. al.⁶⁶ used the Stability Evaluation Test to assess postural stability. Although COP metrics were not directly used to compare balance performance, the Stability Evaluation Test uses a force plate to collect COP and as a result a sway velocity metric is obtained that is specific to this tool.⁶⁶ Hides and colleagues⁶⁶ observed decreased sway velocity (average decrease of 0.3 degrees/sec in the composite score) of concussed participants acutely following the injury (5-days post-concussion) when compared to baseline, indicating concussed athletes assessed under this metric displayed different balance control. This finding opposes Powers, Kalmar, and Cinelli⁵⁶ and contrasts expected findings when postural stability is likely compromised.

All the aforementioned studies^{26,27,50,52,56,63–67,75} used different methodological approaches through a variety of instruments and balance metrics. Furthermore, differences exist in the study

design with comparison groups (matched controls or prospective individual baselines), the wide ranges of evaluation time since the concussion (5-days, 30-days post-injury) and dependent variables (COP displacement, velocity, COP RMS displacement and velocity, COP area, Stability Evaluation Test sway velocity, etc.). Therefore, making a comparison of results between the previous literature is difficult. One study did not observe balance disruptions 30-days post-concussion⁶⁷, while another found postural stability disturbances at RTP (~26 post-injury).⁵⁶ Moreover, two groups have demonstrated balance differences acutely following concussion^{56,66}, but the results for COP velocity or sway velocity within each study noted deviations following concussion in the opposite directions (e.g. an increase⁵⁶ versus a decrease⁶⁶ in velocity).

As illustrated, quiet stance balance control is a prominent area of concussion research. However, how the aforementioned postural responses are affected by external perturbations with respect to concussion is poorly understood. This is important because in the context of contactsports, athletes must regularly manage external perturbations in the form of contact with other players, equipment, and/or playing surface features. All this is performed while they try to maintain their balance and move through the field of play. Therefore, studying the postural responses to external perturbations in concussed individuals may provide a more robust sportspecific context under which to assess athletes. If difficulties persist in the ability of previously concussed athletes to cope with perturbations, it may help explain why these individuals are at an elevated risk of further injury of following concussion.^{81–85} Should an athlete have greater postural instability then when perturbed there is a higher likelihood of loss of balance. This unexplored aspect of postural control has great potential to better understand balance following concussion with the use of a task very applicable to the contact sport environment.

As mentioned earlier, the long-term effects of concussion on postural control are of particular interest, however only one group has attempted to characterize these potential chronic effects in standing balance using precise force plate metrics. Degani and colleagues⁵⁴ assessed a group of participants who previously suffered an mTBI on average 19 months previously compared to a control group. Participants performed quiet stance trials on a force plate under EO and EC conditions. The authors assessed a number of dependent variables including area of COP path, COP amplitude, and COP velocity. Individuals with a previous history of mTBI exhibited larger sway area (average increase of 56%), larger amplitude of displacement in the ML direction (average increase 32%), and slower sway velocities in both the AP and ML directions (average decrease of 56% and 42%, respectively). While this group represents a more diverse population (i.e. some blast induced injuries) than strictly contact-sport athletes, the results are nonetheless significant and help clarify potential disruptions which could also be affecting concussed athletes. Aside from sway velocity, all other balance metrics were increased compared to controls (displacement and sway area). This follows the typical expectation of larger COP movements indicative of decreased postural stability following brain injury. However, similar to Hides et. al.,⁶⁶ Degani and colleagues⁵⁴ observed slower sway velocities in the previously injured group. The authors hypothesized these slowed COP movements do not necessarily indicate better balance control, but rather a conservative strategy to cope with (and limit the impact of) postural stability deficits. With reduced sway velocity those with previous concussions would be afforded greater time to make postural adjustments and therefore reduce the risk of loss of balance. Although, depending on the speed at which environmental or other demands are presented which disturb balance, this conservative adaptive strategy will likely fail.

Overall, the literature regarding postural stability is contradictory and has many limitations. Much of the published data were collected with tools fraught with methodological issues.^{26,27,50,52,63-65,75} For example, although the BESS and SOT assessment tools have been shown to be capable of differentiating group differences in acutely concussed athletes immediately following injury (hours to 1 day) they are likely unreliable for later time points after the injury. In fact, given the current literature, we cannot be certain if balance deficits resolve within or persist longer than 3-5 days post-injury.^{26,27} Additionally, the data from studies employing force plates to collect COP movements have also reported conflicting results.^{56,66,67} As such, research using more consistent and appropriate measures of postural stability as they related to the sport context (such as measures of postural stability during external perturbations) are warranted. Further research is also needed to accurately track the recovery time course for balance deficits over longer durations following acute concussion as well as in athletes who have experienced chronic repeat concussions.

1.3 Attention

Attention is a complex system necessary for successful human performance.⁸⁶ While difficult to strictly define, attention is bound by three main components; alertness; selectivity; and processing capacity. Alertness is the capacity to produce and sustain optimal sensitivity to a given stimulus.⁸⁶ Selectivity is the ability to attend to certain sources or types of information while ignoring extraneous information.⁸⁶ Finally, processing capacity refers to the limited nature of attention, such that when multiple items require the same resources interference and a decrease in performance will occur.⁸⁶

Attention consists of three central functions: the orienting, alerting, and executive networks. Alerting essentially facilitates performance during tasks due to vigilance. When a

warning cue (with no orienting information) is provided prior to the target event, the resting state is replaced with a new prepared state. This prepared state is now primed for detecting and responding to the expected target event.⁸⁷ The orienting function allows one to covertly move attention to a specific spatial location or prioritizes a certain type of information thereby facilitating responding. Spatial orienting requires the disengagement of attention from the currently attended location, movement of attention, and then reengagement in the new location.⁸⁸ Finally, the executive network monitors and resolves conflict.⁸⁷ This network also enables flexibility when switching between different task demands, as well as selecting the appropriate information and ignoring irrelevant stimuli during a given task.⁸⁸

1.3.1 Attention Following Concussion

Following concussion, a number of cognitive symptoms may be present. These could include: confusion; difficulty concentrating or remembering; feeling slowed down or feeling in fog; all of which may be indicative of attention difficulties. The SCAT3³ indirectly or globally assesses attention using concentration tasks embedded in the SAC. However, the intricate networks of alerting, orienting and executive components are not captured in this assessment. To tease apart the networks influenced by concussion, the Attentional Network Test (ANT) has previously been employed.⁸⁸ The ANT is a computer based test in which the subjects are asked to respond to a target symbol (\leftarrow or \rightarrow) by pressing the corresponding key. By using a variety of pre-cue and target conditions combinations this task is able to separately assess alerting, orienting and executive components of attention. In all conditions, the trial begins a when central fixation cross appears (+). On some trials, a pre-cue (in this case an asterisk; *) appears for a short time. Following the pre-cue, the target may appear in one of two locations, above or below the central fixation cross (Figure 1.3a). The participants respond as quickly and accurately as

possible by pressing the corresponding key. There are four possible pre-cue conditions; no precue, centre, spatial, and double (Figure 1.3b). Additionally, there are three target types (two of which are flanker conditions); neutral, congruent (flanker), and incongruent (flanker) (Figure 1.3c). Each networks functioning can be measured by comparing reaction time (RT) across certain trial types. To determine the alerting effect the median RT of trials involving the double pre-cue is subtracted from trials with no pre-cue. The orienting effect is determined by subtracting median RT of spatial pre-cue trials from centre pre-cue trials. Finally, the executive component of attention is determined by subtracting the median RT of the congruent target trials from incongruent target trials.



Figure 1.3. Attentional Network Test. Typical trial progression (pre-cue – spatial; target – neutral; location – below central fixation point). A) Typical trial progression; central fixation cross is present for a variable period (400-1600ms) after which the pre-cue may appear (100ms duration), central fixation cross is present for another 400ms followed by the addition of the target. B) Possible pre-cue presentations. C) Possible target types.
Using the ANT, van Donkelaar and colleagues⁸⁸ assessed attention in a group of acutely concussed individuals (within two days of injury) compared to a control group. When all trial types were collapsed, those who had recently suffered a concussion exhibited increased median RTs. When strictly assessing the alerting effect (Figure 1.3b), it was noted that both groups benefited from a pre-cue thereby shortening RT. However, no group differences were present, thus it was concluded that the alerting effect was not altered due to concussion.⁸⁸ In contrast, when the orienting network was assessed, the authors found that those suffering from concussion experienced disproportionately increased RT when no spatial cue was given. In other words, the concussed individuals took significantly longer to disengage, move, and reengage attention when spatial cues were not present as compared to the control group.⁸⁸ Finally, for the executive component of attention it was found that congruent targets led to comparable RT in both groups. However, when examining only the accurate responses, RT increased for congruent trials in the group of concussed individuals, indicating there may be a subtle effect of concussion on the executive component of attention.⁸⁸

The same group used the ANT to follow concussed individuals through the month following injury.⁸⁹ Participants were serially assessed at 2, 7, 14, and 28-days post-concussion and compared to a control group assessed at the same time points. Similar to van Donkelaar *et. al.*⁸⁸, this follow-up study by Halterman and colleagues⁸⁹ demonstrated an increased RT in the concussed group (compared to the control group) when all trials were collapsed. Furthermore, across the month of testing both groups, concussed and controls, improved their RT, indicating a learning effect. However, significant differences remained between groups throughout the course of the month. Moreover, mimicking earlier findings⁸⁸, no difference in alerting was found between groups.⁸⁹ Orienting displayed a similar initial group difference as previously reported

although the difference between groups resolved over the course of the month.⁸⁹ Unlike the previous study by van Donkelaar and coworkers⁸⁸, Halterman *et. al.*⁸⁹ also observed differences in the executive component of attention, which authors termed a conflict effect (incongruent arrows cause conflict). Concussed athletes exhibited a larger conflict effect (increased difference in median RT between congruent and incongruent trials) compared to controls.⁸⁹ When all trials were collapsed, the conflict effect difference was consistent with the previous findings when all trials were collapsed, as between group differences persisted across the duration of testing. However, it should be noted, both groups still experienced a decrease in RT over the course of the month which once again indicates the likelihood of associated learning effects.⁸⁹ Lastly, when assessing accurate trials across all conditions it was found concussed participants displayed an increased RT relative to inaccurate responses when compared to controls. This increase response time for concussed subjects was apparent across all time points and occurred despite the two groups performing equally as accurate.⁸⁹

Aside from the ANT, other measures of attention following concussion have also been investigated by this group. The RSVP task was explored by McIntire and colleagues⁹⁰ whereas Drew and colleagues⁹¹ employed the Gap Saccade task. The RSVP task probes the temporal distribution of attention while the Gap Saccade task investigates the processes involved in orienting attention, with specific focus on the disengagement component. After comparing acutely concussed individuals and controls using the RSVP task, no between group differences were observed.⁹⁰ Therefore, the researchers concluded an acute concussion has little-to-no effect on the temporal distribution of attention.⁹⁰ Conversely, when the Gap Saccade task was employed, differences between concussed and control groups were evident.⁹¹ Acutely following concussion, saccade RT was increased compared to control groups, especially under conditions

in which the disengagement process was contributing. However, this difference normalized over the following week.⁹¹ Drew and coworkers⁹¹ concluded their findings indicated deficits were present in the acutely concussed subjects within the disengagement process of orienting attention that were able to recover within one week.

Overall the attention system appears to be implicated following concussion. While some networks may be unaffected, others recover rapidly, and others still display deficits which can persist up to a month following injury. Specifically, the ability to maintain attention over time does not appear to be influenced by concussion.⁹⁰ Similarly, concussion may have a limited effect on the alerting network of attention.^{88,89} In contrast, the orienting network seems to be impaired acutely after injury but resolves in the weeks following.^{88,89} This impairment is likely due to deficits in the disengagement processes of orienting attention.⁹¹ Finally, the executive network of attention appears to experience subtle disturbances following concussion⁸⁸ and deficits in dealing with conflict persist up to one month following concussion.⁸⁹ The attentional deficits in orienting and conflict which persist past the typical RTP timeline may have a negative influence on athletes' ability to perform to their pre-injury capabilities. Specifically, these affected networks may cause problems when observing other players "fake" a pass (conflict) or when the game moves rapidly to an unexpected location (orienting). Therefore, the resolution of attentional difficulties following concussion is a very important aspect of impairment and recovery to monitor within this population.

