VESTIBULAR FUNCTION AND SPORTS-RELATED CONCUSSION: AN EXPLORATORY INVESTIGATION OF THE CONSEQUENCES OF SPORTS RELATED CONCUSSION ON VESTIBULAR FUNCTION AND OUTCOMES

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VESTIBULAR FUNCTION AND SPORTS-RELATED CONCUSSION: AN EXPLORATORY INVESTIGATION OF THE CONSEQUENCES OF SPORTS RELATED CONCUSSION ON VESTIBULAR FUNCTION AND OUTCOMES

______________________________

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the
College of Health Sciences
at the University of Kentucky

By

Carolina P. Quintana

Lexington, Kentucky

Co-Directors: Dr. Matthew C. Hoch, Professor of Athletic Training and Clinical Nutrition
and Dr. Anne D. Olson, Professor of Communication Sciences and Disorders

Lexington, Kentucky

2020

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VESTIBULAR FUNCTION AND SPORTS-RELATED CONCUSSION: AN EXPLORATORY INVESTIGATION OF THE CONSEQUENCES OF SPORTS RELATED CONCUSSION ON VESTIBULAR FUNCTION AND OUTCOMES

Sports-related concussions (SRC), or mild traumatic brain injuries that occur as a result of sports or athletic participation, are said to affect approximately 300,000 young adults and 1.4 million youth athletes in the United States on an annual basis. SRC create a significant burden on the health care system by generating an estimated $60 billion dollars in direct and indirect costs in 2000. In addition to the financial burden these injuries create, they additionally impose both short- and long-term effects for those effected and their overall health. Among the many effects of concussions are physical signs as symptoms such as headache, dizziness, emotional/behavioral changes and coordination issues. Traditional diagnosis strategies rely on the individual’s self-report of experienced symptoms. In addition to symptoms, it is well documented that systems within the body are affected by these injuries and manifest in various functional deficits. Among these systems and deficits are those to the vestibular system, which is the system largely responsible for maintaining upright postural stability or balance and the stabilization of gaze during head movements, both crucial in athletic participation. These functions are mediated by the vestibulospinal reflex (VSR) and the vestibulo-ocular reflex (VOR). Advances in technology have made it possible to measure function of these reflexes and identify potential deficits to the system. These advances provide clinicians objective methods of measuring function and may improve current clinical practice and concussion management strategies including better return to play criteria. The primary purpose of this dissertation was to investigate how measures of vestibular function are related to time to medical clearance in athletes with a recent SRC. This dissertation also sought to establish normative estimates for VOR function and explore the relationship between VSR and VOR measures of function. Further, the relationship between objective measures of VSR and VOR function and self-reported symptoms and function was investigated. To achieve this purpose, several aims were investigated. The first aim sought to establish normative values for the DVAT and GST in collegiate athletes and explore the effect of sport, sex, and concussion history on VOR assessments. The second aim explored potential relationships between the Concussion Balance Test (COBALT), Dynamic Visual Acuity Test (DVAT), Gaze Stabilization Test (GST), and self-reported vestibular symptoms in collegiate athletes with and without a history of concussion. The final aim sought to explore potential predictors of prolonged recovery in a sample of adolescent and young adult athletes who have reported to a concussion clinic after sustaining an SRC. This exploratory investigation identified predictors, relative to vestibular function and other factors that influenced the time to recovery. Identified predictors of recovery included the number of days from the injury to the initial visit to the clinic, the number of visits from initial visit to medical clearance, the number of days to a
successful COBALT completion. The results of this dissertation begin to provide more information regarding vestibular function as it relates to SRC as well as identifying factors that may be modifiable to improve outcomes. First, through the establishment of normative estimates of vestibular function, it was discovered that there are differences in normative vestibular function based on sports participation. Thus, it may be suggested that vestibular function may be improved based on the requirements and nature of the sport and can be improved with practice. Additionally, the standards for returning to play based on vestibular function should be unique to the activity an athlete is return. Additionally, understanding the relationships between measures of vestibular function may help in the identification of the most efficacious multi-faceted assessment strategy. Finally, identifying predictors of prolonged recovery relative to the vestibular function can aid in improving outcomes. Thus, further justifying the need for more comprehensive assessments.

KEYWORDS: Sports-Related Concussion, Vestibular Function, Gaze Stability, Balance, Recovery

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04/10/2020
Date
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DEDICATION

“I am not going to let anyone convince me that I was wrong for raising hell about it…”

-Lyman T. Johnson (1906-1997)

In this 70th year of integration at the University of Kentucky, I dedicate this dissertation to Lyman T. Johnson, who courageously fought against the marginalization of African Americans by demanding the right to equal opportunities in pursuing higher education. His actions were selfless. His sacrifice and bravery have made it possible for me, as well as other students of color, to pursue our dreams of achieving the highest academic ranks. May his legacy live on through us.
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TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ iii

LIST OF TABLES ................................................................................................................ viii

LIST OF FIGURES .............................................................................................................. ix

CHAPTER 1 Introduction ..................................................................................................... 1

1.1 Background .................................................................................................................. 1

1.1.1 Significance and Purpose ...................................................................................... 6

1.1.2 Specific Aims ......................................................................................................... 6

1.2 Overview .................................................................................................................... 7

1.2.1 Operational Definitions ....................................................................................... 7

Sports-Related Concussion (SRC) ................................................................................. 8

Return to Participation (RTP) ......................................................................................... 8

Subjective Patient-Reported Clinical Measures ........................................................... 8

Post-Concussion Symptoms Scale (PCSS) ................................................................. 8

Dizziness Handicap Inventory (DHI) ............................................................................. 9

Objective Measures: ....................................................................................................... 9

Dynamic Visual Acuity (DVA) ....................................................................................... 9

Logarithm of the Minimum Angle of Resolution (LogMAR) ........................................... 9

Gaze Stabilization Test (GST) ....................................................................................... 10

Concussion Balance Test (COBALT) ............................................................................. 10

1.3 Assumptions: ............................................................................................................. 11

1.4 Delimitations: ............................................................................................................ 11

1.5 Limitations ................................................................................................................ 11

CHAPTER 2 Vestibular Consequences, Assessment Strategies, and Outcomes following Sports-Related Consequences Concussion .......................................................... 13

2.1 Introduction ................................................................................................................. 13

2.2 Literature Search and Analysis .................................................................................. 15

2.2.1 Data Sources and Searches ................................................................................. 15

2.2.2 Quality Assessment ............................................................................................. 17

2.3 Findings ..................................................................................................................... 17

2.3.1 Description of Included Studies: Anatomical and Physiological Basis for Vestibular Involvement in Sport-Related Concussion ......................................................... 18

2.3.2 Anatomical and Physiological Basis for Vestibular Involvement in Sport-Related Concussion ......................................................................................................................... 19

2.3.2.1 The Peripheral Vestibular System ................................................................... 19
2.3.2.2 The Central Vestibular System, Reflexes, and Cranial Nerves .......... 20
2.3.2.3 Consequences of Concussion to the Vestibular System .................. 21
2.3.3 Description of Included Studies: Current Clinical Assessment Strategies for Vestibular Function ................................................................. 22
2.3.3.1 Balance/Postural Control Assessments ......................................... 22
2.3.3.2 Vestibulo-ocular Reflex and Ocular Motor Assessments .................. 28
2.3.3.3 Symptom Inventories and Patient Reported Outcomes ...................... 33
2.3.4 Description of Included Studies: Influence of Vestibular Function on Outcomes for Patients with a Sport-Related Concussion ......................... 34
2.3.4.1 Vestibular Deficits and Time to Recovery .................................... 35
2.3.4.2 Quality Assessment and Level of Evidence ................................... 36
2.4 Discussion .................................................................................. 37
2.4.1 Clinical Implications and Future Directions ...................................... 40
2.4.2 Limitations ............................................................................ 41
2.5 Conclusions and Recommendations .............................................. 42

CHAPTER 3 Sport-Specific Differences in Dynamic Visual Acuity and Gaze Stabilization in Division-I Collegiate Athletes .................................................. 61

3.1 Introduction ........................................................................... 61
3.2 Methods .............................................................................. 63
3.2.1 Participants ...................................................................... 63
3.2.2 Instrumentation ................................................................. 64
3.3 Procedures .......................................................................... 65
3.3.1 Assessments .................................................................... 65
3.3.2 Statistical Analysis .............................................................. 67
3.4 Results ................................................................................ 68
3.5 Discussion ............................................................................ 69
3.5.1 Limitations ....................................................................... 72
3.5.2 Clinical Implications ........................................................... 74
3.5.3 Future Directions ............................................................... 74
3.6 Conclusion .......................................................................... 74

CHAPTER 4 Relationships Among Baseline Vestibular Evaluation Techniques in Division-I Collegiate Athletes .................................................. 82

4.1 Background .......................................................................... 82
4.2 Methods ............................................................................. 85
4.2.1 Participants ..................................................................... 85
4.2.2 Procedures ...................................................................... 86
4.2.3 Statistical Methods ............................................................... 88
4.3 Results ................................................................................ 88
4.4 Discussion ........................................................................... 89
4.5 Conclusion .......................................................................... 92
CHAPTER 5 Predictors of Time to Recovery in Athletes That Have Sustained a Sports-Related Concussion with Suspected Vestibular Involvement ............................................... 96
  5.1 Introduction ........................................................................................................ 96
  5.2 Methods ........................................................................................................... 98
  5.2.1 Design and Participants .............................................................................. 98
  5.2.2 Clinical Assessments and Outcome Measures .......................................... 99
    5.2.2.1 Demographic, Medical History, and Injury Information .................. 99
    5.2.2.2 Clinical Evaluation, Diagnosis, and Plan of Care ......................... 99
    5.2.2.3 Post-Concussion Symptoms ............................................................ 100
    5.2.2.4 Vestibular Function ........................................................................... 100
    5.2.2.5 Recovery Time .................................................................................... 102
  5.2.3 Statistical Analysis ...................................................................................... 103
  5.3 Results ............................................................................................................. 104
  5.3.1 Participants ................................................................................................. 104
    5.3.1.1 Presentation ....................................................................................... 104
    5.3.1.2 Clinical Outcomes ........................................................................... 104
    5.3.1.3 Linear Regression for Recovery Time ............................................ 105
  5.4 Discussion ....................................................................................................... 106
    5.4.1.1 Limitations ........................................................................................ 109
  5.5 Conclusion ....................................................................................................... 110

CHAPTER 6 Conclusion ............................................................................................ 120
  6.1 Summary .......................................................................................................... 121
  6.2 Future Research ............................................................................................... 122

REFERENCES ........................................................................................................... 125

VITA ............................................................................................................................ 132
LIST OF TABLES

Table 2-1. Summary of search 2 terms: studies using clinical assessment tools of vestibular function.................................................................44
Table 2-2. Summary of search 3 terms: studies that investigated the influence of vestibular consequences following concussion on outcomes..........................................................................................................................52
Table 2-3 Objective 2 Quality Assessment Scores.................................................................................................................................55
Table 3-1 Descriptive Statistics for Subject Demographics, Patient Reported Outcomes, and Concussion History across Division-I Collegiate Athletes Participating in Football, Soccer, and Cheer........................................................................................................................76
Table 3-2 Distribution of DVAT (LogMAR) and GST (°/sec) Percentile Scores for All Participants .................................................................................................................................77
Table 3-3 DVAT (LogMAR) and GST (°/sec) Scores by Sex (median (IQR))..............................................................................................78
Table 3-4 DVAT (LogMAR) and GST (°/sec) Scores by Sport (median (IQR)) ..............................................................................................79
Table 3-5 DVAT (LogMAR) and GST (°/sec) Scores by Concussion History (median (IQR)) ..........................................................80
Table 4-1 Included COBALT Conditions ..................................................................................................................................................93
Table 4-2 Baseline Post-Concussion Symptom Scale Vestibular/Ocular Symptoms Reported ..........................................................94
Table 4-3 Descriptive Statistics for Measures of Vestibular/Ocular Symptoms and Functional Assessments ..................................................................................................................................................95
Table 5-1 COBALT Included Conditions ..................................................................................................................................................111
Table 5-2 Descriptive Statistics of Demographic Variables ......................................................................................................................112
Table 5-3 Descriptive stats for all presentation variables and their correlation to days to recovery ..............................................................113
Table 5-4 Descriptive statistics for all performance variables and their correlation to days to recovery ........................................................................114
Table 5-5 Descriptive statistics of performance variables .............................................................................................................................116
LIST OF FIGURES

Figure 2-1 Objective 1: search for articles examining the anatomy and physiology of the vestibular system and the basis for vestibular involvement following concussion........................................57
Figure 2-2 Objective 2: search for articles that included objective measures/clinical assessments of vestibular function in sports medicine..................................................................................58
Figure 2-3 Objective 3: search for studies that investigated the influence of vestibular consequences following concussion on outcomes...........................................................................59
Figure 2-4 Web of Objective Outcomes.........................................................................................................................60
Figure 3-1 BVA set-up with participant seated 8-feet from laptop screen, wearing mounted headpiece and participant’s view of screen......................................................................................81
Figure 5-1 Flow diagram of patients included in analysis........................................................................................118
Figure 5-2 COBALT Included Conditions........................................................................................................................119
CHAPTER 1 INTRODUCTION

1.1 Background

Sports-related concussions (SRC), or mild traumatic brain injuries that occur as a result of sports or athletic participation, are said to affect approximately 300,000 young adults and 1.4 million youth athletes in the United States on an annual basis.1 SRC create a significant burden on the health care system by generating an estimated $60 billion dollars in direct and indirect costs in 2000.2,3 However, what is even more concerning is the short- and long-term effects of these injuries on brain functioning and overall health.

SRC are induced by a direct or indirect impact to the head, neck, or face,4 and can have negative and serious effects on an individual. These injuries present with clinical signs and symptoms that assist in the identification and diagnosis of the injury. Among the signs and symptoms of SRC are physical signs such as headache, nausea, or dizziness, cognitive impairments such as diminished reaction time, difficulty sleeping, emotional/behavioral changes such as irritability or feeling more emotional than usual, and coordination issues or difficulty maintaining balance.5 Assessing both the observed and reported symptoms is important in the initial recognition and diagnosis of these injuries.

In combination with self-reported symptom questionnaires, clinicians often implement functional assessment strategies, measuring function relative to cognition or other domains commonly affected by concussion, to assess and diagnose SRC as well as monitor recovery. Due to the unique nature of concussion injuries, there are many challenges to the diagnosis and treatment of the injuries. These include the reliance on self-reported symptoms, recognition of signs, and individualized manifestations of concussion sequela. Therefore, it is important that there are objective assessment strategies for clinicians to use as tools to assist in the identification and management of these injuries.
Although many functional impairments can occur in conjunction with SRC, impairments within the vestibular system may be present in many patients. The vestibular system is a sensory system within the body. Because of the nature of the system with both central and peripheral components, there is an increased susceptibility to injury following SRC. The central vestibular system is responsible for processing sensory input from the vestibular sensory organs and nerves to the brain through pathways to the midbrain and vertebral cortex. Among these reflexes are those responsible for upright balance and the stabilization of vision during head movement known as gaze stabilization. These reflexes are known as the vestibulospinal (VSR) and vestibulo-ocular reflexes (VOR), respectively. The peripheral vestibular system is comprised of small organs within the bony labyrinth within the inner ear. Two functional units within the inner ear are formed by the vestibular organs; the otolith organs known as the utricle and saccule are responsible for sensing linear acceleration while the three semicircular canals (anterior, posterior, and horizontal) sense rotational movements. Within the membrane are a system of hair cells and fluid known as endolymph which work through a process of depolarization to mediate these functions. Therefore, the vestibular system is a network of structures that maintains equilibrium within the body as well as works in combination with other systems to perform additional functions, crucial to activities of daily living.

Injury to the vestibular system as a consequence of SRC is likely to be detrimental to maintaining balance, gaze stabilization, and motion detection, which can result in difficulty completing activities of daily living and sport. It is reported that up to 81% of those who suffer an SRC report dizziness. Individuals who report vestibular-related symptoms following SRC, most specifically dizziness, are at a six times increased risk of a prolonged recovery. With both the high incidence and high risk of prolonged recovery, it is imperative that the vestibular system is assessed following these injuries and potential deficits are managed appropriately to ensure a complete and timely recovery.
The Consensus Statement on Concussion in Sport, compiled during the 5th International Conference on Concussion in Sport in Berlin in October 2016, was developed for clinicians who evaluate and treat SRCs. The statement outlines the steps to recognize, rest, rehabilitate, refer, recover and return to sport following these injuries. The domains to be evaluated based on suspected SRC are symptoms, physical signs, balance impairments, changes in behavior, cognitive impairments and sleep and wake disturbances. Contrary to previous consensus statements, this statement emphasizes the importance of assessment, rehabilitation and recovery of the vestibular system. However, it is still not fully understood how the vestibular system is affected and how these effects are manifested following SRC. In order to implement treatment strategies and improve the standard of care, a better understanding of this system relative to SRC is both necessary and important. At this time, limitations exist in the return to play (RTP) processes in which potential deficits may not be fully resolved when an athlete returns to sport. More rigorous RTP criteria may be devised with better understanding of the functions of the vestibular system and their changes following injury.

Currently, assessment strategies for assessing the vestibular system following SRC are both subjective and objective. Symptom inventories use an individual’s self-report of their experienced symptoms and quantify symptom burden and patient-reported outcomes. Similarly, questionnaires such as the Dizziness Handicap Inventory (DHI) quantify an individual’s experience with dizziness, in this case, following injury. Additionally, objective clinical assessment tools exist that are used to evaluate potential deficits in vestibular function. While these assessment tools are useful in providing information relative to the individuals’ experience with the injury and symptoms, questionnaires and self-report inventories cannot serve as a direct measure of function due to their subjective natures.

Injury to the vestibular system may manifest through balance disturbances and impaired function of the vestibular ocular reflex (VOR). These impairments may be subtle and not identifiable by the individual and thus not able to be measured by patient-reported measures of
Therefore, objective measures of VOR function may be required to provide clinicians and researchers the ability to measure function and identify residual deficits. To assess vestibular function following SRC, postural control tasks, especially those with higher vestibular demands, and gaze stabilization provide objective techniques for assessment. These tests challenge the vestibular system and provide quantifiable data of test performance to understand the individual’s function. This is especially important for providing care to an athletic population whose activities require the ability to maintain postural control, rapid head movements, and stable vision. Returning athletes to activity before these functions have fully recovered could have detrimental effects or place the individual at risk for secondary injury such as an additional SRC or musculoskeletal injury.

Balance or the ability to integrate information from the vestibular, visual, and somatosensory system to maintain upright posture is crucial to activities of daily living and sport. Although balance dysfunction may be self-reported or measured and assessed by clinicians, there is evidence to suggest that balance deficits exist even when all symptoms have resolved. There are a number of ways to assess balance from more basic clinical assessments to instrumented assessments. Instrumented assessments provide objective way to assess balance and identify potential deficits while challenging the systems of balance.

A test which uses objective methods to assess balance in a more dynamic and challenging environment is the Concussion Balance Test (COBALT; Bertec Corporation, Columbus, OH). This assessment tool measures a unique function of the vestibular system by providing additional challenges unique to vestibular function and further isolating the function of the system during balance assessments. The COBALT uses a portable force plate to measure sway velocity, a measure of an individual’s ability to maintain a fixed posture in a bipedal stance. Participants are provided additional challenge by adding a headshake, a trunk rotation task, or stance on a foam pad for several COBALT conditions. The reported sway velocities may be interpreted to better understand an individual’s ability to maintain postural control, most specifically when the
vestibular system is under additional strain, as a result of the tasks, thus assessing function of the system, specific to upright postural control, in a dynamic and specific manner.

Additional functions of the vestibular system, such as the ability to maintain gaze and visual acuity during dynamic head movements, must also be examined. Gaze stabilization and dynamic visual acuity measure a different and additionally unique function of the system, also at risk for disruption following injury. The Gaze Stabilization Test (GST) and the Dynamic Visual Acuity Test (DVAT) are two assessment tools that provide objective measurements of the function of the VOR. The GST measures gaze stability while the head is in motion at varying velocities without a changing target size, thus, determining the maximum measured velocity that a stable gaze may be maintained. Conversely, the DVAT determines gaze stability during sinusoidal head movements at a fixed velocity and compares the loss of visual acuity from a static position to the head shake to identify the loss of vision when movement is added. Although the assessments measure different functions, they provide numerical data for the interpretation by a clinician or researcher to better identify potential deficits. The assessments challenge the integration of the vestibular and ocular systems through the reflex which allows individuals to maintain vision while the head is in motion and have demonstrated the ability to discern deficits following SRC.

With the high demands of athletic participation on vision and balance, it is crucial that clinicians managing these injuries have an adequate understanding of the vestibular system, potential vestibular deficits as a result of concussion, and how vestibular involvement may influence medical clearance decision making. It is important to understand levels of function in the athletic population and how they are affected relative to the necessary functions for athletic participation, beyond that of the general population. To better understand the vestibular system and its involvement relative to SRC, it is important to understand the level of function in healthy athletes, the relationship between the different measures of vestibular function or patient complaints, and the relationship between vestibular function and recovery following SRC,
especially as it relates to time to RTP. Therefore, it is necessary to define these values, understand the relationship between current standard of care measures such as self-reported symptoms in relation to computerized, objective measures of vestibular function, and understand the relationship between vestibular function during clinical evaluation and time to medical clearance in athletes with a recent mTBI.

At this time, there are not clearly defined estimates for normative VOR function in an athletic population. Therefore, it is difficult to implement these assessment strategies without an understanding for normative function. Similarly, there is not an understanding for the potential relationship between subjective complaints and objective measures of vestibular function. When transitioning to practice, it is especially important to understand how these variables affect recovery. Understanding the interaction between these variables and recovery is important in identifying individuals who may need additional care or early intervention or rehabilitation to improve outcomes following SRC. These results and could highlight an area for changes in clinical best practices and improved standard of care.

1.1.1 Significance and Purpose

The primary purpose of this dissertation was to investigate how measures of vestibular function are related to time to medical clearance in athletes with a recent SRC. This dissertation also sought to establish normative estimates for VOR function and explore the relationship between VSR and VOR measures of function. Further, the relationship between objective measures of VSR and VOR function and self-reported symptoms and function was investigated.

