THE EFFECT OF RECENT CONCUSSION ON BALANCE DURING SINGLE AND DUAL TASKS IN ADOLESCENTS

by

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Purpose: Returning to normal activity without full recovery from concussion may make athletes with concussion more susceptible to a second more severe concussion. Dual-task balance testing has been suggested to provide better assessment of when to return to normal activity. The purpose was to explore changes during single and dual-task balancing conditions over time and to compare sway between adolescents with and without Sports-related Concussion (SRC).

Participants: 25 adolescents (mean age 15.1±1.9 y) with SRC within the past 10 days and 22 matched controls (mean age 15.9±2.1 y).

Materials/Methods: Adolescents with SRC were assessed 3 times: within 10 days of injury, within 14-27 days after injury, and when cleared from concussion. Controls were assessed once. Sway was assessed using a force plate while subjects stood feet-apart on firm or foam surfaces. Balance tests were performed under single-task (without cognitive-task) and dual-task conditions (with cognitive-task). The cognitive-task was a visual reaction time test where adolescents pressed a thumb-switch that either corresponded to the side of the monitor where a rectangle appeared (simple cognitive-task), or corresponded to the direction an arrow was pointing that appeared on either side of the monitor (complex cognitive-task). The dependent variables were the root mean square (RMS) and the normalized path length (NPL) of the sway. A linear mixed model was performed to investigate the main effects and interactions of group, visit, dual-task, cognitive-task, and surface on sway.

Results: The main findings were: no difference in sway between the SRC and control groups; no difference in sway among visits in the SRC group; a dual-task effect that produced reduced NPL sway and greater RMS sway compared with the single-task; increased RMS sway during the perceptual inhibition task compared with the spatial discrimination task; and increased sway during the foam conditions compared with firm surface, which was dependent on the subject groups.

Conclusions: Contrary to previous research, no differences in balance performance were observed between groups with and without SRC, or over time in adolescents with SRC, indicating that the type of dual-task may be an important factor in assessing return to normal activity.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Concussion was defined by the Consensus Statement on Concussion in Sport held in Zurich in 2012 as "a complex pathophysiological process affecting the brain, induced by biomechanical forces" [1]. The Centers for Disease Control and Prevention declared concussion a serious health concern. Concussion is the most common acquired neurologic disorder in children and young adults (NIH, 2002). The National Council on Youth Sports (NCYS) estimated that 44 million children and adolescents participate in organized sports in the United States each year [2]. There is an estimated 1.6 - 3.8 million sports related concussions annually in the United States [3]. Emergency department visits due to concussion showed an increase of 62% between 2001 and 2009 [4]. In a report to the Congress, the National Center for Injury Prevention and Control estimated that concussion costs the United States of America nearly $17 billion each year (NCIPC, 2003).

Concussion results in a constellation of physical, cognitive, emotional, and/or sleep-related symptoms that usually rapidly resolves spontaneously within a few days [1,5,6]. Physical symptoms of concussion include headache, dizziness, nausea, balance problems, visual problems, vomiting, fatigue, sensitivity to light, and sensitivity to noise. Physical signs of concussion include loss of consciousness (LOC) and amnesia. Cognitive symptoms include impaired concentration, impaired memory, confusion and fogginess. Emotional symptoms include sadness, nervousness and irritability. Sleep disorders include drowsiness, difficulty falling asleep and sleeping more or less than usual [1,5,7,8]. Headache is the most frequently reported symptom of concussion, occurring in

94% of athletes with concussion. Other frequently-reported symptoms include balance problems (79%), dizziness (75%), impaired concentration (54%), sensitivity to light (36%), and nausea (31%)[9,10]. The high prevalence of dizziness and balance problems after concussion motivates the study of vestibular function.

Concussion is considered among the most complex injuries in sports medicine to diagnose, assess, and manage[1]. Assessing concussion requires a multimodal investigation of symptoms, neuropsychological testing, and postural stability testing [1,5]. Cognitive functions and postural stability decline after concussion[10–16]. Consensus panels and concussion guidelines recommend the assessment of the cognitive functioning and postural stability after concussion[1,8].

Traumatic brain injury may compromise different parts of the vestibular system and may result in central and/or peripheral vestibular disorders [17]. Vestibular disorders are common in people with concussion [18,19]. The vestibular system aids in maintaining eye gaze with head movement and balance control. Balance maintenance requires the integration of information from the visual, somatosensory and vestibular systems. The Vestibulo-Ocular Reflex (VOR) maintains visual stability during head and body movement using a feedback mechanism. The vestibular system provides angular and linear acceleration feedback to the balance system via the vestibulospinal tract (VST) [20,21]. Toglia et al. found that 61% of 119 and 44% of 101 closed traumatic head injury patients aged 10 to 75 years had positive vestibular abnormality on caloric test and rotatory test respectively [22]. Davies and Luxon retrospectively investigated vestibular abnormalities after head injury in 100 subjects with vestibular symptoms that resulted from head injury. The severity of head injury was classified as minor in 72 subjects, moderate in 24 subjects, and severe in 4 subjects. They found that 73.6% of individuals with concussion had positive vestibular abnormality findings [23]. The 73.6% prevalence of vestibular abnormalities in individuals with concussion with post-traumatic dizziness reported by Davies and Luxon along with the 75% prevalence of dizziness in individuals with concussion reported by Marar et al. suggest a prevalence of vestibular disorders in individuals with concussion that ranges from 55% to 80% [9,23]. Although evidence suggests a relationship between head injuries and vestibular impairments, the prevalence of peripheral vestibular disorders after Sports-Related Concussion (SRC) is unknown. Furthermore, the change in peripheral vestibular dysfunction after concussion over time is yet to be explored.

Ocular motor impairments such as dizziness, headache, diplopia, increased visual motion sensitivity, eye tracking problems, eye focusing problems, and vision-derived nausea are common after concussion [24–26]. Mucha et al. developed the Vestibular/Ocular Motor Screening (VOMS) which is a brief clinical screening tool that assesses aspects of concussion impairments not included in other concussion assessment tools including vestibular and ocular motor impairments [26]. Balance problems are commonly reported and assessed after concussion [10,12,13,27]. Measuring postural stability is considered to be a part of comprehensive approach to concussion assessment and management [1,5]. Sports activities require high performance on cognitive and balance function simultaneously. In individuals with concussion, postural instability and gait imbalance returned to normal levels within 7-10 days of injury [1,5,8,28]. However, when postural and gait control tests are performed in conjunction with cognitive tasks (i.e. dual-task), they were found to elicit postural instability and gait imbalance in individuals with concussion that persist even after 7 days of the injury. [29,30] Furthermore some studies reported balance deficits months after injury when tested using dual-task paradigms [31–34]. Dual-task balance testing was proposed to be better tool to screen athletes with concussion for dysfunction. [35]

Furthermore, while evidence suggests age-related differences of postural stability and reported symptoms in individuals with concussion [28,36], few studies have focused on children and adolescents with concussion. Also, recent studies have shown that the inclusion of an attention-demanding task when performing postural and gait balance tests may reveal hidden balance impairment in individuals with concussion [30,32,37–39]. It is not clear how performance during single-task and dual-task balance tests relates to evidence of vestibular dysfunction in adolescents with sports-related concussion. Yardley et al. found decrements of balance when performed concurrently with a cognitive task in 48 patients with chronic (several months) vestibular disorders (mean age 47 years). When compared to 24 healthy controls, similar decrements of balance were found [40].

The purpose of this study was to estimate the prevalence of reduced Vestibulo-Ocular Reflex (VOR) function as assessed with the Video Head Impulse Test (vHIT) in adolescents with and without SRC and to investigate the relationship between VOR function and clinical balance tests and symptom provocation tests in adolescents with SRC. Furthermore, we explored changes in single and dual-task balance function in adolescents with and without SRC, using lab-based sway assessment tools (accelerometry and the force plate) and tracked adolescents with SRC over the course of recovery.

1.1 FIRST AIM

To assess VOR function in individuals with and without concussion using the vHIT, and to compare scores on the Balance Error Scoring System (BESS), and the VOMS with VOR gain in individuals with concussion.

1.1.1 First aim rationale

Although dizziness and imbalance are prevalent post-concussion in adults and children [9,10], the prevalence of peripheral vestibular disorders in general, and specifically head impulse test abnormalities after SRC in children is unknown. Furthermore, in individuals with concussion, it is not clear if abnormalities in head impulse testing relate to clinical signs and symptoms of dizziness and imbalance.

1.1.2 First aim hypotheses

1.1.2.1 First hypothesis

Individuals with concussion will have lower VOR gain during the vHIT than individuals without concussion.

1.1.2.2 Second hypothesis

Individuals with concussion will have more errors on the BESS, and greater symptoms increase on the horizontal VOR and the visual motion sensitivity test of the VOMS than individuals without concussion.

1.1.2.3 Third hypothesis

In individuals with concussion, greater VOR impairment as evident by reduced VOR gain using the vHIT, will correlate with an increased number of errors on the BESS, and increased symptoms on the horizontal VOR and the visual motion sensitivity test of the VOMS.

1.2 SECOND AIM

To assess postural sway changes during single-task and dual-task balance tasks in adolescents with and without sports-related concussion using lab-based sway assessment tools (accelerometry and the force plate).

1.2.1 Second aim rationale

Maintaining balance is an intrinsic function that normally does not require much cognition or attention. Although balance assessment is an essential part of concussion assessment [1], assessing balance in isolation of other attention demanding tasks may conceal existing balance deficits in individuals with concussion. However, inclusion of an attention demanding task when balancing may challenge the postural control system and reveal hidden balance impairment in individuals with concussion [30].

1.2.2 Second aim hypotheses

1.2.2.1 First hypothesis

Individuals with concussion will exhibit more sway than individuals without concussion. (Main effect of group on sway)

1.2.2.2 Second hypothesis

In all groups there will be more sway during the single-task balance test compared to the dual-task balance tests. (Main effect of single vs dual-task on sway)

1.2.2.3 Third hypothesis

The increased sway during the single-task balance test compared to the dual-task balance tests will be higher in the concussion group compared to the control group. (Group * single vs dual-task interaction on Sway)

1.2.2.4 Fourth hypothesis

In all groups there will be significantly increased sway as the cognitive-task increases in difficulty. (Main effect of cognitive-task on sway)

1.2.2.5 Fifth hypothesis

As the difficulty of the dual-task increases (from spatial discrimination to perceptual inhibition), there will be a larger increase in sway in the concussion group compared with the control group. (Group * cognitive-task interaction on sway)

1.2.2.6 Sixth hypothesis

There will be significantly increased sway while standing on foam compared to standing on a firm surface. (Main effect of surface on sway)

1.2.2.7 Seventh hypothesis

The increase in sway elicited while standing on a foam surface compared with the firm surface will be larger in the concussion group compared with the control group. (Group * surface interaction on sway)

1.3 THIRD AIM

To assess changes on clinical tests and lab-based sway assessment tools over time in adolescents with sports-related concussion.

1.3.1 Third aim rationale

Returning to normal activity without full recovery from concussion appears to make the concussed athlete more susceptible to a second more severe concussion [5]. Balance assessment should be used as a part of assessment and return-to-play decisions after concussion [1]. Most post-concussion sway assessment tools use clinician ratings to assess balance such as the BESS. However, dual-task balance assessment may provide a more valid test of the ability of individuals with SRC to perform higher-level activities. In a study on 94 collegiate athletes with concussion, balance problems found using BESS were resolved 3 days post-concussion [41]. Powers et al. measured Center of Pressure (COP) using a force plate on 9 athletes with concussion and 9 healthy athletes to investigate the effect of concussion on sway. They found greater sway in the concussion group compared to the healthy group. The elevated sway in the athletes with concussion was statistically significant even at the time of return to play clearance (mean number of days at clearance 26 days), which was based on reported symptoms and other gross balance and motor control assessments [42]. Although balance requires attention, performing a cognitive task and balancing simultaneously will stress resources and may be a reasonable method to test cognition and balance simultaneously [29]. In sports, especially contact sports, balance is maintained while the athlete's attention is challenged by focusing on goals other than maintaining balance. Inclusion of an attention demanding task when balancing may imitate sport situations and reveal hidden balance impairments that may exist for longer time periods in individuals with concussion [30]. Therefore, it may be valuable to use dual-task balance tests to assess recovery as part of the determination of return to play.

1.3.2 Third aim hypotheses

1.3.2.1 First hypothesis

Adolescents with a sports-related concussion will have fewer errors on BESS from the initial visit performed within 10 days of injury, to the second visit performed 4 - 17 days after the initial visit, to the clearance visit performed after clearance by the physician. (Main effect of visit on BESS in the concussion group)

1.3.2.2 Second hypothesis

Adolescents with a sports-related concussion will have less sway during the single and dual-tasks balance experiment from the initial to the clearance visit (Main effect of visit on sway in the concussion group).

1.3.2.3 Third hypothesis

In individuals with concussion, greater reduction in sway across visits will occur during the single-task compared with the dual-task tests (Interaction effect of visit * single vs dual-task on sway). Furthermore, the reduction in sway between visits will be greater in the spatial discrimination task compared with the perceptual inhibition task (Interaction effect of visit * cognitive-task on sway in the concussion group).

1.3.2.4 Fourth hypothesis

In individuals with concussion, the reduction in sway from initial visit to clearance visit will be less on the foam surface compared with the level surface. (Interaction effect of visit * surface on sway in the concussion group)

2.0 REVIEW OF LITERATURE

2.1 DEFINITION OF CONCUSSION

Concussion, as we know it today, was first described in the 10th century by Al-Razi (Muhammad Ibn Zakariya Al-Razi (AD 850-923)). Al-Razi in his book Al-Hawi (The Virtuous Life) described concussion as an “abnormal transient physiologic state without gross brain lesions” [43]. Al-Razi described management of concussion symptoms by avoiding physical and cognitive activities along with the use of some herbs (Al-Razi, 10th century).

The terms concussion and mild traumatic brain injury (mTBI) are often used interchangeably in the sporting context and particularly in the US literature [1]. Commotio cerebri is another term that is used by other countries, especially European countries, to describe concussion [1,44]. Here we will be using the term concussion as an equivalent to the term mild traumatic brain injury (mTBI).

Concussion was defined by the Consensus Statement on Concussion in Sport held in Zurich in 2012 as "a complex pathophysiological process affecting the brain, induced by biomechanical forces" [1]. Concussion is a brain injury that has several common features including: a blow or acceleration to the head or the body with force transmitted to the brain; acute neurological dysfunction that resolves spontaneously within a few seconds to a few hours; a neuropathophysiological cascade affecting the functionality of the brain rather than the brain structures as seen on standard neuroimaging techniques such as a Computed Tomography (CT) scan and Magnetic Resonance Imaging (MRI); clinical and physical symptoms and signs, cognitive dysfunction, behavioral changes, and sleep disorders [1]. The American Medical Society for Sports Medicine (AMSSM) defines concussion as “a traumatically induced transient disturbance of brain function and is caused by a complex pathophysiological process”. According to the AMSSM, concussion is the mildest form of traumatic brain injury [5].

Concussion is considered among the most complex injuries in sports medicine to diagnose, assess, and manage [1]. Concussion is a clinical diagnosis that is based largely on the observed injury mechanism, signs, and symptoms, which varies considerably among athletes. Concussive brain injury results in neurochemical and neurometabolic cascades that put the brain in an energy crisis. The energy crisis results from an imbalance between energy supply and demand [45]. The increased energy demand is driven by the activation of the sodium-potassium (Na^+-K^+) pump, which requires adenosine triphosphate (ATP) (i.e. energy), to restore the disrupted brain homeostasis. The disruption of the brain homeostasis is caused by the diffuse axonal injury which includes axonal stretching, neuronal membrane disruption and opening of K^+ channels that causes indiscriminate ion flux through the ion channels and lets calcium to influx and potassium to efflux from the brain cells [45,46]. The decrease in energy supply to the brain tissue can be measured by monitoring the deoxygenated-hemoglobin using near infrared spectroscopy (NIRS) [47] as well as by monitoring the decreased cerebral blood flow [48].