1.4 Dual Task Paradigms - Postural Stability and Attention

Dual task paradigms are used to assess the effect of a secondary task on a primary task of interest. By performing tasks first individually, then concurrently, the overlap of information-processing resources and therefore the associated "cost" of performing both tasks can be

assessed. There are three assumptions associated with dual task paradigms: 1) the capacity of central information processing is limited; 2) any given task requires a specific portion of the information processing capacity so that it can be successfully performed; and 3) when multiple tasks are being performed simultaneously and whose needs together are greater than the total information processing capacity, performance of one or both tasks will decline.⁹²

The dual task paradigm of interest to this thesis is the primary task of balance, with a secondary attention or cognitive task. Historically, postural control has been deemed an automatic process, in that it does not require attentional resources.⁹² However, more recent research has shown postural control requires cognitive processes, and therefore may compete for the limited attentional resources available.⁹² Nonetheless, as we go through daily life performing complex cognitive tasks or tasks requiring significant attention, we almost never lose our balance. Previous research has suggested this effect is explained by the "posture first principle".⁹³ The posture first principle states under dual task situations, posture will be prioritized first, potentially resulting in deterioration of performance on a secondary task.⁹³ This principle was well demonstrated by Siu and Woollacott⁹⁴ who asked subjects to perform a dual task under varying task priorities. Participants performed a visual spatial memory task while standing with feet together on a force plate under three different conditions where they focused on: 1) both tasks equally, 2) primarily the postural task, and 3) primarily the visual spatial memory task. When prioritizing the visual spatial task the response time decreased therefore indicating a better performance. However, after assessing COP path excursion and average velocity, no difference in postural control was found when participants placed priority on postural control compared to attending to both tasks equally. Therefore, the authors concluded, postural control did not appear to be affected by the allocation of attention resources to the

secondary visual spatial task. This was attributed to sufficient resources being automatically allocated to posture as balance was maintained despite participants altering their focal priority.⁹⁴

Many studies have been undertaken examining the interaction of static balance and a secondary cognitive/attentional task. The majority of these studies used the SOT or a modified version of the SOT.^{30,53,61,62,95} In nearly all studies, an improvement in postural control was noted under dual-task conditions.^{30,53,61,62} The only exception was observed in a study by Shumway-Cook and Woollacott⁹⁵ who observed no change to postural control when a secondary task was employed. Similar findings were noted when the BESS was undertaken during a dual task scenario, as the addition of the dual task did not alter BESS scores.⁵³ Another study assessed postural stability during a secondary task using the force plate metric of body sway.⁹³ Again, an improvement in postural stability (less sway) was observed during the secondary task.⁹³ On the other hand, studies which assessed the effect of postural control on the secondary task (in addition to the effect of the secondary task on posture) found performance on the secondary task performance decreased.^{30,62} It should be noted only the experiments which used the SOT resulted in an increase in balance performance under dual-task scenarios. Other studies using force plate metrics⁹³ or the BESS⁵³ demonstrated little-to-no influence of a secondary task on postural control. There are a few possible explanations why employing the SOT may have resulted in such findings. First, as previously discussed the SOT is subject to learning effects. Therefore, the observed increase in postural control may simply be due to multiple administrations of the SOT. A second explanation of these results is under dual task conditions participants are primarily focusing their attention on the cognitive task and placing less resources towards the sensory stimuli. However, the purpose of the SOT is to systematically disrupt balance by altering sensory information. Therefore, these participants are focusing less on the incorrect sensory feedback

than when performing the dual task, which in turn increased performance. A final explanation is when attention is shifted externally (away from the body, therefore shifted towards the cognitive task) performance may increase due to the constrained-action hypothesis.⁵³ The constrained-action hypothesis explains that internal focus (e.g. actively focusing on balance) disrupts automatic processes, thereby decreasing performance. However, this may not be the case since postural control has been found not to be as automatic as previously believed.⁹²

1.4.1 Dual Task Paradigms and Concussion

As concussions effects are so diverse and relatively poorly understood, it is possible this injury may have compounding effects when attempting to perform tasks which involve competing for the same resources simultaneously (e.g. balance and attention). If this is the case, employing dual-task procedures may enhance diagnostic and RTP decisions. Indeed, there have been many concussion studies over the last 15 years which have focused on dual task procedures in this context. However, the vast majority of work in this field has been completed using a gait task concurrently with an attentional secondary task.^{29,31–33,35,42–48,55,69–74,96} Interestingly, only two studies to date have assessed concussed individuals during a dual task paradigm with quiet stance.^{36,97}

Dorman and coworkers⁹⁷ compared a group of athletes with persistent concussion symptoms (assessed acutely and three additional follow-ups in which the timing of assessments varied between participants) to controls (two assessments, separated by one week). Participants stood on a force plate under four different conditions: eyes-open with no cognitive task, eyesclosed with no cognitive task, eyes-open and cognitive task, eyes-closed and cognitive task. From this experiment COP ellipse area and velocity were obtained. Although the difference between each condition (single vs dual) within groups was not assessed (thereby eliminating an

assessment of dual-task cost), between group and time differences were addressed. They observed increased COP ellipse area and velocity acutely following concussion which decreased across the subsequent visits. Control and concussed athletes were compared on their first two assessments. Significant differences were found between groups at the initial visit for all conditions, but only in the two eyes-closed conditions for the second visit. This study demonstrates concussed individuals perform poorer on a dual task paradigm than controls. However, it should be noted this specific group of concussed athletes exhibited concussed athletes who follow the typical recovery time line. Nonetheless Dorman et al.⁹⁷ provide evidence to support the use of dual-task paradigms involving postural control and attention clinically.

The only other study using quiet stance dual task measures in injured populations was completed by Kleffelgaard and colleagues.³⁶ This study assessed people who experienced an mTBI at one and four years after the injury. Subjects completed a variety of assessments including self-report measures (Rivermead Post-concussion Symptom Questionnaire, Patient-Specific Functional Scale) and a dual task scenario where they performed an arithmetic task while standing on a force plate. There were no comparisons made to pre-injury or acute performance, nor was there a comparison with a control group. Instead, correlations were performed between the many outcome measures. The results on the dual-task test balance task were significantly correlated with self-report balance problems.³⁶ However, it should be noted that these participants were significantly older (40 years old) than the typical elite or collegiate sport group (generally 23 and under). Moreover, this population had more diverse mechanisms of injury than strictly sport concussions as the participants were recruited from a neurosurgical department at the University's hospital. As previously mentioned, within the confines of this

study there were no comparisons were made to determine how differently these individuals performed relative to healthy controls or pre-injury. Therefore, it is difficult to draw firm conclusions from this study.

While the quiet stance dual task literature in the concussion field is currently lacking, dual task gait studies are incredibly abundant.^{29,31–33,35,42–48,55,69–74,96} In general, these studies have shown under dual task conditions, concussed individuals adopt a more conservative gait strategy (slower gait velocity/cadence or shortened strides).^{29,35,42,69,72} Additionally, COP movements have been found to have both greater displacement and velocity during dual task paradigms acutely following concussion.^{31,46} Many of these studies have also noted dual, but not single tasks show significant differences between concussed and control subjects. This may indicate dual task paradigms are more sensitive to subtle alterations in balance control mechanisms following a concussion and could be used as further tools during clinical diagnosis, recovery and RTP decisions. Finally, certain dual-task studies have observed deficits persist longer than the typical recovery timeline of 7-10 days.^{31,55,72} Of greatest concern, as many of these studies have noted, dual task balance deficits were present in athletes after they had been cleared to return to sport, possible leaving these players at risk for future injuries.

While gait dual tasks represent a more complex challenge than quiet stance, an alterative way to challenge balance would be to apply an external force to perturb a subject under dual task scenarios. This experimental design would likely provide the most sport specific context under which to test concussed athletes. In sport, athletes must not only maintain their balance while being pushed and jostled, but also concurrently perform attentional and cognitive tasks with respect to the game play. Since the previous literature has suggested balance was marginally influenced or improved under dual task static stance scenarios but worsened under dual task gait

situations, assessing postural control during exposure to perturbations with a secondary task will likely provide additional clarity regarding how concussions alter this system. If compounding deficits exist when managing perturbations during a secondary task, athletes are more likely to experience a decrease in athletic performance and potentially expose themselves to further injury.

1.5 Knowledge Gap

Although both quiet stance and gait have been studied following concussion^{13,26–74}, the ability to cope with external perturbations has yet to be assessed. This aspect of postural stability is incredibly important to contact sport athletes who need to manage these types of disturbances to balance in game play. Particularly, an assessment which includes balance control and perturbation management may prove very beneficial in clinical diagnoses and RTP decisions. Furthermore, to date there has been significant postural control research performed in the acute stage (still symptomatic) of concussion. However, the potentially chronic and detrimental compounding disturbances to balance following a history of multiple concussions has received far less attention.^{36,54} These long-term problems have the capacity to influence daily living in the years to decades following the initial injuries. Moreover, while the acute deficits more often than not appear to resolve spontaneously in a relatively short period of time, with little medical care, the long-term problems are just beginning to be understood. These long-term problems have the potential to cause enormous strain on our health care system. Specifically, if postural control is implicated chronically in individuals who have suffered from multiple concussions, a higher likelihood of falling and therefore injury may result. This is only compounded by negative influence of aging on the balance control system.

1.6 Purpose

The purpose of this thesis is to explore how a previous history of concussion impacts dual task paradigm performance using external perturbations while maintaining a quiet stance.

1.7 Hypotheses

As per the previous literature, three hypotheses were made. First, a dual task effect is expected, such that regardless of concussion history, individuals will have decreased ability to maintain postural stability (COP variables) and/or other aspects of the dual task (RT, hand kinematics) compared to the single task due to competition for resources. Secondly, it was hypothesized that those athletes with a previous concussion history will perform worse on the task (COP variables, and RT) than those with no concussion history due to chronic disturbances as a result of multiple concussions. Finally, it was hypothesized that the combination of dual task effects and the effects of previous concussion history will result in those with concussion history to perform significantly poorer on the dual task (again, COP metrics and RT) compared to athletes with no concussion history.

2 Chapter: Methods

2.1 Participants

Participants (n=44) were recruited from local junior and collegiate contact sports teams – Okanagan Sun Junior Football (n=23), West Kelowna Warriors Junior Hockey (n=15), and UBC Okanagan Heat Rugby (n=6). All data collection took place at the beginning of the competitive athletic season for each respective sport. Participants were stratified into two groups based on previous history of concussion; 1) no previous concussion history, 2) two or more previous concussions. Concussion history was self-reported and included both diagnosed and undiagnosed concussions. Participants were excluded from the study if they had any of the following: concussion within the 6 months prior to testing, dominant hand/arm injuries, neurological/musculoskeletal disorders and/or drug use that may affect balance and 1 previous concussion (n=12). These exclusion criteria resulted in 12 subjects being removed, with the exclusion criterion of experiencing a single previous concussion as the only factor being met; thus, the results presented in this thesis are based on 32 contact sport athletes (football, n=16; hockey, n=11; rugby, n=5; right handed, n=30). Both the no concussion history (n=16) and 2 or more previous concussions (n=16) had equal representation. Ethical approval was obtained from the Clinical Research Ethics Board (H14-02996) at the University of British Columbia -Okanagan campus prior to study implementation. Informed consent was obtained from all subjects prior to participation, or in cases of subjects under 18 years of age, parental or guardian consent as well as subject assent was obtained prior to participation. Participant demographics by group can be found in Table 2.1.

Table 2.1. Participant demographics by concussion history group. Groups were not significantly different in age or body mass index (BMI). Demographics expressed in average ± standard deviation (range).

	No previous concussion	Two or more previous	
		Concussions	p value
Age (years)	19.3 ± 1.6 (17-23)	$19.5 \pm 1.8 \ (17-24)$	0.68
BMI (kg/m^2)	$28.3 \pm 4.7 \ (23.0-39.0)$	$27.7 \pm 3.5 \ (23.8-36.8)$	0.69
Number of previous concussions	N/A	3.5 ± 2.3 (2-11)	< 0.001
Time since last concussion (months)	N/A	26.1 ±16.6 (6-60)	< 0.001

kg: kilograms, m: metres

2.2 Instruments

The primary instruments used to collect the relevant data include the KINARM end-point robot system (BKIN Technologies, Kingston, ON), True Impulse force plate (NDI, Waterloo, ON), and custom-built reaction time button. Custom written coding programs were designed and implemented with these instruments to address the thesis aims.

2.2.1 KINARM End-Point Robot System

The KINARM End Point Robot System (KINARM) includes two stiff graspable manipulanda for the upper arms and allows the creation of numerous complex scenarios. A 2D augmented reality allows manipulation of the visual display. The visual display and robot arms are coupled and height adjustable (Figure 2.1a,b). The KINARM system includes custom software (Dexterit-E) and the capacity to design tailor-made protocols and tasks. All data collected through the KINARM software are sampled at 1000Hz, synchronized and stored offline. The KINARM allows the flexibility to add other modalities (force plate, EMG, etc.) such that all data are collected and time-locked simultaneously. For the purposes of this experiment, a custom-made reaching and button press task was designed within the Simulink environment, then built in Matlab and converted into a KINARM task.



Figure 2.1. KINARM set up. A) KINARM end-point robot configuration. B) Participant standing on force plate looking into the augmented reality view of KINARM. *Blue stars – manipulanda, left manipulandum folded away; red stars – platform below manipulanda; green stars – augmented reality screen; yellow star – force plate.*

2.2.2 **True Impulse Force Plate**

The True Impulse force plate (force plate) collects COP data at 1000Hz and data collection is time-locked to the KINARM. The force plate is positioned such that a person can stand on the platform while being able to comfortably view the visual display of the KINARM (Figure 2.1b, Figure 2.2). The force plate collects ground reaction forces and moments about the movements that occur as the participant stands on the platform. Measurements of COP are determined in both AP and ML directions.



Figure 2.2. Participant standing on force plate.

2.2.3 **Custom-built Reaction Time Button**

The custom-built reaction time button was designed and integrated into the KINARM system such that data from the button press was synchronized with all other measures (Figure 2.3).



Figure 2.3. Custom-made button to measure reaction time.

2.3 Task

Participants first completed the SCAT3³ (Appendix A) including the symptom evaluation, SAC, and mBESS. Following the SCAT3, three individual tasks were designed to assess postural control and attention, they were initially performed independently to establish task baselines and then concurrently to investigate dual-task attentional costs. All tasks were completed in the same order: 1) single task – button press, 2) the single task – reach with perturbation, and 3) dual task – button press during perturbed reaching.