1.1.2 Specific Aims

**Specific Aim 1:** To establish normative values for the DVAT and GST in collegiate athletes and explore the effect of sport, sex, and concussion history on VOR assessments. It was hypothesized that differences in GST performance would exist between sex, sport, and concussion history.
**Specific Aim 2:** To identify if a relationship exists between the Concussion Balance Test (COBALT), Dynamic Visual Acuity Test (DVAT), Gaze Stabilization Test (GST), and self-reported vestibular symptoms in collegiate athletes with and without a history of concussion.

**Specific Aim 3:** To explore the relationship between self-reported vestibular symptoms and acute performance on the COBALT and GST and the time to medical clearance in adolescent and young adult athletes who have sustained a recent concussion. It was hypothesized that there would be a relationship between self-reported vestibular symptoms, performance on objective measures of vestibular function and the time to medical clearance, Specifically, the greater the amount of self-reported vestibular symptoms, and poorer performance on the objective measures of vestibular function will be correlated with longer times to medical clearance.

1.2 **Overview**

This dissertation is organized in the following order: Chapter 2 presents a scoping review of the literature relative to the anatomical and physiological basis for vestibular deficits following SRC, common clinical assessment strategies, and the evidence regarding the influence of vestibular function on outcomes for patients with a SRC. Chapter 3 presents normative estimates of VOR functioning via the DVAT and GST. Chapter 4 presents data on the relationships between subjective and objective measures of vestibular function in healthy collegiate athletes. Chapter 5 explores the relationship between vestibular function and time to medical clearance in athletes with recent history of SRC.

1.2.1 **Operational Definitions**

For the purposes of this study, the following definitions were used:
Sports-Related Concussion (SRC)

SRCs are defined as traumatic brain injuries induced by mechanical forces.1,4 These injuries are a subset of concussions characterized by the mechanism of injury. Specifically, these injuries are a result of participation in sports or recreation rather than a motor vehicle accident or falling from a height taller than standing.4 SRCs result in a myriad of clinical signs and symptoms, reflecting disturbances in function. Among the most commonly reported symptoms are headache, dizziness, sensitivity to light and noise, and cognitive impairments.

Return to Participation (RTP)

Return to participation is the time point at which an athlete has been deemed safe to return to competitive sports participation without restriction following SRC. This determination is made by a healthcare professional based on organized criteria and clinical decision making. RTP protocols and guidelines include progressions graduated activity through sports-specific exercises to the eventual return to full and unrestricted participation.5,26,27

Subjective Patient-Reported Clinical Measures

Subjective clinical measures included any self-reported symptoms which were reported solely by the subject. Self-reported symptoms will be assessed through the use of two scales, the Post-Concussion Symptoms Scale (PCSS) and the Dizziness Handicap Inventory (DHI).

Post-Concussion Symptoms Scale (PCSS)

The PCSS is a 22-item symptom reporting/evaluation tool used for both baseline and post-injury measurements. 22 symptoms are measured on a 7-point Likert scale from 0-6 based on symptom severity, 0 being asymptomatic and 6 being severe.28 A total symptom score is calculated based on the number of symptoms reported while a symptom severity score is calculated from the sum of the values of the scored symptoms. The PCSS is used for symptom tracking and was routinely
completed by patients at medical visits. Normative data has been reported on the PCSS and reliability has been established. Select symptoms from the PCSS will be used to assess vestibular-related symptoms.

Dizziness Handicap Inventory (DHI)

The DHS is a 25-item self-report tool that evaluates an individual’s perceived effects or disability imposed by dizziness. The 25-item patient-reported outcome measure asks 15 questions regarding dizziness in daily life and are answered by either “yes,” “no” and “sometimes.” The answers are scored based on a point system and result in either mild, moderate or severe handicap or warrant potential referral for vestibular impairments. The DHI has demonstrated high reliability and good internal consistency.

Objective Measures:

Objective clinical measures included assessments of VOR function through gaze stabilization and dynamic visual acuity and a balance assessment using the Concussion Balance Test (COBALT) all assessments from which numeric feedback can be obtained.

Dynamic Visual Acuity (DVA)

The DVA provides a measure of visual acuity (logMAR) during a sustained head movement at a fixed velocity. The results are unique to each direction (left and right eye) and measure the difference in the individual’s static and dynamic acuity. This provides the ability to not only interpret against the performance of others in the same assessment but individually through a “lines lost” interpretation which identifies the number of lines measured on the Snellen chart when a dynamic head motion is added.

Logarithm of the Minimum Angle of Resolution (LogMAR)

LogMAR units have replaced the traditional Snellen chart and offers a more standardized method of reporting visual acuity. The logarithmic scale takes into account adjustments in
viewing distance during assessment. Additionally, logMAR units directly correspond with the traditional visual acuity letter chart (Snellen chart). LogMAR notation is correlated to the previous Snellen acuity as the letter sizes on each line followed a geometric progression. The increase of 1.2589 in decimal acuity and visual angle on the Snellen chart corresponds to 0.1 log unit. The LogMAR value of zero corresponds the 20/20 which is also the standard for perfect vision. The lower the LogMAR, the greater the visual acuity. A negative LogMAR unit represents better than 20/20 vision as the calculation for a LogMAR unit is as follows:

\[
\text{LogMAR Visual Acuity} = 1.1 - (0.02 \times \text{letters missed})
\]

Gaze Stabilization Test (GST)
The GST is a measure of VOR function that requires movement of the head in a yaw plane. The GST measures the highest rotational velocity and individual can achieve while maintaining a standard level of visual acuity. Results are provided immediately by the software and provide the highest velocity (°/sec) at which the participant can maintain visual acuity, in a direction specific manner.

Concussion Balance Test (COBALT)
The COBALT (Bertec Corporation, Columbus, OH) is a 4-condition balance assessment that utilizes a mobile force plate and a foam pad to measure sway velocity under dynamic postural conditions that place higher demands on the vestibular system and conditions which include a head shake and a VOR cancellation task. Both assessment strategies have been validated in this population and have been utilized as a clinical tool in both assessment and rehabilitation of these injuries. Additionally, the COBALT was developed by a group of researchers and clinicians to provide a balance assessment that identifies metrics earlier tests were missing in this population. The COBALT utilizes a force plate, a visual aid and a foam pad to measure sway velocity as well as an error score entered by the examiner’s observations. This assessment uses additional and
more complicated tasks to the vestibular system to better assess the system through higher challenges.

1.3 Assumptions:

1. Participants exerted maximal effort when completing the functional assessments.
2. Participants answered all patient reported outcome questionnaires honestly and to the best of their ability.
3. Participants following SRC were RTP following similar criteria.
4. Participants with SRC were accurately diagnosed by their healthcare providers

1.4 Delimitations:

1. Participants in the normative data establishment and residual deficit exploration were not provided formal familiarization with the testing procedures.
2. Participants participating at the time of RTP, were not always tested on all measures of vestibular function.

1.5 Limitations

Study 1:

1. The sports included in the investigation were limited to football, men’s and women’s soccer, and cheerleading. Thus, the results are not generalizable to sports outside of those included.

Study 2:

1. This investigation was completed in healthy, collegiate athletes, limiting the generalizability to a concussed population.

Study 3:

1. The retrospective nature of the study presented limitations in subject bias as all participants sought medical care from a physician following their injury and the
participants included in the analysis were potentially more complicated cases with vestibular involvement rather than a random sample.
CHAPTER 2  VESTIBULAR CONSEQUENCES, ASSESSMENT STRATEGIES, AND OUTCOMES FOLLOWING SPORTS-RELATED CONSEQUENCES CONCUSSION

2.1 Introduction

Sports-related concussions (SRCs) are a growing public health concern among the active and recreational populations. With the increase of individuals participating in sports and recreation, there has been a rise in the number of diagnosed SRCs. Estimates suggest that as many as 1.7-3.8 million concussions occur annually as a result of participation in sport or recreational activities. With the increase in the incidence of these injuries, recent efforts have focused on better identification, diagnosis, treatment, and management these injuries.

Although these SRC are unique in their manifestation and sequelae, there are common domains that are affected following concussion including changes in cognition, sleep, emotional changes and vestibular consequences or deficits. Among these domains, one of the most commonly effected and least understood is the vestibular system. Injury to the vestibular system following SRC often manifests as difficulties with balance or postural control, vestibular-ocular reflex (VOR) deficits, and symptoms, such as dizziness, sensitivity to light or feeling in a fog. These functional abilities are crucial to not only athletic activities but also activities of daily living and quality of life. Thus, clinicians and researchers have worked to improve the assessment strategies for vestibular systems to better identify and address these deficits to mitigate long term consequences as well as understanding the underlying anatomical and physiological basis for such changes in function.

Current clinical assessment tools of vestibular function range from highly technological to more basic and practical clinical tools. To assess postural control, one of the most commonly used assessments is the Balance Error Scoring System (BESS). The BESS utilizes a double-leg, single-leg, and tandem stance to assess balance while recording errors. Although this assessment
is highly feasible, it has been suggested that there is a learning effect to the test, and these assessments are depended on testing environment. Additionally, the reliability has been reported to range from poor to good depending on the administration, making it difficult to use this assessment during evaluation and clinical decision making. The clear downfalls of this assessment pave the way for stronger, more specific vestibular assessments. These assessments may utilize more objective approaches to measure vestibular function while providing additional challenges to the system, as one would encounter in everyday activities and more specifically, athletic participation. These evaluation strategies and additional challenges strengthen the utility of these assessments in clinical assessment of SRC and clinical decision making.

It has been well documented that the vestibular system is often involved concomitant to sports-related concussion and includes a loss in function or provocation of symptoms. Though the underlying mechanisms remain unknown, it has been postulated that the involvement of the vestibular system be a result of damage to the peripheral receptors or the central processing structures resulting in an inability to properly process sensory input. However important, vestibular function is not always assessed or accounted for and the recovery of these symptoms or functional deficits may not fully recover with rest alone. Recent literature has suggested that patients who experience vestibular deficits are at risk of poorer outcomes including a greater than 6 times risk of a prolonged recovery of greater than 28 days. Experiencing a prolonged recovery can have a myriad of secondary effects that may affect the daily lives and mental health of these individuals. Therefore, there is a unique importance to understanding the influence of vestibular involvement following SRC including the best strategies to assess this aspect of function.

Current research that shapes practice management strategies and recent position statements have reported the need for comprehensive concussion evaluation, treatment and management strategies. In order to implement the best clinical assessment strategies, it is
important to understand the anatomy and physiologic of the vestibular system in the context of SRC, available assessment options, and the consequences of vestibular involvement in conjunction with SRC. Therefore, the purpose of this scoping review is to; (1) identify the anatomical and physiological basis for vestibular involvement in SRC based on the most recent evidence, (2) examine the current clinical assessment strategies for vestibular function following SRC, and (3) investigate the evidence regarding the influence of vestibular function on outcomes for patients with a sport-related concussion. These objectives will not only answer clinical questions to improve patient care, but also identify potential gaps where more research is needed to guide clinical practice.

2.2 Literature Search and Analysis

To investigate the literature regarding the anatomical and physiological basis for vestibular involvement in SRC, the current assessment strategies and related outcomes, three separate searches of the current and available evidence were conducted. Following the search, articles were screened for relevance and eligibility based on a-priori inclusion and exclusion criterion. These strategies were used to assess the literature to assist in satisfying the outlined objectives, specifically; (1) vestibular system anatomy and physiology and injury following concussion (Objective 1), (2) outline the current strategies to assess vestibular function in athletic populations including those with SRC (Objective 2), and (3) report the outcomes in concussed individuals with vestibular compromise (Objective 3).

2.2.1 Data Sources and Searches

The Preferred Reporting Items for Systematic Review and Meta Analyses (PRISMA) were used as guidelines for the literature review through identification, screening, and eligibility
to determine which studies to include in the literature review to answer each question. Individual searches were conducted based on each inquiry. The following electronic databases were used in each literature search: Academic Search Complete, CINAHL with Full Text, Health Source - Consumer Edition, MEDLINE, PsycINFO, SPORTDiscus, and TOPICsearch (EBSCOhost). Databases were searched from the time of inception to March 2020 and articles available online were identified for potential inclusion.

Keywords used to search for Objective 1 included: "(concussion OR head injury OR brain injury) AND (injury OR deficit OR consequences) AND (anatomy OR physiology)". The search for Objective 2 included the following keywords and search terms: "(concussion OR head injury OR brain injury) AND (injury OR deficit OR consequences) AND (vestibular OR vestibulo-ocular OR vestibulospinal) AND (assessment OR test OR evaluation) AND (sport)". The final objective was searched using the following terms: (concussion OR head injury OR brain injury) AND (vestibular OR vestibulo-ocular OR vestibulospinal) AND (outcomes OR recovery) AND (sport). Hand searches of the literature were also performed to identify articles which may not have been located through the electronic search.

Inclusion criteria were set for each objective to identify and include articles relevant to answer each question. Inclusion for all objectives included studies published in peer-reviewed journals in the English language. Inclusion criteria for Objective 1 was articles which included information regarding the anatomy or physiology of the vestibular system and the explanation for the involvement of the system as a result of head trauma. Due to the limited information on the topic, we did not specify that injuries had to be SRCs but rather all mild traumatic brain injuries were included. Thus, mild traumatic brain injury and minor blunt head trauma, head injuries, and concussions not specific to sport mechanism were included. Information regarding the vestibular consequences of blast trauma were specifically excluded due to the differences in the nature and mechanism of injury. For Objective 2, inclusion criteria were studies that reviewed methods of
assessing vestibular function following concussion. Inclusion criteria for this objective accounted for measurements of vestibular function in both healthy and concussed individuals. Studies reporting in healthy populations were used to help describe the assessment and particular reported outcomes. Studies which demonstrated level IV evidence or higher were included that looked at the potential of the assessments in post-concussion populations. Studies were included if the included participants were those representative of the populations who experience the highest rate of SRC; adolescent and young adult populations. Inclusion criteria for the Objective 3 required studies that reported the outcomes and recovery patterns of those with vestibular consequences following concussion. Studies that examined the effects of vestibular consequences on recovery were taken into consideration. Articles in languages other than English, not available in full text, abstracts, conference proceedings, and dissertations were excluded.

2.2.2 Quality Assessment

The identified articles for all objectives were selected by an independent reviewer. Due to the nature of the first two objectives and limited evidence, quality assessment was limited to the inclusion and exclusion criteria. The third objective underwent quality assessment using the modified Downs and Black assessment to appraise each article. The results of the quality assessments are provided in Table 3.

2.3 Findings

A total of 346 studies were identified through the electronic database search and hand search of relevant literature for Objective 1 (anatomy and physiology of the vestibular system and injury). After removing duplicates and screening titles and abstracts, a total of 5 studies were identified for inclusion (Figure 1). The search for Objective 2 (clinical assessments of vestibular function) yielded a total of 315 potential articles for inclusion through database search and other sources. After the removal of duplicates, excluding those in languages other than English, and
applying the pre-determined inclusion and exclusion criteria, 28 articles were retained for inclusion in the review (Figure 2). The search for Objective 3 (vestibular function and outcomes following concussion) returned 201 potential articles. Applying the process used with the prior objectives; the final total of studies included was 6 (Figure 3). The results of each search are displayed in Figures 1-3.

2.3.1 Description of Included Studies: Anatomical and Physiological Basis for Vestibular Involvement in Sport-Related Concussion

Due to the nature of the objective, the articles meeting inclusion criteria did not contain quantitative inquiries or studies but rather were descriptive in nature and provided a basis for which the vestibular system may be compromised by a head injury based on the anatomy and physiology of the system. All included articles were published in peer-reviewed journals between the years of 2001 and 2020. The included articles provided information relative to the anatomy of the vestibular system, how injury may affect the system, and how these injuries are manifested in physical impairments or symptoms. The articles included two reviews, a prospective study identifying the cause of vertigo following injury, and an exploration into the mechanisms not related to the inner ear of vestibular symptoms of vertigo and dizziness. One study provided a comprehensive exploration into vestibular and balance deficits specific to sports-concussion and included a review of relevant literature. Two of the studies included blast mechanisms in relation to vestibular deficits. Despite the limited number of studies, there was much agreement across studies as well as comprehensive explanations about the general anatomical configuration of the vestibular system. This objective serves to provide brief review of vestibular anatomy and physiology while introduction and exploration into the basis for vestibular injury and its manifestation following head injury.
2.3.2 Anatomical and Physiological Basis for Vestibular Involvement in Sport-Related Concussion

The vestibular system is one of the body's three sensory systems responsible for carrying out body processes that are important to not only athletic participation but daily activities. Among those processes are the body's ability to maintain postural control as well as maintain gaze stability while the head is in motion. This unique system has both peripheral, located in the inner ear, and central, integration of the cerebellum and brain stem, components of the system which function together to carry out these processes. The location and anatomical make-up of the system makes it highly susceptible to injury following concussion. The vestibular system may be impaired despite no evidence of damage on imaging such as MRI or CT scan. In addition to loss of function or functional deficits, vestibular consequences of concussion may manifest in symptoms such as dizziness or imbalance. Dizziness occurs in 66-77% of all cases following concussion and has been associated to an increased time to recovery. Thus, vestibular consequences are common following these injuries and require more understanding of the anatomy and physiology of the system and injury.

2.3.2.1 The Peripheral Vestibular System

The peripheral vestibular system is made up of two different types sensory organs (otolithic organs and the semicircular canals) located in the inner ear labyrinth. There are three semicircular canals; the superior, posterior and horizontal, that sense rotational head movement and angular acceleration. The semicircular canals provide information to maintain gaze in the horizontal direction or stable gaze when the head is rotated laterally. The semicircular canals run at separate angles but meet at the vestibule. The semicircular canals are filled with tiny hair cells and fluid called endolymph. When the head turns, the inertia of the endolymph produces a
force across the cupula, or fluid barrier, moving it in the opposite direction of the head and displacing the hair cell. This maintains equilibrium through a push-pull mechanism of stimulation of one side and neural activity of the opposite side. The otoconia are crystals within the ear that enable this process. The otolithic organs, the utricle and saccule, provide sensory input regarding linear acceleration and contribute to postural stability via the vestibulospinal tract. The utricle is positioned horizontally in the inner ear to sense linear acceleration in the lateral plane and the saccule vertically to sense linear acceleration in the horizontal plane. Acceleration in the anterior-posterior plane is maintained by both the utricle and saccule. These organs each take sensory information and process this information into nerve impulses to the brainstem to initiate motor response.

2.3.2.2 The Central Vestibular System, Reflexes, and Cranial Nerves

The central vestibular system is responsible for processing sensory input from the sensory organs and nerves. Made up of the brainstem and cerebellum with pathways to the midbrain and vertebral cortex. In addition to the central vestibular system, there are reflexes that contribute to vestibular functioning and responses through motor output. The vestibulo-ocular reflex (VOR) allows maintenance eye movement while the head is in motion. This reflex pathway includes neurons that connect the balance organs with the extra ocular muscles located around the eyes. The vestibulospinal reflex (VSR) is used to maintain postural stability through both upper and lower extremity mediation in response to acceleration. In addition to the vestibular reflexes, the vestibular system works in conjunction with the following cranial nerves to conduct different processes; optic (II), oculomotor (III), trochlear (IV), abducens (VI), and the vestibulocochlear (VIII). Each of these nerves are in danger of loss of function following head injury and have different clinical presentations of impairment related to their individual and unique functions.

Example of Head Turn and VOR
When the head is turned to the right, the endolymph, located in the semi-circular canals, flows within the ampulla to deflect the cupula to the left. This depolarizes the hair cells within the right ampulla to increase the firing frequency in the afferent fibers to the right vestibular nerve. In reaction, the nerve sends impulses to the ipsilateral superior and medical vestibular nuclei. Excitatory impulses are transmitted to the left abducens nuclei, resulting in the ipsilateral medial rectus and contralateral, lateral rectus contraction, providing a compensatory eye movement to the left.

2.3.2.3 Consequences of Concussion to the Vestibular System

Concussions, or injury to the head, as a result of a blow or other biomechanical forces acting on the head, place the vestibular system, both peripheral and central at risk for injury.44 The peripheral system and labyrinth in the inner ear is susceptible to injury as the inner ear and temporal bone are both at risk of damage from forces acting on the head.44 As bony structures located on the periphery of the head, a bump, jolt, or blow to the head could directly impact these structures and the lack of great protection increases the likelihood of injury. The blunt force to the head itself is thought to compromise the peripheral organs the most rather than the brain injury. This may result in vestibular hypofunction, one consequence of injury to the peripheral system.7 Decreases in otolithic function may be responsible for balance impairments as the otoliths are important in maintaining equilibrium and providing information relative to gravity.7 Similarly, otolith dysfunction may be responsible for dizziness, however, it has also been postulated that this symptom is largely a result of damage to the central system or trauma to the brain.44 In summation, damage to the organs that disrupt the equilibrium may contribute to the instability and dizziness post-concussion. The mechanisms are not well understood but it is thought that slowing of signal processing following injury would affect the integrated systems of the VOR and VSR with the brain stem and cerebellum, responsible for postural control and balance.7,11 Anticipation, judgement, and decision-making processes may also be slowed via damage to the
frontal lobe, further complicating and compromising these processes. Additionally, the nature of concussion injuries as acting on the brain, place the central vestibular system at risk. Abnormalities of the central vestibular system in the cerebellum have been noted in imagining of the head. In order to determine the system that has been compromised, ocular motor testing can be used to determine central function independent of the peripheral vestibular system.

2.3.3 Description of Included Studies: Current Clinical Assessment Strategies for Vestibular Function

To evaluate the current clinical assessment strategies for vestibular function in physically active populations related to SRC, 28 studies were identified that used clinical assessments to assess vestibular function following concussion. These studies varied in purpose, study design, population, methodology, and assessment techniques for vestibular assessment (Table 1). Themes among the studies and assessments were organized to provide a thorough overview of the most contemporary clinical assessments of vestibular assessment associated with SRC. Assessments of all domains of vestibular function including symptoms, balance or postural control and vestibular-ocular reflex testing were represented. Additionally, the assessments were used in both healthy and concussed cohorts, aiding in the description of each. The assessments most commonly appearing in the literature have been described. Their utility in clinical populations and testing strategies and mechanisms have been outlined. Additional data describing the psychometric properties of these assessments were provided via hand search when necessary.

2.3.3.1 Balance/Postural Control Assessments

Twelve studies were identified that evaluated balance or postural control in concussed and/or healthy individuals. There were many assessments utilized throughout the literature, however, the outlined assessments included; the Balance Error Scoring System (BESS), the
Sensory Organization Test (SOT), Head Shake- Sensory Organization Test (HS-SOT), and the Concussion Balance Test (COBALT).