Although the mechanism of decreased energy supply after concussion is not fully understood [49], multiple possible mechanisms have been described. Len and Neary conducted a review to explore the effects of mTBI on blood supply to the brain tissue. They found limited literature discussing the pathophysiology of mTBI [50]. Cerebral blood flow (CBF) was found to decrease after brain injury [45,49]. Maugans et al. conducted a study on twelve children after concussion to study the effect of concussion on the amount of cerebral blood flow. They found a statistically significant reduction of 21% in the cerebral blood flow in children after concussion when compared to matched controlled subjects ($p = 0.027$) [49]. Cerebral blood flow is regulated through different mechanisms such as cerebral autoregulation [51] and the cerebrovascular response [52]. Cerebral autoregulation is the ability of the brain to control the cerebral blood flow in response to blood pressure [51]. Junger et al. conducted a prospective study to investigate the effect of mTBI on cerebral autoregulation on 29 individuals with concussion and 29 matched controls using continuous transcranial Doppler velocity recordings and found a statistically significant difference between the groups ($p = .008$). Cerebral autoregulation was impaired in 28% of the individuals with concussion compared to none of the control individuals [51].

The cerebrovascular response to the partial pressure of arterial carbon dioxide ($PaCO_2$) is more potent than the cerebral autoregulation in regulating the cerebral blood flow [53]. Becelewski and Pierzchala conducted a study on 73 individuals with concussion to investigate the effect of mTBI on cerebrovascular reactivity. The study found that mTBI decreases the cerebrovascular response when compared to matched controls [52]. The increased metabolism of the brain increases oxygen demand [45]. Kontos et al. conducted a study using NIRS and found a reduction of cerebral blood oxygen level in individuals with mTBI compared with matched controls [54]. The cascades discussed above result in an energy crisis that makes the brain unable to respond adequately to another concussion, which makes the brain vulnerable to second more severe concussion [45].

Concussion results in a constellation of physical, cognitive, emotional, and/or sleep-related symptoms that usually rapidly resolve spontaneously within 7 to 10 days [55] and may or may not involve a loss of consciousness [56]. An epidemiological study using the High School Reporting

Information Online (HS RIO) surveillance system with 544 high school athletes with concussion aged 13 to 18 years found that only 4.6% had lost consciousness [57].

Typically concussion presents with normal neuroimaging findings of the brain's structures when standard neuroimaging techniques such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) are used [5]. Such neuroimaging techniques are performed to rule out other serious conditions such as skull fractures and intracranial bleeding [1].

Although multiple concussion severity grading systems exist, none were able to capture the full range of concussion symptoms [58,59]. The available guidelines suggest that each concussion should be managed according to the existing symptoms and impairments[1,5].

2.2 EPIDEMIOLOGY OF CONCUSSION

The Centers for Disease Control and Prevention declared concussion a serious health concern. Concussion is the most common acquired neurologic disorder in children and young adults (NIH, 2002). There is an estimate of 1.6 - 3.8 million sports related concussions annually in the United States [3]. This number is considered an underestimation of the actual number of concussions as many concussions may go unrecognized [3]. Concussion accounts for 5.8% and 8.9% of all collegiate and high school sports related injuries, respectively [60].

Emergency department visits due to concussion showed an increase of 62% between 2001 and 2009 with an annual average of more than 170,000 sports-related concussions [4]. In 2009 the National Electronic Injury Surveillance System estimated that there were 248,418 sport and recreation related concussion emergency department visits in the United States [4].

In 2003, the National Center for Injury Prevention and Control (NCIPC) reported to the United States Congress that concussion costs the nation nearly $17 billion each year, which is considered an underestimation of the actual costs (NCIPC, 2003). A study on 660 workers with concussion showed that 77% of the workers had missed an average of 3 days of work as a result of their concussion [61].

The National Council on Youth Sports (NCYS) estimated that 44 million children and adolescents (66% boys) participate in organized sports in the United States each year [2]. Football has the highest incidence of concussion [9,62]. In a study comparing concussion rates in high school athletes among different sports, football was found to have the highest concussion rate among other contact sports with a rate of 23 concussions per 10,000 athlete exposures (AEs). Girls' concussion rate was highest in soccer at a rate of 9 concussions per 10,000 AEs [9].

Concussion outcomes are influenced by several factors including gender [63], previous history of concussion [64], and age [28]. Age was found to influence recovery from concussion. Concussion recovery time is longer in younger athletes. Field et al. (2003) compared recovery time after sports-related concussion between high school athletes and college athletes. One hundred eighty-three high school athletes (mean age 15.9 years, range 14-18 years) and 371 college athletes (mean age 19.9 years, range 17-25 years) participated in the study and completed baseline neuropsychological evaluation. Nineteen high school athletes and 35 college athletes had concussion and underwent serial neuropsychological testing and were compared with 38 control athletes. Results of the study showed that high school athletes had slower recovery than collegiate athletes. High school athletes had significant cognitive impairment compared to controls at least 7 days after concussion while collegiate athletes had significant cognitive impairment compared to controls 24 hours after concussion and had normal cognitive findings 3 days after concussion [28].

Previous concussions are associated with nearly a two times higher risk of sustaining another concussion [62,65]. In a multicenter study, fifty-three percent of college football athletes were found to have had a history of at least one concussion [66].

In similar sports, female athletes have higher concussion rates than male athletes [9,62]. The decreased neck mass of females compared to males may contribute to weaker muscle force to counter external forces and result in greater head angular acceleration [67].

Playing position was found to be an influence to the risk of sustaining a concussion. A six-year concussion study on National Football League (NFL) players was conducted between 1996 and 2001 to compare incidence of concussion associated with playing position. The study found that the incidence rate of concussion ranged from 1.62 to 0.03 per 100 games depending on the playing position. The most vulnerable playing position to concussions was found to be the quarterback position and the lowest was the holder [68]. Mihalik et al. measured linear and rotational acceleration of head impact in 52 ice hockey players aged 13 to 16 to determine if player position has an effect on the magnitude of head impact. Acceleration results showed no differences between playing position on the magnitude of head impact [69].

2.3 CLINICAL MANIFESTATIONS OF CONCUSSION

A variety of clinical outcomes are associated with concussion [1,5,70,71]. According to a meta-analysis of 39 studies investigating concussion, a significant decline in cognitive function and an increase in self-reported symptoms were found following concussion [11]. Multiple studies also have reported postural deficits following concussion [10,12–14,16]. Consequently, the Zurich Consensus Statement on Concussion and the National Athletic Trainers' Association position statement on sports-related concussion recommended the assessment of cognitive functioning, postural stability and self-reported symptoms in the examination of concussion [1,8].

2.3.1 Signs and symptoms of concussion

A wide range of signs and symptoms is usually observed and reported following a concussion that can be divided into four categories: physical, cognitive, emotional, and sleep disorders [1,5,8]. An epidemiological study on high school athletes that included 544 concussions found that 85% of individuals with concussion had complete resolution of self-reported symptoms within 7 days post-concussion [57].

Physical symptoms of concussion include headache, dizziness, nausea, balance problems, visual problems, vomiting, fatigue, sensitivity to light, and sensitivity to noise [5]. Physical signs include loss of consciousness and amnesia [1]. Cognitive symptoms include impaired concentration, impaired memory, confusion and fogginess. Emotional symptoms include sadness, nervousness and irritability. Sleep disorders include drowsiness, difficulty falling asleep and sleeping more or less than usual [1,5,7,8]. The frequency of concussion signs and symptoms differ greatly. Headache is the most frequently reported symptom of concussion, occurring in 94% of athletes with concussion [9]. Other frequently reported symptoms include dizziness (75%), impaired concentration (54%), sensitivity to light (36%), nausea (31%), and balance problems (79%) [9,10].

Loss of consciousness (LOC) previously was the main sign of a concussion. Several studies found that LOC occurs in less than 10% of sports-related concussions [6,27,57,62,64]. In an epidemiological study of concussion on 17,549 football players, Guskiewicz et al. found a low incidence of LOC, occurring in only 8.9% of the 888 players with concussion [27].

2.3.2 Cognitive function

Although most self-reported symptoms of concussion resolve within one week, cognitive impairment may persist beyond resolution of self-reported symptoms [72]. Broglio et al. conducted a study on 21 collegiate athletes to investigate the presence of cognitive impairment in symptom-free athletes by comparing self-reported symptoms with computerized neuropsychological testing. To determine resolution of self-reported symptoms, concussion symptoms were measured using the Symptom Assessment Scale (SAS) daily post-concussion. The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) was used to measure neurocognitive function. Broglio et al. found that 38% of collegiate athletes with concussion had impaired cognitive performance that lasted beyond the resolution of self-reported symptoms [72].

Neuropsychological tests are used to objectively assess cognitive impairment of brain function after concussion injury and to help in guiding management and recovery after concussion [5]. Although neuropsychological testing has made a significant contribution in concussion management, it should not be used as the sole indicator of return to play [73,74]. In concussion, the most affected cognitive functions are found to be deficits in visual memory, verbal memory, processing speed, and reaction time [75].

Neuropsychological testing can be divided into paper and pencil and computerized tests. Both paper and pencil and computerized neuropsychological tests are useful in identifying concussions [5]. Although paper and pencil (traditional) neuropsychological tests are useful in the diagnoses and management of concussion, they encompass several shortcomings. Traditional neuropsychological tests are mainly performed by neuropsychologists and may take days or weeks to be completed [76]. Also traditional neuropsychological tests are vulnerable to a practice effect (learning effect), which makes them inappropriate to be used multiple times for follow up [73].

Computerized neuropsychological tests can overcome some of the traditional neuropsychological test shortcomings. Computerized neuropsychological tests are convenient as they can be performed faster on larger scales and do not require a neuropsychologist to conduct the tests. Also the countless versions of computerized neuropsychological tests can overcome the learning effect [74]. Several computerized neuropsychological tests exist such as the ImPACT and the Automated Neuropsychological Assessment Metrics (ANAM). The ANAM is a library of computerized test batteries designed by and for the U.S. Military to test cognitive processing [77]. The ImPACT, developed by Lovell et al., tests cognitive functions including reaction time, processing speed, memory and attention [78]. A study assessing the diagnostic utility of ImPACT was conducted on 72 high school athletes with concussion and 66 high school athletes without injury found that the ImPACT has 81.9% sensitivity and 89.4% specificity in classifying high school athletes with and without concussion [76]. Due to the inherent subjectivity and the individual variations of cognitive functions, performing baseline neuropsychological tests before and after concussion can improve the usefulness of the neuropsychological tests [76].

2.3.3 Postural stability

Balance has been defined as “the dynamics of body posture to prevent falling” [79]. The word “balance” is commonly used in rehabilitation settings and is often used with other terms such as stability and postural control; however these terms have no universally accepted definitions [80].

Balance is maintained by the interaction of the sensory system, the motor system and the central nervous system (CNS). The CNS processes and integrates sensory feedback from three sensory systems: the visual system, the somatosensory (proprioceptive) system, and the vestibular system to execute programmed musculoskeletal activities [20].

Balance problems are commonly reported and assessed after concussion [10,12,13,16]. Measuring postural stability is considered to be an essential part of concussion assessment and management [1,5]. Several studies have reported postural instability following concussion [10,13,14,16]. In an epidemiological study to investigate concussion over 3 seasons in 17,549 football players, 5.1% (888) of players sustained a concussion, and Guskiewicz et al. found that 28.6% of concussion injuries had positive Romberg test after injury [16]. Another study used the Sensory Organization Test (SOT) to compute a composite balance score to compare balance between 28 college-age athletes with concussion and 18 uninjured athletes and found differences in balance up to 10 days after concussion [10].

McCrea et al. assessed postural stability of 94 collegiate athletes with concussion. Postural instability was found in 36% of the athletes [13]. Multiple balance assessment methods exist. Balance assessment methods can be divided into qualitative and quantitative methods. In qualitative methods such as the Balance Error Scoring System (BESS) [16], the assessor evaluates the test performance by counting the number of errors committed by the tested person. A prospective study was conducted to determine the interrater and intrarater reliability of the BESS using 30 athletes performing the BESS and 3 scorers. Each scorer was asked to independently score each athlete by viewing a video recording of the athlete while performing the BESS test. The study calculated the intraclass correlation coefficient (ICC) for the interrater reliability (ICC=0.57) and intrarater reliability (ICC 0.74) that demonstrated fair and good reliability, respectively. The study also found that the interrater and intrarater minimum detectable change (MDC) scores were 9.4 errors and 7.3 errors, respectively. The high MDC of the BESS questions its clinical utility [81]. In 30 healthy participants aged 20 to 37 years Brown et al. investigated the instrumentation of the BESS by wearing an inertial measurement unit (IMU) that measures acceleration and angular velocity.

Scores from BESS were highly correlated with acceleration data from the IMU attached to the participants' forehead (ICC = 0.90) [82]. King et al. assessed balance in 13 children with concussion and 13 matched controls using the instrumented BESS. Instrumentation conducted by fixating an inertial measurement unite (IMU) at the participants lower back while performing the BESS. They found that the instrumented BESS was superior to the BESS in classifying children with concussion. Sensitivity and specificity were found to be (38% / 100%) for the instrumented BESS and (23% / 92%) for the BESS respectively [83].

In quantitative methods such as Computerized Dynamic Posturography (CDP), sway is assessed using sensors in a force plate. Peterson et al. compared postural stability between 26 athletes with concussion and 18 controls using a computerized sway assessment method and found balance differences between the two groups 10 days post-concussion [10]. Marchetti et al. conducted a study on 84 healthy individuals and 18 individuals with vestibular disorders to examine test-retest reliability of normalized path length (NPL) of postural sway measured using accelerometers. They found good test-retest reliability in the healthy group (ICC = 0.73) and in the vestibular disorders group (ICC = 0.71) [84]. Salehi et al. investigated the mean velocity of the Center of Pressure (COP) measured using a force plate. They found that in 18 healthy older individuals (age M = 67 SD 2.8) mean velocity was reliable in recording postural stability. Table 2-1 shows the average mean velocity of sway, the standard error of measurement (SEM), the MDC, and the test-retest ICC [85].

Table 2-1: Reliability of the center of pressure measurement

Standing condition	Mean velocity cm/s Mean (SD)	SEM cm/s	MDC cm/s	Test-retest ICC
LS/EO	1.42 (0.13)	0.05	0.14	0.84*
LS/EC	1.58 (0.23)	0.09	0.25	0.82*
FS/EO	2.09 (0.38)	0.09	0.25	0.94*
FS/EC	3.13 (1.12)	0.15	0.43	0.98*

18 healthy older individuals (age M = 67 SD 2.8 years); LS level surface; FS foam surface; EO eyes opened; EC eyes close; M mean; SD standard deviation; SEM standard error of measurement; MDC minimal detectable change; ICC intraclass correlation; cm/s centimeter per second; * $p < 0.05$.

2.4 CONCUSSION ASSESSMENT

Concussion is considered among the most complex injuries in sports medicine to diagnose, assess, and manage [1]. Assessing concussion requires a multimodal investigation of symptoms, neuropsychological testing, and postural stability testing [1,5].

2.4.1 Self-reported symptoms

Symptom self-report scales such as the Post-Concussion Symptom Scale (PCSS) are widely used in the assessment of mild traumatic brain injuries. Several studies found under-reporting of symptoms among athletes with concussion [6,28,72]. McCrea et al. found that 41% of high school athletes did not report concussion because they did not want to leave the game and 22% did not want to let down their teammates [6]. In a study of 371 college athletes with concussion and 183 high school athletes with concussion, cognitive impairments, which were tested using a 25-minute battery of neuropsychological tests, were found 7 days after injury while self-reported symptoms were found to return to baseline levels within 3 days of injury. Furthermore, self-reported symptoms dropped below baseline at 5 to 7 days post injury [28]. Reporting fewer symptoms than the pre-injury level suggests under-reporting of symptoms.