2.3.1 Single Task – Button Press

Participants were asked to remove their shoes and stand with feet hip width apart on the force platform holding the corresponding KINARM manipulandum in their dominant hand and the button in their non-dominant hand. The hand holding the button rested on a platform below the manipulanda (Figure 2.1b). The KINARM was adjusted for participant height. Participants were instructed to stand up-right (ensuring their head was not resting on the KINARM), and

maintain equal weight in both feet. Participants were instructed to respond as quickly as possible to an auditory tone (buzzer) by pressing the button. Twenty trials were undertaken to establish RT under single task conditions. Each trial began with a variable fore-period of 1000-2000ms after which the tone (150ms in duration) was presented. If necessary, participants were asked to keep the dominant hand holding the manipulandum still during trials and focus their attention on the button-press task. Trials were manually advanced by the experimenter enabling bad trials (e.g. participant did not respond) to be identified and repeated. After the experimenter advanced to the next trial the random fore-period would begin, this process was repeated until 20 successful trials were completed. During the single task button press, the KINARM visual surround was blank (black) except for a white circle (radius of 0.75cm) representing the virtual reality position of their dominant hand holding the manipulandum beneath the screen.

2.3.2 Single Task – Reach with Perturbation

Participants continued to hold the button in their non-dominant hand and the manipulanda in their dominant hand. The non-dominant hand was allowed to rest on the platform below the manipulanda. Participants were told this task did not include button presses but to hold the button in the same posture as before. Participants were reminded to stand up-right (with head not resting on the KINARM), and maintain equal weight distribution between both feet. Each trial began with the appearance of the HOME circle. In the augmented reality visual display the HOME was a white circle with a radius of 1.25cm, positioned along the vertical midline of the visual display. In the global coordinate system the HOME position was located at X: -0.13, (0 – midline; positive values – right; negative values – left) and Y: 11.85 (0 – bottom of the screen closest to participant). When the custom program was created, the visual display was in reference to the right manipulandum, therefore in the "handle" coordinate system the position of HOME was (- 22,-5). The hand of the participant was represented by a small white circle (radius of 0.75cm). The participant was instructed to move their hand into HOME and wait for the "go" signal. Once the participant moved their hand into HOME, the beginning on the trial was triggered. A randomized fore-period of 0-1500ms occurred, followed by the appearance of the red TARGET circle. The appearance of the TARGET was the "go" signal. The TARGET had a radius of 1.25cm, and was positioned at (-0.13,36.85) in the global coordinate system. The position of the TARGET relative to HOME was 25cm distal. In the 'handle' coordinate system the TARGET was positioned at (-22,20). The participant was instructed to move as quickly and accurately as possible to the TARGET after the "go" signal by extending the dominant arm away from the body. Upon reaching the TARGET, a colour change of the TARGET from red to green occurred, indicating to the participant they had successfully reached the TARGET (Figure 2.4a). Participants were instructed to stop their arm motion such that their hand landed within the TARGET. The experimenter would then determine if the trial was successful or not and manually advance to the next trial. In order for subjects to be familiar with the task and motion, 5 unperturbed practice trials were performed.



Figure 2.4. A) Unperturbed trial – participant moves hand (small white dot) into HOME (white circle), randomized fore-period occurs after which red TARGET appears, participant moves hand (as quickly and accurately as possible) into TARGET and a colour change from red to green occurs. B) Perturbed trials i) right perturbation; ii) left perturbation – Same as A) but participant receives unexpected perturbation when target appears.

Upon completion of the practice trials the subjects performed a block 60 trials which were used for establishing the metrics for the reach task with and without perturbations. Of the 60 trials 40 were in the unperturbed condition, and 20 were in the perturbed condition (10 right perturbations, 10 left perturbations). Trials were presented in a randomized order. On perturbation trials, a mediolaterally perturbing force (30 N) was applied after the "go" signal (Figure 2.4b). Prior to the start of this block of trials the participant was warned they may experience a push from the manipulandum, however their goal of reaching the TARGET as quickly and accurately as possible remained the same. The perturbation consisted of a 25ms ramp up, with the external 30 N force being applied a duration of 40ms, and a 25ms ramp down. The randomization and ratio of perturbed/unperturbed trials was such that participant would not be able to anticipate when the perturbations would occur. Unsuccessful trials were again randomized and presented at the end of the block. Trials were deemed unsuccessful if the participant did not leave HOME before the perturbation, if the participant made a large right or left deflection on an unperturbed trial, or missed the TARGET on an unperturbed trial.

2.3.3 Dual Task

The dual task consisted of the participant completing both the button press reaction time task and the reaching with perturbation tasks concurrently. The task followed the same outline as described in the single task (Figure 2.4, e.g. 60 trials, 20 of which were perturbed) with the addition of the buzzer being presented on 50% of trials. Therefore, participants were informed they were to respond as quickly as accurately as possible to the reach stimulus (red TARGET appearance, "go" signal) as well as the button press stimulus (buzzer). In the dual task condition the buzzer occurred at the same time as the perturbation (i.e. 25ms after the "go" signal). No

practice trials of the dual task were completed as the subjects were adequately familiar with both individual tasks from the single parameter trials.

In total, 60 dual task trials were completed. Of the 60 trials, 30 required the participant to perform both tasks. Within the 30 dual task trials (reach and button press), 20 reaches were in the unperturbed condition while 10 were perturbed (5 rightward, 5 leftward). The other 30 trials did not necessitate a button press as no auditory tone was presented, however the proportion of trial types was identical (20 unperturbed, 5 right perturbations, 5 left perturbations). All 60 trials were randomized. As with the single task reach, trials were manually advanced after an experimenter determined whether a good or bad trial had occurred. Trials that were deemed bad were repeated in a random order at the end of the block of 60 trials.

2.4 Data Analysis

Data were collected and stored offline for later analysis. Matlab software was used for all data extraction and analyses. BKIN technologies provides Matlab codes to open, extract, and view KINARM (Dexterit-E) data files. Upon extraction, a custom-written Matlab code was created to transform the raw data signals. Analysed data were visually inspected and outliers were removed. Two participants were left hand dominant, and therefore completed the task holding the KINARM manipulandum in their left hand. Hand kinematic data from left-handed participants were inverted (right/left). Thus, although all participants experienced a perturbation outward from the midline of the body (opposite direction for the left-handed participants), for simplicity when discussing the results all movements will be described with respect to righthanded subjects. Therefore, throughout the results and discussion sections of this thesis a perturbation to the right is consistent with a lateral/outward deflection, and a perturbation to the left is consistent with a medial/inward deflection. Individual participant data were averaged within each condition (e.g. unperturbed single-task reaching, perturbed dual-task reaching...) and dependent variable (e.g. COP AP maximum velocity). Following this, group averages were determined for each condition and dependent variable. Data throughout the thesis will be presented as mean \pm SD.

2.5 Dependent Variables

Depending on condition (e.g. no perturbation, right/left perturbation, button press, etc.) different dependent variables were assessed. Table 2.2 provides a summary of which dependent variables were investigated based on trial type.

Table 2.2. Chart of which dependent variables were assessed based on condition. ● indicates this variable was analysed for this condition.



RT: reaction time, AP: anterior/posterior, ML: medial/lateral

2.5.1 SCAT3

The outcomes of interest from the SCAT3 include number of symptoms (e.g. headache,

dizziness, etc., with a maximum 22 symptoms), symptom severity (each symptom scored on 0-6

scale for a maximum possible score of 132), SAC score (measures of memory, concentration,

etc., out of a possible maximum 30 points), and mBESS (total errors during three balance

postures, maximum score of 30). Overall, lower scores indicating better performance for symptoms, symptom severity, and mBESS, while a higher score on the SAC indicates better performance.³

2.5.2 Centre of Pressure

In perturbed conditions (single task reach with perturbation and dual task), maximum displacement and velocity of the centre of pressure in both the AP and ML directions was assessed. Moreover, the time to reach maximum displacement and velocity was assessed for AP and ML components of the COP movement (Table 2.2). However, in unperturbed trials COP was only assessed in the AP direction. This was an *a priori* decision as, due to study design there were no large deviation in the ML direction expected to occur within the unperturbed trials. Therefore, analyses were restricted to displacement, velocity, and timing of displacement and velocity in the AP direction (Table 2.2). Larger maximum displacements and velocities were considered a decrease in postural control.¹⁹ As well, longer time to reach maximum displacement and velocity were viewed as decreased postural control.

2.5.3 Hand Kinematics

Similar to COP, maximum position and velocity of the hand motion were assessed. In both perturbed and unperturbed conditions, an *a priori* decision was made to not analyze the maximal AP position as this position would be the location of the TARGET and consistent across all subjects by the definition of a successful trial. Therefore, in unperturbed conditions, only maximum velocity and time to maximum velocity were assessed in the AP direction. As previously described regarding the COP analysis, ML position and velocity were not considered in the unperturbed trials as no large deviations in hand trajectory were expected. In the perturbed trials maximum velocity and time to maximum velocity in the AP direction were analysed as

well as maximum position, velocity, and time of maximum position and velocity in the ML direction (Table 2.2). Larger maximum displacements and velocities, as well as time to maximum displacement and velocity, were viewed as a decrease in performance on this task.

2.5.4 Reaction Time

The dependent variable of interest during the single task button press was RT. The button press RT was also assessed in the dual task. Button press RT was defined as the duration of time between the start of the auditory tone to the onset of the button press. Furthermore, RT of the hand movement was analysed during all reaching conditions (single and dual tasks). Hand reach RT was defined as the time between "go" signal and when the hand position moved outside of HOME. Longer RTs were seen as a decrease in performance.

2.6 Statistical Analysis

All statistical analyses were performed in SPSS version 24. To address the hypotheses a 2×2 mixed model ANOVA was employed. The first factor of the ANOVA was the withinsubjects factor of task (2 levels; single and dual). The main effect of task was used to answer the first hypothesis. The second factor of the ANOVA was the between-subjects factor of concussion history (2 levels; no previous concussion history and two or more previous concussions (H_x^0 and H_x^{2+})). The main effect of history of concussion was used to answer the second hypothesis. The last hypothesis was assessed by evaluating the interaction effects of the two factors from the ANOVA. Statistical significance was set *a priori* for all statistical tests at <0.05 a priori.

Differences between concussion history groups on the SCAT3 variables were tested using an independent samples T-test. Lastly, an bivariate correlation between SCAT3 measures and all other dependent variables (single and dual task and dual task cost) was undertaken in an exploratory nature. This was performed to determine if any alterations of the clinically relevant data were associated with aspects of the current study. As SCAT3 variables were not normally distributed, a non-parametric (Spearman's) correlation was used. The dual task cost was calculated for all COP, hand kinematic and RT variables using equation 1:

Equation 1: dual task cost = $\frac{(dual \ task - single \ task)}{single \ task} \times 100$

3 Chapter: Results

3.1 Centre of Pressure

3.1.1 Main Effects – Task

Each dependent variable was assessed for significant differences across both history level groups and between single and dual tasks. Within the 2×2 mixed model ANOVA the main effect of task was used to determine differences between each dependent variable when collapsed across concussion history groups, thereby determining a dual task effect. All COP dependent variables are displayed in Table 2.2. Figure 3.1 shows the average COP displacement (a) and velocity (b) in the AP direction for a representative participant under single (black) and dual (grey) task conditions during unperturbed reaches. It is apparent that the time to reach peak displacement and velocity were delayed in the dual task condition. This was confirmed for the group by a significant main effect of task for both time to peak displacement (p=0.001) (Figure 3.2a) and time to peak velocity (p=0.001) (Figure 3.2b, Table 3.1) during unperturbed trials. During left perturbations there was a 5.0% increase in time to maximum displacement in the ML direction during dual task conditions (p=0.016) (Table 3.1). In contrast, maximum ML displacement was decreased in the dual task condition during both right (-13.2%) and left perturbations (-10.5%) (p=0.03, p=0.01, respectively) (Table 3.1). Moreover, maximum velocity was also decreased -24.3% in the dual task condition during left perturbations (p=0.002) (Table 3.1).



Time (ms)

Figure 3.1. Representative participant data of the anterior/posterior (AP) displacement (A) and velocity (B) of centre of pressure (COP) during no perturbation trials over time. In the dual task condition a significant increase in the time to reach maximum displacement and velocity was observed.



Task Level

Figure 3.2. Mean (and SEM) time of maximum centre of pressure (COP) anterior/posterior (AP) displacement (A) and velocity (B) under no perturbation conditions. A significant effect of task was found for both variables, with dual task conditions resulting in longer times to maximum displacement and velocity.