Balance Error Scoring System (BESS)

The BESS test is an assessment of balance that utilizes three stance positions on firm and foam surfaces. The individual maintains their stance (feet together, tandem stance, or single leg stance) with their hands on their hips, and eyes closed while an examiner counts errors for bouts of 20 seconds. Errors include opening the eyes, removing hands from the hips, lowering the raised foot during single leg stance, or lifting the heel or forefoot, or remaining out of the test position for more than 5 seconds. With good reliability (ICC=0.70-0.74) in young athletes, this cost effective and easily administered assessment is common among clinicians in the use of identifying balance deficits following concussion.

Five of the included studies investigated the use of the BESS in healthy adolescents, concussed adolescents, and concussed athletes and matched controls. Postural control deficits in concussed athletes were measured by the BESS and demonstrated a significant group-by-day interaction (p<0.05) and the concussed group had worse postural stability on day 1 following their injury compared to their baseline and scores on day 3 post injury as well as the control group at all time points (day 1, 3, and 5). However, in a similar study, the BESS was only able to identify 1 of 12 individuals with a concussion accurately, with a sensitivity of 8.3%. The same study did not demonstrate any significant differences between the concussed and control group but rather the concussed group performed at or above the level of their matched controls. This was also demonstrated in an investigation by Alkathiry et al., who determined that no differences were demonstrated in a group within 10 days of SRC and healthy controls. In a population of pediatric patients with an SRC within 3 weeks, there were no difference in performance for males and females on all conditions except the double leg first stance which demonstrated a small effect size (p=0.03, ES=0.14). Despite the clinical
friendliness of this assessment, the included studies do not support the use of this assessment to discern concussion status of an individual.

Sensory Organization Test (SOT)

The SOT is a clinical tool used to assess postural control by manipulating the sensory systems that contribute to balance or postural control. The SOT is completed via computerized dynamic posturography (CDP) which provides objective measures of balance through implementation of software and protocols in combination with force plates to provide objective measures of balance. Through six unique conditions, the SOT examines sensory reweighting by systematically challenging the somatosensory, visual, and vestibular systems. The SOT uses conditions of eyes open, eyes closed, and movement of the force plates the individual is standing on and the visual surrounding in which they are standing. The systems are challenged while information is collected regarding the individual’s center of gravity and sway. The more challenging conditions in which the force plates move, or the visual field is altered via sway reference. This means, the force plate and visual surround move in relation to the individual’s center of gravity sway in the anterior-posterior direction to cause further disruption of the visual and vestibular systems. The goal of the assessment is to have a lower amount of sway to maintain a consistent center of gravity. The trials are scored using an equilibrium score as well as a composite score for the entire assessment and scores for each system (vestibular, visual and somatosensory) calculated through ratios of the various conditions. The SOT has been reported to have excellent test-retest reliability in healthy individuals (ICC= 0.83, 0.75-0.88) and collegiate athletes (ICC=0.64-0.87).

Eight of the included studies used the SOT as an assessment tool. One study examined the SOT in healthy controls to determine the relationship between the SOT and other common vestibular tests. Three studies investigated the SOT in athletes following concussion and matched control groups while another compared athletes with and without SRC on
subsets of the assessment. A similar study investigated the SOT in athletes with a history of concussion to discern if lingering postural control deficits exist. The final study investigated the relationship between symptoms, cognitive measures and balance in individuals with a concussion, beginning vestibular therapy.

McDevitt et al. discovered concussed athletes scored significantly lower on the SOT on conditions 3 (p=0.044) and condition 4 (p=0.0333) and demonstrated lower visual ratio scores (p=0.032), suggesting difficulty with visual related conditions. Similarly, a different cohort of concussed athletes demonstrated significant group by day interactions (p<0.01) and worse scores one day following injury than both their baseline scores and matched controls. However, these deficits mostly resolved by days 3 and 5 when compared to the control group. Similarly, athletes with a concussion, tested either 72 hours or two weeks following injury performed significantly worse than healthy athletes with higher sway velocities on all conditions (p<0.001-0.049). The final comparison of SOT performance in athletes with a concussion and a control group demonstrated significant differences in the SOT composite score on day 1 (p=0.011), day 2 (p=0.004), day 3 (0.009), and day 10 (0.025) and the vestibular preference score (0.007).

Finally, in a retrospective cross-sectional study, minimal differences were exhibited between those with and without a history of mTBI. However, as the postural control tasks, or conditions, increased in difficulty, the mTBI group demonstrated increased postural-sway irregularities, not demonstrated by the control group, suggesting a potential residual effect following mTBI.

When comparing performance on the SOT to cognitive and symptom measures, poorer performance on Condition 2 of the SOT was correlated to a greater number of total symptoms reported (r=-0.28,p=0.004). Thus, following concussion, adolescents who are experiencing more symptoms, have significantly worse performance on the standing balance task with eyes closed. These studies demonstrated the SOT’s ability to measure differences in performance in individuals who may have compromised capacity to maintain postural control. In addition, the
studies demonstrated the assessments’ potential to provide information about the system affected by the injury and targets for treatment.

Head Shake- Sensory Organization Test (HS-SOT)

Less common than the traditional SOT, the HS-SOT incorporates head movements into the assessment in Conditions 2 and 5. Active head motions in the horizontal plane, produced by the individual moving their head from left to right as if signaling “no”, are maintained at a rate of approximately 100° per second, while upholding balance.49

Two included studies used this assessment in a cohorts of healthy, asymptomatic individuals in an effort to identify correlations between a numbers of assessments.49,54 The HS-SOT sway score was significantly correlated with the SOT composite score (r=-0.344) and Condition 5 (r=0.78) while the HS-SOT fixed demonstrated a strong relationship with the SOT condition 2 (r=0.81). Additionally, test-retest reliability of the HS-SOT was good to excellent for the HS-SOT fixed (ICC=0.81, 0.73-0.88) and HS-SOT sway (ICC=0.79, 0.69-0.87).49

Cripps et al.54 observed a difference between males and females in the equilibrium score of Condition 2 (p=0.032) with males performing better than females, however, there were no differences on Condition 5. When comparing performance on the HS-SOT with the DVA, symmetry percent loss on the DVA was significantly negatively correlated with Condition 2 of the HS-SOT (r=-0.363, p=0.004) and errors to the right (r=-0.297, p=0.020).

While the outlined studies provide information relative to the psychometric properties of the HS-SOT, there is a lack of evidence on the utility of this assessment strategy in the post-concussion, SRC, and clinical populations. Thus, to assess the efficacy of this assessment as a post-injury measure, research must be done to evaluate the tool, prior to suggesting use in clinical practice.

Concussion Balance Test (COBALT)
The COBALT test was recently created to specifically measure balance in an athletic population following concussion. This assessment challenges the vestibular system by incorporating a head shake with an eyes closed task, and a vestibular-ocular cancellation task. The vestibular-ocular task focuses on maintaining ocular fixation during trunk rotation, forcing the cerebellum to override vestibular input while the eyes closed head shake task requires the individual to maintain a consistent head shake, left and right, with eyes closed while maintaining upright. Performed on both firm and foam surfaces, this assessment may be used for both baseline and post-concussion evaluation. Sway velocity is objectively measured for each condition while the individual maintains balance on a portable force plate. Additionally, the examiner counts the number of errors which include removing hands from hips, inability to maintain head speed, and opening eyes during an eyes closed task. Conditions incorporate eyes open, eyes closed, head shake, torso rotations, and standing on a foam pad. This assessment has been reported to have good intrarater reliability (ICC=0.861, P<0.001) in a small analysis of 10 subjects in 8 conditions rated by three independent examiners.

One of the studies in this scoping review utilized the COBALT as an assessment tool when comparing the differences in performance between concussed and healthy athletes. The retrospective study identified that only 55% of athletes with a concussion could complete the test compared to the healthy group who was able to complete all conditions without proved dizziness or inadequate cervical range of motion. Significant differences existed in the completion rates between injured and uninjured groups (p<0.0001). Error rates in Conditions 7 and 8 were significantly greater for the concussed athletes who completed the test compared to their healthy counterparts ((p<0.0001). Concussed athletes also had higher sway velocities than their healthy counterparts on Condition 4 (P=0.006) and Condition 8 (P<0.001). Based on limited evidence, the COBALT may provide useful information regarding balance in an adolescent athletic
population with SRC however additional evidence into this assessment is required to confirm its relevance in SRC management.

2.3.3.2 Vestibulo-ocular Reflex and Ocular Motor Assessments

VOR and Ocular Motor assessments have been suggested as a part of the post-concussion assessment. These assessments challenge the aspect of the vestibular system that incorporates the ocular motor systems and other ocular and vestibular cranial nerves through functions that utilize both components. A total of 21 studies were identified and included that utilized these assessments in concussed individuals or provided psychometric information in healthy populations. The assessments outlined in this review included the Gaze Stabilization Test (GST), Dynamic Visual Acuity Test (DVAT), Vestibulo-Ocular Motor Screen (VOMS), and King-Devick.

Gaze Stabilization Test (GST)

The GST is a measure of VOR function that objectively quantifies the maximum velocity at which an individual can rotate their head and maintain stable vision. This assessment utilizes a software program and a head mounted sensor to assess rotational head velocity. By discerning the direction (left, right, up, down) of a capital letter “E” on the laptop screen while rotating their head, 30 degrees in each direction at varying velocities, the assessment is able to discern when the VOR fails and record the maximum maintained velocity.

Six included studies performed the GST in various populations. Studies investigated the GST in individuals with an acute concussion in a retrospective analysis with abnormal VOR function, acute concussion referred for vestibular physical therapy, male and female adolescents with a concussion to compare by sex, recently concussed athletes with matched controls, and those with a history of concussion. Despite the unique aims and approaches of these investigations, a commonality was the assessments’ ability to identify deficits as a result of
concussion injury. In a retrospective analysis of pediatric patients with a recent concussion, those who had abnormal gaze stability following concussion had significantly longer time to being fully cleared for sport or returned to school, compared to patients who did not have abnormal gaze stability scores.\textsuperscript{55}

An additional analysis of pediatric patients explored the differences in males and females 3 weeks post-concussion.\textsuperscript{43} Females were more likely to experience abnormal GST than males (p=0.028).\textsuperscript{43} Similarly, in a cohort of 185 individuals who had sustained a concussion and were referred for vestibular physical therapy, male patients performed better than female patients, achieving higher velocities on both horizontal (p=0.02) and vertical (p=0.01) GST.\textsuperscript{24} In an analysis of concussed athletes and matched controls, the GST was significantly correlated with the ability to discriminate health status based on signs and symptom provocation from the testing procedures (p<0.001).\textsuperscript{45} Thus, the test has capabilities to identify potential impairments or abnormalities beyond the original intent of the assessment.\textsuperscript{45} Symptoms following the GST, combined with rapid horizontal eye saccades and optokinetic stimulation assessments, have been identified as individual predictors of concussion (accuracy=89.7%, p=0.001) when combined with near point convergence.\textsuperscript{57}

Further analysis of the side-to-side asymmetry score in the GST, identified differences in collegiate football players with and without a history of concussion, however, those with a history of concussion had larger asymmetries than those without a history of concussion (p=0.008, d=-1.37). Consequently, asymmetry for the GST was only reported in a single study but may provide insight into potential impairments following SRC.

Despite limited information on the psychometric properties of the GST, there is moderate evidence to suggest the utilization of this tool as a post-SRC evaluation strategy. Previous investigations not only support the use of the GST post-SRC as an evaluation technique but also
may be used to discriminate between those who have had a history of SRC and additional identifiers through GST performance.

Dynamic Visual Acuity Test (DVAT)

Four of the included studies utilized the DVAT.\textsuperscript{31,45,49,58} Similarly, to the GST, the DVAT is an objective measure of vestibular function with similar testing procedures, however rather than identifying the velocity at which an individual can maintain stable visual acuity, the assessment measures the acuity of an individual when completing a headshake at a fixed velocity. The size, or optotype in which the “E” appears varies in presentation as the individual completes each trial. This variation is all according to the previous answers and continue to challenge the individual with smaller optotypes until the individual is no longer able to see accurately. When the individual is unable to accurately recognize at least 60% of the time, the test ends and the final score is determined.

One study evaluated the reliability of the DVAT in healthy recreational athletes and determined an ICC value of 0.83 (0.74 to 0.89).\textsuperscript{49} Though reliable, an investigation of the DVAT in concussed athletes and a healthy control group did not demonstrate significant differences between groups (p=0.592) nor was there a correlation to health status (r=0.06; p=0.592).\textsuperscript{45} In adolescent hockey athletes following SRC (average of 4 days), there were significant differences in the leftward direction (p=0.030), but, no difference in the rightward direction.\textsuperscript{58}

Although the DVAT has been reported to have good reliability in healthy athletes, this evaluation technique has not consistently demonstrated the ability to discern between those with and without a concussion. Thus, the DVAT may not be the optimal technical to evaluate the VOR post-SRC, but further research is needed to examine the clinical utility of in this test in various SRC populations.
Vestibulo-Ocular Motor Screen (VOMS)

The VOMS is an assessment of vestibular and ocular motor functioning through the utilization of patient-reported symptoms following brief assessments of 5 specific domains; (1) smooth pursuit, (2) horizontal and vertical saccades, (3) convergence, (4) horizontal vestibular ocular reflex (VOR), and (5) visual motion sensitivity (VMS). The examiner uses standardized instructions while the patients rate their headache, dizziness, nausea, and fogginess symptoms on a scale of 1-10. Both the objective measure of the scores on each assessed domain and the symptoms reported are included in the interpretation of the 5-10-minute assessment.

Ten of the included studies used the VOMS. One investigation reviewed the reliability and validity of the tool. In the clinical population, investigations included used the VOMS to classify patients post-concussion into groups on recovery, explored correlations to other assessment tools, used the tool as a predictor of recovery following concussion, and investigated sex differences demonstrated by the assessment tool. In the exploration of the psychometric properties of the assessment tool, there were no significant differences between those with and without a concussion history (p=0.613) and there were no significant relationships between the VOMS and the BESS or King Devick scores (r = -0.03-0.18, P > 0.05). In a group of concussed athletes, symptom scores following the VOMS test were significantly greater than the healthy control group (p<0.001). Similarly, an additional study demonstrated increased symptoms at baseline and provocation in an SRC group compared to healthy controls. VOMS performance has not demonstrated correlations to motion sickness sensitivity in the first ten days following SRC, however, in the following ten days, there was a relationship between high motion sickness sensitivity and VOMS performance in domains above the clinical cutoff scores.

The VOMS domain with the strongest relationship to the likelihood of concussion was the near point convergence (NPC) distance, or the maximum distance at which the eyes converge. There were significant differences in the concussed and control group for the mean NPC distance.
with significantly greater distances in the concussed group (p<0.001), demonstrating poorer performance. Conversely, the NPC and accommodation were the only domains that did not predict delayed recovery. However, symptom provocation on at least one of the VOMS domains was correlated to slower return to participation than those who did not experience symptom provocation (23.0 ± 6 13.4 versus 13.4 ± 8.2 days; P <0.001). The VOR domain of the VOMS demonstrated significant differences between males and females with females reporting higher numbers of symptoms on average (5.0, 95% CI= 3.5–6.5 and 2.7, 95% CI= 1.4–4.0, p = .0). With that, the VOMS symptom score with a cut point of ≥3 had a 68% sensitivity and 72% specificity in identifying males and females with a history of concussion.

The result of the studies that used the VOMS suggest there is strong evidence to suggest the use as a clinical tool post-SRC. There are many domains of the assessment strategy that have demonstrated the ability to discern between those with and without an SRC. Additionally, the symptom provocation associated with the evaluation, demonstrated increased symptoms in those with an SRC. Based on the results of the included studies, there is evidence to support the use of VOMS in this clinical population.

King-Devick (KD)

The KD is a well validated assessment that uses 3 test cards with a series of numbers to test oculomotor control, attention, and language processes and was used in six of the included studies. To complete the assessment, the individual is asked to read the numbers aloud from left to right as quickly as possible as accurate as possible. Errors are counted by the examiner and calculated as the KD error score. With moderate test-retest reliability (ICC=0.70-0.78).

The KD does not have significant relationships with the individual items on the VOMS or the BESS in healthy young adults (r=−0.03-0.18, p>0.05) which suggests it is measuring a unique
However, the time to complete the test was highly correlated with all domains of the VOMS \((r = 0.325-0.585, P < 0.01)\), demonstrating a fair to moderate correlation \(r\) in adolescents following SRC. When used in a comparison of athletes with a concussion and healthy controls, KD test completion time was not different between groups \((p=0.40)\) and was weakly correlated with health status \((r=0.18, p=0.129)\).

At this time, there is limited information regarding the KD as a post-concussion assessment strategy. The provided studies including the KD provided conflicting information. The KD was not correlated to other measures in healthy athletes while in adolescent athletes with an SRC, demonstrated correlations with the VOMS. Additionally, the test has not demonstrated the ability to discern between individuals with an SRC and healthy controls. Based on the limited information presented, the KD is not the strongest assessment strategy. Caution should be taken when using this tool to drive clinical decision making.

2.3.3.3 Symptom Inventories and Patient Reported Outcomes

Within those studies previously described, 6 studies used self-report symptom inventories in addition to the objective assessment strategies. Self-reported symptom inventories are among the most common post-concussion assessment tools as concussion assessment and diagnosis. Among the symptom inventories and patient reported outcomes described in this review are the Post-Concussion Symptom Scale (PCSS) and the Dizziness Handicap Inventory (DHI).

**Post-Concussion Symptom Scale (PCSS)**

The PCSS is a 22-item inventory in which common concussion symptoms are graded on a 7-point Likert scale. More recent work has organized the symptoms into clusters based on their etiology or concussion domain. For example, the vestibular cluster is known to include dizziness, headache, nausea and other symptoms that may be a result of damage to the vestibular system. These items have been demonstrated to increase risk of prolonged recovery, specifically
patient-reported dizziness following concussion increases the risk of recovery 6.4 times greater than those who do not experience dizziness. These subjective measures are also useful in the clinical assessment of these injuries relative to the vestibular system.

Dizziness Handicap Inventory (DHI)

The DHI is a 25-item questionnaire created to discern between the causes of dizziness and better understand an individual’s experience with dizziness to better characterize the difficulties caused as a result of dizziness. This information may provide clinicians and researchers information regarding the nature and etiology of the dizziness. It is a quick assessment in which the individual completing the questionnaire answers “yes” “no” or “maybe” to questions which used to provide a composite score of their perceived limitations due to dizziness as well as scores based on function, physical or emotion as the root of the dizziness.

When utilized as a self-report measure in a clinical population, the DHI demonstrated a significant relationship ($r=0.39$, $p=0.002$) with the Post-Concussion Symptom Scale (PCSS). Thus, the greater perceived impairment as a result of dizziness, the higher the score on the PCSS, representing overall symptoms and symptom burden.

2.3.4 Description of Included Studies: Influence of Vestibular Function on Outcomes for Patients with a Sport-Related Concussion

A total of six studies met the inclusion criteria that investigated the influence of vestibular function and deficits on outcomes following concussion. These studies measured levels of function and deficits as a result of the injury and used these measures to predict time to recovery or measure the impact on the outcomes for these individuals in comparison to those who did not experience the same impairments in function. Among the populations included in these studies, there is agreement in the evidence to suggest that
conccussions which result in vestibular impairments place individuals at of a prolonged recovery
compared to those without vestibular involvement or compromised function.

The majority of these studies included adolescent and pediatric patients who may present
with different outcomes relative to vestibular maturity compared to adult. While methodology
and outcome measures were not consistent across studies, vestibular measures were predictive of
recovery time following concussion.

2.3.4.1 Vestibular Deficits and Time to Recovery

The included studies used objective measures to assess vestibular function following
concussion. A retrospective chart review of 167 youth and adolescent athletes (15 ±2 years old)
who reported to a concussion clinic and completed the VOMS used a dichotomous (present or not
present) organization to document abnormalities or symptom provocation as a result of the
assessment. In this cohort, the presence of abnormality or symptom provocation was a predictor
of delayed recovery (≥21 days) when compared to those who did not display abnormalities or
experience symptom provocation. Similarly, the other retrospective investigation used patients
who reported to a clinic within 14 days of injury and experienced headache and vision. Due to the
bias in those reporting greater than 14 days of injury, those patients were removed from the
analysis of predictors of prolonged recovery. Within this subgroup, vestibular deficits
demonstrated through balance impairments in a gait task (p=0.007), symptom provocation in the
VOR assessment (p=0.001) and smooth pursuits (p=0.02) was predictive of prolonged recovery,
greater than 28 days.

In a similar prospective study, 69 patients diagnosed with a sports-related concussion
completed the PCSS, Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT),
VOMS and a clinical interview within 7 days following injury. The concussion cases were
divided into three categories based on recovery time (≤14 days, 15-29 days and 30-90 days).
Each of the six VOMS domains were univariate predictors of recovery time of 30-90 days with odds ratios ranging from $6.5 \pm 4.2$ to $10.6 \pm 6.8$. Sufrinko and colleagues used a prospective design to examine a similar question in investigating performance on neurocognitive, vestibular, and ocular motor assessments to predict recovery. They determined poorer VOMS scores, measured within seven days of concussion diagnosis, and were significant predictors of a recovery time of 30-90 days, far beyond the average recovery time.

When classified into groups based on vestibular function (none, improve, persist) at 0-10 days following injury and 11-21 days, the group with ongoing vestibular deficits via the VOMS demonstrated a significant increase in the days to recovery ($p=0.028$). In a retrospective review, patients who exhibited vestibular involvement based on impairments in tandem gait or VOR performance, required significantly more days to return to school (median 59 days vs 6 days, $P=.001$) and achieve medical clearance (median 106 days vs 29 days, $P=.001$) than those who did not have abnormal tests. An included study, unique from those aforementioned, identified on-field predictors of prolonged recovery, greater than 21 days. Dizziness, a common vestibular symptom, when reported at the time of injury, places an individual at a 6.34 times greater risk of a recovery on the prolonged timeline. Therefore, this suggests that despite the function being tested, or the type of assessment being used, vestibular abnormalities following concussion are related to increased recovery times and decreased outcomes.