Broglio et al. conducted a study on 21 collegiate athletes to investigate the presence of cognitive impairments in symptom-free athletes by comparing self-reported symptoms with computerized neuropsychological testing. To determine resolution of self-reported symptoms, concussion symptoms were measured using the Symptom Assessment Scale (SAS) daily post-concussion. Broglio et al. found that 38% of collegiate athletes with concussion had impaired cognitive performance that lasted beyond the resolution of self-reported symptoms [72]. Although self-report of symptoms is an important tool in managing concussion, relying on results of self-reported symptoms may not be an accurate indicator for RTP decision.

2.4.2 Balance assessment

Balance deficits are commonly reported in individuals with mTBI [10,13,14,16]. Tests of static standing balance can be divided into two categories: instrumented tests and non-instrumented tests. In non-instrumented tests the assessor evaluates the performance; while in instrumented tests, tools are used to measure certain aspects of the task. Most clinical balance assessments incorporate non-instrumented methods to assess balance while lab-based balance assessments incorporate tools such as accelerometers and force plates.

2.4.2.1 Clinical balance assessment

Balance testing has been used in diagnosing and managing concussion, especially Sports-Related Concussion (SRC) [5]. The Balance Error Scoring System is a widely used balance assessment tool for concussion assessment [16]. The BESS is a short static standing balance test that can be used in clinic or on field. The BESS consists of six 20 seconds balancing tasks with three stances: double leg standing (eyes closed with hands placed on hips and feet on contact with each other side by side), single leg standing (eyes closed with hands placed on hips standing on the non-dominant foot and the dominant foot flexed 20° at the hip and 45° at the knee), and tandem standing (eyes closed with hands placed on hips and the dominant foot is placed in front of the non-dominant foot with the heel of the front foot touching the toe of the posterior foot) the three stances are performed on firm and foam surfaces. During the test the adolescent is asked to take off shoes and to maintain each position with closed eyes and hands on hips for twenty seconds while the examiner counts the number of times the adolescent makes an error. Errors include: taking the hands off the hips, opening the eyes, taking a step, stumble, fall, abducting or flexing of the hip more than 30˚, lifting the forefoot or the heel of the surface, remaining out of the position for more than five seconds. If multiple errors were committed in the same time only one error is recorded. The maximum number of errors for any condition is ten errors.

The Balance Error Scoring System (BESS) is used as a part of the Sport Concussion Assessment Tool 2 (SCAT2), which was recommended as an important tool in managing athletes with concussion by the 2012 consensus statement on concussion in sport. A new version (SCAT3) is available [86,87]. No cutoff score is available to distinguish balance abnormalities; interpretation of BESS scores depends on comparing pre-injury and post-injury scores of the individual tested.

Reliability of the BESS was found to range from moderate to good reliability with an ICC ranging from 0.6 in high school football athletes [88] to 0.96 in active young adults [89].

In a study comparing BESS scores between 94 collegiate athletes with sports-related concussion and 56 matched controls, statistically significant differences were found between groups on the total BESS score at the time of concussion that resolved within 3 to 5 days post-concussion [41]. Furman et al. compared BESS scores between 43 children (aged M 16 SD 1.3) with acute (within 14 days of injury) and sub-acute (more than 14 day of injury) SRC, with 27 controls (aged M 15 SD 1.2). Furman et al. found no statistically significant differences between groups on the total BESS scores [14]. King et al. found superiority of using the BESS along with an accelerometer compared to the BESS alone in identifying children with concussion [83]. The practice effect of BESS has been considered an important factor to be acknowledged when administering BESS to track recovery in athletes. Valovich et al. tested thirty-two healthy adolescents (mean age 17 years SD 2 years) using BESS over 4 visits (day 1, 3, 5, 7, and 30) and found significant improvement on the total BESS on days 5 and 7 compared with day 1 and found significant improvement of foam BESS on day7 compared with day 1 while no significant effect of visit was seen during firm BESS furthermore, no significant difference was found between day 1 and day 30 [90].

2.4.2.2 Lab-based balance assessment

Lab-based balance assessment tools incorporate sway measurements to infer balance. Body sway can be assessed by measuring movement of the body or parts of the body or by measuring forces between the body and the base of support. An accelerometer is a small, inexpensive tool that can be placed at the level of the Center of Mass (COM) of the body (i.e. level of the iliac crest) to measure acceleration of the COM. The COM of the body is a hypothetical point in the body that represents the center of the distribution of the body mass. Marchetti et al. investigated the test-retest reliability of measuring postural sway using accelerometers in 84 healthy participants and 18 participants with vestibular disorders. Marchetti et al. found that accelerometry has good test-retest reliability separated by a 15-minute seated rest, the concussion group ICC range was 0.46 to 0.87 and the control group ICC range was 0.28 to 0.86 [84].

A force plate is a platform that uses load cells to calculate reaction forces between feet and ground. Reaction forces can be used to calculate the COP, which represents the center of the net summation of all forces acting between the feet and the ground. Although the COP and COM are different entities, they were found highly correlated [91,92].

Powers et al. measured COP using a force plate on 9 athletes with concussion and 9 healthy athletes to investigate the effect of concussion on sway. They found greater sway in the concussion group compared to the healthy group. The elevated sway was significant even after return to play clearance, which was based on reported symptoms and other gross balance and motor control assessments [42].

2.4.3 Neuropsychological assessment

The ImPACT is a computerized neuropsychological test designed to assess baseline and post injury neurocognitive function in sport settings. The ImPACT tests cognitive functions including reaction time, processing speed, memory and attention. The ImPACT battery consists of six tests: word memory, design memory, three letter memory, symbol match, color match, and X’s and O’s. Scores from the six tests are used to calculate four composite scores: reaction time, visual-motor processing speed, visual memory, and verbal memory. Cognitive function impairments are common post-concussion [72]. Athletes with concussion demonstrate decreased performance on postural stability tests as well as decreased cognitive performance [93]. In a study comparing cognitive function in 9 symptomatic participants with concussion with 5 matched healthy controls using the ImPACT, Kontos et al. found that the group with concussion had worse performance on the ImPACT compared to healthy controls [54]. Most concussion management guidelines recommend performing cognitive tests in managing individuals with concussion [1,5].

2.4.4 Dual-task balance performance

Sports activities require high performance on cognitive and balance function simultaneously. Cognitive function impairments and balance deficits are common post-concussion. [10,13,14,16,72]. Assessing postural stability and cognitive function are important in managing concussions [1,5].

Howell et al. conducted a prospective study to assess walking balance in 23 high school students with concussion using single-task balance assessment (balance test without cognitive task) and dual-task balance assessment (balance test with cognitive task). Howell et al. measured balance while participants walked at a self-selected speed using motion analysis system to calculate the center of mass (COM) anterior velocity and medial/ lateral displacement and velocity. Howell et al. used 3 dual-tasks and one single-task walking tests. The 3 dual-tasks were the single auditory Stroop, multiple auditory Stroop and question and answer task. During the single-task balance test athletes with concussion showed greater stability and less sway than during the dual-task balance tests [94]. Other studies of healthy and individuals with concussion showed similar results of increased sway in dual-task balance tests compared to single-task balance tests [30,31]. Dorman et al. compared static standing postural stability between 18 adolescents with concussion and 26 injury-free adolescents. Balance was measured using a force plate by calculating the COP 95% ellipse area and the COP velocity. Four balance conditions were tested: single-task with eyes open and closed and dual-task with eyes open and closed. Participants with concussion were tested within 10 days from the injury and were retested again 3 times, during their visit to the clinic, along the course of their recovery. The time between the visits varied with an average of 23 days. Controls were tested twice with one week between tests. On the first visit, significant differences between groups were found in both measures in all conditions, while in second visit, significant differences between groups were found only in the 95% ellipse area in the dual-task conditions. Participants with concussion had significantly higher COP 95% ellipse area and velocity in the first visit compared with the rest of the visits on all conditions except for COP 95% ellipse area in the dual-task with eyes open [30].

2.4.5 Vestibular testing

Normally the eyes can keep focus on a fixed target even if the head is moving. Maintaining the eyes on a target while the head is moving is achieved using the VOR function of the peripheral vestibular system, which produces movements of the eyes that are equal magnitude and opposite direction to the head movement.

2.4.5.1 The Video Head Impulse Test (vHIT)

The Head Impulse Test (HIT) is a clinical test of peripheral vestibular function. It was first described be Halmagyi and Curthoys in 1988 [95]. The HIT tests the peripheral vestibular function by testing VOR function. With an intact peripheral vestibular system, the VOR is activated when angular acceleration is detected by the semicircular canals, which generates a neuronal signal that travels through the vestibular nerve to both eyes and produces eye movement that is equal magnitude and opposite direction to that angular acceleration. The HIT is performed by rotating the head in the plane of one pair of the semicircular canals, usually the horizontal semicircular canals.

Rotating the head to one direction tests the horizontal semicircular canal on the same side as the rotation direction. In the case of VOR dysfunction, movement of the eyes fails to compensate for the head movement and the eyes cannot be maintained on the fixed target during the quick head movement. The HIT is performed as a bedside test of VOR function in which the clinician sits in front of the patient and holds the patient's head with both hands and delivers random head rotations with small amplitude and high velocity while asking the patient to look at the clinician's nose. The clinician tries to detect a saccadic correction of the eyes to reach the therapist's nose after the head thrust, which indicates failure of the VOR to move the eyes in accordance with the head movement. Two types of saccadic correction of eye position have been noted: overt saccades and covert saccades [96]. Overt saccades occur after the head movement is completed to move the eyes to the fixed target while covert saccades occur during the head movement [96]. During the HIT, overt saccades are usually easily detected with the naked eye while covert saccades cannot be detected. To be able to quantify overt and covert saccades, eye movement measurement techniques such as the scleral search coils and video-oculography were introduced to the HIT.

The scleral search coils developed by David Robinson in 1963 are an electromagnetic tool used to record eye movement. The scleral search coil consists of a scleral contact lens with a coil of wire embedded inside it. The position of the eye is located by measuring the change in voltage generated by the coil as it is exposed to a magnetic field [97]. Although the use of scleral search coils is considered the gold standard in measuring eye movement during the HIT, this method of measuring eye movement is considered a lab-based method, as it is uncomfortable to wear the wired contact lens. Weber et al. measured VOR gain in 12 healthy subjects using search coils while passively moving the subject's head horizontally at an acceleration of 6000°/sec^2 and amplitude of 5-25°. They found a mean VOR gain of 0.84 with standard deviation of 0.055 [98].

Video-Oculography (VOG) is the use of video technology to record eye movement. Recently, the HIT was combined with VOG to be able to objectively quantify eye movement during head impulse [99]. The Video Head Impulse Test (vHIT) was found to be equivalent to the scleral search coil technique in recording eye movement in response to head movement [99]. The vHIT consists of VOG, which is a high-speed digital video camera that detects eye position and an IMU to detect head movement. Data from the VOG and IMU are processed to compute the eye and the head movement velocity. Eye and head velocities are used to calculate velocity gain. Velocity gain is the ratio of the mean velocity of the eye and the head. The vHIT is performed by rotating the head in the plane of one pair of the semicircular canals, usually the horizontal semicircular canals. Unlike using scleral search coils, the vHIT is easy to perform with short tests that can be used in clinical sittings and has less patient burden [99]. MacDougall et al. measured eye movement during horizontal head thrusts using the search coils and the vHIT simultaneously to compare the diagnostic accuracy of the vHIT with the search coils in 8 healthy participants and 8 participants with a vestibular disorder. They found that VOR gain measured using the search coils and the vHIT were equally able to differentiate between the vestibular disorder group and the healthy group [99]. The VOR gains from different studies are shown in Table 2-2.

Table 2-2: VOR gain results in individuals with/without peripheral vestibular disorders

Study	Tools	Head thrust	Clinical condition (n)	Age mean (range)	Gain mean (SD)	
MacDougall et al. (2009) [99]	vHIT sampling rate 250 Hz	Acceleration 750 - 5000°/s^2 Velocity 50 - 250°/s Range 5° – 20° Number of thrusts 50	Healthy (8)	35 (25 - 66)	0.96 (0.12)	
			VN (6)	52 (38 - 59)	0.42 (0.18)	
			U Meniere's (1)	53	0.26	
			BVL (1)	72	0.08	
Weber et al. (2008) [98]	Search coils	Acceleration 750 - 6000 °/s^2 Velocity 50 - 250°/s Range 5 – 25° Number of thrusts >80			750°/s^2	6000°/s^2
			Healthy (12)	42 (27 - 65)	0.98 (0.06)	0.84 (0.05)
			UVD (15)	52 (31 – 74)	0.47 (0.06)	0.13 (0.05)
			VN (13)	56 (36 – 68)	0.59 (0.08)	0.29 (0.11)
Zellhuber et al. (2014) [100]	vHIT	Acceleration 8000°/s^2 Velocity 126 - 306°/s	VN (19)	54 SD 16	34.9% (23.6%)*	
Schmid-Priscoveanu et al. (2001) [101]	Search coils	Acceleration 10000°/s^2 Velocity 250°/s Range 15° – 25° Number of thrusts 10	Acute VN (10)	50.6 (26 – 89)	0.70 (0.09)	
			Chronic VN (14)	53.4 (26 – 78)	0.73(0.10)	

VOR: vestibulo-ocular reflex; VN: vestibular neuritis; U: unilateral; BVL: bilateral vestibular loss; UVD: unilateral vestibular deafferentation; *: gain asymmetry; SD: standard deviation; n: sample size; vHIT: video head impulse test; Search coils sampling rate 1000 Hz

2.4.6 The Vestibular/Ocular Motor Screening (VOMS)

The VOMS [26] is a symptom provocation test designed at the University of Pittsburgh Medical Center (UPMC) to screen vestibular-ocular and ocular-motor systems. The VOMS consists of seven physical exams: smooth pursuits, horizontal and vertical saccades, near point of convergence (NPC), horizontal and vertical vestibular-ocular reflex, and visual motion sensitivity test. Participants are asked to rate their symptoms using a scale of 0 to 10 on four domains: headache, dizziness, nausea, and fogginess. Symptom assessment is performed before testing (i.e. baseline) and after each of the seven physical exams. NPC is assessed by the reported symptoms and by measuring the distance of NPC. A study on 85 children with concussion (aged M = 14, SD = 2.75) and 85 controls (aged M = 12.7, SD = 1.8) found a significant difference between groups in all items of the VOMS. All items of the VOMS were moderately correlated with the post-concussion symptom scores (PCCS). None of the VOMS items were correlated with the BESS suggesting that the VOMS is measuring a different component of the vestibular system than the BESS. Using a cutoff point of ≥ 2 points increase of symptoms in VOMS items or a NPC distance of ≥ 5 cm indicated an increased likelihood of having a concussion that ranged from 25% to 44% [26].

In a study of 263 injury-free NCAA Division I collegiate student-athletes, VOMS was found to possess a high internal consistency (Cronbach $\alpha = 0.97$) [17]. Using the cutoff level of a score of ≥ 2 for any item of the VOMS and NPC distance of ≥ 5 cm, reported by [26], Kontos et al. found a false-positive rate of 11%. The study found an increased likelihood of false-positive finding in female athletes (odds ratio, 3.0) as well as in history of motion sickness (odds ratio, 7.7) [17].

2.5 VESTIBULAR SYSTEM

The peripheral vestibular system consists of the semicircular canals and the otolithic organs. The semicircular canals consist of three perpendicular canals the horizontal canal, the anterior canal and the posterior canal, which detect and respond to angular acceleration of the head. The otolithic organs consist of the saccule and the utricle, which detect linear acceleration. The ampulla, which is a part of the semicircular canal, houses the hair cells that detect and transmit angular acceleration through the ampullary nerve. The maculae, which are the receptors of the otolithic organs, are composed of hair cells and calcium carbonate crystals (the otoconia). The maculae detect and transmit linear acceleration through the vestibular nerve.