	Dependent Variable	Single Task Average	Dual Task Average	p value
No				
Perturbation				
	AP			
	Max displacement (cm)	1.08 ± 0.45	1.15 ± 0.54	0.431
	Time to max displacement (ms)	655.70 ± 77.57	704.32 ± 88.03	*0.001
	Max velocity (cm/ms)	7.62 ± 3.10	7.57 ± 3.22	0.480
	Time to max velocity (ms)	522.37 ± 63.64	564.87 ± 77.48	*0.001
Right Perturbation				
	AP			
	Max displacement (cm)	1.31 ± 0.55	1.40 ± 0.69	0.435
	Time to max displacement (ms)	737.26 ± 93.31	748.44 ± 137.87	0.554
	Max velocity (cm/ms)	9.25 ± 3.55	8.43 ± 3.72	0.073
	Time to max velocity (ms)	546.42 ± 66.85	537.56 ± 57.02	0.907
	ML			
	Max displacement (cm)	1.74 ± 0.79	1.51 ± 0.67	*0.030
	Time to max displacement (ms)	715.43 ± 104.16	711.61 ± 65.04	0.517
	Max velocity (cm/ms)	17.05 ± 6.91	15.19 ± 8.27	0.082
	Time to max velocity (ms)	615.98 ± 66.56	607.98 ± 70.62	0.897
Left Perturbation				
	AP			
	Max displacement (cm)	1.01 ± 0.48	1.07 ± 0.68	0.433
	Time to max displacement (ms)	646.67 ± 103.40	658.59 ± 132.34	0.449
	Max velocity (cm/ms)	8.31 ± 3.04	7.89 ± 4.33	0.366
	Time to max velocity (ms)	608.49 ± 107.80	590.68 ± 143.31	0.338
	ML			
	Max displacement (cm)	2.39 ± 0.90	2.14 ± 0.86	*0.01
	Time to max displacement (ms)	662.47 ± 46.85	696.17 ± 46.35	*0.016
	Max velocity (cm/ms)	22.91 ± 10.37	17.35 ± 6.75	*0.002
	Time to max velocity (ms)	594.80 ± 54.52	598.17 ± 58.03	0.680

Table 3.1 2×2 mixed model ANOVA, main effect of task p value for all centre of pressure(COP) variables. Significance denoted by *. Group averages for single and dual tasks
to show direction of significance.

cm: centimeters, ms: milliseconds; AP: anterior/posterior, ML: medial/lateral

3.1.2 Main Effects – Concussion History

Significant differences between groups (collapsed across both task levels) were assessed by the main effect of concussion history in the 2×2 mixed model ANOVA. Figure 3.3 displays the average COP displacement (a) and velocity (b) in the AP direction for two representative participants (no previous concussion history – black, two or more previous concussions – grey) during trials with no perturbation. These figures show evidence of greater displacements and velocities of the COP in the group with a history of multiple concussions. This observation was supported by a significant main effect of group for both maximum COP AP displacement (p=0.019, Figure 3.4a) and maximum COP AP velocity (p=0.004, Figure 3.4b). The same relationship was shown for AP and ML maximum displacement and velocity during left perturbation conditions (Table 3.2). In the group with two or more previous concussions AP maximum displacement increased 44.7% (p=0.033), AP maximum velocity increased 47.3% (p=0.007), ML maximum displacement increased 33.3% (p=0.021), and ML maximum velocity increased 30.7% (p=0.044) in left perturbation conditions. Moreover, a similar increase of 52.9% was noted in the ML maximum velocity during right perturbations (p=0.002) (Table 3.2).



Figure 3.3. Representative participant data of centre of pressure (COP) anterior/posterior (AP) displacement (A) and velocity (B) during no perturbation conditions. When collapsed across both task levels, larger AP displacements and velocities of the COP were observed in the group with multiple previous concussions.



Figure 3.4. Significant differences between mean maximum anterior/posterior (AP) displacement (A) and velocity (B) of centre of pressure (COP) during no perturbation conditions between concussion history groups.

	Dependent Variable	Hx ⁰ Average	H _x ²⁺ Average	p value
No				
Perturbation				
	AP			
	Max displacement (cm)	0.94 ± 0.48	1.29 ± 0.45	*0.019
	Time to max displacement (ms)	695.58 ± 88.82	661.79 ± 80.01	0.180
	Max velocity (cm/ms)	6.06 ± 2.57	9.03 ± 2.95	*0.004
	Time to max velocity (ms)	530.34 ± 43.02	555.76 ± 93.03	0.259
Right Perturb	ation			
	AP			
	Max displacement (cm)	1.23 ± 0.68	1.49 ± 0.52	0.235
	Time to max displacement (ms)	745.13 ± 82.61	740.58 ± 144.72	0.909
	Max velocity (cm/ms)	7.75 ± 3.83	10.02 ± 3.04	0.071
	Time to max velocity (ms)	556.43 ± 55.26	527.19 ± 65.64	0.075
	ML			
	Max displacement (cm)	1.45 ± 0.76	1.82 ± 0.66	0.125
	Time to max displacement (ms)	709.68 ± 117.39	717.55 ± 45.40	0.405
	Max velocity (cm/ms)	12.71 ± 7.03	19.44 ± 6.69	*0.002
	Time to max velocity (ms)	596.74 ± 71.10	626.46 ± 62.90	0.102
Left Porturbation				
I enturbation	AP			
	Max displacement (cm)	0.85 ± 0.45	1.23 ± 0.64	*0.033
	Time to max displacement (ms)	636.13 ± 94.35	669.08 ± 136.51	0.442
	Max velocity (cm/ms)	6.53 ± 3.01	9.62 ± 3.72	*0.007
	Time to max velocity (ms)	592.10 ± 104.66	607.60 ± 145.83	0.648
	ML			
	Max displacement (cm)	1.95 ± 0.96	2.60 ± 0.65	*0.021
	Time to max displacement (ms)	676.22 ± 51.02	680.66 ± 48.11	0.579
	Max velocity (cm/ms)	17.62 ± 9.59	23.04 ± 8.26	*0.044
	Time to max velocity (ms)	588.86 ± 50.92	603.81 ± 60.12	0.402

Table 3.2 2×2 mixed model ANOVA, main effect of concussion history p value for all centre of
pressure (COP) variables. Significance denoted by *. Group averages for no previous
concussion history (H_x), and two or more previous concussions to show direction of
significance.

cm: centimetres, ms: milliseconds, AP: anterior/posterior, ML: medial/lateral

3.1.3 Interaction Effects

In contrast to the significant main effects of task and group for a number of COP variables, there were no significant interactions found for any COP variable (p > 0.054).

3.2 Hand Kinematics

3.2.1 Main Effects – Task

The effect of performing a dual task or the "cost" of performing a secondary task was assessed by the main effect of task in the 2×2 ANOVA. Under left perturbations, as seen in the representative trace of a single participant (Figure 3.5) a larger ML deviation (displacement) of the hand was noted under dual task conditions. When the task effects were assessed, not only was an increased maximum ML displacement under dual task conditions noted (p<0.001, Figure 3.6a) but also an increased maximum ML velocity (p<0.001, Figure 3.6b) was observed in the dual task when participants experienced a left perturbation. Furthermore, an average increase of 7.3% was shown under dual task conditions in AP time to peak velocity when no perturbation occurred (p<0.001, Table 3.3). Finally, ML maximum velocity during right perturbations saw a 5.1% increase when performed under dual task conditions.

Conversely, two hand kinematic metrics resulted in a decreased in velocity when performed in the dual task context. Under trials in which no perturbation occurred, or participants experiences rightward perturbations, peak velocity in the AP direction decreased -5.3% and -3.4%, respectively (p=0.009, p=0.033, respectively, Table 3.3).



Figure 3.5 Maximum medial/lateral (ML) hand displacement during left perturbation. Single participant representative trace, displacement under single and dual task conditions are shown.



Figure 3.6. Maximum medial/lateral (ML) hand displacement (A) and velocity (B) during left perturbation. Group averages are displayed between single and dual task levels. Dual task scenarios resulted in significantly larger and faster ML hand movements.

		Single Task	Dual Task	
	Dependent Variable	Average	Average	p value
No				
Perturbation				
	AP			
	Max velocity (m/s)	1.31 ± 0.28	1.24 ± 0.26	*0.009
	Time to max velocity (ms)	501.43 ± 52.83	538.16 ± 60.00	*<0.001
Right Perturbation				
	AP			
	Max velocity (m/s)	1.46 ± 0.30	1.41 ± 0.30	*0.033
	Time to max velocity (ms)	475.40 ± 44.85	473.24 ± 43.61	0.723
	ML			
	Max displacement (m)	0.08 ± 0.01	0.08 ± 0.01	0.787
	Time to max displacement (ms)	580.48 ± 45.57	581.56 ± 41.26	0.834
	Max velocity (m/s)	0.78 ± 0.09	0.82 ± 0.07	*0.011
	Time to max velocity (ms)	470.42 ± 42.75	466.77 ± 42.23	0.698
Left				
I citurbation	ΔP			
	May velocity (m/s)	1.20 ± 0.27	1 14 + 0.24	0 156
	Time to may valuative (ma)	1.20 ± 0.27	1.14 ± 0.24	0.150
	Time to max velocity (ms)	525.04 ± 59.55	552.08 ± 58.74	0.285
	MIL	~~~ ~~		
	Max displacement (m)	0.07 ± 0.01	0.08 ± 0.01	*<0.001
	Time to max displacement (ms)	554.05 ± 43.38	554.05 ± 44.10	0.611
	Max velocity (m/s)	0.75 ± 0.09	0.80 ± 0.09	*<0.001
	Time to max velocity (ms)	462.78 ± 33.44	462.23 ± 45.48	0.693

Table 3.3. 2×2 mixed model ANOVA, main effect of task p value for all hand kinematicsvariables. Significance denoted by *. Group averages for single and dual tasks to showdirection of significance.

m/s: metres/second, ms: millisecond, m: metres, AP: anterior/posterior, ML: medial/lateral
3.2.2 Main Effects – Concussion History

Effects of previous concussion history on hand kinematics were assessed by the main effect of concussion history in the 2×2 ANOVA. Only one dependent variable resulted in a significant difference. Under right perturbation conditions, maximum AP velocity was increased in the group of athletes with two or more previous concussions (p=0.041). During right perturbation conditions, those with no previous concussion history exhibited an average maximum AP hand velocity of 1.34m/s while those individuals with two or more previous concussion had an average maximum hand velocity of 1.53m/s, resulting in a 14.2% increased in the multiple previous concussion group.

3.2.3 Interaction Effects

Figure 3.7a displays the average AP hand velocity for two representative participants (one with no previous concussion history (black), the other with multiple previous concussions (grey)) under single (solid) and dual (dashed) task conditions during right perturbations. Here, it is revealed that both groups performed differently from each other and from themselves on the different task levels. This effect is shown even more clearly when we examine the group data (p=0.014) (Figure 3.7b). On average, in those with zero previous concussions there was a -9.2% decrease in velocity in the dual task. Alternatively, those with a previous concussion history experienced a minimal increase in velocity (2.6% on average) when performing the dual task. Taken together, a disparity between the two groups based on their concussion history under the dual task paradigm is evident.



Figure 3.7. (A) Representative anterior/posterior (AP) velocity traces of each of the four group/task combinations. (B) Significant interaction displaying group averages (and SEM) of the maximum hand AP velocity under right perturbation conditions. Significance between both groups and task levels is noted.

3.3 Reaction Time

3.3.1 Reach Task Reaction Time

3.3.1.1 Main Effects – Task

The duration of time for participants to respond to the target or "go" signal in the reaching with perturbation task and dual task was assessed with a 2×2 mixed model ANOVA for each condition. When collapsed across both groups of participants, RT was shown to be 7.5% increased during the dual task condition (p<0.001) when the reaching motion was performed without external perturbation (Table 3.4). However, there were no main effects for the reach task RT during either right (p=0.399), nor the left (p=0.058) perturbation conditions (Table 3.4).

Table 3.4. 2×2 mixed model ANOVA, main effect of task p value for hand RT. Significancedenoted by *. Group averages of RT under single task reach with perturbation and dualtask.

Dependent Variable	Single Task Average	Dual Task Average	p value
No Perturbation (ms)	333.79 ± 30.62	358.81 ± 26.07	*<0.001
Right Perturbation (ms)	332.49 ± 29.37	326.88 ± 39.89	0.399
Left Perturbation (ms)	339.42 ± 30.12	327.97 ± 28.98	0.058

ms: milliseconds

3.3.1.2 Main Effects – Concussion History

Contrasting the aforementioned main effects findings for task (Table 3.4) where no effects were noted during the right perturbation condition, a main effect of concussion history was observed (p=0.047). On average, the RT of those athletes who had never sustained a concussion was 10.6% faster as compared to those with at least two previous concussions (Figure 3.8). This finding only was present for the rightward perturbations as neither the left

(p=0.054) nor no perturbation condition (p=0.105) revealed any significant effects regarding concussion history.



Figure 3.8. Significant interaction effect of hand reaction time (RT) during right perturbation conditions. A significant effect of group (increased RT for those with multiple previous concussions) is noted.

3.3.1.3 Interaction Effects

When further examining the RT during the right perturbation conditions, a significant interaction effect of hand RT was observed (p=0.009) (Figure 3.8). Namely, despite having comparable RT in both the no previous concussion group (330.40ms) and the multiple previous concussion group (334.71ms) under the single task condition, those with no previous concussions managed to improve RT by 6.4% during the dual task condition while the additional complexity associated with this task slowed the group with two previous concussions RT by 3.3%.

3.3.2 Secondary Task Reaction Time

3.3.2.1 Main Effects – Task

As per study design, there were significant effects of task observed for all three conditions (no perturbation, right perturbation, and left perturbation) with button press RT occurring a minimum of 162.8% longer in all three cases when the button press was added to the reaching task (Table 3.5).

Table 3.5. 2×2 mixed model ANOVA, main effect of task p value for button press reaction time
(RT). Significance denoted by *. Group averages of RT for each condition.

Dependent Variable	Average	p value
Button Press Only (ms)	160.91 ± 31.57	
Button Press + No Perturbation (ms)	422.91 ± 65.83	*<0.001
Button Press + Right Perturbation (ms)	442.73 ± 78.33	*<0.001
Button Press + Left Perturbation (ms)	433.75 ± 81.60	*<0.001

ms: milliseconds

3.3.2.2 Main Effects – Concussion History

Contrary to the main effects of the additional task complexity associated with the addition of the reaching task to the secondary task RT, there were no significant effects of concussion history were observed with respect to the button press when RT was collapsed across both task levels (p>0.268).