2.3.4.2 Quality Assessment and Level of Evidence

The average score for the modified Downs and Black checklist was $68.75 \pm 4.70$, representing a moderate quality sample. Level of evidence for each study was graded based on the Oxford Centre for Evidence-Based Medicine 2011. The studies included in this systematic review were considered low, with no study being higher than Level 3 evidence. Three of the studies were Level 3 evidence and three of the studies were Level 4 evidence. Based on the
studies included and the nature of the study design and results, the author chose to give this body of evidence a grade of C as the body of literature was often inconsistent in the methodology and findings and the quality was limited.

2.4 Discussion

To provide a comprehensive understanding of vestibular impairments and outcomes following SRC, this scoping review sought to achieve three objectives; review the anatomy and physiology relative to vestibular deficits following SRC, determine the most commonly utilized assessment strategies in the sports medicine setting, and explore the influence of vestibular impairment on recovery related outcomes following SRC. Three independent search strategies were utilized to identify appropriate investigations to answer each objective. While the anatomy and physiology were outlined, the latter two objectives provided much to be synthesized to drive clinical utility. The primary and most clinical meaningful findings suggest that despite the many emerging technologies, there is not one clear standout test of postural control post-SRC. However, in the investigation of VOR or ocular motor assessments, the VOMS and GST appear to provide the most consistent clinical information to guide decision making following SRC. Additionally, it is abundantly clear that those who experience vestibular impairments following SRC are at a disadvantage in the recovery process related to their counterparts who do not experience vestibular involvement. Therefore, there are many assessment tools that clinicians can consider based on the setting, the patient, and the environment to evaluate vestibular function following SRC and potentially improve outcomes for patients with SRC.

There were five assessment techniques identified and described to test balance or postural control, a function mediated by the vestibulospinal reflex (VSR). Among the tests were those ranging from instrumented technology to tests that required minimal to no equipment. This versatility provides clinicians a range of possible options when assessing balance. Balance deficits are one of the many consequences of SRC as 30% of individuals report balance deficits.
As the window of deficits has been reported to be 72 hours to 7 days following injury, it is important that these tools are sensitive to identifying impairments and recovery patterns. The BESS test although widely used with great feasibility, demonstrated weaknesses in the ability to measure post-concussion deficits and accurately measure recovery of balance. The SOT demonstrated the ability to discern differences by group and by day. While this tool may demonstrate strength in the ability to track recovery, there are limitations to identifying deficits beyond the 72-hour window. Additionally, the nature of the test does not challenge the postural stability in a dynamic way, making it less ideal for athletic populations. While the HS-SOT more directly incorporates the VOR, the literature does not provide information relative to this assessment strategy in a population with SRC. However, the COBALT also incorporates head movements in an upright posture and provides a more challenging task for athletes recovering from SRC. Novel to many previous assessments, the incorporation of vestibular cancellation tasks provides an additional challenge. The mere completion of all conditions on this test has identified differences between those with and without an SRC. Additionally, symptom provocation as a result of the assessment provides clinicians a better idea of the mechanisms that are impaired. To support the utility of this mechanism, the computerized software and portable force plate calculate objective scores through sway velocity. Improvements may be observed in either sway velocity or the errors counted by the examiner during each condition. Although the presented information points to the clinical utility of the COBALT in this population, it is important to recognize that the results are presented only in a single study in an adolescent population. Previous investigations have demonstrated differences in the recovery of this mechanism in adolescents and adults, thus, further research is necessitated when determining the clinical usefulness of this tool in adults with SRC.

Among the four assessments that evaluate the VOR or integration of the vestibular and ocular motor systems, there were unique assessments ranging from highly technical to quick
sideline assessments. However, the VOMS was the most highly investigated, being reported in ten of the included studies, and demonstrated a strong ability to identify those with a concussion with significant differences between those with and without an SRC. Unique domains of the assessment were able to identify independently and demonstrate impairments. Another strength of this tool is the multifaceted nature in that not only records symptoms but in five domains, providing insight into more specific impairments and the nature or etiology of the impairment. With much research on the tool, there is more evidence supporting the reliability and validity of the tool.47 The VOMS has also demonstrated its uniqueness from other tests as studies have investigated its correlations to other assessment strategies outlined in this review. Additionally, the results are not limited to adolescent populations, providing the ability to generalize these results. An additional test that showed promise in the assessment of SRC was the GST. Despite less data and more equipment than the VOMS, the GST correlated with health status in individuals following SRC45 and through the evaluation of asymmetries, was able to discriminate between those with and without a history of SRC.56 Additionally, performance on the GST was able to predict those who were at risk longer recovery,68 which has large clinical applications. Further research using this tool would provide stronger support for the clinical use of this assessment.

Arguably, the strongest and clearest results of this study are those of the third objective. Through different measures, the link between vestibular deficits following SRC and outcomes are clear. Unanimously, poor performance on vestibular assessments, the presence of dizziness, and/or other signs of vestibular impairments were either predictors of prolonged recovery or placed individuals at an increased risk of recovery. However, all reported studies were in pediatric, adolescent, and young adult populations. There must be caution when interpreting these results and applying them to adult populations as previous research has suggested differences in recovery patterns in pediatric and adult patients.
To best utilize the information provided in this scoping review, combinations of vestibular assessment strategies should be explored to determine the optimal methods for clinical evaluation and potential to categorize those with SRC and plan of care to expedite recovery. The risk of poorer outcomes and longer and more complicated recoveries strengthens the need for quality assessments. With the understanding of the underlying mechanism and potential for damage to both the peripheral and central aspects of the system and functions of the VOR and VST, there is a necessity for multifaceted and comprehensive assessments. Utilizing combinations of assessments may yield stronger clinical utility and improve the overall integrity and strength of the evaluation.

2.4.1 Clinical Implications and Future Directions

In addition to considering the strength of these measures to discern impairments, in order to make clinical suggestions, the feasibility of implementation must also be considered. While ideally, clinicians would have access to any of the aforementioned assessment strategies, the reality is, the setting and environment may place limitations on what is feasible or possible. Many of these tools are limited in the environment in which they may be used as many are not portable. While they may provide the most objective results and have been demonstrated to be effective in the concussed and athletic populations, these may not be feasible for many clinicians. Thus, future clinical translational research may require additional exploration into the feasibility of use for different clinical settings, professions and populations, including those of different age ranges.

Among those studies not included in the current review were those who implemented a rehabilitation strategy in the populations demonstrating post-SRC vestibular deficits. This demonstrates the ability to intervene to improve outcomes that have been proven to be poorer in those with vestibular deficits. Systematically evaluating rehabilitation strategies in these populations and based on deficits demonstrated is an additional next step to improve overall standard of care post-SRC.
2.4.2 Limitations

Despite every attempt to use rigorous, standardized, and transparent methods to complete this review of the available literature, including a thorough database search, pre-determined inclusion and exclusion it is important to recognize and consider the limitations to the review process as well as the body of literature. We sought to explore specific objectives regarding vestibular consequences following sports-related concussion. The unique and diverse nature of the chosen objectives each required strategies for search, analysis, and interpretation. In such an investigation, it is preferred that the information regarding each objective be the highest level of evidence achieved through the review of prospective inquiries. The included studies were among the highest quality of those available through a rigorous and systematic search strategy.

Though the anatomy and physiology of the vestibular system is clear, it is difficult to understand the mechanism by which concussion injuries effect this system is a more complicated question. With the wide range of injuries to the head, from sports mechanism to blast injuries, it was difficult to parse out the detriments to the vestibular system as a result of sports participation or similar mechanisms. Although there was clear agreement on the consequences on the vestibular system following head injury, the studies included were not specific in regard to mechanism. Thus, it is difficult to discern where differences may exist in the nature of injury consequences and the manifestation of subsequent deficits.

In the investigation of clinical assessment strategies, there was a wide variety of assessments included, however, common themes among the assessment tools were identified. Many of these investigations were completed in healthy populations. While performing these investigations in healthy participants helps clinicians and researchers understand the
assessment tools, their psychometric properties, and other useful information and metrics, more evidence is needed within patients with a history of SRC.

Finally, the search terms and criteria for inclusion for the final objective yielded limited results as only six studies\textsuperscript{15,20,40,41,61,63} were identified for inclusion. Within the included studies and overall objective, sample size may be the most apparent limitation. The intent of the stringent inclusion criteria was to eliminate those who had participated in a vestibular-specific treatment or rehabilitation. Additionally, two of the studies\textsuperscript{20,40} were retrospective investigations, thus, not providing the strongest evidence as retrospective studies are at a greater risk for bias.

Additionally, the majority of the individuals included in the studies were adolescent and pediatric patients. This limits the generalizability of these studies to adult populations.

2.5 Conclusions and Recommendations

This scoping review of the literature suggests that there are anatomical and physiological consequences following concussions and other head injuries. Although the mechanism of injury and the subsequent consequences are not fully understood, the current body of literature provides a basis for the consequences following injury. Assessment strategies to measure the functional manifestations of vestibular involvement are becoming increasingly common in concussion assessment and evaluation. This review provided a compilation of assessment strategies, an understanding of the nature of the test, and the application of assessments in sports medicine. From the provided information, clinicians may better understand not only the options available to them for assessment of vestibular function following SRC but also the benefits and weaknesses of each strategy. Finally, the review supported the hypothesis that vestibular involvement following concussion can affect patient outcomes. Together the results suggest the need to identify individuals early following their concussion to avoid potential adverse outcomes. To strengthen the evidence on this topic, more high-quality studies including SRC patients are needed; particularly in adults. Thus, it is clear this is an area of research that should be further explored to
improve the quality of care, treatment, and management strategies of the populations of individuals experiencing vestibular consequences following concussion.
Table 2-1. Summary of search 2 terms: studies using clinical assessment tools of vestibular function

<table>
<thead>
<tr>
<th>Study</th>
<th>Cohort</th>
<th>N (Concussed/Control)</th>
<th>Design</th>
<th>Clinical Assessment Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkathiry et al., (2019)</td>
<td>Symptomatic adolescents between the ages of 12 and 19 years old with a SRC within the last 10 days and healthy controls ages 13-20</td>
<td>25/22</td>
<td>Cross-Sectional Study</td>
<td>Video Head Impulse Test (vHIT)</td>
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<td></td>
<td>Balance Error Scoring System (BESS)</td>
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<td></td>
<td></td>
<td></td>
<td>Vestibular Ocular Motor Screening (VOMS)</td>
</tr>
<tr>
<td>Anzalone et al., (2017)</td>
<td>Patients with a sports-related concussion presenting to a concussion clinic</td>
<td>167</td>
<td>Prospective Cohort</td>
<td>Vestibular Ocular Motor Screening (VOMS)</td>
</tr>
<tr>
<td>Alsalaheen et al., (2016)</td>
<td>Patients referred to vestibular therapy after being diagnosed with a concussion</td>
<td>60</td>
<td>Retrospective Case Series</td>
<td>Dizziness Handicap Inventory</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Functional Gait Assessment</td>
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<td>Sensory Organization Test</td>
</tr>
<tr>
<td>Cheever et al., (2017)</td>
<td>Students participating in NCAA DI athletics or club sports</td>
<td>89 (58/21)</td>
<td>Prospective Repeated Measures</td>
<td>Rapid Horizontal Eye Saccades</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slow and Fast Smooth Pursuit Optokinetic Stimulation</td>
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<td>Horizontal Gaze Stabilization Test</td>
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<td>Near Point of Convergence</td>
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<td>King-Devick</td>
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</tbody>
</table>
Table 2.1. Summary of search 2 terms: studies using clinical assessment tools of vestibular function - Continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Sample Size</th>
<th>Study Design</th>
<th>Assessment Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corwin et al., (2018)</td>
<td>Patients ages 5-18 years with concussion</td>
<td>247</td>
<td>Retrospective</td>
<td>VOR testing (gaze stability), Tandem gait</td>
</tr>
<tr>
<td>Dunlap et al. (2018)</td>
<td>Patients referred to vestibular physical therapy after a concussion</td>
<td>158</td>
<td>Retrospective Chart Review</td>
<td>Horizontal Gaze Stability Test, Vertical Gaze Stability, Dizziness Handicap Inventory</td>
</tr>
<tr>
<td>Gray et al. (2020)</td>
<td>Adolescent males and females with a concussion reporting to sports medicine center between January 2015 and August 2017</td>
<td>578 (197 females, 381 male)</td>
<td>Retrospective Medical Record Review</td>
<td>Balance Error Scoring System, Tandem Gait, Gaze Stability, Near Point Convergence</td>
</tr>
<tr>
<td>Guskiewicz et al., (2001)</td>
<td>Division I college athletes with and without a concussion</td>
<td>72</td>
<td>Cohort</td>
<td>SOT, BESS</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Sample Size</td>
<td>Design</td>
<td>Tests Used</td>
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<tr>
<td>Heick et al., (2017)</td>
<td>Healthy individuals ages 14-24</td>
<td>60</td>
<td>Prospective</td>
<td>King Devick, SOT, HS-SOT, DVAT, UCLA dizziness questionnaire</td>
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<tr>
<td>Kontos et al., (2017)</td>
<td>VOMS</td>
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<tr>
<td></td>
<td>King-Devick</td>
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<tr>
<td></td>
<td>DHI</td>
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<table>
<thead>
<tr>
<th>Marquez et al., (2017)</th>
<th>Division I Football Players</th>
<th>67</th>
<th>Descriptive</th>
<th>Dynamic Visual Acuity (DVA)</th>
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<table>
<thead>
<tr>
<th>Massingale et al. (2018)</th>
<th>Adolescent athletes 13-18 years old</th>
<th>246</th>
<th>Retrospective Cohort</th>
<th>COBALT</th>
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<tr>
<td></td>
<td>(132, 106)</td>
<td></td>
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Table 2. Summary of search 2 terms: studies using clinical assessment tools of vestibular function - Continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Participants</th>
<th>Sample Size (N, N)</th>
<th>Design</th>
<th>Tests Administered</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDevitt et al., (2016)</td>
<td>Cross-sectional</td>
<td>Active college/intramural student athletes</td>
<td>72 (12/60)</td>
<td>SOT, BESS, NPC, HES, Smooth and Fast Pursuits, Optokinetic Stimulation, Horizontal GST and DVAT, Head Thrust, King Devick</td>
<td></td>
</tr>
<tr>
<td>Mucha et al., (2014)</td>
<td>Cross-sectional study</td>
<td>Concussed patients and healthy controls (64, 78)</td>
<td>142</td>
<td>VOMS</td>
<td></td>
</tr>
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</table>
Table 2.1. Summary of search 2 terms: studies using clinical assessment tools of vestibular function - Continued

<table>
<thead>
<tr>
<th>Study Reference</th>
<th>Population Description</th>
<th>Sample Size</th>
<th>Study Design</th>
<th>Outcome Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray et al., (2014)</td>
<td>Healthy and Post-Concussion Athletes</td>
<td>18</td>
<td>Cross-Sectional Study</td>
<td>Nintendo WiiFit® soccer heading game; gaze deviations and gaze fixation</td>
</tr>
<tr>
<td>Peterson et al., (2003)</td>
<td>Athletes participating in football, soccer, basketball, softball, and cheerleading.</td>
<td>46</td>
<td>Prospective Observational</td>
<td>SOT, self-reported symptoms</td>
</tr>
<tr>
<td>Russell-Giller et al., (2018)</td>
<td>Patients between ages of 10 and 18 with a diagnosis of concussion who had completed the King Devick Testing and VOMS assessment</td>
<td>71</td>
<td>Retrospective</td>
<td>VOMS, King-Devick</td>
</tr>
<tr>
<td>Sinnott et al., (2019)</td>
<td>Adolescent athletes with a diagnosed SRC in the last 10 days</td>
<td>49</td>
<td>Prospective Repeated Measures</td>
<td>Post-Concussion Symptom Scale, Vestibular Ocular Motor Screening</td>
</tr>
<tr>
<td>Schneider et al., (2018)</td>
<td>Elite ice hockey players ages 13-17</td>
<td>97 (69 completed at least 1 test)</td>
<td>Prospective Cohort Study</td>
<td>Head Thrust Test, Dynamic Visual Acuity, Functional Gait Assessment</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Sample Size</td>
<td>Study Design</td>
<td>Assessment Tools</td>
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<tr>
<td>Sosnoff et al., (2011)53</td>
<td>Patients with mTBI</td>
<td>224</td>
<td>Retrospective cross-sectional</td>
<td>SOT</td>
</tr>
<tr>
<td>Sufrinko et al., (2017)64</td>
<td></td>
<td>64</td>
<td>Prospective</td>
<td>VOMS</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Cross-Sectional</td>
<td></td>
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<tr>
<td>Sufrinko et al. (2019)60</td>
<td>Adolescents and adults diagnosed with SRC in the last 10 days</td>
<td>124</td>
<td>Cross-Sectional</td>
<td>Vestibular Ocular Motor Screening</td>
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<td></td>
<td></td>
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<td>Standardized Concussion Symptom Inventory</td>
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<tr>
<td>Sufrinko et al. (2017)64</td>
<td>Patients diagnosed with an SRC in the last 7 days</td>
<td>69</td>
<td>Cohort</td>
<td>Vestibular/Ocular Motor Screening</td>
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<td></td>
<td>Post-concussion Symptom Scale</td>
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<tr>
<td>Yorke et al., (2017)47</td>
<td>Healthy adolescents</td>
<td>105</td>
<td>Cross-Sectional Descriptive</td>
<td>VOMS</td>
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<td>King-Devick</td>
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<tr>
<td>Study</td>
<td>Population Description</td>
<td>Sample Size</td>
<td>Data Collection Methods</td>
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<tr>
<td>Zhou and Brodsky (2015)</td>
<td>Pediatric patients with balance and/or vestibular complaints following sports-related concussion</td>
<td>42</td>
<td>Case series with Chart Review Video nystagmography</td>
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<td></td>
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<td>Spontaneous/evoked nystagmus</td>
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<td>Ocular motor function</td>
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<td>Bithermal caloric test</td>
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<td>Rotation</td>
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<td>Vestibulo-ocular reflex gain</td>
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<td>Vestibulo-ocular reflex phase</td>
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<td>Asymmetry Fixation</td>
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<td>Visual vestibulo-ocular reflex</td>
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<td>Dynamic Visual Acuity Test</td>
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<td>Cervical vestibular evoked myogenic potential</td>
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<td>Threshold Latency Amplitude</td>
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<td>Computerized dynamic posturography</td>
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<td>Sensory Organization Test composite score</td>
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<td>Sensory analysis</td>
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<td>Center-of-gravity alignment</td>
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<td>Motor function</td>
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<td>Adaptation</td>
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<td>Subjective visual vertical test</td>
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</tbody>
</table>

Table 2-1. Summary of search 2 terms: studies using clinical assessment tools of vestibular function- Continued
Table 2-2. Summary of search 3 terms: studies that investigated the influence of vestibular consequences following concussion on outcomes

<table>
<thead>
<tr>
<th>Study</th>
<th>Cohort</th>
<th>N</th>
<th>Design</th>
<th>Post-Concussion Timeframe</th>
<th>Outcome/Results as a Result of Vestibular Consequences</th>
<th>Level of Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anzalone et al. (2017)</td>
<td>Patients (mean age 15 ± 2 years) with a sports-related concussion</td>
<td>167</td>
<td>Cohort Study (prognosis)</td>
<td>Within 14 days of initial injury</td>
<td>Patients who did not experience symptom provocation during VOMS testing or clinical abnormalities returned to participation quicker than those who reported symptom provocation on at least one domain (13.4 ± 8.2 days and 23 ± 13.4 days, p&lt;0.001)</td>
<td>3</td>
</tr>
<tr>
<td>Corwin et al. (2015)</td>
<td>Patients with a concussion referred to a sports medicine clinic from July 2010 to December 2011</td>
<td>247</td>
<td>Retrospective Cohort Study</td>
<td>Median 12 (1-730) days post-injury</td>
<td>81% of patients demonstrated abnormal vestibular function on clinical evaluation (69% abnormal VOR, 80% abnormal tandem gait). Patients with abnormal vestibular function took significantly longer to return to school (median 59 days vs. 6 days, p = 0.001) and be fully cleared (median 106 days vs. 29 days, p = 0.001)</td>
<td>4</td>
</tr>
<tr>
<td>Lau et al. (2011)</td>
<td>Male high school football athletes</td>
<td>107</td>
<td>Cohort Study (prognosis)</td>
<td>Mean 2.4 days following injury</td>
<td>Athletes who reported dizziness at the time of injury were 6.34 (p=0.01, CI:1.39-29.7) times more likely to experience a protracted recovery (≥ 21 days)</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 2-2. Summary of search 3 terms: studies that investigated the influence of vestibular consequences following concussion on outcomes- Continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Sample Characteristics</th>
<th>Outcomes</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master et al. (2018)</td>
<td>Retrospective</td>
<td>Patients ages 5-18 with a new diagnosis of concussion who presented to a concussion clinic; 432</td>
<td>Within one year of injury</td>
<td>Balance deficits, provocation of symptoms in VOR testing or smooth pursuits in patients reporting less than 14 days following injury was predictive of a prolonged recovery (p=0.007, 0.001 and 0.02)</td>
</tr>
</tbody>
</table>
| Sufrinko et al. (2017)        | Cohort Study (prognosis) | Patients with sports-related concussion (mean age 15.3 ± 1.9 years); 69               | Within 7 days following initial sports-related concussion                 | VOMS scores were univariate predictors of recovery time between 30 and 90 days:  
Smooth Pursuit: OR= 6.5 ± 4.2, p < 0.001  
Horizontal saccade: OR = 7.7 ± 6.2, p= <0.001  
Vertical Saccade: 9.4 ± 8.4, <0.001  
Convergence (cm): OR = 7.4 ± 7.3, p = 0.01  
Horizontal VOR: 8.9 ± 6.4, p < 0.001  
Vertical VOR: OR= 9.1 ± 6.4, p<0.001  
VMS: OR= 10.6 ± 6.8, p<0.001 | 3 |
Table 2-2. Summary of search 3 terms: studies that investigated the influence of vestibular consequences following concussion on outcomes- Continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Design</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinnott et al. (2019)</td>
<td>Patients ages 12-20 seeking care at an outpatient clinic between October 2014 and March 2017</td>
<td>49 Prospective Cohort Study</td>
<td>Patients that demonstrated vestibular impairments at the second clinical visit took significantly longer to recover (34.9±11.6 days) than the group who did not demonstrate any vestibular impairments (22.9 ± 14.9 days; p=0.03)</td>
</tr>
<tr>
<td>Study</td>
<td>1</td>
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<tr>
<td>Anzalone et al., 2017</td>
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<tr>
<td>Corwin et al., 2015</td>
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<tr>
<td>Lau et al., 2011</td>
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<tr>
<td>Master et al., 2018</td>
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<tr>
<td>Sufrinko et al., 2017</td>
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</table>
Table 2-3. Summary of search 3 terms: studies that investigated the influence of vestibular consequences following concussion on outcomes