Information transmitted by the peripheral vestibular system is used for two main purposes: to maintain eye position with head movement and to maintain balance. Eyes are maintained on target during head movement using the VOR, which moves the eyes with equal magnitude and opposite direction to the head movement using sensory feedback from the semicircular canals and otolithic organs. Optimal balance maintenance requires the integration of information from the visual, somatosensory and vestibular systems. The vestibular system provides angular and linear acceleration feedback to the balance system via the vestibulospinal tract (VST) [20].

Vertigo is the illusory sensation of spinning or whirling movement of self or the surrounding [102]. Vertigo occurs when there is a mismatch between the inputs from the three sensory systems: the visual system, the somatosensory system, and the vestibular system [103].

Different parts of the vestibular system are susceptible to impairment during traumatic brain injury [104]. Ernst et al. conducted a retrospective study on 63 patients complaining of vertigo after traumatic head or neck injury to investigate vestibular deficits following traumatic injury. Several combinations of vestibular disorders were found in trauma patients that included: Benign Paroxysmal Positional Vertigo (BPPV) 57%, cervicogenic vertigo 27%, otolith disorder 25%, labyrinthine concussion 19%, Secondary Endolymphatic Hydrops (SEH) 19%, perilymphatic fistulae 5%, and central vestibular disorders 5% [104]. Each vestibular disorder presents with its own symptoms of imbalance and requires a different management plan. Differentiation between vestibular disorders may be important when comparing balance in individuals with vestibular disorders.

2.5.1 Traumatic vestibular disorders

Benign paroxysmal positional vertigo (BPPV) [105,106] is a common cause of dizziness after concussion with an incidence rate ranging from 28% to 61% of individuals with dizziness after traumatic brain injuries (TBI) [18,23]. During injury the trauma causes the otoconia to dislodge from the macula and escape into the semicircular canals. Movement of the otoconia inside the affected canal moves the hair cells and stimulates the ampullary nerve of that canal causing the vertigo [107]. The three semicircular canals are oriented perpendicular to each other, which make the maneuvers for each semicircular canal different. Posterior semicircular canal BPPV can be tested using the Dix-Hallpike maneuver [106] in which while the head is turned 45 degrees toward the tested side the subject is rapidly brought down from sitting upright to the supine position with slight extension of the neck. The test is positive when there is vertigo along with torsional up-beating nystagmus. The lateral (horizontal) canal BPPV can be tested using the Pagnini-McClure maneuver, in which the subject is in the supine position and the head is turned to one side then back to the middle then turned to the other side and back to the middle. The test is positive when there is horizontal nystagmus when returning the head to the middle or to the side [106]. The side with the more intense horizontal nystagmus is considered the affected side. The anterior semicircular canal is tested using the Dix-Hallpike maneuver and the test is positive when there is down beating torsional nystagmus that fatigues.

Labyrinthine concussion is an injury to the membranous labyrinthine following a concussion [108]. Transmitted forces of the head trauma may cause shearing forces to rupture or bleed within the membranous labyrinth. Labyrinthine concussion symptoms include hearing loss, tinnitus and dizziness [109].

Unilateral vestibular loss can be induced by traumatic brain injury. Mechanisms of injury include: direct trauma that injures the labyrinth even without fracture of the skull or trauma-induced demyelination of the vestibulocochlear nerve or ischemic changes of the labyrinth [108].

Perilymphatic fistulae result from an abnormal opening of the round window or the oval window [75]. Head trauma may lead to rupture of the round and/or oval window that connects the middle ear and the inner ear perilymphatic spaces, which cause the perilymphatic fluids to leak from the inner ear to the middle ear [110]. Perilymphatic fistulae symptoms include: vertigo, postural instability, sensorineural hearing loss, deafness, tinnitus, and/or bleeding and discharge from the ear [108].

Davies and Luxon retrospectively investigated vestibular abnormalities after head injury in 100 subjects with vestibular symptoms that resulted from the head injury. They found that 71% of the subjects had positive vestibular abnormality findings. The severity of head injury was classified as minor in 72 subjects, moderate in 24 subjects, and severe in 4 subjects. Classification was based on the presence of skull fracture and the duration of post-traumatic amnesia. Assessment of vestibular abnormalities was done using caloric irrigation and electronystagmography (ENG). Caloric testing was based on normal ranges of canal paresis and directional preponderance that were calculated on the control group. The normal range for canal paresis was from -4.0% to 4.2% and the normal range for the directional preponderance was from -7.9% to 6.6%. Positive ENG assessment of vestibular abnormalities was based on finding of spontaneous nystagmus with 5 or more successive beats, slow saccades < 300°/s, or optokinetic asymmetry of >20% or gain of <0.75. Findings of Davies and Luxon suggest that 71% of vestibular symptoms after head injury arise from peripheral vestibular dysfunction. Although the results of their study showed that a high percentage of the vestibular complaints was caused by peripheral vestibular dysfunction, the incidence rate of the peripheral vestibular disorders after sports concussion in adolescents is not known.

2.6 RETURN TO PLAY AND SCHOOL

Basing the return to play decisions on self-reported symptoms is inadequate. Melvin et al. conducted a study to compare pre- and post-concussion symptoms on 554 high school and college athletes. Melvin et al. found that the athletes reported fewer symptoms after concussion compared to symptoms before the concussion. Reporting fewer symptoms after concussion raises the concerns of underreporting of symptoms in this population [28].

Premature return to play (Premature RTP) is referred to clearing an athlete with concussion to participate in sports with persistent symptoms [5]. Premature RTP exposes the athlete to several health risks. Second impact syndrome (SIS) is when an athlete sustains a second concussion before being fully recovered from their initial concussion. Second impact syndrome is believed to be attributed to disturbed autoregulation of cerebral blood flow that may affect intracranial pressure and herniate the brain, which may lead to coma or death [5]. Returning to play with symptoms such as decreased reaction time [73] may impair performance and make the athlete susceptible to another injury.

There are few studies that discuss return to learn (RTL) or return to school after concussion, which limits the development of evidence-based guidelines for the management of students with concussion [111]. Although concussion guidelines [1,5] advise that RTP should not be allowed before returning to the pre-injury level of academic performance, none of these guidelines have evidence-based recommendations for RTL.

2.7 LITERATURE LIMITATIONS ADDRESSED IN THIS STUDY

Managing concussion and peripheral vestibular impairment are well established in the literature for different patient groups especially in older and athletic patients. Evidence suggests a relationship between head injuries and vestibular impairments. The prevalence of peripheral vestibular disorders after a recent SRC in adolescents is unknown. While evidence suggests differences in concussion in different age groups, few studies had focused on children and adolescents with concussion.

3.0 METHODS

3.1 PARTICIPANTS

A sample of twenty five symptomatic male and female adolescents aged 12 to 19 years with a recent (within 10 days) Sports-Related Concussion (SRC) and twenty two male and female controls aged 13 to 20 years were assessed. Adolescents in each group were matched for age (+/- 1 year) and sex as evidence suggests age and sex-related differences in postural stability [28,112]. Individuals with SRC were recruited by neuropsychologists after an extensive history, interview, survey of symptoms, and computerized neurocognitive testing exam were performed. The following criteria were used to make a concussion diagnosis: presence of signs or symptoms at the time of injury (such as posttraumatic anterograde amnesia, posttraumatic retrograde amnesia, loss of consciousness, dizziness, or headache), worse neurocognitive test score from pre-concussion, or increased post-concussion symptoms from pre-concussion levels [113,114]. The treating neuropsychologist asked the adolescent and/or his/her guardian if they were interested in participating in the study. If the adolescent decided that they were interested, one of the study investigators explained the study in greater detail and obtained informed consent from the adolescent and his/her guardian. Controls were recruited from middle and high schools in the greater Pittsburgh area and from the University of Pittsburgh.

Adolescents in both groups were excluded if they had neck pain or injury, an injury with symptoms to the lower body, a history of a musculoskeletal disorder, a history of brain surgery, a history of substance abuse, a history of a major psychiatric or neurological disorder, a history of vestibular disorder, special education, or a history of TBI with a Glasgow Coma Score <13.

Adolescents in the control group met the previous exclusion criteria and did not have a concussion. The study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh.

3.2 STUDY DESIGN

Sway was measured during the single-task and dual-task conditions while the adolescent was standing on firm and compliant surfaces. There were 4 sway assessment trials: 2 surfaces X 2 dual-task conditions. The single-task and one of the dual-task conditions were performed during the same trial, in a pattern of single-task:dual-task:single-task. The trials started and ended with 20 seconds during which the adolescent was asked to stand quietly while maintaining balance, which was the single-task condition. The dual-task conditions were performed in the middle of the trials for a variable amount of time, depending on the type of cognitive task. Before starting the sway assessment, adolescents were asked to perform a short training of the cognitive tasks. To control for any fatigue effect between the sway conditions, the order of the type of surface was randomized. Furthermore, adolescents with SRC were assessed on three visits, the first visit was within 10 days of the concussion injury, the second visit was performed according to the adolescents availability within seventeen days after the first visit (range 4 – 17 days after first visit), and the third visit was at the time of clearance as decided by the treating physician, while adolescents in the control group had one assessment.

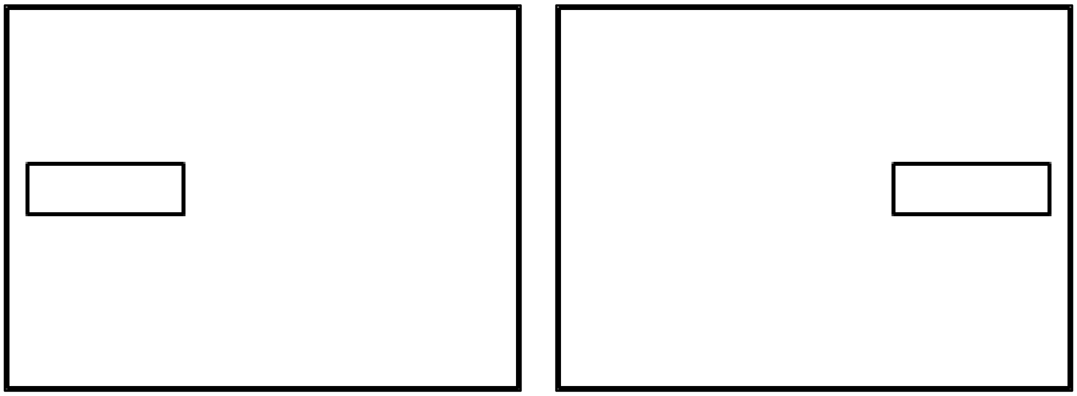
3.3 PROCEDURES

Demographics, medical history, and concussion history were completed via questionnaire. After completing the demographic data collection, the single and dual-task balance testing and the Balance Error Scoring System (BESS) was completed. Next, the Vestibular/Ocular Motor Screening (VOMS) was administered by one of the study co-investigators. Finally, the Video Head Impulse Test (vHIT) was administered by the primary investigator while the adolescent was sitting in a chair facing the wall. Last, the Post-Concussion Symptom Scale (PCSS) was obtained from the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) computerized test from the medical records if the adolescent had completed the ImPACT on the same day of testing in the clinic as a part of the usual care; otherwise the adolescent completed the ImPACT before the balance testing. The procedures took about 50 minutes to be completed.

3.3.1 Sway Assessment

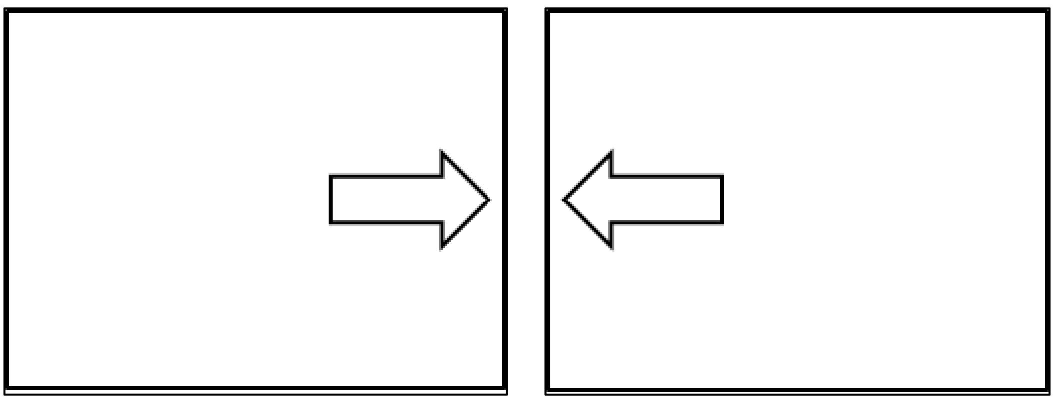
Single and dual-task balance testing was performed while the adolescent was standing on a force plate and wore an accelerometer. The accelerometer was strapped on the adolescents' back at the level of the iliac crest. The dual-task consisted of the subject performing a cognitive task while maintaining balance and the single-task consisted of maintaining standing balance without the cognitive task.

The cognitive task included a subset of the Motor and Perceptual Inhibition Test (MAPIT) [115–117]. First a forced choice spatial discrimination test was performed as a control condition (35 seconds ± 1 second) (Figure 3-1). The spatial discrimination task required the adolescent to operate a thumb activated switch on the right or the left hand in accordance with an on-screen rectangle that appeared to the right or the left of the screen. A total of 20 stimuli were displayed in random order, with an average inter-stimulus interval of 1.75 seconds. After this priming spatial discrimination task, a perceptual inhibition task (average of 75 seconds ± 3 seconds) required the adolescent to push on the right or the left switch in accordance with the direction of an on-screen arrow that appeared on the right or the left side of the screen. Two types of stimuli were provided during the perceptual inhibition task: congruous (Figure 3-2) and incongruous (Figure 3-3) stimuli. For the congruous stimulus, the arrow appeared on the side of the screen that corresponded to the direction of the arrow, while for the incongruous stimulus, the arrow appeared on the side of the screen that was opposite to the direction of the arrow. During the perceptual inhibition task, the adolescent was instructed to respond to the direction of the arrow, not the side of the screen on which the arrow appeared. A total of 40 stimuli were displayed in random order, with an average inter-stimulus interval of 1.88 seconds. The duration of the perceptual inhibition task was approximately twice as long as the spatial discrimination task so that the same number of each stimulus would be displayed. The adolescent was asked to maintain their balance while standing 125 cm away from the MAPIT monitor. The monitor resolution was 1920 X 1080 pixels and the refresh rate was 60Hz. The MAPIT reaction times and accuracy results were not used in the analysis.



Response = left
Response = right

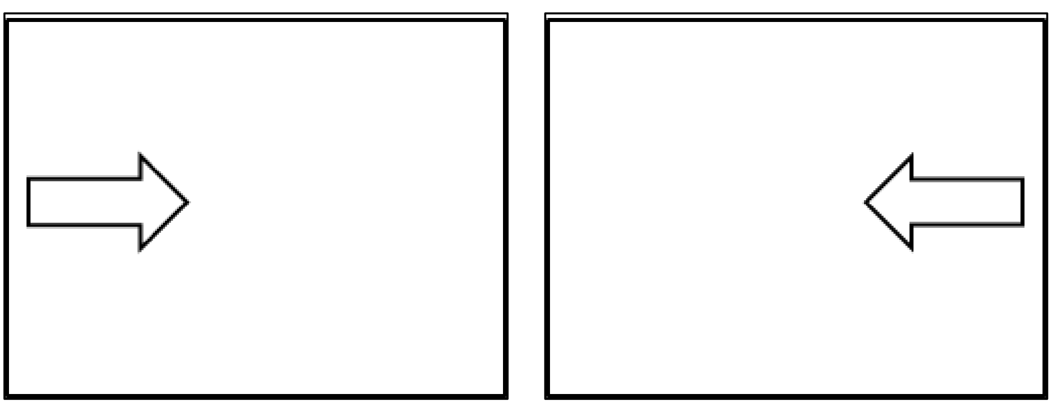
Figure 3-1: Forced choice spatial discrimination task



Response = right
Response = left

Congruent stimulus

Figure 3-2: Congruent forced choice perceptual inhibition task



Response = right
Response = left

Incongruent stimulus

Figure 3-3: Incongruent forced choice perceptual inhibition task

Body sway was estimated from an accelerometer and a force plate. The accelerometer was developed for the National Institutes of Health (NIH) Toolbox as an inexpensive tool designed to quantify sway in clinical settings. The accelerometer was a bi-axial accelerometer that measured acceleration in the anterior-posterior (AP) and medial-lateral (ML) directions. The acceleration was measured in mG at a sampling rate of 100 Hz and transmitted through a Bluetooth connection to a computer. The accelerometer was attached to the back of a gait belt that fit snugly around the participant's waist at the level of the iliac crest, using Velcro. The iliac crest approximates the level of the Center of Mass (COM) (Figure 3-4).