3.3.2.3 Interaction Effects

Consistent with the main effects of concussion history, there were no significant interaction effects were observed across any of the button press RT conditions (p>0.319).

3.4 SCAT3 Metrics

Differences between concussion history groups on SCAT3 metrics was assessed using an independent t-test. No significant differences between symptom score, symptom severity, SAC or BESS were noted between groups (p>0.106, Table 3.6). To determine the relation between clinical measures of concussion symptoms and task performance, the SCAT3 metrics were correlated to all other dependent variables (COP, hand kinematics, RT) for both levels of task complexity. Moreover, the dual task cost was calculated for all COP, hand kinematic and RT variables using Equation 1. The cost associated with the dual task for each dependent variable was also correlated to SCAT3 metrics. All significant correlations are presented in Table 3.7.

Table 3.6. Independent samples t-test *p*-values and group means for SCAT3 metrics. No significant differences between no previous concussion history (H_x^{0}) and two or more previous concussion (H_x^{2+}) groups on any metric.

Dependent Variable	$\mathbf{H_{x}^{0}}$	$\mathbf{H_x^{2+}}$	p value
Total Number of Symptoms	2.07 ± 1.94	3.07 ± 2.31	0.322
Symptom Severity	3.00 ± 3.00	5.13 ± 3.93	0.106
SAC	27.27 ± 1.58	26.80 ± 1.93	0.475
BESS	4.87 ± 4.31	6.47 ± 3.44	0.271

			r	p value
Single Task				
	Sympto	om Scores		
		COP, No Perturbation, Time to Max Displacement (AP)	-0.443	0.014
	Sympto	om Severity		
		COP, No Perturbation, Time to Max Displacement (AP)	-0.419	0.021
		COP, Left Perturbation, Maximum Velocity (AP)	0.362	0.049
	SAC			
		COP, Right Perturbation, Time to Max Displacement (ML)	-0.364	0.048
Dual Task				
	SAC			
		COP, Right Perturbation, Time to Max Velocity (ML)	-0.415	0.035
		Hand, No Perturbation, Max Velocity (AP)	0.384	0.048
		Hand, No Perturbation, Time to Max Velocity (AP)	-0.403	0.033
		Hand, Left Perturbation, Time of Max Velocity (AP)	-0.457	0.022
	BESS			
		COP, Left Perturbation, Time to Max Velocity (ML)	0.418	0.027
		Hand, Left Perturbation, Max Displacement (ML)	0.369	0.049
		RT, Button Press, No Perturbation	0.382	0.041
Cost				<u> </u>
	Sympto	om Score		
		COP, Left Perturbation, Time to Max Displacement (AP)	0.382	0.049
		Hand, Right Perturbation, Max Velocity (AP)	0.536	0.004
	Sympto	om Severity		
		COP, No Perturbation, Max Displacement (AP)	-0.378	0.043
		Hand, Right Perturbation, Max Velocity (AP)	0.458	0.016
	SAC			
		Hand, Left Perturbation, Max Displacement (AP)	0.404	0.033
		RT, Hand, Right Perturbation	-0.404	0.033
	BESS			
		COP, Right Perturbation, Max Displacement (ML)	0.405	0.040
		Hand, Right Perturbation, Max Displacement (ML)	0.458	0.014
		Hand, Left Perturbation, Max Displacement (ML)	0.490	0.008
SAC: Standa	ardized	assessment of concussion, BESS: Balance error sco	oring syste	m, COP: ce

Table 3.7. Correlation coefficients (r) and significance values for all variables that were significantly correlated to SCAT3 metrics under single and dual task conditions. Dual task cost was calculated for each variable and correlated to the SCAT3 metrics as well.

of pressure, AP: anterior/posterior, ML: medial/lateral

4 Chapter: Discussion

The hypotheses of this study were three-fold: 1) regardless of previous concussion history, a decrease in performance will occur under dual task scenarios (dual task cost or effect), 2) those with a previous history of concussion will perform poorer on the task than those with no previous concussion history, 3) the two effects of dual task cost and previous concussion history will interact and those with two or more previous concussion will perform significantly worse under dual task than those with no previous concussion history. Each hypothesis will be discussed in turn in relation to the current results and previous literature.

4.1 Dual Task Effect

A number of significant effects of task were noted in COP, hand kinematics and RT variables (Table 3.1, 3.3 - 3.5, Figure 3.1, 3.2, 3.5 - 3.7). In the COP variables, all significant differences in which dual task was increased compared to single task involved the timing of the variable rather than the magnitude. Time to maximum displacement and time to maximum velocity for COP in the AP direction under no perturbation conditions were both increased in the dual task (Figure 3.1, 3.2, Table 3.1). Therefore, the results demonstrate participants took longer to capture and slow the COP under dual task, no perturbation conditions in the AP direction. This effect was also seen in the ML time to maximum displacement under left (or across-body) perturbations. Therefore, it appears the COP was as tightly controlled when the secondary button-press task was completed concurrently. These findings appear in contrast to those previously reported in the literature for dual task balance studies.^{30,53,61,62,93,94} As noted earlier, studies which employed the SOT resulted in an increased postural stability under dual task paradigms.^{30,53,61,62} Moreover, another study that used other tools such as the BESS showed little-to-no effect of a secondary task on postural control.⁵³ Consistent with the study presented in this thesis, the aforementioned studies were also performed using a quiet stance postural control

task. The main difference between the previous studies and the present study, was the additional aspect regarding the use of arm reaching movements either, with or without, perturbations to displace the COP. As the reaching with perturbation task employed in the current design is significantly more challenging for the balance control system, it follows this task likely demands more attentional resources and therefore be more heavily influenced by the addition of a secondary task. Is it possible the previously employed quiet stance dual task paradigms were not sensitive enough to elicit the effects noted in the current study as a result of the relative ease of maintaining static stability.

In contrast, a number of COP metrics that were statistically different between tasks resulted in an increase under the single task condition (Table 3.1). These metrics were all magnitude based variables, including maximum ML displacement under both right and left perturbations as well as maximum velocity during left perturbations (Table 3.1). Therefore, when perturbed displacement of the COP was larger in single task conditions than in dual task conditions. Although these results were unexpected, the constrained action hypothesis⁵³ may provide one possible explanation. This hypothesis of this theory states internal focus disrupts the automatic processes of balance and results in a decrease in performance.⁵³ While participants were not explicitly told to focus on maintaining their balance in either the single or dual task, it is possible the addition of the secondary task disrupted any overt attention to balance control and thus resulted in balance being shifted away from a focal point into a more "automatic" process. However, as previously stated this idea of balance being controlled automatically is outdated⁹², and therefore this explanation solely accounting for the current findings is questionable. Alternatively, a learning effect may also partially explain this observation. In particular, while the order of trials within the experimental tasks was randomized, the order in which all

participants completed the experimental tasks was not. Subjects completed all experimental tasks in the same order (single task – button press, single task – reach with perturbation, dual task) with each additional task adding a layer of complexity to the study design. Since the first time the participants were exposed to the perturbation occurred during the single task block, postural responses may be larger than during the dual task as they had already had a block of trials where they were exposed to the perturbation. As noted previously all perturbations within this experimental design occurred at the same magnitude and timing each time they were presented. However, to mitigate any potential anticipatory adjustments, they were presented in a randomized fashion so as to not be expected. Even without anticipating the forthcoming perturbation, participants have may been able to tune their response to the perturbation more efficiently in the latter portions of the experiment which could have minimized the COP disturbance.

Many hand kinematic variables also resulted in a significant effect of task. Similar to COP, the only timing variable that was significantly altered between tasks (time to maximum velocity, AP, no perturbation) was increased under dual task conditions (Table 3.3). Other variables that were significantly increased in the dual task scenario were maximum velocity (right and left perturbations) and maximum displacement (left perturbation) all in the ML direction (Figure 3.5, 3.6, Table 3.3). Therefore, when perturbed in either direction, the hand moved faster (and further when the perturbation occurred to the left) laterally before being controlled and redirected to the target when a secondary task was also being undertaken. In contrast, AP velocity was decreased during the dual task (no perturbation, and right perturbation trials) (Table 3.3). Although this may seem counter-intuitive, as participants were explicitly asked *to move as quickly and accurately as possible* to the target. This instruction requires the

participant to move with as much velocity as possible in the AP direction. Therefore, although previously stated that an increase in velocity is viewed as a decrease in performance, in the case of AP hand velocity an increased velocity is indicative of a better performance. The increase in AP velocity of the hand under single task conditions indicates participants may be moving slower in the dual task condition due to the high task demands. Therefore, all hand kinematic metrics which resulted in significant differences between levels of task support the first hypothesis. Under dual task conditions participants hand experienced larger and faster movements in the ML direction. This indicates a reduction in control due to dual task demands. Moreover, under dual task conditions when unperturbed, participants displayed slower maximum velocity and an increased time to peak velocity despite receiving the same instructions, *to move as quickly and accurately as possible*.

Finally, two different RTs were measured, the RT of the hand in response to the "go" signal (red target appearance) and the secondary task RT to press the button in response to the auditory tone. The hand RT was significantly longer when performing two tasks concurrently under no perturbation conditions (Table 3.4). Moreover, in all three trial types (no perturbation, right perturbation, and left perturbation) button press RT was significantly larger under dual task conditions (Table 3.5). In the RT metrics, the secondary task specifically was heavily implicated (button press RT increased from ~160ms to ~433ms average of all three conditions) when performing a reaching and perturbation management task. The current findings are supported by the work of Resch, May, and Tomporowsk⁶² who measured the performance on a primary balance task (SOT) and the secondary task (auditory switch task) alone and concurrently. This group observed increased response times and increase in errors made during an auditory switch task under dual task conditions (on switch trials).⁶² Therefore, the authors speculated the

secondary task was impaired by performing a challenging balance task. When assessing the results from the current study, a similar finding was noted. There was a decrease in performance on the secondary task under dual task situations as well as a decrease of postural stability when performing both tasks. This indicates both tasks likely demand overlapping attentional resources.⁹² As the attentional system is limited in nature⁸⁶ once all of the available resources have been used, performance on one or both tasks declines.⁸⁶

Taken together, these results support the first hypothesis that under conditions in which the subject must perform two tasks concurrently, performance of either task will decrease (increased maximum displacement/velocity and time to maximum displacement and velocity in the dual task condition for COP and hand kinematics, and increased RT, Table 3.1, 3.3 - 3.5, Figure 3.1, 3.2, 3.5 - 3.7). While some unexpected findings were observed in COP variables between task levels, on the whole the results from these comparisons indicate: 1) there is a significant cost to performing a dual task, and, 2) postural control requires attention.⁹² Not only were some COP variables affected by the dual task, but the other metrics (hand kinematics and RT) specifically the RT of the button press (secondary task) were greatly affected when the participant was also required to maintain balance while performing a focal movement (potentially being perturbed). Therefore, this experiment provides support for the idea postural control is not an automatically controlled response but rather demands attentional. Furthermore, the additional complexity associated with this dual-task design likely provided a sensitive mechanism to investigate the subtle balance control differences previously speculated to occur in individuals with a history of concussive injuries.

4.2 The Influence of Multiple Previous Concussions

The second overarching theme of this thesis is the influence of multiple previous concussions. This was assessed with the second main effect of previous concussion history. In particular, the group of athletes with a history of previous concussions performed worse across a variety of variables compared to athletes who had never sustained a concussion. In the case of COP metrics, maximum displacement was significantly larger in the AP direction during no perturbation and left perturbation trials (Table 3.2, Figure 3.3, 3.4) and in the ML direction during right and left perturbations when performing the dual task (Table 3.3). Moreover, in dual task scenarios an increased maximum velocity was noted in the AP direction under no perturbation and left perturbations as well as in the ML direction under left perturbation conditions (Table 3.3). Taken together, these results indicate athletes with a history of multiple previous concussions display increased displacement and velocity of the COP during a reaching and perturbation task compared to athletes who have never sustained a concussion. This indicated previous concussed players have worse balance control and thus these findings may help further clarify the little research on chronic static balance disturbances which are present following concussion.^{36,97} The present findings are supported by Degani and colleagues⁵⁴ who found those with previous concussion history displayed larger and slower COP movements compared to controls on a static balance task. Moreover, the current findings along with those of more recent studies^{54,56}, call into question the early studies of postural stability following concussion which concluded balance deficits resolve 3-5 day after the concussive injury.^{26,27}

This previously speculated timeline of recovery needs to be updated, which in turn will enable rehabilitation measures to be put in place to manage these persisting balance deficits. Although this type of experiment has not been employed in an acutely concussed population, the

current findings indicate it is sensitive enough to detect differences in a group of athletes who sustained a concussion on average 26 months prior to testing (range 6-60 months, Table 2.1). Moreover, compared to previous literature (quiet stance and gait), this experimental paradigm (unexpected postural perturbations) more closely mimics a contact sporting context, thus the current results are more likely to translate to on-field situations. Given all of this information, this type of testing paradigm may prove highly valuable in future research paradigms.