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<th>12</th>
<th>75</th>
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<tbody>
<tr>
<td>Sinnott et al., (2019)</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>12</td>
<td>75</td>
</tr>
</tbody>
</table>
Figure 2-1 Objective 1: search for articles examining the anatomy and physiology of the vestibular system and the basis for vestibular involvement following concussion

- Records identified through database searching (n = 357)
- Additional records identified through other sources (n = 3)

Records identified as peer-reviewed (n = 240)

Records after duplicates removed (n = 168)

Records screened (n = 168)

- Records excluded (n = 160)
- Full-text articles assessed for eligibility (n = 8)
- Full-text articles excluded, with reasons (n = 3)

Studies included in qualitative synthesis (n = 5)
Figure 2-2 Objective 2: search for articles that included objective measures/clinical assessments of vestibular function in sports medicine

Records identified through database searching (n = 315)

Additional records identified through other sources (n = 9)

Records after duplicates removed (n = 177)

Records screened (n = 63)

Records excluded (n = 201)

Full-text articles assessed for eligibility (n = 31)

Full-text articles excluded, with reasons (n = 6)

Studies included in qualitative synthesis (n = 29)
Figure 2-3 Objective 3: search for studies that investigated the influence of vestibular consequences following concussion on outcomes

Records identified through database searching (n = 201)

Additional records identified through other sources (n = 1)

Records after duplicates removed (n = 105)

Records screened (n = 105)

Records excluded (n = 84)

Full-text articles assessed for eligibility (n = 21)

Full-text articles excluded, with reasons (n = 15)

Studies included in qualitative synthesis (n = 6)
Figure 2-4 Web of Objective Outcomes

- Anatomy
  - Central
  - Peripheral
- Vestibular Consequences Following Sports Related Concussion
- Clinical Assessment Strategies
  - Balance/Postural Control Assessments
    - Balance Error Scoring System (BESS)
    - Sensory Organization Test (SOT)
    - Head Shake-Sensory Organization Test (HS-SOT)
    - Concussion Balance Test (COBALT)
  - Vestibulo-ocular Reflex and Ocular Motor Assessments
    - King-Devick (KD)
    - Vestibulo-Ocular Motor Screen (VOMS)
    - Gaze Stabilization Test (GST)
    - Post-Concussion Symptom Scale
  - Symptom Inventories or Patient Reported Outcomes
    - Dizziness Handicap Inventory (DHI)
- Outcomes
  - Increased Time to Recovery
  - Increased Time to Recovery
CHAPTER 3  SPORT-SPECIFIC DIFFERENCES IN DYNAMIC VISUAL ACUITY AND GAZE STABILIZATION IN DIVISION-I COLLEGIATE ATHLETES

3.1 Introduction

Sport-related concussions (SRC) present a significant public health burden.\textsuperscript{2,3} Although the true number of these injuries remains unknown, it is clear that the incidence of these injuries continues to rise.\textsuperscript{2,3,35,73} SRCs are unique injuries because they may not always be outwardly apparent and often rely on the patient to report their experienced symptoms. Self-reported symptoms are often used to help in the evaluation and diagnosis of SRCs,\textsuperscript{5,28} however, clinical examinations that rely solely on the patient’s self-reported symptoms are not ideals\textsuperscript{5,27,74} as they rely on the memory and biases of the individual report and thus only tell one part of the concussion story. With the increasing population at risk for SRC the need for better recognition, management, and treatment strategies is clearly needed.

One of the sensory systems commonly involved following concussion is the vestibular system.\textsuperscript{6,8,12,21,75,76} Comprised of small sensory organs in the inner ear, the brain stem, and cerebellum, the vestibular system is responsible for both sensory and motor function.\textsuperscript{6,8,77} Through integration with the ocular system, the vestibular-ocular reflex (VOR) stabilizes retinal images during dynamic head motion.\textsuperscript{76} Following concussion, 60% of patients report vestibular complaints while 30% report visual problems.\textsuperscript{28} These complaints can result in a number of symptoms including dizziness, blurred vision and balance dysfunction.\textsuperscript{8} Dizziness is one of the most commonly reported symptoms with 67-77% of collegiate and high school athletes who have suffered SRC reporting these symptoms.\textsuperscript{8} Additionally, the presence of dizziness in the acute phase following SRC has been associated with a 6-fold greater risk for a prolonged recovery (greater than 21 days).\textsuperscript{15} Therefore, it is imperative that vestibular function be evaluated following SRC and that function has returned to a level equivalent to that before the injury was sustained, or returned to baseline before an athlete returns to full athletic participation.
Assessments of vestibular function, specifically the VOR, largely depend on the testing environment that includes; the type of examination (on-field or off), time availability, and resources. The Vestibular-Ocular Motor Screen (VOMS) was developed to serve as a brief clinical assessment tool to measure symptoms in response to several domains of function. The VOMS also serves as a screening tool developed to identify the presence of oculomotor and vestibular deficits following concussion. The VOMS assesses five domains (smooth pursuits, horizontal and vertical saccades, convergence, horizontal vestibular ocular reflex and visual motion sensitivity). It also measures the provocation of symptoms following each assessment via self-report of dizziness, nausea, headache and other related symptoms. This test serves as a brief assessment that can be administered on the sideline to assess vestibular-ocular deficits following concussion. While the VOMS has been shown to be a useful clinical tool, the outcome of this test battery is based on symptom reporting. Objective measures of VOR function may further enhance post-concussion evaluation by providing a performance-based measure to inform clinical decision making.

To address this gap, instrumented strategies that objectively assess functional deficits that may exist following SRC are the Dynamic Visual Acuity Test (DVAT) and the Gaze Stability Test (GST). To accurately measure VOR function, the DVAT and GST require two baseline tests; the Baseline Visual Acuity (BLVA) and Visual Processing Time (VPT). The DVAT and GST assess functional deficits in VOR function and gaze stability due to peripheral vestibular pathology as well as discern. Therefore, these assessments may serve as objective clinical measures to monitor the VOR during SRC management.

Current management strategies often lack emphasis on the assessment of vestibular function following concussion. The DVAT and GST are promising clinical tests that may enhance SRC evaluation for athletes with suspected VOR involvement. There have been many investigations of these assessment strategies in athletic populations that suggest that these
measures are reliable and valid. However, there is a lack of normative data in the athletic population using this more recent technology; previous studies utilized older systems while the current investigation is one of the first reported to use the Bertec Vision Advantage™ (Bertec Corporation, Columbus, Ohio, USA). Having normative values for clinical tests that are specific to the population a clinician is treating is critical for situations where they are returning athletes to participation without a baseline evaluation in these measures. It is important that along with normative estimates, clinicians have evidence that helps them understand the additional factors that may influence performance on objective VOR assessments. Therefore, the primary purpose of this study was to establish normative DVAT and GST values in collegiate athletes. The secondary purpose of the study was to explore the effect of sex, sport, concussion history, and baseline symptoms on the DVAT and GST to determine if differences exist within subgroups of athletes. The results of this study will provide baseline, normative data on VOR functioning to enhance the interpretation of these measures in clinical practice.

3.2 Methods

A cross-sectional study design was used to establish normative estimates on the DVAT and GST in collegiate athletes. Additionally, the effects of sex, sport, concussion history, and baseline symptoms on the DVAT and GST were evaluated to determine how these variables may influence baseline assessments. The dependent variables included DVAT and GST scores.

3.2.1 Participants

All participants provided written informed consent which was approved by the University Institutional Review Board. Volunteers were eligible to participate in the study if they were collegiate athletes aged 18-24, medically cleared to participate in athletics without restrictions at the time of data collection, and reported no history of neurological/vestibular disorders (excluding
concussion), motion sickness, vertigo, currently experiencing neck pain, or limited cervical range of motion, or were currently using allergy medications. Participants were recruited via access to the athletic departments and athletic training departments. Recruitment for this study placed a priority on football, soccer, and cheerleading athletes due to the higher incidence of concussion in these sports. Participants self-reported concussion history. Participants who had corrected vision were able to participate and completed testing with corrected vision. Due to the athletic population, athletes who needed vision correction wore contacts.

3.2.2 Instrumentation

The Bertec Vision Advantage™ (Bertec Corporation, Columbus, Ohio, USA) was used to administer the DVAT and GST. The Bertec Vision Advantage system included a wireless inertial measurement unit mounted in the center of the participant’s forehead using an elastic headband and a 15” Windows laptop equipped with Bertec Balance Advantage™ software. The inertial measurement unit was used to quantify velocity and identify direction of head rotation during the head turn trials.

The measures of visual acuity were recorded in Logarithm of the Minimum Angle of Resolution (LogMAR) units. LogMAR units have replaced the traditional Snellen chart and offers a more standardized method of reporting visual acuity.32,33 The logarithmic scale takes into account adjustments in viewing distance during assessment and directly corresponds with the traditional Snellen chart.34 The LogMAR value of zero corresponds the 20/20 which is also the standard for normal vision. The lower the LogMAR, the greater the visual acuity. A negative LogMAR unit represents better than 20/20 vision.
### 3.3 Procedures

Prior to testing, participants completed a demographic questionnaire. The questionnaire included questions such as; age, height, weight, and injury history, and previous concussion history. Participants self-reported concussion history. The research personnel did not verify the diagnosis of the previous concussion or capture the severity. Participants completed self-report baseline symptom inventories using the Post-Concussion Symptom Scale (PCSS)\(^{29}\) and the Dizziness Handicap Inventory (DHI).\(^{18}\) Next, participants completed the DVAT and GST in a quiet, well-lit, standardized testing room which was free from distractions. The room set up was standardized for continuity across testing dates and locations and one assessor completed the assessments for all participants. Participants were seated in a stationary chair, 8-feet away from a table of adjustable height with a laptop. Based on each subject’s height the table height was adjusted to ensure the best view of the laptop screen.

#### 3.3.1 Assessments

For each of the BLVA, VPT, DVAT and GST, the software projected an optotype capital letter “E” on the center of the laptop screen in black print against a light blue background, as seen in Figure 3.1. As the orientation of the letter “E” changed, the participant was responsible for verbally stating the orientation the “E” (left, right, up, or down) during each of the four tasks. The testing procedures required two baseline assessments to measure BLVA and VPT to individualize the dynamic assessments to the individual being tested. These tests must be completed before DVAT and GST may be performed. During the BLVA, the optotype E appeared in varying sizes to test visual acuity. For the VPT, the optotype size remained the constant while the time the “E” remained on the screen varied to determine processing time. These assessments were used to set the parameters for the DVAT and GST.
Dynamic Visual Acuity Test (DVAT): The DVAT provided a measure of visual acuity during a sustained head movement of 20° in each direction, at a target velocity of approximately 100 °/sec. The amount of time that the “E” was visible on the screen was based on the results of the VPT. To complete the DVAT, the examiner moved the participants head from left to right in the yaw plane (left/right head rotation) at a target velocity of 100°/sec on average, with a range of velocities on the acceptable range. The participant maintained their gaze on the screen and identified the “E” in varying orientation and sizes. The optotype stimulus presentation was adaptive such that it began at a difficulty level based on individual subject baseline measurements. Following correct subject responses, the stimuli became smaller and more challenging. Following incorrect responses, the stimuli became larger and less challenging. Once the head was rotating at the appropriate speed and orientation the letter would appear. The lowest optotype, or best level at which the participant correctly identified the orientation of the “E” at a rate of 60%, was identified as the cut-off point in which the assessment ended and that was the final score. This was completed on both the left and right side. The DVAT has demonstrated moderate to good test-retest reliability in athletic populations with an intraclass correlation coefficient of 0.770 in the yaw plane.

Gaze Stability Test (GST): For the GST, the test parameters included the VPT value calculated in the baseline test, individual test direction (left or right), and optotype set at 0.2 LogMAR above their BLVA. To complete the assessment the examiner moved the participants head from left to right, in a reciprocating motion, 20° in each direction, in the yaw plane. For this assessment, the starting direction was randomly selected by the software. Based on the population being assessed, participants were tested using the high-performance GST; testing velocity began at 120 °/sec, opposed to the standard GST which begins at 80°/sec and does not reach velocities higher than 150°/sec. The velocity increased based on the individual’s ability to accurately denote the orientation of the E at a constant optotype. Once the participant was unable to
successfully identify the orientation of the letter E correctly, the highest rotational velocity the orientation of the “E” was accurately identified at a rate of 60% was used as the GST score. This was completed on both the left and right side.

3.3.2 Statistical Analysis

Normal distribution of the DVAT and GST variables were examined with a Kolmogorov-Smirnov non-parametric test (p>0.05). Results indicated that all variables were not normally distributed. Therefore, non-parametric tests were utilized for all statistical analyses. Descriptive statistics including median, and interquartile range (IQR) were used to describe DVAT and GST scores presented in LogMAR units and °/sec respectively. Percentile scores were calculated for each assessment.

Kruskal-Wallis tests were used to compare differences across sports. When indicated, post-hoc Mann-Whitney U tests were used to examine pairwise differences between sports (football, soccer, cheerleading) and concussion history (0, 1, 2 or more concussions). Additionally, Mann-Whitney U tests were used to compare differences based on sex (male, female) across all sports. Preliminary analyses demonstrated lack of significant differences between sex, within sports, thus, sex was explored across the entire cohort. Spearman’s rho correlations were used to explore the relationship between the time since the last concussion, baseline symptoms, and DVAT and GST scores. Spearman’s correlations were interpreted as weak (r = 0.20-0.29), moderate (r = 0.30-0.39), strong (r = 0.40-0.69) and very strong (r ≥0.70).85 Alpha was set a-priori to p < 0.05 for all analyses. IBM SPSS Statistics Version 25 (IBM, Corp., Armonk, NY, USA) was utilized for all statistical analyses.
3.4 Results

A total of 124 athletes Division-I collegiate athletes from two University athletic departments participated in the study (Table 1). Participants were representative of intercollegiate sports including football (n=44), soccer (n=45), and cheerleading (n=35). Cheerleaders reported higher symptom severity at baseline (10.43 ± 16.20) than both football (3.47 ± 6.12) and soccer (3.77 ± 5.52), however perceived handicap as a result of dizziness was similar across groups (0.49-1.89). The results of the PCSS and DHI suggest a relatively minimal to no symptom burden for the sample. Within the sample, 26.6% reported a history of one concussion, 19.4% reported a history of two or more concussions. There was a range of 1-96 months (28.55±24.61) since the most recent concussion. One participant was unable to complete the dynamic head movements due to lack of neck range of motion and was removed from analysis. Two participants were unable to complete the bilateral GST after experiencing dizziness with high velocities but were included in the analysis. For these participants the individual direction scores were used for the direction that was completed because they did not have results in each direction. However, these data were considered valid because bilateral comparison and asymmetries were not explored in the purpose of this study. The percentile scores on DVAT LogMAR units and GST °/sec in the rightward and leftward directions for all 124 athletes are displayed in Table 2.

Effect of Sex, Sports Participation and Concussion History

There were no significant differences based on sex for any DVAT or GST variables (p≥0.15, Table 3). A significant main effect for sport was detected for DVAT-R (p=0.008), DVAT-L (0.009), and GST-R (p=0.010, Table 4). Cheerleading demonstrated worse DVAT-L and DVAT-R scores compared to football (p=0.007) and soccer (p=0.006). Despite worse DVAT
scores, cheerleading demonstrated significantly better GST (higher rotational velocities) compared to soccer in GST-R (p=0.003).

No significant differences were identified in any DVAT or GST variables (p≥0.107) based on history of previous concussion (Table 5). Additionally, no significant relationships were demonstrated between the number of previous concussions and performance on the DVAT and GST (r≤0.106, p≥0.437). All correlations between the time since last concussion (in months) and the DVAT and GST variables were weak and not statistically significant (r ≤0.265, p≥0.053). Similarly, the correlations between baseline symptoms and all other variables were weak and not statistically significant. Specifically, there was no relationship between the total DHI score and any of the DVAT and GST variables (r ≤0.165, p≥0.068). There were weak and not statistically significant relationships between the PCSS-symptom severity score and DVAT and GST scores. Symptom scores were collected prior to testing and were not repeated following testing.

3.5 Discussion

This study provides normative data for the DVAT and GST in Division-I collegiate athletes. Additionally, the effects of sex, sport, and concussion history were explored to further understand factors which may influence DVAT and GST performance. Normative estimates within this population were defined and organized into percentiles. Despite the lack of statistically significant differences in any of the variables based on sex, there were differences based on sport. Cheerleading demonstrated poorer dynamic visual acuity and the fastest gaze stability velocities compared to football and soccer athletes. Additionally, it was determined that no significant differences in DVAT and GST performance were present based on concussion history and there were no significant relationships between self-reported baseline symptoms and DVAT or GST performance.
Previous investigations in the literature support the findings in this study and provide further information that is useful for clinicians treating these populations following concussion. Additionally, uniqueness of the performance in athletes, by sport, has been highlighted. Similar to what our data suggested, Massingale et al.,84 demonstrated differences in gaze stability velocities elite baseball athletes and the general population. Thus, normative values from healthy individuals cannot be applied to athletic populations who have demonstrated superior performance, even unique to sport, as demonstrated in the current study.

Kaufman et al., examined the reliability of the DVAT and GST in collegiate and high school football athletes. While these computerized assessments were completed on a different system, many of the results from the first testing session follow the same trends noted in the football cohort of the current study. The results of the DVAT in the collegiate athlete group were an average of -0.04 ± 0.13 LogMAR units compared to the current group with a median performance of -0.03(0.20) LogMAR units. Similarly, the GST reported in the yaw plane was 187 ± 39 deg/sec compared to a velocity of 147.5 deg/sec. The superior performance reported in the previous investigation may be attributed to the practice provided while the current study did not include a familiarization opportunity but rather reported on the initial performance. Additionally, Kaufman et al.,78 completed the DVAT at a different velocity than the current study which in addition to the instrumentation, may explain the slight variations. The GST scores presented in this study also closely match those presented by Honaker et al.,56 in collegiate football athletes, with mean velocities of 147 and 150 deg/sec, further providing confidence in the results of the current study.

Sport-related differences in DVAT and GST performance may reflect VOR adaptations based on the individual demands as a result of sport-specific activities. While cheerleaders exhibited the fastest rotational velocities on the GST, they demonstrated the worst dynamic visual
acuity evaluated using the DVAT. These postulations are supported by previous research which identified figure skaters demonstrated sports-specific adaptations in VOR function.\textsuperscript{86} Additionally, differences in performance in DVAT have been identified between athletes and non-athletes further identifying the need for population specific norms.\textsuperscript{87} Between sport differences are important to acknowledge when applying these results clinically so that appropriate standards are used when assessing function of athletes from different sports participation. While percentiles provide a general interpretation of GST and DVAT norms in an athletic population, it is apparent that these values may vary based on the sports investigated in this study.

While there were no significant differences identified based on sex or concussion history, these are both important findings with clinical application. The lack of any differences based on sex potentially suggests that these measures are not affected by this biological factor, in an otherwise healthy state. Thus, any observed differences may be attributed to specific training, or adaptations and habituation as a result of other activities. Similarly, there were no observed differences based on concussion history or the number of previously experienced concussions and no significant relationships between athletes who had a history of one or more concussions and those without a history of concussion. While there were no differences based on concussion history, without understanding baseline performance, we are unable to definitively conclude whether or not this may demonstrate that athletes who have sustained a concussion may regain GST and DVAT performance within normal limits of their counterparts who have not sustained a concussion. This may also mean these measures may not be sensitive enough to detect longer-term deficiencies in vestibular function. However, these results differ from previous reports. Dunlap et al., found significant differences in GST performance between sexes (p=0.02, p= 0.01) in individuals’ post-concussion (215 ± 241 days). Given the differences in the populations examined, there may be factors contributed to the concussion and recovery that explain these
differences in performance by sex. While the current study did not evaluate asymmetries, a previous investigation of asymmetries elucidated differences based on concussion history.56

Finally, there were no notable relationships between the self-report symptom scores on the PCSS and DHI, and the DVAT and GST. This means that self-reported symptoms and scores on functional assessments at baseline are two independent measures without significant correlations. However, it is important to recognize the potential bias introduced using self-report measures. There was limited variability within the number of symptoms reported and the overall severity or symptom impact via the PCSS (mean: 5.67±10.42). Similarly, the DHI scores were low with very low variability (≤1.89±3.18). This low variability in DHI scores was also evident in a cohort of football athletes without a history of concussion (0.64±1.70). However, the group of athletes with a history of concussion had slightly higher variability (3.60±10.80) with a range of 0-42 on the DHI, barely falling below the minimally important change previously identified as 11 points.88 Differences were also demonstrated in the performance on the GST, with the group with a history of concussion demonstrating larger asymmetry values, indicative of a difference between performance on the left and right. This may suggest that experienced symptoms effect GST performance.

3.5.1 Limitations

This study is not without limitations. This study explored the normative estimates of the DVAT and GST using the Bertec Vision AdvantageTM system and passive head movements. At the current time, the reliability of the system has not yet been explored. This presents a significant limitation for the understanding of the system and its psychometric properties. Additionally, the study explored the effect of previous concussions on the assessment scores. However, this presented a potential limitation as the information regarding concussion history, number of
previous concussions, and time since concussion was collected based on self-reported retrospective recall. Thus, it is possible that this information was susceptible to recall bias. Additionally, it is possible that the athletes had previous concussions that were unreported or undiagnosed, and athletes may have experienced concussions that were not reflected in the data collected.

The lack of generalizability of this study serves as an additional limitation. Due to the limited number of sports included in this study and the identified differences based on sports, these findings cannot be generalized to other sports. However, these findings provide clinical significance in the advancement of concussion evaluation and management through the definition of normative values and baseline function in specific athletic populations that are at risk of SRCs. These data can be used for comparisons if baseline data is not available for concussed individuals as they recover and attempt to meet return to participation levels and criteria. It is important to emphasize that these findings are limited to baseline data and may not be generalized to post-concussion function. At this point, it is not possible to determine how sport-specific differences will manifest post-concussion. Future research should expand normative baseline measures to determine if the same baseline benchmark values can be used for other sports.