The force plate (BP5050, Bertec, Inc.) contains 4 load cells that measured the vertical ground reaction force and ground reaction moments about the AP and ML axes of the plate, from which the Center of Pressure (COP) was calculated. The force plate was connected to a computer using a USB cable and the ground reaction force and moments were recorded at a sampling rate of 100 Hz. Both the accelerometer and force plate data were collected using a custom made LabVIEW program (National Instruments Corporation). Although the COP and COM are different entities, they were found highly correlated [91,92].

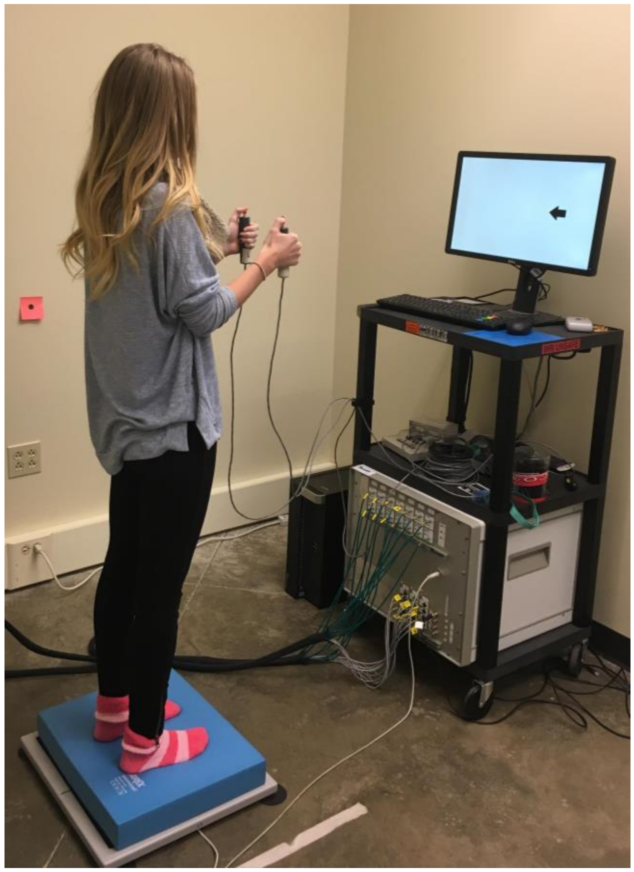


Figure 3-4: Sway measurement setting. Adolescent is standing on force plate with a compliant surface with an accelerometer attached to the participant's lower back using a Velcro belt, while holding two thumb-activated switches to respond to a visual stimulus.

3.3.2 The Balance Error Scoring System (BESS)

The BESS [89] consists of 6 tasks, each tested barefoot with eyes closed and hands on hips for 20 seconds. There are 3 stance tasks: double leg stance (standing with feet together), single leg stance (standing on the non-dominant foot), and tandem stance (standing with on foot front of the other with non-dominant foot in back). Each stance task is performed on a level surface and on an Airex® foam pad (Appendix A). Timing starts when the adolescent assumes the position and closes their eyes. A hand held stopwatch is used to time each task. Tasks are scored by counting number of times the adolescent moves out of the position.

3.3.3 The Post-Concussion Symptom Scale (PCSS)

The PCSS is a 22-item self-reported symptom questionnaire performed as a part of the ImPACT computerized test. The PCSS uses a 7 point Likert scale (range 0 – 6) to assess concussion related symptoms such as headache, vomiting, nausea, dizziness, imbalance, visual problems, fatigue, drowsiness, sleeping disorders, sensitivity to light and noise, emotional symptoms, irritability, nervousness, sadness, numbness, feeling slowed down or foggy, and difficulties with concentrating and remembering. Higher PCSS scores indicate worse symptoms [118]. The procedures described above took about 50 minutes to be completed.

3.3.4 The Video Head Impulse Test (vHIT)

The vHIT is a test of the horizontal VOR during head impulses (EyeSeeCam, Interacoustics). The vHIT consists of VOG, which is a high-speed digital video camera that detects eye position and an Inertial Measurement Unit (IMU) to detect head movement. Data from the VOG and IMU are processed to compute the eye and the head movement velocity. Eye and head velocities are used to calculate velocity gain. Velocity gain is the ratio of the mean velocity of the eye and the head. The vHIT is performed by rotating the head in the plane of one pair of the semicircular canals, usually the horizontal semicircular canals. Unlike using scleral search coils, the vHIT is easy to perform in clinical sittings and has less patient burden [99]. The vHIT incorporates a high-speed camera to measure eye movements and an inertial measurement unit to record the velocity of the head impulse at a rate of 220 Hz. The sensors are incorporated into lightweight goggles that fit on the head like swimming goggles, with an elastic band to ensure fixation of the camera and to minimize slipping of the goggles. Adolescents sat on a chair facing a wall (150cm away) with a mark in front of their visual field. When compared to the caloric test, the gold standard test of vestibular function, the vHIT showed low sensitivity (31% - 41%) and high specificity (98% - 92%) to detect vestibular hypofunction as reported by several groups [119,120].

The vHIT was first calibrated by asking the adolescent to move their eyes vertically and horizontally between 4 laser points emitted from the goggles, with a range of 10 degrees from the center position. After calibrating the device, the adolescent was asked to keep their eyes on a fixed target in front of their eyes while the examiner held the adolescents' head with both hands and provided the adolescents with unpredictable small amplitude, high velocity head movement to the right or left. The range of motion for the head impulse was 10 to 20 degrees with an angular velocity of 150 to 300 degrees/second, and angular acceleration of 3000 to 6000 degrees/second^2. Head thrusts in the horizontal plane in each direction were randomly provided. The vHIT gain was defined as the ratio of the mean eye angular velocity to the mean head angular velocity. Normally vHIT gain should approximate one (EyeSeeCam Manuals, 2016). To minimize patient burden during the vHIT testing, the first four adolescents were provided with five head impulses in each direction which was increased to ten impulses in each direction as all of the four participants did not report any increase of symptoms with the five impulses.

Head velocity was measured with the angular velocity sensor on the vHIT goggles. Eye position was measured using the calibrated video eye recordings, and then differentiated with a phaseless two-point difference equation. There is no gold standard for calculating vHIT gain. Two methods to calculate vHIT gain were used. The first method to calculate vHIT gain was using the instantaneous velocity. The instantaneous vHIT gain is the ratio of the eye angular velocity to the head angular velocity. From the time-series recordings of head and eye velocity, the instantaneous gain was calculated at three different time points; at the peak velocity, 20 milliseconds before peak velocity, and 40 milliseconds before peak velocity. The average was calculated from 5 samples around each of the time points (approximately -10ms to +10ms). The second method of vHIT gain was calculated by estimating the regression slope between the eye velocity and the head velocity. The slope was computed both with and without an intercept. The intercept point of zero assumed that at time zero the eye and the head were not moving. Gain was calculated separately for the right and the left head impulses. The mean of the head impulses on each side was used in the computation of the gain. A valid head impulse must be 150 degree/sec and reach the peak velocity within 80 ms from the start of the impulse. In order to determine if there were any abnormalities the impulses from the side with the lower gain values was used in the statistical analysis.

3.3.5 The Vestibular/Ocular Motor Screening (VOMS)

The VOMS is a symptom provocation test developed to screen for potential vestibular and ocular-motor system dysfunction [26]. The VOMS was administered by one of the lab assistants who had experience in multiple research projects. The VOMS consists of seven tasks: smooth pursuits, horizontal saccades, vertical saccades, near point of convergence, horizontal VOR, vertical VOR, and visual motion sensitivity test. After performing each task adolescents rated their symptoms using a 0 to 10 Likert scale where 0 indicates no symptoms and 10 indicates severe symptoms. Symptoms include headache, dizziness, nausea, and fogginess. A baseline symptom rating is performed at the beginning of the VOMS. The near point of convergence was performed 3 times.

Each time the distance between the tip of the nose and the gaze target was measured in cm and the average of the 3 distances was calculated.

Symptom provocation was calculated by subtracting VOMS baseline total symptoms (headache, dizziness, nausea, and fogginess) from the total symptoms reported after each of the 7 VOMS items (smooth pursuits, horizontal saccades, vertical saccades, near point of convergence, horizontal VOR, vertical VOR, and visual motion sensitivity test) [26]. The VOMS was considered provocative if the magnitude of the reported total symptoms in any of the VOMS items were ≥ 2 points higher than the magnitude of the baseline total symptoms [26]. Furthermore, a near point of convergence of 5 cm or longer resulted was considered a positive finding, as this threshold has resulted in a 50% increase in probability of having a concussion [26].

In a study of 263 injury-free NCAA Division I collegiate student-athletes, the VOMS was found to possess high internal consistency (Cronbach $\alpha = 0.97$), furthermore, the study showed an 11% false-positive rate of finding positive VOMS scores in these injury free athletes. The study found an increased likelihood of the false-positive finding in female athletes (odd ratio, 3.0) as well those with a history of motion sickness (odd ratio, 7.7) [17].

3.4 DATA ANALYSIS

3.4.1 Sway Assessment

A considerable number of adolescents did not complete the single task at the end of the trial because they started moving their arms and feet while they should have stood quietly for 20 seconds. Due to the lack of statistically significant difference between the single-task performed before and after the dual-task in valid trials, sway data from the second single-task assessment (post-dual-task) was not used. In cases when the sway data from the first single-task (pre-dual-task) assessment was unable to be analyzed, due to equipment problems or participant's lack of cooperation, sway data from the second single-task (post-dual-task) was used.

Using a custom Matlab program, data from the accelerometer and force plate were processed using a low-pass filter with a frequency cutoff of 2 Hz. A frequency analysis of sway showed that a cutoff frequency of 2 Hz retained 97% (range 90% - 99%) of the adolescents' sway. Four measures of sway were computed for both the acceleration and COP: the root mean square (RMS) (Equation 3-1) and the normalized path length (NPL) (Equation 3-2) in the AP and ML directions. The RMS and NPL were defined as:

Equation 3-1

$$RMS = \left[\frac{[\sum_{n=1}^{N-1} Sway[n]^2]}{N}\right]^{\frac{1}{2}}$$

N: $number\ of\ sway\ samples$
Sway $[n]$: $individual\ sway\ sample - the\ mean\ of\ all\ sway\ samples$

Equation 3-2

$$NPL = \left[\sum_{n=1}^{N-1} |Sway[n+1] - Sway[n]|\right] / duration$$

3.4.2 Balance Error Scoring System (BESS)

The BESS is scored by counting the number of errors committed during each of the six 20 second testing periods. Errors include opening eyes, taking hands off hips, raising heel or forefoot, step, stumble or fall, abduction or flexion of the hip more than 30°, or remaining out of the testing position for more than 5 seconds. Multiple errors occurring at the same time are counted as one error. The maximum number of errors for each task is 10 with a total of 60 for the whole test. A higher score indicates worse performance on the test [89]. The number of errors committed while performing each of the balance tests was summed. A total BESS score was calculated by summing the number of errors in all 6 balancing conditions. A total firm BESS and a total foam BESS were calculated by summing the 3 firm surface conditions and the 3 foam pad conditions, respectively.

3.5 STATISTICAL ANALYSIS

The statistical analysis was conducted using SPSS, with a significance level of $\alpha < 0.05$. Between-group differences in demographic data were tested using independent samples t-test for normally distributed data and Mann-Whitney U test for non-normal data. For dichotomous data, chi square tests were used.

3.5.1 First aim

A Mann-Whitney U test was conducted to compare VOR gain values in adolescents with concussion and injury free adolescents. A non-parametric test was chosen because the data were not normally distributed.

A Mann-Whitney U test was conducted to evaluate the hypothesis that adolescents with SRC would score higher, on average, than injury free adolescents on the total symptoms of the individual VOMS items and on the total firm BESS score. A non-parametric test was chosen because the BESS data were not normally distributed. Furthermore, the VOMS data was ordinal data. A Chi-square test of independence was conducted to compare the frequency of having a provocative VOMS test and the frequency of having a NPC of 5cm or further in adolescents with and without SRC.

Spearman rank order correlation coefficients were used to test the relationship of the VOR gain with number of errors on BESS and the symptoms provocation on the VOMS.

3.5.2 Second aim

A linear mixed model was performed using a compound symmetry covariance structure to investigate the fixed effects of group (concussion and control), surface (firm and foam), and task (single and dual) as well as the interaction effects of group * surface, and group * task on the magnitude of eight sway measures: the NPL and the RMS of the AP and the ML displacement of COM and COP.

To investigate the effect of cognitive test (spatial discrimination and perceptual inhibition) as well as the interaction effect of group * cognitive test, a separate linear mixed model was performed using a compound symmetry covariance structure. A separate analysis was needed because the design of the dual-task balancing paradigm included performance of the single-task and the dual-task in a continuous manner which resulted in having the single task confounded within each dual-task test. Higher order interactions (3-way and above) were not tested to preserve model simplicity and because we did not have hypotheses of interest for these interactions.

3.5.3 Third aim

An Intention-to-treat analysis using a last observation carry-forward approach was adopted. A linear mixed model was performed using a compound symmetry covariance structure to investigate the effect of visit, surface, and task as well as the interaction effect of visit * surface, and visit * task on the magnitude of eight sway measures: the NPL and the RMS of the AP and the ML displacement of COM and COP. As fixed effects, we entered visit (initial, second, and clearance visits), surface (firm and foam), and task (single and dual) as well as the interaction terms visit * surface and visit * task.

To investigate the effect of cognitive test as well as the interaction effect of visit * cognitive test, a separate linear mixed model was performed using a compound symmetry covariance structure. As fixed effects, we entered visit, surface, and cognitive test (spatial discrimination and perceptual inhibition), as well as the interaction terms visit * surface and visit * cognitive test were entered into the model. A separate analysis was needed because the design of the dual-task balancing paradigm included performance of the single-task and the dual-task in a continuous manner which resulted in having the single task confounded within each dual-task test. Higher order interactions (3-way and above) were not tested to preserve model simplicity and because we did not have hypotheses of interest for these interactions.

A non-parametric Friedman's analysis was conducted to compare the effect of visit on BESS and PCSS scores during the initial, second, and clearance visits. A post-hoc test was performed using the Wilcoxon matched-pair signed rank test to investigate the between- visit difference. Post-hoc results were adjusted using Bonferroni correction to control for multiple comparisons.

Statistical analysis was conducted using other models to confirm robustness of results. A per protocol approach and an intention to treat approach resulted in similar results. Repeated measures ANOVA analysis using subjects who had complete data sets resulted in similar results of the linear mixed model. To assess the effect of the drop out from the clearance visit, an analysis of the data using first and second visits, which had 23 adolescents, showed similar results to the analysis of the three visits (14 adolescents completed the third visit).

3.6 POWER ANALYSIS

The study is powered to detect balance differences between groups as well as balance improvement over time. Power analysis to calculate sample size was performed using G*Power version 3.1.9. Effect sizes and partial η^2's were used directly from published literature if reported, otherwise effect sizes and partial η^2's were estimated from other reported parameters such as sample size and F-value using Psychometrica [121]. Graph data were estimated using WebPlotDigitizer, which is a web-based tool to extract data from plots (http://arohatgi.info/WebPlotDigitizer/) (Table 3-1).