The changes to COP movements noted in the current study with respect to multiple previous concussions may provide some context to the findings of increased lower extremity injury^{81–85} and subsequent concussion risk following concussion.^{13,14} In general, these studies have found associations between lower extremity injury and concussion history⁸³, namely there is an increased odds/risk (2.48 - 3.39) of sustaining a lower extremity musculoskeletal injury 90-days following concussion.^{82,84} Furthermore, Nordstrom, Nordstrom, and Ekstand⁸⁵ observed an elevated risk of injury following concussion which progressively increased over the following year after the concussion (0-3 months after: 1.56; 6-12 months after: 4.07). The effects these authors observed remained even after adjusting for injury risk prior to concussion.⁸⁵ Finally, Lynall and associates⁸¹ found an increased lower extremity musculoskeletal injury risk following concussion of 1.64 over the subsequent year. Despite the different values, all groups^{81–85} consistently identified an increased risk of lower extremity musculoskeletal injury following concussion.

Given this evidence, there appears to be a relationship between sustaining a concussion and future injury. Importantly, this relationship has also been noted for future concussion risk. In a seminal study by Guskiewicz and colleagues¹³ authors discovered a "dose response" relationship between the previous number of concussions and risk of future concussion. Those

athletes with one previous concussion were determined to be at a 1.4 times risk, those with 2 previous concussions were at a 2.5 times increased risk, and those with three or more previous concussions were at a 3 times elevated risk of concussion compared to an athlete that has never sustained a concussion.¹³ The due to the constraints of the present study prevent determination of a direct relationship between postural control deficits and subsequent injury risk. However, it is possible and should be noted, due to the increased movements of COP during perturbations, athletes with a previous concussion history may have decreased postural stability and therefore fall and injure/concuss themselves more readily. Should this be the case appropriate balance training interventions need to be developed and implemented into the recovery of concussed athletes to mitigate these risks.

Previous concussion history was also found to have a significant effect on AP hand velocity during right perturbations and hand RT during right perturbations. Athletes with prior history of concussion took longer to react to the "go" signal under right perturbation condition but also moved their hand faster in the AP direction in these trials. It is unclear why this result was only present in the right perturbation condition, as participants were unaware of which trial type was going to be presented next.

The majority of significant effects related to concussion history occurred in the COP metrics. Larger and faster deviations of the COP movements indicate a previous history of multiple concussions may produce chronic disturbances to balance control. While these postural stability deficits were previously thought to resolve within 3-5 days after an acute concussion^{26,27} the tools used in these early studies (SOT and BESS) have been shown to have a number of flaws. Not only has the present experimental paradigm shown differences between concussion history groups it uses a significantly more challenging postural stability test to better simulate a

complex contact sporting scenario (external perturbations). In the future, this type of task (postural perturbations with a secondary task) could be used to aid in diagnosis and to help develop balance training interventions for those who have had multiple previous concussions.

4.3 The Interaction of Dual Task and Previous Concussions

Two significant interaction effects were observed from this experiment. First, AP maximum velocity of the hand during right perturbations. In this metric, it was noted that while those with two or more previous concussions performed similarly on both task levels (velocity of 1.51m/s single task, 1.55m/s dual task (Figure 3.7) the group with no history of concussions performed differently. The participants with no concussion history displayed an overall slower velocity than the previously concussed athletes. On the single task trials the no concussion history group produced an average maximum velocity of 1.40m/s which then decreased under dual task conditions to 1.27m/s (Figure 3.7). Although it is unclear why this trend only happened in the right perturbation trials, it is also counter-intuitive, those with two or more previous concussions produced greater AP velocity consistently when compared to the other group as well as when performing under a dual task scenario. Since participants were instructed to move their hand as quickly and accurately as possible to the target (in the AP direction), and concussion in general impairs performance this is the opposite of what would be expected.

The second interaction effect was observed in the RT of the hand to the "go" signal during right perturbations. Despite both groups performing very similarly on the single task trials (RT of 330.40ms no previous concussion group, and 334.71ms two or more previous concussions), both groups performed very differently on the dual task. RT increased in the group with multiple previous concussions to 345.77ms while the group with no previous concussion history displayed a decreased RT of 309.16ms (Figure 3.8). What remains odd about these

findings is the decreased RT of the group with no previous concussions in the dual task. However, it is necessary to bear in mind that no significant main effect of task was found within this variable. Therefore, the effect of previous concussion history appears to be driving this interaction. Again, it is remains unclear why only the trials in which the participant was perturbed to the right resulted in this effect.

4.4 Relating to the SCAT

As the SCAT3 is such a widely-used tool in the concussion assessment and RTP decision making process (McCrory *et. al.*³ currently cited >1500 times) it was necessary to compare the current experimental paradigm to this well-established metric. According to the SCAT3 metrics (symptom score, symptom severity, SAC, and BESS), the two concussion history groups were not significantly different on any metric (Table 3.6). Previous literature has shown the SCAT3 is only able to detect clinical changes in functioning within a day following injury.¹⁰ Therefore, while highly used, this measure leaves much to be desired as a tool for assessment of the potential long term effects of concussion history. Moreover, although the SCAT3 metrics did not detect differences between groups (specifically the mBESS) those with a previous history of two or more concussions displayed deficits in their postural stability in the present paradigm. Furthermore, the mBESS findings in the current study are consistent with the recent study by Wright *et al.*⁹⁸, where despite no significant differences in mBESS in either acutely concussed or athletes with a previous concussion history were detected in a larger sample size. Thus, it further appears although the SCAT does have clinical utility, the mBESS is insufficient at detecting impairments following a concussion. Combined, these findings highlight the limited ability of the balance scoring system embedded within the widely-used SCAT3 and

the current findings indicate dual task postural perturbation scenarios provide a more sensitive option for assessing postural control in concussed and recovering athletes.

Despite this lack of differences between the groups on the SCAT3, when both groups were considered together, a number of significant correlations were observed between a number of the task performance variables and the scores on the SCAT3 (Table 3.7). In general, these were in line with what would be expected: individuals having more or greater severity of symptoms as assessed by the SCAT3 were associated with poorer balance control or reduced reaching performance and greater dual task costs across a variety of variables. Thus, although the current study was unable to detect clinical symptom changes previously noted between concussion naïve and previously concussed individuals, clinical symptoms were not the focus of the current investigation. The current study was designed to determine postural control deficits in those with a previous history of multiple concussions, and the additional complexity associated with the novel dual-task paradigm did accomplish this goal. This further highlights the broader application of the dual-task paradigm for assessing postural control in a more complex and sport applicable nature.

4.5 Limitations and Future Directions

As this study was the first to use postural perturbations in a dual task paradigm with previously concussed athletes it presents new information to the constantly evolving field of concussion research. However, this study is not without its limitations. A few limitations of note exist in the methodology and participant group that was used.

First, the experimental paradigm included three blocks of trials; 1) single task – button press, 2) single task – reach with perturbation, and 3) dual task. Although trial types were randomized (perturbations, secondary tasks) so as to be unexpected, each participant completed

the three blocks in the same order. Without randomizing the order of the blocks between participants potential learning effects cannot be discounted. That is, as participants had experience with the perturbation during single task, they may have developed strategies to counter this perturbation when presented in the dual task. These potential learning effects may be mitigating the dual task effects. However, since the perturbation occurred very quickly and on only 1/3 of the trials (total 20 perturbations presented in the single task) it is possible this potential learning effect wold have minimally impacted the current findings. Future studies would benefit from randomization of the blocks of trials, and determining if a learning effect is present within this task.

Secondly, although this is the first study to use external perturbations in a concussion context and provides a task designed to mimic the demands of contact sport, rarely are athletes perturbed only at the level of the arm in game play. In the future, studies should employ perturbations to the COM to more realistically simulate contact sports. Moreover, studies could implement a secondary task specific to the sport. For example, participants could watch short video clips of their sport being played and have to identify in each clip which direction the ball/puck/etc. was passed as quickly as possible.

Moreover, the group of individuals used in this protocol represents a very small subsection of the actual population that may be able to benefit from this type of research. Only collegiate/junior male contact sport athletes were assessed in this paradigm. In the future, research should include both male and female groups and different age ranges (children, adolescents, adults, and elderly). Moreover, this task could be used in different populations outside of sports concussion, such as individuals who have suffered from blast related

concussions or mTBI from other sources (e.g. motor vehicle accident, falls, etc.) or other pathologies such as stroke.

Finally, although not present in current population, depressive symptoms have been related to concussion history.⁹⁹ While the participants of the present study did not report any pre-existing mood disorders, the potential compounding effects of depressive symptoms should be evaluated in this population moving forward.

5 Chapter: Conclusion

Sport concussion is a prevalent public health issue with the potential to cause long-term deficits after repeat exposure. The influence of concussion is wide spread with postural control being heavily implicated following the injury. Specifically, quiet stance balance control has been investigated following concussion.^{26,27,50,52,56,63–67,75} The results of these studies indicated that postural control difficulties resolve in 3-5 days after injury.^{26,27} However, much of this research was completed using tools that have been shown to have moderate reliability and large learning effects.^{76–78,80} Moreover, while these studies of quiet stance have been informative the static stance task is quite simple in nature. To better evaluate concussed contract sport athletes an assessment that mimics the demands of sport would be beneficial. One of the more challenging balance control aspects of sport is coping with external perturbations. Moreover, athletes are coping with perturbations while also dividing attention among many aspects of game play. Therefore, employing a dual task paradigm in which athletes must cope with postural perturbations while also performing an attentional task has the ability to simulate the demands of game play and best assess disturbances due to concussion.

Despite the growing concern for acute concussion management emphasis needs to be placed on the potential chronic disturbances that can occur due to exposure to multiple concussions. In the majority of cases, the acute effects of concussion resolve within 1-2 weeks following the injury.³ In contrast, the subtle changes that result from multiple concussions persist years following the injuries and have the capacity to influence the future career of the athlete as well as their day to day life. Therefore, the aim of this thesis was to explore how a previous history of concussion impacts the ability to perform a dual task using external perturbations and an attentional task. The hypotheses made were three-fold: 1) when performed simultaneously

performance would decrease as compared to the performance of each task alone, 2) previous concussion history would compromise performance on this task, 3) both the effects of task and concussion history would interact and produce a significantly worse performance under dual task conditions in the group with a history of previous concussion.

We employed a custom made dual task and found many significant dual task effects as well as a number of variables affected by history of multiple previous concussions. The primary variables affected by completing both tasks concurrently were timing variables of the COP, hand velocity, and RT of the secondary button press task. Taken together, these results indicate that postural stability requires attentional resources as both tasks resulted in a decreased in performance when completed at the same time. Therefore, both tasks were using the same limited attentional resources and when the demands of the task became too substantial performance suffered. Furthermore, we observed differences between the two concussion history groups. Specifically, those with two or more previous concussions mainly showed deficits in managing the movement and velocity of the COP. This finding may provide insight as to why athletes who have experienced a concussion display higher rates of lower extremity musculoskeletal injury in the months to year following the concussive injury. Moreover, these findings highlight the need to monitor concussed athletes for a longer period of time after overt symptom resolution. This task provided a more sport specific context and we observed deficits in postural control in athletes who had experienced a concussion on average 26 months prior. It is possible that the currently used balance assessments (mBESS) which assess static stance are not sensitive enough to these disturbances. The findings of decreased postural stability in those with a previous history of multiple concussions also indicates the need for specialized balance interventions to be developed and implemented into the concussion recovery process. Lastly,

very few interaction effects were observed in this task. It appears that the dual task cost and the influence of previous concussion affect difference aspects of the task (e.g. timing vs. magnitude, COP vs. secondary task RT).

Taken together, the implications of this research are far reaching. As it was the first study to explore postural perturbations in this population it provides critical information to the understanding of how concussion influences postural stability. With the knowledge that the effects of chronic concussion result in long term balance difficulties, this research could spark further investigation into the mechanisms responsible, as well as inventions to assist those who have suffered multiple previous concussions. Furthermore, this tool may prove useful in the assessment and diagnosis of acute concussion, as well as aid clinicians in making RTP decisions.