Further analyses within sport should be conducted with information regarding handedness, position played within their sport and other factors that would allow for further stratification and analysis. This information may provide explanation to better understand more specific VOR adaptions based on sport-specific activities. An additional limitation to this study was that specific player position within their sport was not recorded. Previous research has identified that “position players” in football scored higher than their lineman counterparts in an exploration of gaze stability in football athletes.10,89 This exploration could be replicated within football and other dynamic sports and activities.
3.5.2 Clinical Implications

It has been well documented that the vestibular and ocular systems are vulnerable to injury as a result of concussions and the consequences manifest in functional deficits as well as physical symptoms.\textsuperscript{8,12,19,28} It has also been recognized that current concussion management practices lack quality assessments of the vestibular system, most specifically the integration of the vestibular and ocular systems via the VOR.\textsuperscript{45} The normative data provided by this study are a foundation for clinicians to interpret these measures within collegiate athlete patient populations. Additionally, it also highlights the need for individualized care and the recognition of sports participation and its effect on these measures. Based on the current findings, cheerleaders may require their GST to return to a higher level compared to a football player to ensure a safe return to that sport. Thus, athletes who compete in sports with a higher rotary component may require different return to participation values than those who do not.

3.5.3 Future Directions

While normative estimated for the DVAT and GST have been reported based on a cohort of colligate athletes, further research could expand these findings by reporting on larger sample sizes with a wider variety of sports included. Additionally, these measures should be used to evaluate athletes in the acute and return to participation phases following SRC to better understand the clinical recovery of the VOR.

3.6 Conclusion

This study presents normative estimates on objective VOR testing in Division-I collegiate athletes and the effect of different variables including, sex, sports participation and concussion history on these measures. Additionally, this study explored the relationships between self-
reported symptoms and measures of dizziness and objective measures of vestibular function. The results of this investigation suggested that while there were no differences based on sex or concussion history, there are differences based on sports participation. Additionally, there are no significant relationships at baseline between self-reported symptoms and measures of function at baseline. While baseline performance data are not always available, the organization of normative data, and understanding the effect of these variables on performance, may provide clinicians with useful information to inform decision making based on post-injury data. Furthermore, contextual factors, such as sex, concussion history, and baseline symptoms, do not appear to influence performance on these assessments.
Table 3-1 Descriptive Statistics for Subject Demographics, Patient Reported Outcomes, and Concussion History across Division-I Collegiate Athletes Participating in Football, Soccer, and Cheer

<table>
<thead>
<tr>
<th></th>
<th>Football (n=44)</th>
<th>Soccer (n=45)</th>
<th>Cheerleading (n=35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>44 males</td>
<td>13 male, 32 females</td>
<td>15 male, 20 female</td>
</tr>
<tr>
<td>Age (years)</td>
<td>20.32 ± 1.44</td>
<td>18.91 ± 1.04</td>
<td>20.26 ± 1.38</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.86 ± 0.08</td>
<td>1.69 ± 0.08</td>
<td>1.65 ± 0.15</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>108.52 ± 18.49</td>
<td>63.87 ± 7.52</td>
<td>65.10 ± 20.33</td>
</tr>
<tr>
<td>Post-Concussion Symptom Scale (PCSS)-Severity</td>
<td>3.47 ± 6.12</td>
<td>3.77 ± 5.52</td>
<td>10.43 ± 16.20</td>
</tr>
<tr>
<td>Dizziness Handicap Inventory (DHI)</td>
<td>1.36 ± 6.26</td>
<td>0.49 ± 1.96</td>
<td>1.89 ± 3.18</td>
</tr>
<tr>
<td>History of Concussion</td>
<td>25 (56.8%)</td>
<td>14 (31.1%)</td>
<td>18 (51.4%)</td>
</tr>
</tbody>
</table>
Table 3-2 Distribution of DVAT (LogMAR) and GST (°/sec) Percentile Scores for All Participants

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percentile</th>
<th>5</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>90</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVAT-R</td>
<td>0.27</td>
<td>0.2</td>
<td>0.10</td>
<td>0</td>
<td>-0.07</td>
<td>-0.15</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td>DVAT-L</td>
<td>0.25</td>
<td>0.22</td>
<td>0.09</td>
<td>0</td>
<td>-0.07</td>
<td>-0.15</td>
<td>-0.20</td>
<td></td>
</tr>
<tr>
<td>GST-R</td>
<td>120</td>
<td>120</td>
<td>130</td>
<td>150</td>
<td>175</td>
<td>205</td>
<td>229</td>
<td></td>
</tr>
<tr>
<td>GST-L</td>
<td>120</td>
<td>120</td>
<td>130</td>
<td>145</td>
<td>170</td>
<td>205</td>
<td>231</td>
<td></td>
</tr>
</tbody>
</table>
Table 3-3 DVAT (LogMAR) and GST (°/sec) Scores by Sex (median (IQR))

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVAT- R</td>
<td>0 (0.15)</td>
<td>0 (0.17)</td>
<td>0.675</td>
</tr>
<tr>
<td>DVAT-L</td>
<td>0 (0.14)</td>
<td>-0.03 (0.17)</td>
<td>0.757</td>
</tr>
<tr>
<td>GST-R</td>
<td>150 (50)</td>
<td>155 (40)</td>
<td>0.191</td>
</tr>
<tr>
<td>GST-L</td>
<td>140 (40)</td>
<td>150 (50)</td>
<td>0.275</td>
</tr>
</tbody>
</table>
Table 3-4 DVAT (LogMAR) and GST (°/sec) Scores by Sport (median (IQR))

<table>
<thead>
<tr>
<th></th>
<th>Football</th>
<th>Soccer</th>
<th>Cheerleading</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVAT- R</td>
<td>-0.03(0.20)</td>
<td>0 (0.15)</td>
<td>0.06 (0.16)</td>
<td>0.008</td>
</tr>
<tr>
<td>DVAT- L</td>
<td>-0.03(0.14)</td>
<td>-0.03 (0.13)</td>
<td>0.05 (0.24)</td>
<td>0.009</td>
</tr>
<tr>
<td>GST- R</td>
<td>150 (40)</td>
<td>145 (40)</td>
<td>157.5 (66)</td>
<td>0.010</td>
</tr>
<tr>
<td>GST- L</td>
<td>135 (50)</td>
<td>145 (35)</td>
<td>152.5 (66)</td>
<td>0.110</td>
</tr>
</tbody>
</table>
Table 3-5 DVAT (LogMAR) and GST (°/sec) Scores by Concussion History (median (IQR))

<table>
<thead>
<tr>
<th></th>
<th>No History of Concussion</th>
<th>History of Concussion</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVAT- R</td>
<td>0 (0.17)</td>
<td>0 (0.17)</td>
<td>0.738</td>
</tr>
<tr>
<td>DVAT-L</td>
<td>-0.03 (0.85)</td>
<td>0 (0.70)</td>
<td>0.107</td>
</tr>
<tr>
<td>GST-R</td>
<td>150 (40)</td>
<td>150 (45)</td>
<td>0.819</td>
</tr>
<tr>
<td>GST-L</td>
<td>145 (35)</td>
<td>145 (50)</td>
<td>0.839</td>
</tr>
</tbody>
</table>
Figure 3-1 BVA set-up with participant seated 8-feet from laptop screen, wearing mounted headpiece and participant’s view of screen
4.1 Background

Sports-related concussions (SRCs) have received increased attention from the medical, science and even public communities in the last decade. The increased awareness for these injuries has prompted better management and practices, especially in youth, collegiate, and professional sports. With the unique and extremely individual nature of SRCs, it has been suggested that a multi-faceted approach be used to assess these injuries and create the best plan of care. While it is common practice and suggested in many position statements to assess signs and symptoms and evaluate both balance and cognition, more recent recommendations have also began to suggest the inclusion of assessments for ocular and vestibular function. Screening for vestibular/ocular deficits has revealed that impairments in these aspects of function are not only common following SRC but may place the individual at a risk of prolonged recovery.

The vestibular system is responsible for both sensory and motor function and works in conjunction with other systems and reflexes to maintain postural control and stable vision during head accelerations. The vestibular system is made up of three semicircular canals and two otolithic organs within the inner ear which detect rotational and linear accelerations of the head, respectively. These sensory structures transmit movement information to the brainstem to illicit a compensatory response. In combination with the ocular system, the vestibulo-ocular reflex (VOR) manages stable and dynamic vision during head movements, while the vestibulospinal reflex (VSR) has both an upper and lower limb response to stabilize and maintain upright posture.

Vestibular deficits following concussion may manifest as both symptoms and functional deficits. Dizziness is among one of the most commonly experienced symptoms, reported in
50% of all athletes with a concussion. Additionally, dizziness is an especially significant symptom as it has been associated with a six times greater risk of a prolonged recovery (>21 days) when reported in the acute phase following injury. Among the functional consequences of vestibular involvement are deficits in balance, spatial orientation and stable vision. As crucial functions to athletic participation, it is imperative that the clinicians managing these injuries are equipped with the knowledge and tools to make informed clinical decisions relative to return to participation or activity resumption.

The current standard of care in concussion management includes the use of self-report symptom checklists such as the Post-Concussion Symptom Scale (PCSS). These tools systematically document the nature of the injury by having the patient rate their perceived symptoms and their severity on a series of Likert scales. Indicators on these commonly used scales include symptoms of different concussion domains that can be grouped by function. For example, among the symptoms that suggest vestibular involvement are headache, dizziness, nausea, sensitivity to noise, and difficulty with balance. Despite their widespread use and clinical feasibility, symptom scores alone may not provide a comprehensive assessment of impairments and recovery following SRC. There are many reasons for this, including but not limited to the reliance on individuals to report their symptoms introducing potential recall bias, false or under-reporting, and variability between measurements. Therefore, monitoring the vestibular system during SRC recovery may be enhanced by implementing objective assessment strategies which can complement symptom checklists.

Objective measures of function and recovery are important in the management of SRCs to reduce subjective comparisons to pre-injury or normative levels of function. Improvements in technologies have created objective measures that are capable of measuring function and in turn, identifying potential deficits. Among these advancements in technology are assessments that measure function of the VOR through tests of visual acuity with incorporated headshakes.
Additionally, similar assessments of the VSR use challenging conditions to tax the peripheral vestibular and central systems. For example, the head shake and vestibular cancellation tasks have both been developed to elevate the level of difficulty from more commonly used clinical assessment strategies and potentially provide information to differentiate peripheral from central vestibular involvement. While each test is designed to evaluate a unique function of the vestibular system, it is important to understand the relationships between assessments to identify the best methods for evaluation.

A multifaceted vestibular assessment battery may enhance SRC evaluation by identifying deficits that may not have been otherwise recognized and providing a method for improving return to activity practices. However, it is important to optimize the efficiency of testing and therefore it is important to determine if relationships exist within the test battery. To date, only two studies have examined the relationship between measures of vestibular function. These previous investigations used unique combinations of common vestibular assessments to explore potential relationships between the measures including the King-Devick (K-D) test, Sensory Organization Test (SOT), Head Shake-Sensory Organization Test (HS-SOT), and Dynamic Visual Acuity (DVA) and the Vestibular/Ocular Motor Screening (VOMS), the K-D and the Balance Error Scoring System (BESS). However, it was concluded in both studies that the assessments were measuring unique aspects of function and did not have significant relationships. These previous investigations differ from the current study in test batteries evaluated and combination of assessments.

With a number of clinical assessments available, it is important to understand the relationships between the assessments and how best to utilize each assessment to ensure the most efficacious and efficient assessment strategies or battery is used. There has not been a study that has evaluated the relationship between the two specific assessments chosen in this study. Therefore, the purpose of this study was to investigate the relationships between measures of
vestibular function and self-reported symptoms in collegiate athletes. It was hypothesized that there would be significant relationships between symptom and performance on objective vestibular assessments but there would not be significant relationships between measures of the VSR and VOR via balance and gaze stability as they are measuring independent and unique functions.

4.2 Methods

A cross-sectional design was used to explore the relationships between vestibular-related symptoms and objective measures of VOR and VSR function.

4.2.1 Participants

A total of 135 student-athletes from Division-I collegiate programs in two University athletic departments participated in the study (82 men, 53 women). Participants were representative of intercollegiate sports including football (54 men), soccer (13 men, 33 women), and cheerleading (18 men, 17 women). Recruitment for this study placed a priority on these sports due to the higher incidence of concussion. Volunteers were eligible to participate in the study if they were collegiate athletes aged 18-24, medically cleared to participate in athletics without restrictions at the time of data collection, and reported no history of neurological/vestibular disorders (excluding concussion), motion sickness, vertigo, neck pain, or limited cervical range of motion, or currently using allergy medications. Participants completed a demographics questionnaire that included health history questions including self-report of concussion history. A total of 64 participants reported a lifetime history of concussion (46%). Of those reporting a history of concussion, 26.6% reported a history of one concussion, 19.4% reported a history of two or more previous concussions. All participants provided written informed consent which was approved by the University Institutional Review Board.
4.2.2 Procedures

This study was part of a larger longitudinal study. Once enrolled in the study, participants completed a battery of assessments and questionnaires including the PCSS. The PCSS is a 22-item symptom inventory with moderate test-retest reliability \((r=0.65)\) with the ability to discriminate between concussed and non-concussed athletes. Participants were instructed to rate each listed symptom based on how they felt in that moment. Symptoms were rated on a 7-point Likert scale with 0 representing no symptom to 6 representing severe experienced symptom. Six of the 22 included symptoms were extracted for this analysis based on their relation to the vestibular system. Among the extracted symptoms were: headache, dizziness, balance problems, visual problems, sensitivity to noise, and feeling slowed down. This modified version of the PCSS was noted as the PCSS-vestibular and based on the exploratory factor analysis completed by Kontos et al., which defined the vestibular-somatic symptoms.

Participants completed the GST to assess the VOR. The GST is a measure of VOR function that requires movement of the head in a yaw plane. For this assessment, the examiner determines the participant’s static visual acuity (SVA) and the visual perception time (VPT) of a target, determined by the SVA. These values are utilized by the software to create the parameters for the GST, approximately 0.2 logMAR above the SVA.

The GST was completed using a commercially available system composed of a wireless inertial measurement unit mounted in the center of the participant’s forehead using an elastic headband and a 15” Windows laptop (Bertec Vision Advantage™, Bertec Corporation, Columbus, Ohio, USA). The inertial measurement unit was used to quantify velocity and identify direction of head rotation during the head turn trials. To complete the GST, participants were seated in a chair, 8-feet from the laptop monitor. Participants wore corrective eyewear as they would normally wear on a daily basis. Prior to testing, they were provided with verbal instructions by the examiner. Baseline assessments including Baseline Visual Acuity (BLVA) and
Visual Processing Time (VPT) were completed before the GST and provided the participants
with an opportunity to become familiar with the system and process. To complete the GST, the
examiner rotated the participant’s head from left to right, in the yaw plane, at varying velocities
as indicated by the software (Bertec Balance Advantage™). Once the minimal velocity was met,
the letter “E” appeared on the screen at a fixed size or optotype. The participant was directed to
maintain their gaze on the laptop screen despite the head rotations. The “E” would appear
following three consecutive motions at the target velocity were achieved and the head was in the
direction being measured. Once it appeared, participants were asked to identify verbally “left”,
“right”, “up”, or “down” based on the orientation of the “E”. Based on their responses, either
correct or incorrect, the velocity of the headshakes either increased or decreased. Once the
participant was unable to correctly identify the orientation of the letter “E” at a rate of 60% for a
given velocity, the test was deemed complete and the fastest velocity was recorded in deg/sec.
This was completed in both the left and right direction. Results were provided immediately and
provide the highest velocity (°/sec) at which the participant can maintain visual acuity, in a
direction specific manner.

As an objective measure of balance, participants completed four selected conditions from
the Concussion Balance Assessment Tool (COBALT) with high rater agreement for counted
errors (ICC=0.861, p<0.001). The COBALT is an 8-condition double-limb balance assessment,
building from the modified Clinical Test of Sensory Interaction on Balance (mCTSB), that
utilizes a mobile forceplate and foam pad to assess dynamic postural control during conditions
that challenge the vestibular system through the incorporation of a headshake and vestibular-
ocular cancellation task. These conditions were created to better replicate or mimic the
requirements of athletic participation. Participants completed two 20-second trials of each of the
four conditions described in Table 1. Sway velocity (°/sec) and the number of balance errors were
recorded for each trial. The examiner visually inspected for errors and recorded them within the
software. Errors included: lifting one or both hands off their hips, opening eyes on eyes closed conditions, moving feet out of position, losing balance, or being unable to maintain head turns with the beat of the metronome for two or more beats. Sway velocity was averaged for the two trials of each condition. Balance errors were summed for each condition as well as total errors across all eight trials.

4.2.3 Statistical Methods

Descriptive statistics were used to describe the population using means, standard deviations and ranges for all demographic data. Normality of each of the variables was examined using Shapiro-Wilk tests for normality. Results indicated that all but one of the variables were not normally distributed (COBALT sway 8 average, p=0.519). As a result, Spearman’s rho correlations were used to examine the relationships between the measures recorded from the PCSS-Vestibular, GST, and COBALT. Spearman’s rho correlations were interpreted as weak ($r = 0.20$-$0.29$), moderate ($r = 0.30$-$0.39$), strong ($r = 0.40$-$0.69$) and very strong ($r \geq 0.70$). Alpha was set a-priori to $p<0.05$ for all analyses. IBM SPSS Statistics Version 25 (IBM, Corp., Armonk, NY, USA) was utilized for all statistical analyses.

4.3 Results

Of the 135 participants, 41 reported one or more vestibular-related symptom at baseline with severity ranging from 0-13 out of a potential score of 36 (Table 2). There were no significant correlations between the PCSS-vestibular scores and any of the GST ($r=-0.10$-$0.07$, $p=0.30$-$0.91$), COBALT sway velocity ($r=-0.07$-$0.17$, $p=0.06$-$0.47$), or the number of COBALT balance errors ($r=-0.052$-$0.174$, $p=0.056$-$0.566$).

There were no significant relationships between any of the GST variables and the sway velocities of the four COBALT conditions ($r=-0.15$-$0.08$, $p=0.12$-$0.79$). However, there were weak to moderate, significant relationships between measures of GST and COBALT errors.
Specifically, weak to moderate relationships were observed between gaze stability leftward and balance errors on Condition 7 \( (r=0.30, p=0.001) \), Condition 8 \( (r=0.22, p=0.02) \), and total errors \( (r=0.31, p=0.001) \). Similarly, gaze stability rightwards demonstrated fair relationships with balance errors on Conditions 3 \( (r=0.25, p=0.008) \), Condition 4 \( (r=0.27, p=0.004) \), Condition 7 \( (r=0.25, p=0.008) \), Condition 8 \( (r=0.20, p=0.03) \), and total errors \( (r=0.28, p=0.003) \).

4.4 Discussion

The purpose of this study was to explore potential relationships between measures of vestibular function and self-reported symptoms in healthy collegiate athletes. The primary finding was baseline measures of objective vestibular function and self-reported vestibular symptoms demonstrated weak correlations. Thus, the hypothesis that there would be relationships between vestibular function and self-reported symptoms was rejected. However, several moderate and statistically significant relationships were identified between the GST and balance errors on the COBALT, rejecting the hypothesis that relationships would not exist between these measures. These relationships also demonstrate clinical meaningful correlations with several clinical implications to these findings.

This study identified moderate relationships between GST performance and COBALT errors. The direction of these relationships indicated that greater COBALT errors was associated with greater GST performance. These relationships may be attributed to the difficulty created by the foam conditions and the integration of more complex sensory tasks required to maintain balance during the more difficult conditions. Errors counted during the COBALT conditions are representative of an inability to continuously satisfy all aspects of the task. Therefore, higher error counts represent a sacrifice or compromise in strategy. In this study, it is possible that individuals were focusing on maintaining posture and decreasing sway rather than the accompanied movements and stance. The correlations may suggest an underlying physiological crossover
between the VOR and VSR that is being manifested in these observations. The COBALT presents an additional challenge and places higher demands on the vestibular system through the incorporation of the head shake and VOR cancellation tasks. The addition of the VOR challenge in a VSR assessment elevates the difficulty of this task beyond that of traditional balance assessments. The correlations between the assessments demonstrate this challenge and incorporation while also demonstrating their uniqueness with the lack of relationships.

Clinically, it is not entirely surprising that the measures of the VOR and VSR are related, albeit moderate correlations. However, the results of this study and the correlations revealed are unexpected and require further and careful interpretation. While those athletes with higher GST velocities reported more errors on the balance tasks, it does not mean that having a higher GST velocity would translate into tasks which challenge vestibular integration during balance. It may be theorized that the passive rotational vestibular demands during the GST allowed for a simpler sensory processing than the active rotational velocity while also necessitating sensory organization and integration during the balance task. These differences illustrate the different system functions and sensory integration requirements of the VOR and VSR. These data suggest that there may be adapted balance strategies by the participants. While athletes may have been preforming well in regards to sway, data suggests that there are more errors per condition. This may suggest a compromise in the individual’s balance strategy, which may be driving these correlations. This could be a result of difficulty with sensory integration or slowed signal processing.

Additionally, it may be argued that there is a disconnect between the performance on the COBALT, as demonstrated by sway velocity values and the total errors. While measuring errors presents the potential for tester biases with its subjectivity, both sway velocity and observing errors are measures of balance. Sway velocity values provided unique information relative to an individual’s ability to maintain upright and constant posture via the VSR. The counted errors
provided information relative to the integration of sensory systems including both the VSR and VOR, relative to the additional sensory challenges of each task. Through one clinical assessment, various functions of the system are measured, that assist in the understanding of potential impairments.

The results of this study have strong clinical implications that assist in demonstrating the potential need for more comprehensive assessments of affected systems including the vestibular system in concussion management. The lack of consistent moderate-to-strong correlations suggests that these assessment strategies are evaluating unique and individual facets of the same system. Clinicians evaluating and managing these injuries should be cautious when assessing the vestibular system as it is a multifaceted system with both central and peripheral components that are manifested in unique functions and abilities. Ensuring there are assessments of more than one function of the system and both central and peripheral aspects is crucial as these operations do not seem to correlate to one another.