Table 3-1: Power analysis

Design	Participants	Outcome	Effect size	n	Reference
Group effect on BESS	94 colligate football player with concussion/ 56 controls	BESS on the time of injury	d = 1.88	5	McCrea (2003) [41]
Group effect on single-task sway	18 children with concussion/ 26 controls	Single-task COP velocity within 10 days of concussion	$\eta^2 = 0.17$	16	Dorman et al. (2013) [30]
Group effect on dual-task sway	18 children with concussion/ 26 controls	Dual-task COP velocity within 10 days of concussion	$\eta^2 = 0.25$	9	Dorman et al. (2013) [30]
Cognitive task effect on sway	23 adolescents with concussion/ 23 matched controls	Single/dual-task walking peak ML COM velocity measured at 3, 7, 14, 30, 60 days after concussion	$\eta^2 = 0.21$	3	Howell et al. (2014) [94]
Group * Cognitive task interaction on sway	23 adolescents with concussion/ 23 matched controls	Single/dual-task walking ML COM displacement measured at 3, 7, 14, 30, 60 days after concussion	$\eta^2 = 0.11$	5	Howell et al. (2014) [94]
Visit effect on sway	23 adolescents with concussion/ 23 matched controls	Single/dual-task walking ML COM displacement measured at 3, 7, 14, 30, 60 days after concussion	$\eta^2 = 0.10$	9	Howell et al. (2014) [94]

d: Cohen's d; η^2: partial eta squared; BESS: balance error scoring system; COP: center of pressure; COM: center of mass; ML: medial-lateral; n: sample needed in each group

4.0 VESTIBULO-OCULAR REFLEX FUNCTION IN ADOLESCENTS WITH SPORTS-RELATED CONCUSSION

4.1 INTRODUCTION

Concussion was defined by the Consensus Statement on Concussion in Sport held in Zurich in 2012 as "a complex pathophysiological process affecting the brain, induced by biomechanical forces" [1]. Concussion is the most common acquired neurologic disorder in children and young adults [122]. The National Council on Youth Sports (NCYS) estimated that 44 million children and adolescents participate in organized sports in the United States each year [2]. There is an estimated 1.6 - 3.8 million Sports-Related Concussions (SRC) annually in the United States across all age groups [3]. Emergency department visits due to concussion showed an increase of 62% between 2001 and 2009 [4]. In a report to the Congress, the National Center for Injury Prevention and Control estimated that concussion costs the United States of America nearly $17 billion each year [123].

Concussion results in physical, cognitive, emotional, and/or sleep related symptoms that usually rapidly resolve spontaneously within a few days [1,5,8]. Concussion symptoms include headache, dizziness, nausea, balance problems, visual problems, vomiting, fatigue, sensitivity to light, and sensitivity to noise [1,5,7–10]. Headache is the most frequently reported symptom of concussion, occurring in 94% of athletes with concussion [9]. Other frequently-reported symptoms include balance problems (79%), dizziness (75%), impaired concentration (54%), sensitivity to light (36%), and nausea (31%) [9,10]. The high prevalence of dizziness and balance problems after concussion motivates the study of vestibular function in this population.

Traumatic brain injury may compromise different parts of the vestibular system and may result in central and/or peripheral vestibular disorders [104]. Vestibular disorders are common in the individuals with concussion [18,19] including labyrinthine concussion [108], unilateral vestibular loss [108], and perilymphatic fistulae [75].

Several studies have examined the prevalence of vestibular function test abnormalities after head injury. Toglia et al., found that in patients (aged 10 to 75 years) with closed traumatic head injury who complained of dizziness, 61% had positive caloric testing and 44% had positive rotatory chair test [22]. Davies and Luxon retrospectively investigated vestibular abnormalities after head injury in 100 subjects with vestibular symptoms that resulted from head injury. They classified the severity of head injury as minor in 72 subjects, moderate in 24 subjects, and severe in 4 subjects. The causes of head injury included blows to the head, falls, and traffic accidents. They found that 74% of individuals with minor head injury had positive caloric test findings [23]. Ellis et al. conducted a retrospective review to examine the prevalence of vestibulo-ocular dysfunction (defined as reporting a visual disturbance, dizziness, or motion sensitivity, as well as having near point of convergence (NPC) greater than 6 cm, abnormal extraocular movements or smooth pursuits, abnormal or symptomatic horizontal or vertical saccades, or abnormal vestibulo-ocular reflex (VOR)) among children with SRC in a multidisciplinary concussion program [124]. They found that 22 (29%) children out of 77 children (mean age 14 years SD 2 years) with SRC within 30 days and 15 (63%) children out of 24 children (mean age 16 years SD 2 years) with SRC for more than 30 days met the criteria of vestibulo-ocular dysfunction [124]. Although evidence suggests a relationship between head injuries and vestibular impairments, the prevalence of peripheral vestibular disorders after SRC in adolescents is unknown.

Oculomotor impairments such as diplopia, eye tracking problems, and eye focusing problems are common after concussion [24–26]. Oculomotor functions including accommodation, vergence, version, and saccades are essential functions during reading [125,126]. Those functions are vulnerable during concussion injury and are commonly impaired [24–26,125,127]. Samadani et al. found that adults with concussion injury showed worse horizontal eye disconjugacy than adults with a non-head injury [128]. In 12 participants with concussion, Thiagarajan et al. found decreased reading rate (number of words per minute) compared to normative values, and the decreased reading rate was correlated with NPC, the Convergence Insufficiency Symptom Survey, and the Visual Search and Attention Scale [126]. Storey et al. retrospectively assessed charts of 275 children (mean age 14 years range 8 – 18 years) with concussion (50% had SRC) the number of days since injury range was 1 – 188 days with a mean of 16 days. Twenty-four percent of children had an abnormal NPC defined as having an NPC distance greater than 6 cm [129]. Mucha et al. developed the Vestibular/Ocular Motor Screening (VOMS) which is a brief clinical screening tool that assesses vestibular and ocular motor impairments not included in other concussion assessment tools [26]. Another test has recently been developed to test semicircular function includes the head impulse test.

The Head Impulse Test (HIT) is a clinical test of peripheral vestibular function. It was first described be Halmagyi and Curthoys in 1988 [95]. The HIT tests peripheral vestibular function by testing the VOR. An intact peripheral vestibular system produce’s eye movement that is opposite and equal to head angular acceleration. Recently, the HIT was combined with Video-Oculography (VOG) to be able to objectively quantify eye movement during the head impulse [99]. The Video Head Impulse Test (vHIT) was found to be equivalent to the scleral search coil technique in recording eye movement in response to head movement [99]. MacDougall et al. measured eye movement during horizontal head impulses using the search coils and the vHIT simultaneously to validate the diagnostic accuracy of the vHIT with the search coils in 8 healthy participants and 8 participants with a vestibular disorder (6 with vestibular neuritis, 1 with unilateral gentamicin vestibulotoxicity, and 1 with bilateral gentamicin vestibulotoxicity). The VOR gain measured using the vHIT was as accurate as the search coils in identifying subjects with vestibular disorders and controls [99]. Alshehri et al. (manuscript accepted) reported no deficits in VOR function as measured with the vHIT in persons post-concussion (Alshehri et al., manuscript accepted). Balaban et al. assessed the computer controlled rotation head impulse test (crHIT) gain, which provide whole body impulses using a rotational chair while recording eye movement, and found that crHIT gain decreased in 100 participants with concussion (83% were tested within 4 days of injury) compared with 200 controls (both groups age range 18 - 45 years) [127].

Balance problems are commonly reported and assessed after concussion [10,12–14,16]. Measuring postural stability is considered to be a part of comprehensive approach to concussion assessment and management [1,5]. Balance testing has been used in diagnosing and managing concussion, especially SRC [5]. The Balance Error Scoring System (BESS) is a widely used balance assessment tool for concussion assessment [16]. The BESS is a short static standing balance test that can be used in the clinic or on the field and is used as a part of the Sport Concussion Assessment Tool 3 (SCAT3), which was recommended as an important tool in managing athletes with concussion by the 2012 consensus statement on concussion in sport [1]. Corwin et al. conducted a retrospective cohort study of 247 children with a concussion and reported that of children with concussion have abnormal tandem gait early after concussion. Furthermore the children with abnormal tandem gait had significantly longer recovery time than those without abnormal tandem gait [130].

Consequently, although dizziness and imbalance are prevalent post-concussion in adults and children [9,10], the prevalence of peripheral vestibular disorders in general, and specifically head impulse test abnormalities after SRC in children is unknown. Furthermore, in individuals with concussion, it is not clear if abnormalities in head impulse testing relates to clinical signs and symptoms of dizziness and imbalance.

4.2 PURPOSE

The purpose of this study was to estimate the prevalence of reduced vestibulo-ocular reflex (VOR) function as assessed with the vHIT in adolescents with and without SRC. Furthermore, we investigated the relationship between vHIT gain and BESS and VOMS tests in adolescents with SRC.

4.3 METHODS

4.3.1 Participants

A cross sectional sample of twenty five symptomatic male and female adolescents aged 12 to 19 years with a recent (within 10 days) SRC and twenty two male and female controls aged 13 to 20 years were assessed. Adolescents in each group were matched for age (+/- 1 year) and sex as evidence suggests age and sex-related differences in postural stability [28,112]. Individuals with SRC were recruited by neuropsychologists after an extensive history, interview, survey of symptoms, and computerized neurocognitive testing exam were performed. The following criteria were used to make a concussion diagnosis: presence of signs or symptoms at the time of injury (such as posttraumatic anterograde amnesia, posttraumatic retrograde amnesia, loss of consciousness, dizziness, or headache), worse neurocognitive test score from pre-concussion, or increased post-concussion symptoms from pre-concussion levels [113,114]. The treating neuropsychologist asked the adolescent and/or his/her guardian if they were interested in participating in the study. If the adolescent decided that they were interested, one of the study investigators explained the study in greater detail and obtained informed consent from the adolescent and his/her guardian. Controls were recruited from middle and high schools in the greater Pittsburgh area and from the University of Pittsburgh.

Adolescents in both groups were excluded if they had neck pain or injury, an injury with symptoms to the lower body, a history of a musculoskeletal disorder, a history of brain surgery, a history of substance abuse, a history of a major psychiatric or neurological disorder, a history of vestibular disorder, special education, or a history of TBI with a Glasgow Coma Score <13. Adolescents in the control group met the previous exclusion criteria and did not have a concussion. The study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh.

4.3.2 Procedures

Demographics, medical history, and concussion history were completed via questionnaire (Appendix B). After completing the demographic data collection, the BESS was completed. Next, the VOMS was administered by one of the study co-investigators. Finally, the vHIT was administered by the primary investigator while the adolescent was sitting in a chair facing the wall. Additional data were gathered from the adolescents, including a dual-task balance test, the

Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), and two follow-up visits, are not examined in this report. The procedures took about 50 minutes to be completed.

4.3.2.1 Video Head Impulse Test (vHIT)

The vHIT (Appendix C) is a test of the horizontal VOR during head impulses (EyeSeeCam, Interacoustics). The vHIT consists of VOG, which is a high-speed digital video camera that detects eye position and an Inertial Measurement Unit (IMU) to detect head movement. Data from the VOG and IMU are processed to compute the eye and the head movement velocity. Eye and head velocities are used to calculate velocity gain. Velocity gain is the ratio of the mean velocity of the eye and the head. The vHIT is performed by rotating the head in the plane of one pair of the semicircular canals, usually the horizontal semicircular canals. Unlike using scleral search coils, the vHIT is easy to perform in clinical sittings and has less patient burden [99]. The vHIT incorporates a high-speed camera to measure eye movements and an inertial measurement unit to record the velocity of the head impulse at a rate of 220 Hz. The sensors are incorporated into lightweight goggles that fit on the head like swimming goggles, with an elastic band to ensure fixation of the camera and to minimize slipping of the goggles. Adolescents sat on a chair facing a wall (150 cm away) with a mark in front of their visual field. When compared to the caloric test, the gold standard test of vestibular function, the vHIT showed low sensitivity (31% - 41%) and high specificity (98% - 92%) to detect vestibular hypofunction as reported by several groups [119,120].

The vHIT was first calibrated by asking the adolescent to move their eyes vertically and horizontally between four laser points emitted from the goggles, with a range of 10 degrees from the center position. After calibrating the device, the adolescent was asked to keep their eyes on a fixed target in front of their eyes while the examiner held the adolescents' head with both hands and provided the adolescents with unpredictable small amplitude, high velocity head movement to the right or left. The range of motion for the head impulse was 10 to 20 degrees with an angular velocity of 150 to 300 degrees/second, and angular acceleration of 3000 to 6000 degrees/second^2. Head thrusts in the horizontal plane in each direction were randomly provided. The vHIT gain was defined as the ratio of the eye angular velocity to the head angular velocity. Normally vHIT gain should approximate one (EyeSeeCam Manuals, 2016). To minimize patient burden during the vHIT testing, the first four adolescents were provided with five head impulses in each direction, which was increased to 10 impulses in each direction as the four participants did not report any increase of symptoms with the 5 impulses.

Head velocity was measured with the angular velocity sensor on the vHIT goggles. Eye position was measured using the calibrated video eye recordings, and then differentiated with a phaseless two-point difference equation. There is no gold standard for calculating vHIT gain. Two methods to calculate vHIT gain were used. The first method to calculate vHIT gain was using the instantaneous velocity. The instantaneous vHIT gain is the ratio of the eye angular velocity to the head angular velocity. From the time-series recordings of head and eye velocity, the instantaneous gain was calculated at three different time points; at the peak velocity, 20 milliseconds before peak velocity, and 40 milliseconds before peak velocity. The average was calculated from 5 samples around each of the time points (approximately -10 ms to +10 ms). The second method of vHIT gain was calculated by estimating the regression slope between the eye velocity and the head velocity. The slope was computed both with and without an intercept. The intercept point of zero assumed that at time zero the eye and the head were not moving. Gain was calculated separately for the right and the left head impulses. The mean of the head impulses on each side was used in the computation of the gain. A valid head impulse must have a peak velocity of at least 150 degree/sec and reach the peak velocity within 80 ms from the start of the impulse. In order to determine if there were any abnormalities, the impulses from the side with the lower gain values were used in the statistical analysis.

4.3.2.2 Vestibular/Ocular Motor Screening (VOMS)

The VOMS (Appendix D) is a symptom provocation test developed to screen for potential vestibular and ocular-motor system dysfunction [26]. The VOMS was administered by one of the lab assistants who had experience in multiple research projects. The VOMS consists of seven tasks: smooth pursuits, horizontal saccades, vertical saccades, near point of convergence, horizontal VOR, vertical VOR, and visual motion sensitivity test. After performing each task adolescents rated their symptoms using a 0 to 10 Likert scale where 0 indicates no symptoms and 10 indicates severe symptoms. Symptoms include headache, dizziness, nausea, and fogginess. A baseline symptom rating is provided at the beginning of the VOMS. The near point of convergence was performed 3 times. Each time the distance between the tip of the nose and the gaze target was measured in cm and the average of the three distances was calculated.

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11% false-positive rate of finding positive VOMS scores in these injury free athletes. The study found an increased likelihood of the false-positive finding in female athletes (odd ratio, 3.0) as well those with a history of motion sickness (odd ratio, 7.7) [17].

4.3.2.3 Balance Error Scoring System (BESS)

The BESS (Appendix E) consists of 6 tasks, each tested barefoot with eyes closed and hands on hips for 20 seconds. The BESS was administered by two personnel: the primary investigator as well as one of the lab assistants. There are three stance tasks: double leg stance (standing with feet together), single leg stance (standing on the non-dominant foot), and tandem stance (standing with one foot front of the other with the non-dominant foot in the back). Each stance task was performed on a firm surface and on an Airex® foam pad (Appendix A). Timing started when the adolescents assumed the position and closed their eyes. A hand held stopwatch was used to time each task. Tasks were scored by counting the number of times the adolescent moved out of the position. Errors included opening the eyes, taking the hands off the hips, raising the heel or the forefoot, step, stumble or fall, abduction or flexion of the hip more than 30°, or remaining out of the testing position for more than 5 seconds. Multiple errors occurring at the same time were counted as one error. The maximum number of errors for each task was 10 with a total of 60 for the whole test. A higher score indicated worse performance on the test [89].