REFERENCES

- Langlois J, Rutland-Brown W. The epidemiology and impact of traumatic brain injury: a brief overview. *The Journal of head* 2006; 21:375–378.
- Black A, Sergio L, Macpherson A. The Epidemiology of Concussions: Number and Nature of Concussions and Time to Recovery Among Female and Male Canadian Varsity Athletes 2008 to 2011. *Clin J Sport Medicine Official J Can Acad Sport Medicine*. 2016; Publish Ahead of Print.
- McCrory P, Meeuwisse WH, Aubry M, Cantu B. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British journal of sports* 2013; 47:250–258.
- Guskiewicz K, Mihalik J, Shankar V, Marshall S, Crowell D, Oliaro S, Ciocca M, Hooker D. Measurement of Head Impacts in Collegiate Football Players: Relationship Between Head Impact Biomechanics and Acute Clinical Outcome After Concussion. *Eur Man Med.* 2007; 61:1244–1253.
- Broglio S, Eckner J, Surma T, Kutcher J. Post-concussion cognitive declines and symptomatology are not related to concussion biomechanics in high school football players. *J Neurotraum.* 2011; 28:2061–8.
- 6. McCrory P, Meeuwisse W, Dvorak J, Aubry M, Bailes J, Broglio S, Cantu RC, Cassidy D, Echemendia RJ, Castellani RJ, Davis GA, Ellenbogen R, Emery C, Engebretsen L, Feddermann-Demont N, Giza CC, Guskiewicz KM, Herring S, Iverson GL, Johnston KM, Kissick J, Kutcher J, Leddy JJ, Maddocks D, Makdissi M, Manley GT, McCrea M, Meehan WP, Nagahiro S, Patricios J, Putukian M, Schneider KJ, Sills A, Tator CH, Turner M, Vos PE. Consensus statement on concussion in sport-the 5(th) international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*. 2017;

- Eckner J, Sabin M, Kutcher J, Broglio S. No Evidence for a Cumulative Impact Effect on Concussion Injury Threshold. *J Neurotraum*. 2011; 28:2079–2090.
- Kerr Z, Register-Mihalik J, Kroshus E, Baugh C, Marshall S. Motivations Associated With Nondisclosure of Self-Reported Concussions in Former Collegiate Athletes. *Am J Sports Medicine*. 2015; 44:220–225.
- Donaworth M, Grandhi R, Logan K, Gubanich P, Myer G. Is current medical education adequately preparing future physicians to manage concussion: an initial evaluation. *Physician Sportsmed*. 2016; 44:1–7.
- Yengo-Kahn A, Hale A, Zalneraitis B, Zuckerman S, Sills A, Solomon G. The Sport Concussion Assessment Tool: a systematic review. *Neurosurg Focus*. 2016; 40:E6.
- Alsalaheen B, Stockdale K, Pechumer D, Broglio S. Validity of the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT). *Sports Med.* 2016; 46:1487– 1501.
- Manley G, Gardner A, Schneider K, Guskiewicz K, Bailes J, Cantu R, Castellani R, Turner M, Jordan B, Randolph C, Dvořák J, Hayden K, Tator C, McCrory P, Iverson G. A systematic review of potential long-term effects of sport-related concussion. *Br J Sports Med.* 2017; 51:969–977.
- Guskiewicz K, McCrea M, Marshall S, Cantu R, Randolph C, Barr W, Onate J, Kelly J.
 Cumulative Effects Associated With Recurrent Concussion in Collegiate Football
 Players: The NCAA Concussion Study. *Jama*. 2003; 290:2549–2555.
- Wasserman E, Kerr Z, Zuckerman S, Covassin T. Epidemiology of Sports-Related Concussions in National Collegiate Athletic Association Athletes From 2009-2010 to

2013-2014: Symptom Prevalence, Symptom Resolution Time, and Return-to-Play Time. *Am J Sports Medicine*. 2015; 44:226–233.

- 15. Elbin R, Covassin T, Henry L, Whalen D, Wedge J, Kontos A. Sport-Related Concussion: "How many is too many?"*Transl Stroke Res.* 2013; 4:425–431.
- McKee A, Cantu R, Nowinski C, Hedley-Whyte E, Gavett B, Budson A, Santini V, Lee H-S, Kubilus C, Stern R. Chronic Traumatic Encephalopathy in Athletes: Progressive Tauopathy After Repetitive Head Injury. *J Neuropathology Exp Neurology*. 2009; 68:709–735.
- 17. Kiernan P, Montenigro P, Solomon T, McKee A. Chronic Traumatic Encephalopathy: A Neurodegenerative Consequence of Repetitive Traumatic Brain Injury. *Semin Neurol*. 2015; 35:020–028.
- 18. Shumway-Cook A, Woollacott MH. Motor control: translating research into clinical practice. 2007;Available from: http://books.google.com/books?hl=en&lr=&id=BJcL3enz3xMC&oi=fnd&pg=PA1&dq= motor+control+translating+research+into+clinical+practice&ots=lDyfixEOsT&sig=z4-N40eCjZ6ojRzcUv0AUmcGmLs
- Winter D. Human balance and posture control during standing and walking. *Gait & posture*. 1995; 3:193–214.
- 20. Oie K, Kiemel T, Jeka J. Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. *Cognitive Brain Res.* 2002; 14:164–176.
- Massion J. Movement, posture and equilibrium: interaction and coordination. *Prog. Neurobiol.* 1992; 38:35–56.

- 22. Krishnan V, Aruin A, Latash M. Two stages and three components of the postural preparation to action. *Exp Brain Res.* 2011; 212:47–63.
- Friedli WG, Cohen L, Hallett M, Stanhope S, Simon SR. Postural adjustments associated with rapid voluntary arm movements. II. Biomechanical analysis. *J. Neurol. Neurosurg. Psychiatr.* 1988; 51:232–43.
- 24. McIlroy WE, Maki BE. Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? *Neurosci Lett.* 1993; 164:199–202.
- Lowrey C, Nashed J, Scott S. Rapid and flexible whole body postural responses are evoked from perturbations to the upper limb during goal-directed reaching. J *Neurophysiol.* 2016; 117:1070–1083.
- Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train*. 2001; 36:263–273.
- 27. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc*. 1997; 29:S213–21.
- Guskiewicz K. Balance Assessment in the Management of Sport-Related Concussion. *Clin Sport Med.* 2011; 30:89–102.
- 29. Catena R, Donkelaar P, Chou L-S. The effects of attention capacity on dynamic balance control following concussion. *J Neuroeng Rehabil*. 2011; 8:8.
- 30. Teel E, Register-Mihalik J, Blackburn J, Guskiewicz K. Balance and cognitive performance during a dual-task: preliminary implications for use in concussion assessment. *J Sci Medicine Sport Sports Medicine Australia*. 2012; 16:190–4.
- Howell D, Osteig L, Chou L. Return to Activity after Concussion Affects Dual-Task Gait
 Balance Control Recovery. *Medicine & Science in Sports & Exercise*. 2015; 47:673.

- 32. Parker T, Osternig L, van Donkelaar P, Chou L-S. Balance control during gait in athletes and non-athletes following concussion. *Medical Eng Phys.* 2008; 30:959–967.
- Howell D, Osternig L, Chou L-S. Dual-Task Effect on Gait Balance Control in Adolescents With Concussion. *Arch Phys Med Rehab*. 2013; 94:1513–1520.
- Reed-Jones R, Murray N, Powell D. Clinical Assessment of Balance in Adults with Concussion. *Seminars Speech Lang.* 2014; 35:186–195.
- 35. Catena RD, van Donkelaar P. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *Journal of* ... [Internet]. 2009;Available from: http://jneuroengrehab.biomedcentral.com/articles/10.1186/1743-0003-6-25
- 36. Kleffelgaard I, Roe C, Soberg H, Bergland A. Associations among self-reported balance problems, post-concussion symptoms and performance-based tests: a longitudinal followup study. *Disabil Rehabil*. 2011; 34:788–794.
- Cavanaugh J, Guskiewicz K, Stergiou N. A Nonlinear Dynamic Approach for Evaluating Postural Control. *Sports Med.* 2005; 35:935–950.
- 38. Ruhe A, Fejer R, Gänsslen A. Assessing Postural Stability in the Concussed Athlete What to Do, What to Expect, and When. *Sports Health: A* 2014; 6:427–433.
- Guskiewicz KM. Assessment of postural stability following sport-related concussion.
 Curr Sports Med Rep. 2003; 2:24–30.
- Guskiewicz K. Postural Stability Assessment Following Concussion: One Piece of the Puzzle. *Clin J Sport Med.* 2001; 11:182.
- 41. Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. *J Athl Train*. 1996; 31:300–6.

- 42. Howell D, Osternig L, Chou L-S. Single-task and dual-task tandem gait test performance after concussion. *J Sci Med Sport*. 2017;
- Howell D, Osternig L, Chou L. Adolescents Demonstrate Greater Gait Balance Control Deficits After Concussion Than Young Adults. *Am J Sports Medicine*. 2014; 43:625–632.
- Howell D, Osternig L, Christie A, Chou L-S. Return to Physical Activity Timing and Dual-Task Gait Stability Are Associated 2 Months Following Concussion. *J Head Trauma Rehabilitation*. 2016; 31:262.
- Howell D, Beasley M, Vopat L, Meehan W. The Effect of Prior Concussion History on Dual-Task Gait following a Concussion. *J Neurotraum*. 2016; 34:838–844.
- Howell DR, Osternig LR, Koester MC, Chou L-SS. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res*. 2014; 232:1773–82.
- 47. Howell D, Oldham J, DiFabio M, Vallabhajosula S, Hall E, Ketcham C, Meehan W, Buckley T. Single-Task and Dual-Task Gait Among Collegiate Athletes of Different Sport Classifications: Implications for Concussion Management. *J Appl Biomech*. 2016;:1–25.
- 48. Fino P, Nussbaum M, Brolinson P. Locomotor deficits in recently concussed athletes and matched controls during single and dual-task turning gait: preliminary results. J Neuroeng Rehabil. 2016; 13:65.
- 49. Johnston W, Coughlan G, Caulfield B. Challenging concussed athletes: the future of balance assessment in concussion. *Qjm.* 2016;:hcw228.

- 50. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *Journal of athletic training* [Internet].
 2000;Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1323433/
- 51. Cavanaugh J, Guskiewicz K, Giuliani C, Marshall S, Mercer V, Stergiou N. Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *Brit J Sport Med.* 2005; 39:805–811.
- 52. Cavanaugh J, Guskiewicz K, Giuliani C, Marshall S, Mercer V, Stergiou N. Recovery of postural control after cerebral concussion: new insights using approximate entropy. *J Athl Training*. 2006; 41:305–13.
- 53. Ross L, Register-Mihalik J, Mihalik J, McCulloch K, Prentice W, Shields E, Guskiewicz K. Effects of a single-task versus a dual-task paradigm on cognition and balance in healthy subjects. *J Sport Rehabil*. 2011; 20:296–310.
- 54. Degani A, Santos M, Leonard C, Rau T, Patel S, Mohapatra S, Danna-dos-Santos A. The effects of mild traumatic brain injury on postural control. *Brain Injury*. 2016;:1–8.
- 55. Fino P. A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait. *J Biomech.* 2016; 49:1983–1988.
- Powers K, Kalmar J, Cinelli M. Recovery of static stability following a concussion. *Gait Posture*. 2014; 39:611–614.
- 57. Powers K, Kalmar J, Cinelli M. Dynamic stability and steering control following a sportinduced concussion. *Gait Posture*. 2013; 39:728–32.
- Broglio S, Puetz T. The Effect of Sport Concussion on Neurocognitive Function, Self-Report Symptoms and Postural Control. *Sports Med.* 2008; 38:53–67.

- Martini D, Sabin M, DePesa S, Leal E, Negrete T, Sosnoff J, Broglio S. The Chronic Effects of Concussion on Gait. *Arch Phys Med Rehab*. 2011; 92:585–589.
- 60. Sosnoff JJ, Broglio SP, Shin S. Previous mild traumatic brain injury and posturalcontrol dynamics. *Journal of athletic* ... [Internet]. 2011;Available from: http://www.natajournals.org/doi/abs/10.4085/1062-6050-46.1.85
- BROGLIO S, TOMPOROWSKI I, FERRARA M. Balance Performance with a Cognitive Task: A Dual-Task Testing Paradigm. *Medicine Sci Sports Exerc*. 2005; 37:689.
- Resch JE, May B, Tomporowski PD. Balance performance with a cognitive task: a continuation of the dual-task testing paradigm. *Journal of athletic* ... [Internet].
 2011;Available from: http://www.natajournals.org/doi/abs/10.4085/1062-6050-46.2.170
- McCrea M, Guskiewicz K, Marshall S, Barr W, Randolph C, Cantu R, Onate J, Yang J, Kelly J. Acute Effects and Recovery Time Following Concussion in Collegiate Football Players: The NCAA Concussion Study. *Jama*. 2003; 290:2556–2563.
- 64. McCrea M, Guskiewicz K, Randolph C, Barr WB, Hammeke TA, Marshall SW, Powell MR, Ahn K, Wang Y, Kelly JP. Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *Journal of the International Neuropsychological Society*. 2013; 19:22–33.
- 65. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the Concussion Assessment Battery. *Neurosurgery*. 2007; 60:1050???1058.
- 66. Hides J, Smith M, Mendis M, Smith N, Cooper A, Treleaven J, Leung F, Gardner A,McCrory P, Choy N. A prospective investigation of changes in the sensorimotor system

following sports concussion. An exploratory study. *Musculoskelet Sci Pract*. 2017; 29:7–19.

- Slobounov S, Cao C, Sebastianelli W, Slobounov E, Newell K. Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability. *Clin Neurophysiol.* 2008; 119:281–289.
- Slobounov S, Sebastianelli W, Moss R. Alteration of posture-related cortical potentials in mild traumatic brain injury. *Neurosci Lett.* 2005; 383:251–255.
- 69. Catena R, Donkelaar P, Chou L-S. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture*. 2006; 25:406–11.
- 70. Catena R, van Donkelaar P, Chou L. Cognitive task effects on gait stability following concussion. *Experimental brain research*. 2007; 176:23–31.
- Parker T, Osternig L, van Donkelaar P, Chou L-S. Recovery of cognitive and dynamic motor function following concussion. *Brit J Sport Med.* 2007; 41:868–873.
- Parker T, Osteig L, vanDonkelaar P, Chou L. Gait Stability following Concussion.
 Medicine & Science in Sports & Exercise. 2006; 38:1032.
- 73. Parker T, Osternig L, Lee H-J, Donkelaar P, Chou L-S. The effect of divided attention on gait stability following concussion. *Clin Biomech*. 2005; 20:389–395.
- 74. Van Donkelaar P, Osternig L, Chou L-SS. Attentional and biomechanical deficits interact after mild traumatic brain injury. *Exerc Sport Sci Rev.* 2006; 34:77–82.
- 75. Peterson CL, Ferrara MS, Mrazik M, Piland S, Elliott R. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. *Clin J Sport Med.* 2003; 13:230–7.