This study is not without limitations. When investigating the correlations between measures of vestibular function, these relationships were explored in healthy, collegiate athletes. The relationships may differ in athletes who have sustained a concussion. Similarly, it is not yet known what effect a concussion may have on the relationships between these measures and how they may change throughout the recovery process in a concussed sample. Additionally, the number of sports represented was limited to football, men’s and women’s soccer and men’s and women’s cheerleading, and cannot be generalized to all collegiate athletes. Finally, this investigation was part of a larger, longitudinal study with baseline concussion assessments and all participants did not complete the testing in the same order. Therefore, it is possible that elements of testing could have changed or altered the way in which an individual would report their symptoms in that moment compared to an athlete who had completed the symptom report prior to engaging in any other testing activities.
4.5 Conclusion

This study explored measures of vestibular function including symptom report and objective measures of balance and gaze stabilization to elucidate potential relationships in a cohort of healthy, collegiate athletes. Generally, weak relationships were exhibited amongst vestibular measures with the exception of the moderate relationships demonstrated between the GST and the number of balance errors. The lack of strong correlations may suggest these assessment tools are examining different aspects of vestibular system function in healthy collegiate athletes. These assessments strategies are relatively novel to the field and require further investigations into the manner in which the psychometric properties and clinical populations affect these relationships. Collectively, the combination of symptom reporting, GST, and COBALT may provide a multifaceted battery of measures to further examine vestibular involvement and recovery following SRC.
<table>
<thead>
<tr>
<th>Assessment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 3</td>
<td>The participant’s eyes are closed, feet apart at appropriate markers, hands on iliac crests. The participant rotates their head side to side at 30° each direction with a metronome set at 120 bpm with the goal of achieving a 60° sweep each direction, to the beat.</td>
</tr>
<tr>
<td>Condition 4</td>
<td>The participant’s eyes are open, and their feet are together in the center of the force plate. The participant clasps their hands and thumbs with their arms outstretched in front of them. With focus on their thumbs, the participant completes a rotation at the torso from side to side at 30° each direction to the beat of the metronome at 40 bpm.</td>
</tr>
<tr>
<td>Condition 7</td>
<td>Condition 3 is repeated standing on a foam pad placed on top of the force plate.</td>
</tr>
<tr>
<td>Condition 8</td>
<td>Condition 4 is repeated standing on a foam pad placed on top of the force plate.</td>
</tr>
</tbody>
</table>
Table 4-2 Baseline Post-Concussion Symptom Scale Vestibular/Ocular Symptoms Reported

<table>
<thead>
<tr>
<th>Symptom</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headache</td>
<td>110</td>
<td>14</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>Nausea/Vomiting</td>
<td>125</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>Dizziness</td>
<td>124</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>Balance Problems</td>
<td>124</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>Blurred Vision</td>
<td>124</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>Sensitivity to Noise</td>
<td>128</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>135</td>
</tr>
</tbody>
</table>
Table 4-3 Descriptive Statistics for Measures of Vestibular/Ocular Symptoms and Functional Assessments

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCSS-Vestibular/Ocular Score</td>
<td>0.87 ± 1.91</td>
<td>0-13</td>
</tr>
<tr>
<td>Condition 3- Sway Velocity</td>
<td>0.36 ± 0.13</td>
<td>0.14-0.80</td>
</tr>
<tr>
<td>Condition 4- Sway Velocity</td>
<td>0.74 ± 0.17</td>
<td>0.40-1.40</td>
</tr>
<tr>
<td>Condition 7- Sway Velocity</td>
<td>1.30 ± 0.39</td>
<td>0.60-2.56</td>
</tr>
<tr>
<td>Condition 8- Sway Velocity</td>
<td>0.94 ± 0.19</td>
<td>0.60-2.56</td>
</tr>
<tr>
<td>Condition 3- Errors</td>
<td>0.65 ± 1.26</td>
<td>0-8</td>
</tr>
<tr>
<td>Condition 4- Errors</td>
<td>0.05 ± 0.33</td>
<td>0-3</td>
</tr>
<tr>
<td>Condition 7- Errors</td>
<td>3.33 ± 3.28</td>
<td>0-15</td>
</tr>
<tr>
<td>Condition 8- Errors</td>
<td>0.07 ± 0.38</td>
<td>0-3</td>
</tr>
<tr>
<td>COBALT- Total Errors</td>
<td>4.07 ± 4.22</td>
<td>0-24</td>
</tr>
<tr>
<td>Gaze Stabilization- Leftward</td>
<td>155.12 ± 32.64</td>
<td>120-255</td>
</tr>
<tr>
<td>Gaze Stabilization- Rightward</td>
<td>157.58 ± 34.107</td>
<td>120-300</td>
</tr>
<tr>
<td>Gaze Stabilization- Asymmetry</td>
<td>123.8525-23.42375</td>
<td>0-115</td>
</tr>
</tbody>
</table>
CHAPTER 5 PREDICTORS OF TIME TO RECOVERY IN ATHLETES THAT HAVE SUSTAINED A SPORTS-RELATED CONCUSSION WITH SUSPECTED VESTIBULAR INVOLVEMENT

5.1 Introduction

Sports-related concussions (SRCs) are considered a mild form of traumatic brain injury, induced by biomechanical forces on the head, neck or face, particularly as a result of athletic participation. These injuries have gained more attention in recent years and research has focused on improving the understanding and clinical outcomes of these injuries. SRCs typically present as a number of clinical signs and symptoms including but not limited to headache, fatigue, and emotional and sleep disturbances; however, the clinical manifestation can be unique to individual patients. Signs and symptoms resolve within 7-10 days for the majority of patients. However, concussion related symptoms and impairments have been known to last anywhere from weeks to months following the injury, and may involve many neurological systems including the vestibular and oculomotor systems.

Among patients who experience a prolonged recovery, vestibular impairments are often reported. Involvement of the vestibular system in as a result of SRC manifests in an array of clinical signs and symptoms including dizziness, difficulty with balance, and challenges with gaze stabilization. In particular, reports of dizziness following SRC has been associated with a six times greater risk of prolonged recovery beyond 28 days. Additionally, a retrospective analysis of adolescents identified vestibular involvement as a predictor of recovery requiring greater than 21 days, compared to patients without vestibular involvement. This was similar to an additional investigation which discovered that poorer VOMS scores within 7-days of injury are significant predictors of recovery time of 30-days and 90 days, beyond the average recovery timeline. In addition to the high risk of prolonged recovery associated with post-SRC dizziness, performance on the VOMS has overwhelming evidence to suggest those with vestibular abnormalities are
more likely to have prolonged recovery. Given that vestibular and oculomotor systems are heavily taxed during athletic activities, it is important to understand the deficits to these systems and the potential for prolonged recovery in athletes sustaining an SRC. The incorporation of a thorough examination of the vestibular system following SRC to identify and track deficits throughout recovery is important. Additionally, reexamining these functions at the time of return to participation for decision making is vital to ensuring these mechanisms are truly recovered and the athlete is truly prepared to return to their previous activities.

The Concussion in Sports Groups’ (CISG) latest recommendation in the 2016 Consensus Statement provides suggestions on follow-up evaluations including “comprehensive history and detailed neurological examination including a thorough assessment of mental status, cognitive functioning, sleep/wake disturbance, ocular function, vestibular function, gait and balance.” Despite this recommendation to incorporate vestibular assessments as a part of the SRC evaluation, no assessment strategies were put forth to evaluate these systems. Although the position statement falls short of recommending specific vestibular evaluation techniques, there are two specific subsystems within the vestibular system which can be clinically evaluated. The vestibular reflexes combine the sensory, central, and motor components of the vestibular system through the vestibular reflexes. The vestibulocular reflex is the reflex responsible to responding to movements of the head and the maintenance of stable vision through mediation of the ocular motor system. Another important reflex is the vestibulospinal reflex, the reflex responsible for providing stability of the body. Both reflexes mediate responses to stimuli that are inherently necessary in athletic participation, thus must be examined and evaluated following SRC and throughout the clinical decision-making process.

Advances have been made in both technology and the understanding of the need to incorporate more challenging assessments in the evaluation of SRC. From this, a number of approaches have been developed. Among these strategies are balance and gaze stabilization...
assessments that more directly measure vestibular function and potential impairments in a manner that aligns with the specific demands of athletic participation. One of these assessments is the Concussion Balance Assessment (COBALT), which is uniquely designed to expand on the Modified Clinical Test of Sensory Interaction in Balance and mimic the level of balance required for athletic participation. To incorporate the oculomotor system, the Dynamic Visual Acuity Test (DVAT) and Gaze Stabilization Test (GST) are also used to assess vision in dynamic tasks. These assessments may elevate current assessment strategies through the implementation of objective, instrumented assessments. Building on what is already known regarding SRC and those strategies currently utilized, these assessments may have the ability to better assess those functions required for athletic participation.

Objective vestibular assessments may aid in the initial evaluation and management of SRC particularly when combined with other factors known to influence recovery time following SRC. Additionally, they may also provide an indication of patients who may experience a prolonged recovery and could benefit from further intervention. Therefore, the purpose of this study was to explore measures of vestibular function as potential predictors of recovery time following sports-related concussion based on a clinical sample within measures routinely collected in the clinic and better understand the population. We hypothesized that a combination of greater vestibular symptoms, poorer performance on assessments of vestibular function, and other patient or contextual factors would be predictive of time to recovery.

5.2 Methods

5.2.1 Design and Participants

A retrospective cohort study was conducted via review of electronic medical records and acquisition of data from athletes diagnosed with sports-related concussions at a multi-disciplinary concussion clinic between August 1, 2016 and July 31, 2017. Patients were referred to the
concussion clinic by the emergency departments, athletic trainers, other healthcare professionals, or self-referred to the clinic. These patients were eligible for the study if they were between 14 and 24 years of age, had been diagnosed with a sports-related concussion, and presented to the clinic within 14 days of initial injury. Additionally, participants must have had physician suspected vestibular involvement as a result of signs or symptoms, a brief balance assessment, and completed objective vestibular function testing within the clinic. Exclusion criteria included moderate to severe traumatic brain injuries, neurological disorders, history of brain surgery, neurologic or cognitive disorder, or other pathologies that affected the vestibular system such as vertigo. Data were collected via electronic medical records and manually imported into a database in the Research Electronic Data Capture (REDCap) tool. Additional information was taken from databases of objective testing scores and de-identified into the REDCap database. The review of clinical data was approved by the Institutional Review Board at the University of Arizona.

5.2.2 Clinical Assessments and Outcome Measures

5.2.2.1 Demographic, Medical History, and Injury Information

Patients reporting to the concussion clinic were seen by healthcare professionals with experience and expertise in the area of concussion. Patients completed demographics and medical history questionnaires that included age, sex, sport participation, history of previous injury, personal or family medical history including migraines, motion sickness, anxiety/depression and other important demographic variables. The date of initial visit was recorded in addition to the date of initial visit to the clinic so that time from injury to initial visit to the clinic could be calculated for analysis.

5.2.2.2 Clinical Evaluation, Diagnosis, and Plan of Care
A sports-medicine physician or physician’s assistant completed a clinical assessment upon presentation. From there, the SRC was diagnosed or confirmed, based on the guidelines and definitions outlined in the Consensus on Concussion in Sport. Providers performed a clinical evaluation on each patient including a brief balance assessment, using a double and single limb stance task, similar to the BESS, but abbreviated, to identify potential disruption of the vestibular system. Based on the clinical evaluation, the provider delivered a plan of care, which included a referral to at least one of the following: physical therapy, vestibular therapy, neuro-ophthalmology, and follow-up care. Patients were referred for follow-up with physical therapists who specialize in vestibular therapy for objective testing and rehabilitation.

5.2.2.3 Post-Concussion Symptoms

Relative to the current injury, patients completed the Post-Concussion Symptom Scale (PCSS). The PCSS is a symptom inventory tool that is commonly used to measure patient-reported symptoms. Patients reported whether or not they were experiencing one of 21 symptoms, and rated their experience of each symptom on a 7-point Likert scale from none (0) to severe (6). The PCSS is scored as a total symptom severity from 0-126.

As this investigation place a significant focus on the burden of the vestibular consequences of SRC, a variable was created to identify the role of vestibular specific symptoms. Symptoms known to be related to the vestibular system and identified in previous literature were used to evaluate the role of the specific symptoms and were identified as the PCSS-Vestibular score. These symptoms included headache, dizziness, nausea, visual problems, balance difficulties, and sensitivity to noise. This identifier variable was created based on symptoms reported in the PCSS, used solely for analysis. The severity for the six included symptoms were summed for a PCSS-vestibular total.

5.2.2.4 Vestibular Function
Patients were assessed by physical therapists for follow-up or potential vestibular rehabilitation. It is unknown whether all participants completed a vestibular rehabilitation program. Among the assessments were objective measures of dynamic visual acuity, gaze stability, and balance. Timing of all assessments was at the discretion of the physical therapist.

Dynamic visual acuity was measured via the Dynamic Visual Acuity (DVA) Test utilizing the Bertec® Vision Advantage™ system (Bertec Corporation, Columbus, OH). The patients were seated 5-feet away from a laptop screen and equipped with a mounted headpiece with an inertial measurement unit, measuring the velocity of head movements. The physical therapist passively moved the patients head from left to right, in a sweeping motion within the yaw plane at a standard velocity of 100 deg/sec. The patients were instructed to maintain their gaze on the screen and identify the direction of an “E” that would appear in varying sizes on the screen, either left, right, up, or down. The physical therapist would record responses until the software identified the smallest optotype, or sized “E”, in which the patient could maintain accuracy. If patients were unable to complete the test due to provocation of symptoms, this was noted. Similarly, if testing provoked symptoms, but the patient was still able to complete the test, this was also noted.

The Gaze Stabilization Test (GST) utilized the same methods as the DVA however, the GST software would increase the velocity of the head movements based on the patient’s response. The physical therapist recorded responses until the software identified the fastest velocity where patients could maintain accuracy in both leftward and rightward directions. For each variable, the performance on the test was utilized as well as day to successful completion of each test. For the DVAT, performance was measured in LogMAR units for the best achieved optotype and lines lost for, when compared to static visual acuity (SVA) in each direction. The maximum achieved velocity for head rotations in each direction was the recorded performance measure for the GST recorded in deg/sec.
Balance was measured via four conditions from the COBALT performed on the Bertec Portable Essential dual balance force plate (Bertec Corporation, Columbus, OH) which measured sway velocity (deg/sec). All conditions were completed in double limb stance, barefoot, on either a firm or foam surface (Table 5.1, Figure 5.1). The conditions included two tasks on a firm surface, an eyes closed, head shake task (Condition 3) and a visual motion sensitivity task with a trunk twist in a sweeping motion and arms extended (Condition 4). The two conditions (3 and 4) are repeated on a foam pad (Conditions 7 and 8 respectively). Foot placement was specified for each of the conditions; for Conditions 3 and 7, foot position was marked on the force plate based on height, for conditions 4 and 8, feet were placed together at the center of the force plate where the left and right plates met. For conditions that required head turns (3 and 7), participants were equipped with a headlamp that was used to measure excursions on a wall chart marked with the appropriate distancing. The force plate was positioned a standardized distance from the way and wall chart to maintain consistency. For each condition, a metronome was used to maintain the specified head turn velocity.

These conditions were utilized based on the demands they place on the vestibular system. Additionally, the balance tasks incorporated in these conditions better simulate the demands on balance in sport. The physical therapist administering the assessment recorded errors based on subjective observations of the patient. Errors included; lifting hands off hips, opening eyes during an eyes closed trial, stepping off force plate or moving feet from starting position, or the inability to maintain action with beat of the metronome for two or more consecutive beats. Participants attempted to complete two, 20-second trials of all four conditions. The outcomes included in the analysis for COBALT included average sway velocity and average counted errors for each condition and the number of days to successful completion of the four conditions.

5.2.2.5 Recovery Time
Recovery time was defined as the time from injury to the time of medical clearance by the treating physician, measured in days. As reported in previous literature,²⁰,¹⁰⁴ the variable was created by subtracting the date of injury from the date of medical clearance. The physician made decisions on medical clearance based on the consensus guidelines, after evaluating symptom reports, and reviewing results of other clinical measures.

5.2.3 Statistical Analysis

Descriptive statistics including means, standard deviations, medians and interquartile ranges were used with all continuous variables. Descriptive statistics for all categorical and dichotomous variables were presented as frequencies or percentages. Pearson’s correlations were used to determine if significant relationships existed between any of the independent variables and the dependent variable, time to recovery. Continuous variables that demonstrated significant relationships were plotted using scatterplots to provide a visualization of the data and ensure significant relationships were not a consequence of outliers. Variables with significant relationships to time to recovery were entered into a forward linear regression model against time to recovery. Additional demographic variables reported in the literature and known to effect concussion recovery were also included in the model. These variables included sex (male/female), age (years), history (yes/no) and number of previous concussions (0, 1, 2 or more), time since previous concussion (0-6 months, 7-12 months, greater than 12 months), loss of consciousness (yes/no) or amnesia (yes/no), and sport participation (football, soccer, basketball, hockey, softball, cheerleading, other). Alpha was set a priori at $p \leq 0.05$. All statistical analyses were performed using IBM SPSS Statistics Version 25 (IBM, Corp., Armonk, NY, USA).
5.3 Results

5.3.1 Participants

Of the 180 patients seen at the clinic, 159 were seen from injury through medical clearance and assessed for eligibility. Nineteen patients were excluded for being outside the age range at the time of injury. A total of 127 were excluded as they did not include one or more of the objective vestibular assessments. Thirty-four (19%) patients met the eligibility criteria and were included in the exploration and analysis. (Figure 1). The included group of patients (21 males, 11 females) had an average age of 15.34 ± 1.47 years (range: 14-20 years) and represented 7 sports both contact (3) and non-contact (3). Within the included patients, 15 self-reported a history of concussion; 3 reported a history of 2 or more. Of those with a history of concussion, 2 experienced a concussion within the last 6 months, 4 reported a concussion within the last 7-12 months and 7 reported suffering a concussion over 12 months prior.

5.3.1.1 Presentation

As summarized in Table 2, the average time from injury to the initial visit was 5.97 ± 3.71 days with a range from 0-32 days. All patients were referred for vestibular testing following clinical evaluation by the sports medicine physician. The average symptom severity reported upon presentation was 40.56 ± 20.76 and PCSS-Vestibular of 11.69 ± 5.81. With the current injury, three patients reported a loss of consciousness and seven reported amnesia at the time of injury. Pearson’s correlations demonstrated moderate to good relationships between days to recovery and the number of days from injury to initial visit (r=0.46, p=0.01), and number of total visits (r=0.79, p=0.00).

5.3.1.2 Clinical Outcomes
Of the 32 patients referred for vestibular follow-up, all patients completed the COBALT assessment, 31 completed the GST, and 28 completed the DVAT. Eleven of the 32 patients who completed the COBALT were unable to complete the test on their first attempt while 20 experienced post-traumatic dizziness as a result of the testing on their first attempt, regardless of completion.

Pearson’s correlations demonstrated moderate to good relationships between days to recovery and DVAT lines lost in the leftward direction (r=0.39, p=0.04), COBALT Condition 8 sway velocity (r=0.44, p=0.01), and days to successful completion of the COBALT (r=0.63, p=0.00).

5.3.1.3 Linear Regression for Recovery Time

Variables that demonstrated significant relationships with time recovery (days to initial visits, number of total visits, DVAT lines lost to the left, COBALT Condition 8 sway velocity and days to successful COBALT completion) were plotted against time to recovery to ensure that correlations were not a result of an outlier and check for linear relationships. Additionally, multicollinearity was assessed within the variables. A multiple linear regression was calculated to predict time to medical clearance based on the included variables. All variables were identified to have true correlations and were entered into the linear regression in a forward fashion. A significant regression equation was found (F(3,24)=43.54) p<0.000) with an R² of 0.85. Participants' predicted time to recovery was equal to -7.603 + 0.320 (days to COBALT) + 0.974 (days to initial visit) + 6.764 (number of visits) where days to COBALT and initial visit were measured in days and number of visits was measured as a count. The number of days to clearance increased 6.764 days for each additional visit, 0.974 days for every day until initial visit, and 0.32 for days until COBALT completion. The overall model was significant (p<0.020, R²=0.85). No other variables were retained in the final regression model.
5.4 Discussion

The current study sought to identify predictors of time to recovery following SRC in high school and collegiate aged athletes, referred for vestibular follow-up. Different measures of vestibular function and self-reported function were used to understand the population and explore potential factors influencing time to recovery. We hypothesized that a combination of greater vestibular symptoms, poorer performance on assessments of vestibular function, and contextual factors would be predictive of time to recovery. The data suggested that the factors that predict time to recovery included; the number of days from injury to successful completion of the COBALT, the number of total visits to the clinic, and time from initial visit to visit to the clinic. Together, this combination of factors may help clinicians identify patients who are prone to prolonged recovery when vestibular involvement is suspected following SRC.

In the current study, time from initial injury to the time of initial visit to the clinic was associated with the time to recovery, suggesting those who reported to the clinic earlier had better outcomes. A previous investigation by Kontos et al., sought to examine the association between time from injury and initial clinical care to recovery time. In this investigation, the group of patients with “late” visits, 8 to 20 days following injury, were 5.8 times more likely to experience a recovery greater than 30 days than their counterparts who received care in the first 7 days following injury. The group who sought care earlier recovered an average of 20 days sooner than those who delayed clinical care. This has large clinical implications as this suggests that time to recovery could largely be influenced through clinical care, a largely modifiable factor that could improve overall outcomes. The earlier an individual is evaluated by a healthcare professional, the earlier a plan of care can be made. Additionally, any deficits or needs for intervention can be identified and appropriate referrals can be made. Those who receive care earlier and can be referred to other healthcare professionals to provide necessary care or rehabilitation may also receive more care through additional visits to the various providers. The
total number of visits from initial visit to the visit in which the patient was medically cleared, was a predictor of recovery time. Thus, the more visits to the clinic necessary, the longer the time to medical clearance. As visits were not clarified by type of visit, we cannot say whether or not the patients who had higher number of total visits were attending visits with the physical therapist to receive an intervention or if each of the visits were visits to see the physician. Thus, it is possible that number of visits is an indirect indicator of concussion severity.

Among the most novel findings from this study were those involving COBALT results. Time to a successful completion of all four conditions of the COBALT was included in the final model for predicting time to recovery. Despite a correlation between time to recovery and the sway velocity on Condition 8, there were no performance measures included in the final model. This suggests that the whether or not a patient was able to perform the test, without a provocation of symptoms was a strong indicator of recovery to the healthcare professionals in this particular clinic. As a new and novel assessment strategy, there are limited clinically accessible guidelines for the utilization and interpretation of sway scores. Identifying a better method of interpretation may provide a more direct way of determining if this variable plays a larger role as a factor in defining recovery. Having baseline scores to use as comparison post-injury to identify deficits would be considered the best way to measure post-injury performance. There have been many tests utilized as post-concussion assessment strategies however, this assessment provides a higher challenge to the vestibular system. Previous methods of measuring post-concussion balance have identified balance deficits but they are not likely sensitive enough to detect subtle deficits. The completion of the COBALT task without symptom provocation may be an indication of recovery of the vestibular system as it incorporates the sensory integration and additional challenge on the system in a dynamic manner. In a population already experiencing vestibular related symptoms, they may resolve and no longer be an issue in daily activities however with the demands of this
clinical assessment, clinicians may be able to identify recurrence of symptoms, indicating true recovery has not been achieved.