Because no cutoff score is available to distinguish balance abnormalities, interpretation of BESS scores depends on comparing pre-injury and post-injury scores of the individual tested. Reliability of the BESS was found to range from moderate to good reliability with an ICC ranging from 0.6 in high school football athletes [88] to 0.96 in active young adults [89]. In 25 injury-free males (mean age 20.9 years SD 2.7) and 23 females (mean age 19.9 years SD 0.7), the test-retest reliability of BESS was 0.92 for males and 0.91 for females using a generalizability theory analysis

[131]. In a study comparing BESS scores between 94 collegiate athletes with SRC and 56 matched controls, statistically significant differences were found between groups on the total BESS score at the time of concussion that resolved within 3 to 5 days post-concussion [41].

The number of errors committed while performing each of the balance tests was counted. A total BESS score was calculated by adding the number of errors in the 6 balance conditions. A total firm BESS (modified BESS) [1] and a total foam BESS were calculated by adding the 3 firm surface conditions and the 3 foam pad conditions respectively.

4.3.3 Statistical analysis

Statistical analysis was conducted using SPSS with a significance level of $p<0.05$. Differences on demographic data were tested using independent samples t-tests for normally distributed data and the Mann-Whitney U Test for non-normal data. For dichotomous data, the Chi square test was used.

4.3.3.1 First hypothesis and analysis

The first hypothesis was that individuals with concussion will have lower VOR gain measured using the vHIT than individuals without concussion. A Mann-Whitney U test was conducted to compare VOR gain values in adolescents with concussion and injury free adolescents. A non-parametric test was chosen because the data were not normally distributed.

4.3.3.2 Second hypothesis and analysis

The second hypothesis was that individuals with concussion will have more errors on the BESS, and greater symptom increase on the horizontal VOR and the visual motion sensitivity test of the

VOMS than individuals without concussion. A Mann-Whitney U test was conducted to evaluate the hypothesis that adolescents with SRC would score higher, on average, than injury free adolescents on the total symptoms of the individual VOMS items and on the total firm BESS score. A non-parametric test was chosen because the BESS data and the VOMS data were ordinal data. A Chi-square test of independence was conducted to compare the frequency of having a provocative VOMS test and the frequency of having a NPC of 5cm or further in adolescents with and without SRC.

4.3.3.3 Third hypothesis and analysis

The third hypothesis was that in individuals with concussion, greater vHIT impairment as evident by reduced VOR gain using the vHIT will correlate with an increased number of errors on the BESS, and increased symptoms on the horizontal VOR and the visual motion sensitivity test of the VOMS. Spearman rank order correlation coefficients were used to test the relationship of the VOR gain with number of errors on BESS and the symptoms on the horizontal VOR and the visual motion sensitivity test of the VOMS.

4.4 RESULTS

4.4.1 Participants

Two hundred and seventy-six adolescents visiting the concussion clinic were approached to be recruited for this study. A flow chart (Figure 4-1) shows reasons for exclusion or inability to recruit.

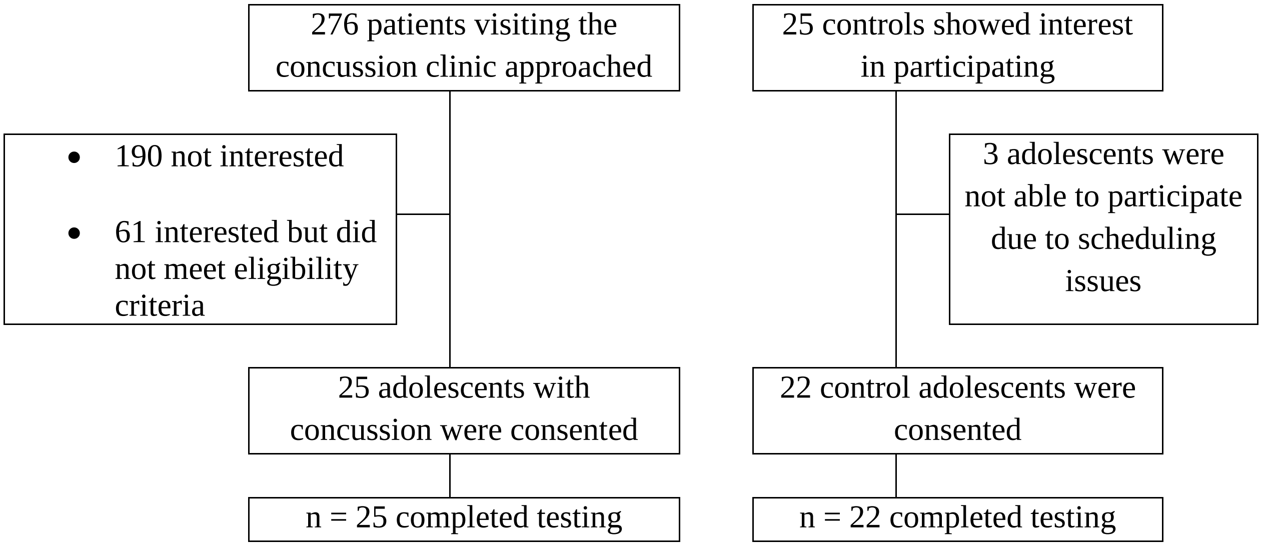


Figure 4-1: Subject enrollment flow chart flow chart

Twenty-five (16 male, 9 female) adolescents (9% of 276 patients who were approached) who had a SRC within the past 10 days (mean days since injury 5.8 days, SD 2.7 days, range 0 – 10 days) and aged between 12 to 19 years old (mean age 15.1 years, SD 1.9 years, range 12-19 years) were deemed eligible and agreed to participate in the study. Twenty-two (15 male, 7 female) healthy adolescents (mean age 15.6 years, SD 2.1 years, range 13-20 years) were recruited. Demographic data are reported in Table 4-1. The sports played during injury were: football (five adolescents); basketball and soccer (three adolescents each); hockey (two adolescents); baseball, cheerleading, diving, softball, volleyball, and wrestling (one adolescent each); recreational activity (six adolescents). Groups BESS scores were not significantly different, as adolescents with concussion averaged 12 errors (SD = 5) and controls averaged 10 errors (SD = 4). While the Post-Concussion Symptom Scale (PCSS) was significantly different between groups ($p < 0.001$), adolescents with concussion had a mean symptom score of 30.4 (SD = 18.3) and controls had a mean symptom score of 6.4 (SD = 13.7).

There was not a significant difference in the age, gender, height, weight, and handedness for adolescents with SRC and adolescents without SRC (Table 4-1).

Table 4-1: Demographics and physical characteristics for concussion and control groups

Characteristics	Concussion Group n=25	Control Group n=22	P value
Age, years, mean (SD)	15.1 (1.9)	15.6 (2.1)	0.515^
Gender	9 female	7 female	0.763*
Weight, kg, mean (SD)	64.1 (16.3)	60.0 (8.9)	0.284#
Height, cm, mean (SD)	171.0 (10.7)	168.0 (10.5)	0.346#
Handedness	20 Right, 4 left	19 Right, 3 left	1.000*

*: Pearson chi-square; ^: Mann-Whitney U Test; #: independent samples t-test

Adolescents with SRC more frequently reported headache and fogginess at the time of recruitment than controls (Table 4-2).

Table 4-2: Symptoms reported at the time of testing

Symptoms reported at the time of recruitment	Concussion Group n=25	Control Group n=22	Pearson chi square test p-value
Headache, n (%)	22 (88%)	6 (27%)	< 0.001
Fogginess, n (%)	13 (52%)	1 (5%)	0.001
Dizziness, n (%)	7 (28%)	2 (9%)	0.151
Nausea, n (%)	5 (20%)	3 (14%)	0.710

Adolescents with SRC reported experiencing immediate symptoms at the time of the concussion including dizziness, confusion/ disorientation, amnesia, and LOC (Table 4-3).

Table 4-3: Immediate symptoms of concussion

Immediate symptoms of concussion	n=25, n (%)
Dizziness during injury	24 (96%)
Confusion/disorientation at injury	13 (52%)
Anterograde amnesia at injury	4 (16%)
LOC during injury	2 (8%)
Retrograde amnesia at injury	0

LOC: loss of consciousness

No significant association was found for history of attention deficit disorder (ADD), history of learning disabilities (LD), migraine, or motion sickness between adolescents with and without SRC. None of the adolescents reported any history of LD (Table 4-4).

Table 4-4: Frequency of past medical history for concussion and control groups

Pearson chi-square			
Characteristics	**Concussion n=25**	**Control n=22**	**p value**
History of ADD	1	1	1.000
History of LD	0	0	N/A
History of migraine	4	0	0.112
History of motion sickness	8	4	0.242

Pearson chi-square; ADD: Attention Deficit Disorder; LD: Learning Disabilities; N/A: not applicable (the variable was constant in all subjects)

4.4.2 Video Head Impulse Test (vHIT)

Five variables of vHIT gain were analyzed; the instantaneous ratio of eye to head velocity was calculated at three different time points; at peak velocity and 20 and 40 milliseconds before peak velocity as well as the regression slope of the eye and the head velocity with and without an intercept of zero. Only 2 vHIT gain variables, the instantaneous ratio of eye to head velocity 20 milliseconds before peak velocity and the regression slope of the eye and the head velocity with an intercept point of zero, were used to address the aforementioned aims. These two variables were selected as they showed the least variability of gain values across subjects.

The Shapiro-Wilk test of normality showed that VOR gain ratio and VOR gain slope values were normally distributed in the injury free group ($p = 0.906$ and 0.929), whereas the normality assumptions were violated in the group with SRC ($p = 0.005$ and 0.014) respectively.

A Mann-Whitney U test was conducted to compare vHIT gain values in adolescents with concussion and injury free adolescents, indicating that the vHIT gain ratio was not significantly different for adolescents with concussion (Median = 0.945) and for injury free adolescents (Median = 0.98), ($U = 230.5$, $p = .791$). Another Mann-Whitney U test indicated that vHIT gain slope value was also not significantly different for adolescents with concussion (Median = 0.93) and for injury free adolescents (Median = 0.965), ($U = 241.0$, $p = .596$) (Figure 4-2).

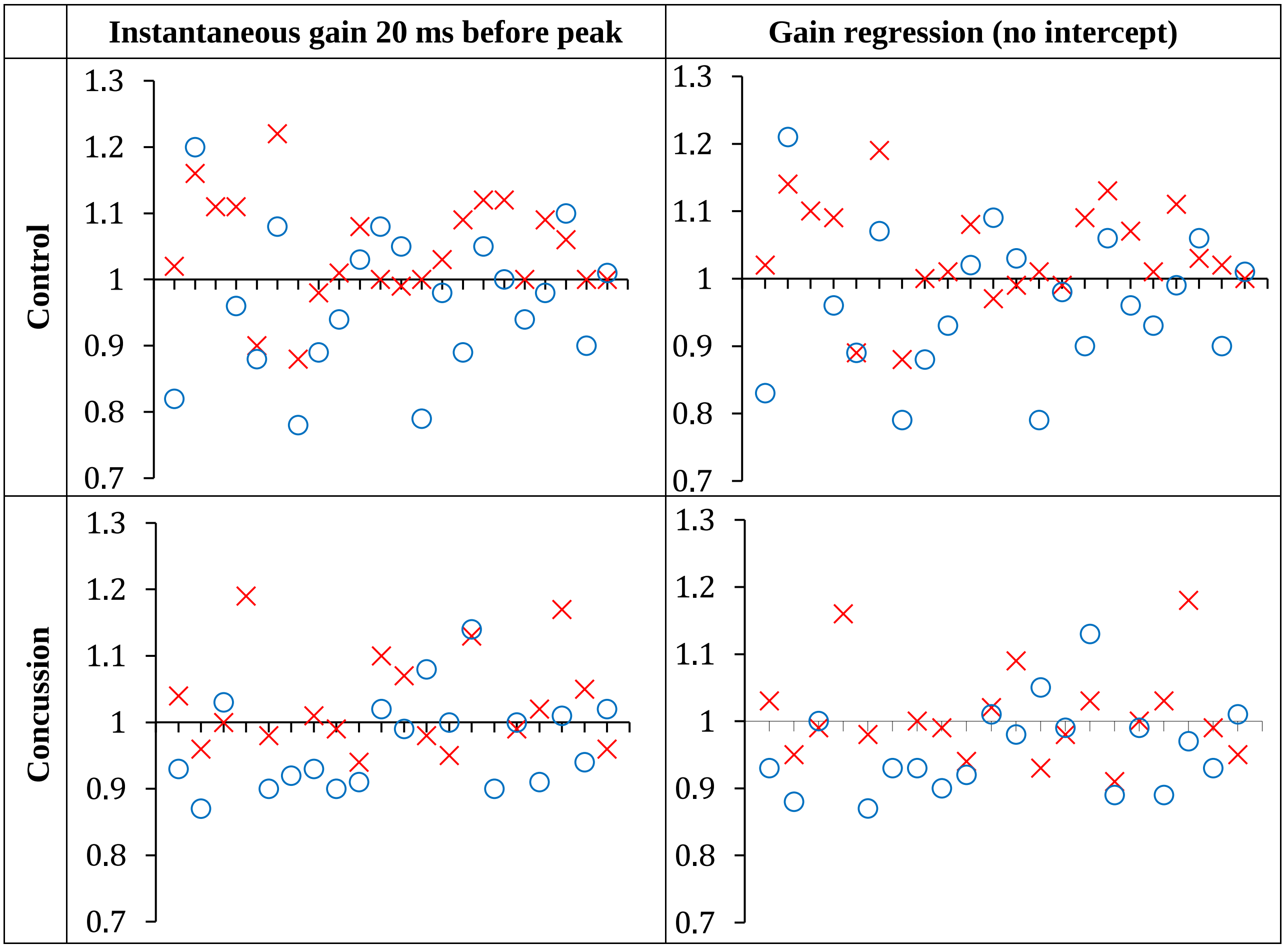


Figure 4-2: Individual video head impulse test (vHIT) gain values from right (x) and left (o) side head impulses for controls (n=22) and adolescents with SRC (n=20) are presented.

4.4.3 Vestibular/Ocular Motor Screening (VOMS)

A Mann-Whitney U test indicated that the baseline symptoms, the VMS, and the distance of NPC were significantly different between groups. Adolescents with concussion had worse baseline symptoms, a greater increase in symptoms during the VMS, and a longer NPC distance, compared with adolescents without concussion (Table 4-5).

Table 4-5: VOMS scores in adolescents with and without sports-related concussion

VOMS items	Concussion n=24		Controls n=21		Mann-Whitney U test p value
	Median	IQR	Median	IQR	
Baseline symptoms	7.5	5 – 13.5	0	0 - 2	< 0.001
Smooth pursuits	0	-1 – 0	0	0	0.798
Horizontal saccades	0	0 – 1	0	0	0.110
Vertical saccades	0	-1 – 2	0	0	0.990
NPC - symptoms	0	-3 – .5	0	0	0.595
Horizontal VOR	1	-2 – 3	0	0	0.110
Vertical VOR	1	-.5 – 2	0	0	0.055
VMS	1.5	0 - 4	0	0	0.036
NPC - distance (cm)	3.8	2 – 12.9	0.5	0 – 1.3	0.001

VOMS: vestibular/ocular motor screening; VOR: vestibulo-ocular reflex; VMS: visual motion sensitivity; NPC: near point of convergence; IQR: interquartile.

We used the cutoff scores of VOMS, proposed by Mucha et al., (2014), to classify the concussion and the control groups. They defined a positive VOMS as reporting an increase of symptoms on any of the VOMS items by 2 points or more and defined a positive near point of convergence as a distance of 5 cm or longer. Adolescents with a SRC were more likely to have a provocative VOMS and NPC of ≥ 5cm (58.3%) and (45.8%) than controls (4.8%) and (9.5%) respectively (Table 4-6).