- Hunt TN, Ferrara MS, Bornstein RA, Baumgartner TA. The reliability of the modified Balance Error Scoring System. *Clin J Sport Med.* 2009; 19:471–5.
- 77. Finnoff J, Peterson V, Hollman J, Smith J. Intrarater and Interrater Reliability of the Balance Error Scoring System (BESS). *Pm R*. 2009; 1:50–54.
- Mulligan I, Boland M, McIlhenny C. The Balance Error Scoring System Learned Response Among Young Adults. *Sports Heal*. 2013; 5:22–26.
- Koo T, Li M. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Medicine*. 2016; 15:155–163.
- Wrisley D, Stephens M, Mosley S, Wojnowski A, Duffy J, Burkard R. Learning Effects of Repetitive Administrations of the Sensory Organization Test in Healthy Young Adults. *Arch Phys Med Rehab.* 2007; 88:1049–1054.
- Lynall RC, Mauntel TC, Padua DA, Mihalik JP. Acute Lower Extremity Injury Rates
 Increase after Concussion in College Athletes. *Med Sci Sports Exerc.* 2015; 47:2487–92.
- Herman DC, Jones D, Harrison A, Moser M, Tillman S, Farmer K, Pass A, Clugston JR, Hernandez J, Chmielewski TL. Concussion May Increase the Risk of Subsequent Lower Extremity Musculoskeletal Injury in Collegiate Athletes. *Sports Med.* 2016;
- 83. Gilbert FC, Burdette GT, Joyner AB, Llewellyn TA, Buckley TA. Association Between Concussion and Lower Extremity Injuries in Collegiate Athletes. *Sports Health*. 2016; 8:561–567.
- Brooks A, Peterson K, Biese K, Sanfilippo J, Heiderscheit B, Bell D. Concussion
 Increases Odds of Sustaining a Lower Extremity Musculoskeletal Injury After Return to
 Play Among Collegiate Athletes. *The American Journal of Sports Medicine*.
 44:0363546515622387.

- Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *Br J Sports Med*. 2014; 48:1447–50.
- Posner MI, Petersen SE. The attention system of the human brain. *Annu. Rev. Neurosci.* 1990; 13:25–42.
- Petersen SE, Posner MI. The attention system of the human brain: 20 years after. *Annu. Rev. Neurosci.* 2012; 35:73–89.
- Van Donkelaar P, Langan J, Rodriguez E, Drew A, Halterman C, Osternig L, Chou L-S.
 Attentional deficits in concussion. *Brain Injury*. 2005; 19:1031–1039.
- Halterman C, Langan J, Drew A, Rodriguez E, Osternig L, Chou L-S, Donkelaar P.
 Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury.
 Brain. 2006; 129:747–753.
- 90. McIntire A, Langan J, Halterman C, Drew A, Osternig L, Chou L-S, Donkelaar P. The influence of mild traumatic brain injury on the temporal distribution of attention. *Exp Brain Res.* 2006; 174:361–366.
- 91. Drew A, Langan J, Halterman C, Osternig L, Chou L-S, Donkelaar P. Attentional disengagement dysfunction following mTBI assessed with the gap saccade task. *Neurosci Lett.* 2007; 417:61–65.
- 92. Pellecchia G. Postural sway increases with attentional demands of concurrent cognitive task. *Gait Posture*. 2003; 18:29–34.
- Andersson G, Hagman J, Talianzadeh R, Svedberg A, Larsen H. Effect of cognitive load on postural control. *Brain Res Bull.* 2002; 58:135–139.

- 94. Siu K-C, Woollacott M. Attentional demands of postural control: The ability to selectively allocate information-processing resources. *Gait Posture*. 2007; 25:121–126.
- Shumway-Cook A, Woollacott M. Attentional demands and postural control: the effect of sensory context. J. Gerontol. A Biol. Sci. Med. Sci. 2000; 55:M10–6.
- 96. Chiu S-L, Osternig L, Chou L-S. Concussion induces gait inter-joint coordination variability under conditions of divided attention and obstacle crossing. *Gait Posture*. 2013; 38:717–722.
- 97. Dorman J, Valentine V, Munce T, Tjarks J, Thompson P, Bergeron M. Tracking postural stability of young concussion patients using dual-task interference. *J Sci Med Sport*. 2015; 18:2–7.
- 98. Wright A, Smirl J, Bryk K, van Donkelaar P. A prospective transcranial Doppler ultrasound-based evaluation of the acute and cumulative effects of sport-related concussion on neurovascular coupling response dynamics. *Journal of Neurotrauma*. 2017;
- 99. Finkbeiner N, Max J, Longman S, Debert C. Knowing What We Don't Know: Long-Term Psychiatric Outcomes following Adult Concussion in Sports. *Can J Psychiatry*. 2016; 61:270–276.

APPENDIX

Appendix A - Sport Concussion Assessment Tool 3 (SCAT3)

Downloaded from http://bjsm.bmj.com/ on June 26, 2017 - Published by group.bmj.com



1

Name

Date/Time of Injury: Date of Assessment

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 supersades the orig-inal 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 or use by medical professionals. If you are not qualified, please use the Sport oncussion Recognition Tool⁷. 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 requives 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?

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 profes-sional 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:	Y	N
"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

Glasgow coma scale (GCS)	
Best eye response (E)	
No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	з
Eyes opening spontaneously	4
Best verbal response (V)	
No verbal response	1
Incomprehensible sounds	2
Inappropriate words	з
Confused	4
Oriented	5
Best motor response (M)	
No motor response	1
Extension to pain	2
Abnormal flexion to pain	з
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.	

Maddocks Score³

"I am going to ask you a few guestions, please listen carefully and give your best effort." Modified Maddocks questions (1 point for each correct answer) 0 1 What venue are we at today? 0 1 Which half is it now? Who scored last in this match? 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 deterioratio (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 diag-nosed with concussion should be returned to sports participation on the day of Injury.

SCATS SPORT CONCUSSION ASSESSMENT TOOL 3 | PAGE 1

© 2013 Concussion in Sport Group 259
Downloaded from http://bjsm.bmj.com/ on June 26, 2017 - Published by group.bmj.com

BACKGROUND

Name:	Date:	Date:				
Examiner:						
Sport/team/school:	Date/time of injury:					
Age:	Gender:	м	F			
Years of education completed:						
Dominant hand:	right left	neith	ler			
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 m	ost recent concussion?					
Have you ever been hospitalized or had a head injury?	medical imaging done for	Y	N			
Have you ever been diagnosed with heat	Y	N				
Do you have a learning disability, dyslexi	Y	N				
Have you ever been diagnosed with depression, anxiety or other psychiatric disorder?			N			
Has anyone in your family ever been diag any of these problems?	anosed with	Y	N			
Are you on any medications? If yes, plea	se list:	Y	N			

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

SYMPTOM EVALUATION

How do you feel?

					-	hand a	-	-
land a sha	nu			-	7	act atte		
Readache			-	- 2	3	4	5	6
Pressure in head			-	- 2	3	4	5	6
Neck Pain			-	- 2	3	4	5	6
vausea or vomiting			-	- 2	3	4	5	6
Dizziness Sharradulalara			-	- 2	3	4	5	6
siurred vision			-	- 2	3	4	5	6
Salarice problems			-	- 2	3	4	5	6
sensitivity to light		J	1	2	3	4	5	ь
Sensitivity to noise		0	1	2	3	4	5	6
Feeling slowed down		D	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 concentratin	ig (0	1	2	3	4	5	6
Difficulty rememberin	9 (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
rritability	(0	1	2	3	4	5	6
Sadness	(0	1	2	3	4	5	6
Nervous or Anxious	0	0	1	2	3	4	5	6
Total number of ser	notoms Mari		n newibi	• 221				
Symptom severity s	core (Maximur	1 00	wible 13	25				
, , , , , , , , , , , , , , , , , , , ,								_
Do the symptoms get	worse with p	hys	ical act	ivity?			Y	
Do the symptoms get worse with mental activity? Y								
self rated self rated and clinician monitored								
clinician interview self rated with parent input								
Overall rating: If you	u know the at	thie /he	te well r usual :	prior t self 7	o the in	ijury, h	ow diff	erent
Please circle one response								
			_					

7

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

Cognitive assessment Standardized Assessment of Concussion (SAC) ⁴									
Orientatio	n (1 po	int for	each o	priect	enswer)			
What mont	What month is it? 0 1								1
What is the	date t	today/	2					0	1
What is the	day o	f the v	week7					0	1
What year is	s it?							0	1
What time i	What time is it right now? (within 1 hour) 0 1							1	
Orientatio	Orientation score of 5								of 5
Immediate	Immediate memory								
List	Tri	al 1	Tri	al 2	Tri	al 3	Alternative w	ord 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	mem	tory s	core	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 0 1 5-3-9-1-4-8 8-3-1-9-6-4 7-2-4-8-5-6 7-1-8-4-6-2 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

Neck Examination:

5

6

8

SCATS SPORT CONCUSSION ASSESMENT TOOL 3 | PAGE 2

F

ange of motion	Tenderness	Upper and lower limb sensation & strength
indings:		

Balance examination
Do one or both of the following tests.

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

Modified Balance Error Scoring System (BESS) testing*	
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 ^{4,7}	
Time (best of 4 triak): seconds	

Coordination examination Upper limb coordination		
Which arm was tested:	Left	Right
Coordination score		of 1
		91.1

SAC Delayed Recall⁴

Delayed recall score

© 2013 Concussion in Sport Group

of 5

Downloaded from http://bjsm.bmj.com/ on June 26, 2017 - Published by group.bmj.com

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 evercise

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, repe back as many words as you can remember, in any order."

Trials 283:

"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 repartless of score on trial 1.8.2. 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 5-1-2" me backy

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

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing*

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)*. 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 by 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 desand on your non-some non-grees of high favion and 45 degrees of kine flavion. Again, you should by 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 fleet. 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 belancing. I will start timing when you are set and have closed your eyes."

Balance testing – types of errors

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

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 a 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 50 cm x40 cm x6 cm).

Tandem Gait^{4,7}

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 accurately as possible earing a somm more poors speg. 5 more intervent an attentiate toor heel to-too gait ensuring that they approximate their heel and the or each strop. 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 this are done and the beat time is retained. Athletes should complete the tests in 14 seconds. Athletes fail the test if they step off the time, have a sparation between their heel and they or if they touch or grab the examiner or an object. In this case, the time is automated of the starting and the starting tests and the starting and the starting and they are the starting the starti 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 eves compared with post of the starting position, where a constitution of the class with Jodit Heal open and jour am (hither right or left) outstretched (shoulder Read to 30 degrees and elbow and fingers extended), pointing in front of you. When give a start signal, I would like you to perform the successive finger to nose repetitions using your indust finger to buch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

Scoring: S 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 amazonar Cohernala Heering in Cohernalo III aport Heerin John, Johnson Heering III (2012) In November 2012. The full details of the conference outcomes and the authors of the tool are published in The BISM 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 heils by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made

2. McCrory P et al., Consensus Statement on Concussion in Sport - the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. British Journal of Sports Medicine 2009; 43: 176-89.

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.

4. McCrea M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176-181.

5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24-30.

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 screen-ing in sport-related concussion. Journal of Science and Medicine in Sport. 2010; 13(4): 382-386

ATHLETE INFORMATION

Any athlete suspected of having a concussion should be removed from play, and then seek medical evaluation.

Signs to watch for

Problems could arise over the first 24-48 hours. The athlete should not be left alone and must go to a hospital at once if they:

- Have a headache that gets worse
- Are very drowsy or can't be awakened
- Can't recognize people or places
- Have repeated vomiting
- Behave unusually or seem confused; are very irritable
- Have seizures (arms and legs jerk uncontrollably) - Have weak or numb arms or legs
- Are unsteady on their feet; have slurred speech
- Remember, it is better to be safe.

Consult your doctor after a suspected concussion.

Return to play

Athletes should not be returned to play the same day of injury. When returning athletes to play, they should be medically cleared and then follow a stepwise supervised program, with stages of progression.

For example:

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

There should be at least 24 hours (or longer) for each stage and if symptoms recur the athlete should rest until they resolve once again and then resume the program at the previous asymptomatic stage. Resistance training should only be added in the later stages.

If the athlete is symptomatic for more than 10 days, then consultation by a medical practitioner who is expert in the management of concussion, is recomm nded

Medical clearance should be given before return to play.

Patient's name

Date/time of injury

Date/time of medical review

Treatingphysician



SCAT3 SPORT CONCUSSION ASSESMENT TOOL 3 | PAGE 4

© 2013 Concussion in Sport Group

Scoring Summary: Test Domain Score Date: Date: Date: Number of Symptoms of 22 Symptom Severity Score of 132 Orientation of 5 Immediate Memory of 15 Concentration of 5 Delayed Recall of 5 SAC Total BESS (total errors) Tandem Gait (seconds) Coordination of 1

Notes:



CONCUSSION INJURY ADVICE

(To be given to the person monitoring the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, dizziness, worsening head-ache, double vision or excessive drowsiness, please contact your doctor or the nearest hospital emergency department immediately.

Other important points:

- Rest (physically and mentally), including training or playing sports until symptoms resolve and you are medically cleared
- No alcohol
- No prescription or non-prescription drugs without medical supervision. Specifically: No sleeping tablets
- · Do not use aspirin, anti-inflammatory medication or sedating pain killers Do not drive until medically cleared
- Do not train or play sport until medically cleared

Clinic phone number