Previous reports demonstrate that balance impairments following concussion; measured by the BESS, resolve to baseline levels within three days for the firm conditions and five days for the foam conditions. Similarly, the Sensory Organization Test has detected balance deficits day one following SRC compared to baseline performance as well as matched controls, however, recovery occurred between days 1 and 3 for the concussed group. Significant differences were demonstrated days 3 and 5 between the SRC and control group, however, by this point, the SRC group had returned to baseline levels of performance. These assessment strategies have been used to assess balance following SRC however, there is evidence to suggest that balance impairment are present following clinical recovery, up to two months, measured through more difficult assessment strategies such as dual task gait and balance exercises. The additional challenges presented by the COBALT may provide a manner of assessing and detecting deficits that persist beyond clinical recovery.

Despite a weak correlation between DVAT lines lost leftward and time to recovery, there were no other relationships between performance on DVAT and GST as well as symptom severity. DVAT lines lost in the leftward direction did not remain in the model, thus, none of these variables are significant predictors of time to recovery. Additionally, contrary to previous literature, sex, history of ADHD, depression, and learning disabilities did not have an effect on the time to recovery. It is highly probable that the performance variables may have been predictive if these factors were contextualized and better interpreted.

There has been movement towards including objective vestibular assessments in the evaluation of SRC, however, there is limited understanding of how these measures change throughout recovery and their potential to predict the time to recovery following SRC. Despite suggestions to utilize these assessments, there is a lack of understanding for their true clinical
utility. In addition, there is foundational information that could strengthen the interpretation of these variables and ensure that all factors are truly representative of their role in recovery. To best interpret the variables that may influence recovery, it is imperative to determine cut off scores for each performance measure to truly define what constitutes a true deficit and to better clarify the interpretation. Additionally, understanding how these performance variables are affected by different characteristics such as sex, sport, concussion history, or medical conditions is important to be able to properly understand what performance may look like for different groups. This information is especially important when baseline data is not available, as in the current evaluation. However, this is the first study to our knowledge that examines objective measures of vestibular function as potential predictors of recovery time.

5.4.1.1 Limitations

The nature of this exploratory, retrospective cohort study presents many inherent limitations. Patients who presented at the clinic may have already been representative of those at risk for prolonged recovery or were experiencing more complications or consequences of the SRC. This may impact the generalizability of the results. However, this sample provided a very unique opportunity to examine the role of vestibular symptoms and function using the contemporary measures in a real-world clinical setting. Additional limitations exist surrounding the format of the clinical data. The patients included in the sample were patients whose charts were deemed complete based on the variables observed in this sample. Therefore, this study was subject to several of the limitations in retrospective cohort studies including missing data and the inability to include all patients because they lacked the data of interest. Additionally, as this study was retrospective in nature, the measures were not systematically collected and timing for each varied from patient to patient and therefore results must be interpreted with caution. Despite these limitations, this study provides strong support for future prospective studies which can further pursue this research in similar patient populations.
5.5 Conclusion

This research study contributes to our field in several ways. Evaluating factors that influence time to recovery in individuals post-SRC is a step towards improved practice and management strategies. Predictors of time to recovery in adolescent and young adult athletes reporting to a concussion clinic following SRC with suspected vestibular involvement included; the time from injury to initial visit, the number of total clinic visits, loss of consciousness at the time of injury, and the time to successful completion of the COBALT. The identified factors that are modifiable may aid in improving outcomes following SRC. To continue to improve care, using these identified factors to implement a systematic collection of the variables in post-SRC populations could strengthen the data suggested in this exploratory study. Additionally, more challenging assessments may be required to assess deficits or function that may not be reflected in previously utilized assessment strategies.
Table 5-1 COBALT Included Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Eyes:</th>
<th>Foot Placement:</th>
<th>Arm/Hand Placement</th>
<th>Surface:</th>
<th>Head Shake/Rotation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Closed</td>
<td>Feet apart- at appropriate markers</td>
<td>Hands on iliac crests</td>
<td>Firm</td>
<td>Participant rotates their head side to side at 30° each direction with a metronome set at 120 bpm with the goal of achieving a 60° sweep each direction, to the beat</td>
</tr>
<tr>
<td>4</td>
<td>Open-fixed on thumbs in front</td>
<td>Feet together at center of plate</td>
<td>Hands clasped and thumbs together, arms outstretched in front of body</td>
<td>Firm</td>
<td>Participant completes a rotation at the torso from side to side at 30° each direction to the beat of the metronome at 40 bpm</td>
</tr>
<tr>
<td>7</td>
<td>Closed</td>
<td>Feet apart- at appropriate markers</td>
<td>Hands on iliac crests</td>
<td>Foam</td>
<td>Participant rotates their head side to side at 30° each direction with a metronome set at 120 bpm with the goal of achieving a 60° sweep each direction, to the beat</td>
</tr>
<tr>
<td>8</td>
<td>Open-fixed on thumbs in front</td>
<td>Feet together at center of plate</td>
<td>Hands clasped and thumbs together, arms outstretched in front of body</td>
<td>Foam</td>
<td>Participant completes a rotation at the torso from side to side at 30° each direction to the beat of the metronome at 40 bpm</td>
</tr>
</tbody>
</table>
Table 5-2 Descriptive Statistics of Demographic Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Descriptive Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>15.34 ± 1.47</td>
</tr>
<tr>
<td>Sex (m/f)</td>
<td>21/11</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>68.37 ± 15.47</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>171.29 ± 8.44</td>
</tr>
<tr>
<td>Sport (n)</td>
<td>Football (15)</td>
</tr>
<tr>
<td></td>
<td>Soccer (8)</td>
</tr>
<tr>
<td></td>
<td>Basketball (1)</td>
</tr>
<tr>
<td></td>
<td>Hockey (3)</td>
</tr>
<tr>
<td></td>
<td>Softball (1)</td>
</tr>
<tr>
<td></td>
<td>Cheerleading (2)</td>
</tr>
<tr>
<td></td>
<td>Other (2)</td>
</tr>
<tr>
<td>Medical History (n)</td>
<td>Anxiety/Depression (1)</td>
</tr>
<tr>
<td></td>
<td>ADD/ADHD (3)</td>
</tr>
<tr>
<td></td>
<td>Other (1)</td>
</tr>
<tr>
<td>Previous Concussions (n)</td>
<td>None (19)</td>
</tr>
<tr>
<td></td>
<td>1 (10)</td>
</tr>
<tr>
<td></td>
<td>2 or more (3)</td>
</tr>
<tr>
<td>Time Since Previous Concussion (months)</td>
<td>0-6 months (2)</td>
</tr>
<tr>
<td></td>
<td>7-12 months (4)</td>
</tr>
<tr>
<td></td>
<td>&gt;12 months (7)</td>
</tr>
<tr>
<td>Time to Initial Visit (days)</td>
<td>5.97 ± 3.71 (0-32)</td>
</tr>
</tbody>
</table>
Table 5-3 Descriptive stats for all presentation variables and their correlation to days to recovery

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
<th>Pearson’s correlation</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days to Initial Visit</td>
<td>5.97 ± 3.71 (0-32)</td>
<td>0.46*</td>
<td>0.01</td>
</tr>
<tr>
<td>Total Number of Visits</td>
<td>3.62 ± 1.26 (2-7)</td>
<td>0.79*</td>
<td>0.00</td>
</tr>
<tr>
<td>Number of Previous Concussions</td>
<td>0.69 ± 1.26 (0-6)</td>
<td>-0.07</td>
<td>0.69</td>
</tr>
<tr>
<td>Months Since Previous Concussion</td>
<td>27 ± 24.94 (6-96)</td>
<td>0.23</td>
<td>0.44</td>
</tr>
<tr>
<td>PCCS- Symptom Severity</td>
<td>40.59 ± 20.76 (5-99)</td>
<td>0.05</td>
<td>0.79</td>
</tr>
<tr>
<td>PCSS- Vestibular Symptom Severity</td>
<td>11.69 ± 5.81 (0-25)</td>
<td>0.07</td>
<td>0.71</td>
</tr>
<tr>
<td>Age</td>
<td>15.34 ± 1.47 (14-20)</td>
<td>-0.33</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Table 5-4 Descriptive statistics for all performance variables and their correlation to days to recovery

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
<th>Pearson’s correlation</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVAT-R (Acuity)</td>
<td>0.09 ± 0.11 (-0.07-0.42)</td>
<td>-0.02</td>
<td>0.90</td>
</tr>
<tr>
<td>DVAT-R (Lines Lost)</td>
<td>1.50 ± 1.07 (0.2-5)</td>
<td>0.12</td>
<td>0.56</td>
</tr>
<tr>
<td>DVAT-L (Acuity)</td>
<td>0.06 ± 0.07 (-0.05-0.28)</td>
<td>0.32</td>
<td>0.10</td>
</tr>
<tr>
<td>DVAT-L (Lines Lost)</td>
<td>1.17 ± 0.52 (0.2-1.17)</td>
<td>0.39*</td>
<td>0.04</td>
</tr>
<tr>
<td>GST-R</td>
<td>190.16 ± 46.18 (125-300)</td>
<td>-0.24</td>
<td>0.20</td>
</tr>
<tr>
<td>GST-L</td>
<td>200.6 ± 45.91 (130-300)</td>
<td>-0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>GST Asymmetry</td>
<td>29.35 ± 21.40 (0-95)</td>
<td>-0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>COBALT-Condition 3 (Sway Velocity)</td>
<td>0.37 ± 0.10 (0.23-0.65)</td>
<td>0.10</td>
<td>0.58</td>
</tr>
<tr>
<td>COBALT-Condition 3 (Errors)</td>
<td>0.09 ± 0.39 (0-2)</td>
<td>0.00</td>
<td>0.99</td>
</tr>
<tr>
<td>COBALT-Condition 4 (Sway Velocity)</td>
<td>0.88 ± 0.19 (0.53-1.24)</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td>COBALT-Condition 4 (Errors)</td>
<td>0.19 ± 0.59 (0-3)</td>
<td>0.26</td>
<td>0.15</td>
</tr>
<tr>
<td>COBALT-Condition 7 (Sway Velocity)</td>
<td>0.94 ± 0.26 (0.60-1.72)</td>
<td>-0.04</td>
<td>0.81</td>
</tr>
<tr>
<td>COBALT-Condition 7 (Errors)</td>
<td>1.03 ± 1.36 (0-6)</td>
<td>0.02</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table 5-4 Descriptive statistics for all performance variables and their correlation to days to recovery - Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD (Range)</th>
<th>Correlation</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>COBALT-Condition 8 (Sway Velocity)</td>
<td>1.20 ± 0.18 (0.89-1.50)</td>
<td>0.44*</td>
<td>0.01</td>
</tr>
<tr>
<td>COBALT-Condition 8 (Errors)</td>
<td>0.38 ± 0.49 (0-1.5)</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>COBALT Total Errors</td>
<td>2.28 ± 2.36 (0-8)</td>
<td>0.06</td>
<td>0.73</td>
</tr>
<tr>
<td>Days to COBALT Completion</td>
<td>14.72 ± 8.35 (0-40)</td>
<td>0.63*</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 5-5 Descriptive statistics of performance variables

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Days to Completion</th>
<th>Abnormal</th>
<th>Symptom Severity</th>
<th>Vestibular Symptom Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acuity (LogMAR)</td>
<td>0.09 ± 0.11</td>
<td>17.36 ± 4.85</td>
<td>14.60 ± 12.69</td>
</tr>
<tr>
<td>Left</td>
<td>Lines Lost</td>
<td>1.50 ± 1.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DVAT (n=28)</td>
<td>Acuity (LogMAR)</td>
<td>0.06 ± 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Lines Lost</td>
<td>1.17 ± 0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left (deg/sec)</td>
<td>190.116 ± 46.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GST (n=31)</td>
<td>19.19 ± 6.86</td>
<td></td>
<td>Post-Traumatic Dizziness (1)</td>
<td>9.85 ± 8.00</td>
</tr>
<tr>
<td>Right (deg/sec)</td>
<td>200.16 ± 45.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5-5 Descriptive statistics of performance variables – Continued

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sway Velocity (deg/sec)</th>
<th>Errors</th>
<th>Post-Traumatic Dizziness (n)</th>
<th>Sway Velocity (deg/sec)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.37±0.10</td>
<td>0.09±0.39</td>
<td></td>
<td>0.88±0.19</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.88±0.19</td>
<td></td>
<td></td>
<td>0.94±0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.03±1.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.20±0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.38±0.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14.74±8.35</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>7.44±5.17</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25.00±17.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(11)</td>
<td></td>
</tr>
<tr>
<td>COBALT (n=32)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-1 Flow diagram of patients included in analysis

Assessed for Eligibility (n=180)

Excluded (n=146)
Outside of age range at time of injury (n=19)
Did not complete one or more objective assessment (n=127)

Included in analyses (n=32)

Completed COBALT (n=32)

Completed GST (n=31)

Completed DVAT (n=28)
Figure 5-2 COBALT Included Conditions

Eyes Closed, Head Shake (60°, 120 bpm)

Eyes Open, Torso Rotation (60°, 40 bpm)
CHAPTER 6  CONCLUSION

The primary purpose of this dissertation was to explore the effects of vestibular consequences following SRC on outcomes following injury. To best achieve this aim, additional studies were completed with the purpose of defining and better understanding vestibular function in a healthy, athletic population, and how these variables interact with one another to better inform clinical decision making in the event of an SRC. The specific outcomes for the included studies were:

Specific Aim 1: To establish normative values for the DVAT and GST in collegiate athletes and explore the effect of sport, sex, and concussion history on VOR assessments. It was hypothesized that differences in GST performance would exist between sex, sport, and concussion history.

Specific Aim 2: To identify if a relationship exists between the Concussion Balance Test (COBALT), Dynamic Visual Acuity Test (DVAT), Gaze Stabilization Test (GST), and self-reported vestibular symptoms in collegiate athletes with and without a history of concussion.

Specific Aim 3: To explore the relationship between self-reported vestibular symptoms and acute performance on the COBALT and GST and the time to medical clearance in adolescent and young adult athletes who have sustained a recent concussion. It was hypothesized that there would be a relationship between self-reported vestibular symptoms, performance on objective measures of vestibular function and the time to medical clearance. Specifically, the greater the amount of self-reported vestibular symptoms, and poorer performance on the objective measures of vestibular function will be correlated with longer times to medical clearance.
6.1 Summary

Each of the included studies yielded unique results to provide evidence regarding vestibular function and SRC to drive clinical practice:

In exploration of the first, we sought to define normative estimates of vestibular function relative to the VOR in healthy Division I Collegiate athletes. Additionally, we explored the differences in performance based on sex, sports participation and concussion history to better understand factors that may influence performance or affect function. The results of this investigation provided normative estimates for vestibular function via the DVAT and GST in 124 athletes from 3 unique sports. Within the cohort, we were able to identify that sport-specific differences in performance were identified. More specifically, cheerleading achieved higher velocities on the GST in both the leftwards and rightward directions. There were no significant differences in performance based on sex or concussion history. Thus, it was concluded that using normative estimates for the DVAT and GST may assist in the clinical interpretation of outcomes when used in post-concussion evaluation for collegiate athletes. Although sex and previous concussion history had no effect on the DVAT or GST, performance on these measures may be influenced by sport type. These differences may be driven by the nature or requirements of the sport. Therefore, when evaluating an athlete following SRC and making clinical decisions regarding return to participation, it is important to take into account the activities in which the athlete is returning to in order to ensure any potential deficits in function have resolved and the individual is able to achieve levels necessary for their sport or activity.

The secondary aim sought to expand upon the previous aim to investigate the relationships between measures of vestibular function and self-reported symptoms with the ultimate goal of providing evidence to guide clinical management of SRC with vestibular consequences. Through a cross-sectional design, 135 Division I collegiate athletes participated in the study and completed measures of VOR and VSR function in addition to completing a self-
The results demonstrated weak to moderate relationships between GST and counted errors on the COBALT. These relationships were seen in GST in the leftward direction and errors in the two foam conditions of the COBALT (7 and 8) as well as the overall total errors. GST in the rightward direction demonstrated the same correlations but additionally was correlated to the firm COBALT conditions as well (3 and 4). Of note, there were no significant correlations between function and self-reported symptoms. The lack of strong and significant relationships provide evidence to support the belief that these assessment strategies are assessing different mechanisms and functions of the vestibular system, through the isolation or challenge of the VOR and VSR. Additionally, self-reported symptoms do not provide information regarding more specific and intricate functions of the vestibular system and may not be the best mechanism for assess whether or not the system has been compromised. Thus, utilization of one single mechanism for assessing may not provide clinicians with the necessary information to understand the full picture of the injury and a multifaceted assessment strategy should be utilized in the evaluation of SRCs in order to make the best clinical decisions.

Finally, through the third aim, we sought to understand the role of these deficits in the process of recovery in individuals who have been recently diagnosed with an SRC. Within a cohort of 32 individuals, diagnosed with an SRC and treated at a concussion clinic, there were good correlations between the number of days to recovery and the number of days from injury to initial visit to the clinic, the number of total visits to the clinic, the days to a successful completion of the COBALT test, and the average sway velocity on Condition 8. A multivariate analysis identified predictors of recovery time. Among the identified predictors were days to successful completion of COBALT, number of total visits, and days to initial visit to the clinic.

6.2 Future Research

The investigation and completion of the aims described, provides information relative to vestibular function following SRC, building on an area that is currently limited. In addition, the
work conducted provided a path for future research and identified questions to build on the foundational work. Based on the novelty of the measures used in this dissertation, it is crucial that it be confirmed that these assessment strategies be successful in measuring function in these populations and the psychometric properties. Among the identified as an area of exploration was the need for a prospective investigation of vestibular function following SRC and the recovery trajectory. The natural progression for improving standard of care in this population would be to identify rehabilitation strategies to assist in mitigating the factors that predispose individuals to prolonged recoveries and improving vestibular function.

A necessary next step is to evaluate the psychometric properties and define cutoff scores to better understand the efficacy of these measures and strategies in a concussed population. Exploring the reliability of the DVA, GST, and COBALT will help strengthen the argument to use these tools in this population. While these properties have been explored in healthy and athletic populations, it is important to understand the assessments relative to an SRC population. Additionally, assessing the validity provides a stronger understanding for the uses of the tool or what the clinical utility compared to other, older, methods of assessment. Determining a value of the minimal detectable change of the measures will be pivotal in the clinical translation of these strategies as it will provide a clear definition of impairment or conversely, recovery. A test-retest design in individuals who have suffered an SRC would be the basis for answering the questions regarding the psychometric properties. In designing this experiment, it is important to follow the timelines described in previous literature as those times that have been identified as crucial time points in the recovery following SRC.

The careful design of a prospective study could provide many answers to build on the foundational work provided. Based on the demonstrated importance for understanding factors that influence baseline performance on the described assessment tools, beginning with baseline measures would strengthen the analysis. Additionally, there is plenty of evidence to suggest that
the vestibular system is affected following SRC. When an individual has suffered an SRC, repeating the same battery of measurements, to not only identify if impairments exist, but where. This would allow for change over time to be explored as well as correlations within the measures in a truly clinical population. Following individuals overtime, from injury, to participation, through standard of care treatment, would provide information relative to the recovery of these systems and data to demonstrate whether or not these systems have recovered at the time of normal return to participation. When complete, the data may be examined to better understand the influence of the vestibular system and recovery.

Finally, with an understanding of the measures within an SRC population and applying these measures to a prospective analysis, we may be able to understand areas in which interventions may be used to improve outcomes for individuals following SRC that have been identified to be at risk of prolonged recovery. The literature suggests that these individuals in particular are at an increased risk for poor outcomes.\textsuperscript{15,40,41,68} Utilizing these tools as intervention strategies may improve outcomes for those who were not identified for at risk, but generally elevating the current standard of care.
REFERENCES


63. Sufrinko AM, Marchetti GF, Cohen PE, Elbin RJ, Re V, Kontos AP. Using Acute Performance on a Comprehensive Neurocognitive, Vestibular, and Ocular Motor


86. Alpini D, Botta M, Mattei V, Torinese D. Figure ice skating induces vestibulo-ocular adaptation specific to required athletic skills. *J Sport Sciences for Health*. 2009;5(3):129-134.


89. LM. N. Gaze stabilization test scores of professional athletes In: Clackamus O, ed2007.


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Education

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Scholarship

Peer-Reviewed Publications


Morelli N, Heebner NR, Bergin RT, Quintana C, Hoch MC. The effect of cognitive dual-tasks on dynamic postural sway during gait using inertial measurement units. Physiological Measurement. (Accepted).


Peer-Review Published Abstracts


Honors and Awards

- Lyman T. Johnson Diversity Fellowship Recipient, University of Kentucky Graduate School [Fall 2018-Spring 2020]
- 2020 Dr. Benjamin Nero Student Inclusive Excellence Award Nominee, University of Kentucky’s Center for Graduate and Professional Diversity Initiatives and the Graduate School’s Office of Diversity [Spring 2020]
- District 9- Bobby Barton Scholarship Recipient, National Athletic Trainer’s Association Research and Education Foundation [Spring 2019]
- Professional Development Funds Award Winner, University of Kentucky Center for Graduate and Professional Diversity Initiatives [Spring 2018]
- College of Health Sciences’ Enhancement Scholarship, University of Kentucky College of Health Sciences [Fall 2017 and 2018]
- 2016 International Society of Neurogastronomy Travel Grant Award Recipient, National Institutes of Health [Fall 2016]
- Academic and Leadership Graduation Stole Recipient- Hispanic Faculty/Staff Caucus, New Mexico State University [Spring 2015]
- New Mexico State University Athletic Trainer of the Year [Spring 2015]
- Athletic Training Education Program Distinguished Senior, Northern Arizona University College of Health and Human Services [Spring 2013]
- Michael E. Nesbitt Sports Medicine Scholarship, Northern Arizona University Blue and Gold Association [Spring 2012]