Table 4-6: Chi-Square of group by VOMS provocation and NPC (cm)

Pearson Chi-Square		Concussion n=24	Control n = 21	p-value	Effect size
VOMS	**Provocative**	14	1	0.001	0.567
	Non-provocative	10	20		
NPC (cm)	**≥ 5 cm**	11	2	0.007	0.400
	< 5 cm	13	19		
VOMS+NPC	**Provocative & ≥ 5 cm NPC**	7	0	0.007	0.401
	Non-provocative or < 5 cm NPC	17	21		

VOMS: vestibular/ocular motor screening; NPC: near point of convergence.

4.4.4 Balance Error Scoring System (BESS)

The Shapiro-Wilk test of normality showed that the total BESS and foam pad BESS were normally distributed in both groups, while the normality assumptions for the firm BESS were violated in both groups ($p < 0.05$) (Appendix F). There was not a significant difference in any of the BESS scores for adolescents with and without SRC (Table 4-7).

Table 4-7: BESS mean number of errors and groups comparisons

BESS	Concussion n=24	Control n=22		P value

	Median	Range	Median	Range	U statistic	
Firm	3.5	(0 – 12)	3.0	(0 – 10)	212.5	.252
Foam pad	9.0	(2 – 16)	7.5	(2 – 13)	187.0	.088
Total	11.5	(4 – 28)	10.5	(2 – 20)	203.5	.182

BESS: balance error scoring system

4.4.5 The Relationship between vHIT and VOMS and BESS

A series of Spearman rank-order correlations were computed in order to determine if there were any relationships between the value of the vHIT gain and BESS scores in adolescents with a SRC. A two-tailed test of significance indicated that there was no significant relationship between the BESS scores and the value of the vHIT gain in adolescents with a SRC (Table 4-8).

Table 4-8: vHIT/ BESS Spearman rank-order correlation (n=20)

Spearman rank-order correlation	Instantaneous gain	Gain regression
Firm	.304	.199
Foam pad	-.098	-.181
Total	-.036	-.148

No significant correlations; BESS: balance error scoring system; vHIT: video head impulse test.

A series of Spearman rank-order correlations were computed in order to determine if there were any relationships between the VOMS provoked symptoms and the value of the vHIT gain in adolescents with a SRC. A two-tailed test of significance indicated the there was no significant relationship between the VOMS items and the value of the vHIT gain (Table 4-9).

Table 4-9: vHIT/ VOMS Spearman rank-order correlation (n=20)

VOMS items	Instantaneous gain	Gain regression
Smooth pursuits	-.105	-.190
Horizontal saccades	-.057	-.168
Vertical saccades	.104	.064
NPC - symptoms	.148	.160
Horizontal VOR	.130	.064
Vertical VOR	-.100	-.128
VMS	-.038	-.041
NPC - distance (cm)	.098	.193

No significant relationship of VOMS items and the value of vHIT gain; VOMS: vestibular/ocular motor screening; VOR: vestibulo-ocular reflex; VMS: visual motion sensitivity; NPC: near point of convergence; vHIT: video head impulse test.

4.5 DISCUSSION

The aim of this study was to assess the prevalence of reduced vHIT function in adolescents with and without SRC, and also to compare scores on the BESS and the VOMS with vHIT gain in adolescents with SRC.

The vHIT gain value was not significantly different for adolescents with and without SRC. Furthermore, in this study, none of the adolescents with SRC had clinically reduced vHIT gain values which was defined as having vHIT gain ratio or slope lower than 0.80 [119,120,132,133]. The current findings support previous research of adolescent and adults with concussion (Alshehri's, manuscript accepted), where no abnormalities were found on vHIT gain values. Participants in Alshehri's study were more chronic (median number of days since concussion was 51, range 11 -

803 days) than our sample (mean days since concussion 5.8 days, SD 2.7 days). Therefore, the vHIT gain may not be a useful tool to differentiate adolescents with and without concussion. Balaban et al. assessed the computer controlled rotation head impulse test (crHIT) gain, which provide whole body impulses using a rotational chair while recording eye movement, and found that crHIT gain decreased in 100 participants with concussion (83% were tested within 4 days of injury) compared with 200 controls (both groups age range 18 - 45 years) [127].

Caloric testing was not performed with these adolescents. Given the low sensitivity (31% - 41%) and the high specificity of the vHIT (98% - 92%) reported by van Esch et al. and Mahringer and Ramold, a negative vHIT finding might require performing the caloric test in order to determine if a vestibular disorder is present[119,120]. Negative vHIT findings could lead to missing VOR dysfunction, while positive vHIT findings would be sufficient to determine VOR dysfunction.

Although evidence suggests a relationship between blast and blunt head injuries with vestibular impairments [18,19,22,23], all of these studies had participants with more chronic concussion than our sample. Furthermore, they have focused on individuals with concussion who had complaints of dizziness or other vestibular symptoms. The current study included symptomatic adolescents with a SRC and did not focus on any subset of symptoms such as physical, cognitive, or emotional symptoms, while the previous studies limited their investigated population to those with vestibular complaints.

A retrospective study of 247 children (age range 5 to 15 years) with concussion in a tertiary sports medicine clinic found that 69% of patients had a positive VOMS provocative test [130]. To date, there are no published studies that prospectively have investigated vestibular dysfunction using quantitative methods such as caloric testing in adolescents with SRC. The study findings confirm that performing the vHIT test in symptomatic adolescents with SRC within 10 days of the injury and follow-up testing to recovery is feasible in this population, although its value is questioned.

One of the goals of the study was to compare BESS scores in individuals with and without SRC. No difference was found between groups on their BESS scores. The current findings support previous findings from the McCrea et al. study of collegiate athletes with a SRC (n=94; mean age 20.0 years, SD 1.4 years) and healthy controls (n=56; mean age 19.2 years, SD 1.5 years), in which the number of errors on the BESS was not different between the two groups when tested 3 to 5 days after injury. Participants were tested using the BESS immediately after the injury and 3 hours after the injury as well as on days 1, 2, 3, 5, 7, and 90 after the injury. They reported differences between groups on the number of errors on the BESS up to 3 to 5 days after the injury [41]. Our BESS results were also consistent with findings of high school students with and without concussion injury in which there was no difference on the number of errors on modified BESS and total BESS between groups [14]. Furthermore, our BESS results were consistent with findings from the King et al. study of adolescents with and without concussion, in which they did not find a difference in the number of errors on BESS and modified BESS between groups [83].

In contrast to our results and the majority of published studies [14,41,83], a study by Chin et al. (2016) compared the BESS and the modified BESS in adolescents with a SRC and controls. There were group differences on days 1 and 8. Although there were differences between the groups, the differences of the mean scores between the groups was less than 1 error in the BESS and 1.5 errors in the modified BESS, suggesting that the differences found between the groups may not be clinically meaningful [134].

Another goal of the study was to compare VOMS symptom provocation in adolescents with and without SRC. As expected, the baseline symptoms were higher (worse) in adolescents with concussion. Furthermore, differences were found between groups on the VMS provoked symptoms and NPC mean distance, which was worse in adolescents with concussion. The current findings support a previous study by Mucha et al. Adolescents with a SRC showed a greater increase of symptoms on the VMS and had longer (worse) NPC distance than healthy controls [26]. Although Mucha et al. found an increase in symptom provocation in the people with SRC compared to the healthy controls in all VOMS items, results of the current study showed differences on the VMS symptoms and the NPC distance but not for any of the other VOMS items. An explanation for the inconsistency between the results of this study and Mucha et al. may be that some adolescents (in both groups) in the current study reported lower (decreased) symptoms after some of the VOMS items than their baseline symptoms while in the Mucha et al.'s study none of the participants reported a decrease in symptoms [26]. Another explanation for the inconsistency may be that the smaller sample size of the current study didn't possess enough statistical power to demonstrate differences between groups. Our results suggest that the VOMS is superior to the vHIT, the BESS, and the modified BESS in distinguishing adolescents with and without concussion.

Contrary to our expectation, no correlation of vHIT gain was found with the VOMS in adolescents with SRC. Although vHIT and VOMS were proposed to assess vestibular function, the vHIT tests the horizontal semicircular canals at a higher frequency than the VOMS VOR provocation test. Furthermore, these tools are measuring different aspects of vestibular system performance as the VOMS measure the provocation of symptoms while the vHIT measures the vestibulo-ocular gain.

4.6 LIMITATIONS AND FUTURE DIRECTIONS

The main limitation of this study is its lack of a gold standard test of vestibular dysfunction such as caloric testing. Inclusion of such a test would help in confirming vestibular system involvement. Given the low sensitivity of the vHIT (31% - 41%) [119,120] a negative vHIT finding is not sufficient to rule out VOR dysfunction. A test with low sensitivity could lead to missing true VOR dysfunction.

The included adolescents were within 10 days of their SRC which is considered a wide range for injury onset as other studies found resolution of reported symptoms as well as resolution of balance impairment (assessed using BESS) within 3 to 7 days after the SRC injury [41,57]. These studies that showed balance problems in participants with concussion had seen their participants earlier than our adolescents. Recruiting adolescents within the first 3 days of injury may have revealed balance impairments and allowed the investigators to detect change over time in postural control.

One of the goals of the study was to compare BESS scores in individuals with and without SRC. Given the onset of the injury and time-dependent nature of the concussion injuries, the BESS may not have been the optimal tool to assess balance in this population. An instrumented sway assessment tool may have been a more relevant tool to assess sway in this population [83].

When we examined the VOMS symptoms we found that some adolescents in both groups reported lower (decreased) symptoms after some of the VOMS items than the baseline symptoms. The VOMS is a test of symptom provocation and the expected outcome of the test is to have an increase or no change in symptoms. While in the Mucha et al. study none of the participants reported decreased symptoms [26], it could be that the instructions given to the adolescents were not clear enough to make the adolescents understand the goal of the test which was to report their symptoms after each provocative test compared to baseline symptoms.

4.7 CONCLUSION

Concussion is present with wide variations of signs and symptoms and involves multiple functions and structures of the brain [1,5,8,70,71,73,104] making a one-size-fit-all approach an unrealistic approach. When studying concussion injury, a more focused and narrower definition of concussion (using specific signs or symptoms) may lead to better conclusions that can be implemented in managing the concussion injury.

Multiple assessment tools of concussion exist such as the BESS, VOMS, and vHIT that may be sensitive to the onset of the injury, the reported symptoms, and the involved structures. When managing patients with a concussion injury, choosing assessment tools that are relevant to the patient's condition may improve injury management and reduce patient and therapist load by reducing the number of tools used in managing the injury and use the relevant tools, which would improve the efficiency and quality of the care.

Although the BESS has been a useful and valid sideline balance test, it may not be a sensitive enough tool for follow-up or for making a return to play decision. The VOMS appears to be a promising test to complement concussion management and follow-up testing.

4.8 CLINICAL RELEVANCE

Different concussion injuries may require different assessment tools. Choosing the right assessment tools that are more relevant to the patient's condition and presentation may improve injury management and reduce patient burden and therapist load and would improve the efficiency and quality of the care. We do not recommend the assessment of head impulse function in adolescents with SRC unless more definitive signs of peripheral vestibular injury (such as spontaneous nystagmus, vertigo, hearing changes) are present. We recommend using the Vestibular/Ocular Motor Screening (VOMS) to assess symptoms of suspected SRC injury in adolescents.

5.0 SINGLE VS DUAL-TASK BALANCE PERFORMANCE IN ADOLESCENTS WITH AND WITHOUT SPORTS-RELATED CONCUSSION

5.1 INTRODUCTION

Concussion was defined by the Consensus Statement on Concussion in Sport held in Zurich in 2012 as "a complex pathophysiological process affecting the brain, induced by biomechanical forces" [1]. Concussion is the most common acquired neurologic disorder in children and young adults [122]. The National Council on Youth Sports (NCYS) estimated that 44 million children and adolescents participate in organized sports in the United States each year [2]. In 2006 it was estimated that 1.6 - 3.8 million sports related concussions occurred annually in the United States across all age groups [3]. Emergency department visits due to concussion showed an increase of 62% between 2001 and 2009 [4]. In a report to the Congress, the National Center for Injury Prevention and Control estimated that concussion costs the United States of America nearly $17 billion each year[123].

Concussion results in physical, cognitive, emotional, and/or sleep-related symptoms that usually rapidly resolve spontaneously within a few days [1,5,8]. Physical symptoms of concussion include headache, dizziness, nausea, balance problems, visual problems, vomiting, fatigue, sensitivity to light, and sensitivity to noise [1,5,7,8]. Physical signs of concussion include loss of consciousness (LOC) and amnesia [1,5,7,8]. Cognitive symptoms include impaired concentration, impaired memory, confusion and fogginess [1,5,7,8]. Emotional symptoms include sadness, nervousness and irritability [1,5,7,8]. Sleep disorders include drowsiness, difficulty falling asleep and sleeping more or less than usual [1,5,7,8]. Headache is the most frequently reported symptom of concussion, occurring in 94% of athletes with concussion [9,10]. Other frequently-reported symptoms include balance problems (79%), dizziness (75%), impaired concentration (54%), sensitivity to light (36%), and nausea (31%) [9,10]. The high prevalence of dizziness and balance problems after concussion motivates the study of vestibular function in this population.

Concussion is considered among the most complex injuries in sports medicine to diagnose, assess, and manage [1]. Assessing concussion requires a multimodal investigation of symptoms, neuropsychological testing, and postural stability testing [1,5]. Cognitive function and postural stability decline after concussion [10–14,16]. Balance problems are commonly reported and assessed after concussion [10,12,13,16]. Consensus panels and concussion guidelines recommend the assessment of cognitive functioning and postural stability after concussion [1,8].

Maintaining balance is an intrinsic function that normally does not require much cognition or attention in adolescents and young adults. In individuals with concussion, postural instability and gait imbalance typically return to normal levels within 7-10 days of injury [1,5,8,28]. Although balance assessment is an essential part of concussion assessment [1], assessing balance in isolation of other attention-demanding tasks may conceal existing balance deficits in individuals with concussion. In sports, especially contact sports, balance is maintained while the athlete's attention is challenged by focusing on other goals than maintaining his/her balance. Therefore, inclusion of an attention-demanding task when balancing may imitate sport situations and reveal hidden balance impairments in individuals with concussion [30]. When postural and gait control tests are performed in conjunction with cognitive tasks (i.e. dual-task), postural instability and gait imbalance in individuals with concussion have persisted for more than 7 days after the injury. [29,30,37] Furthermore some studies reported balance deficits months after injury when patients were tested using dual-task paradigms [31–34]. Dual-task balance testing was proposed to be better tool than single-task balance testing to screen athletes with concussion for dysfunction [35]. While evidence suggests there are age-related differences (high school age vs college age) in postural stability and reported symptoms in individuals with concussion [28], few studies have focused on adolescents with concussion.

5.2 PURPOSE

The purpose of this study is to explore changes in single and dual-task balance function in adolescents with and without Sports-Related Concussion (SRC), using lab-based sway assessment tools (accelerometry and a force plate).

We hypothesized that adolescents with SRC will sway more than controls. Furthermore sway will increase during dual-tasking and during conditions when the balance challenge is greater.

5.3 METHODS

5.3.1 Participants

A cross sectional sample of twenty-five symptomatic male and female adolescents aged 12 to 19 years with a recent (within 10 days) SRC and twenty-two male and female controls aged 13 to 20 years were assessed. Adolescents in each group were matched for age (+/- 1 year) and sex as evidence suggests age and sex-related differences in postural stability [28,112]. Individuals with SRC were recruited by neuropsychologists who made the diagnosis of concussion after an extensive history, interview, survey of symptoms, and computerized neurocognitive testing exam were performed. The following criteria were used to make a concussion diagnosis: presence of signs or symptoms at the time of injury (posttraumatic anterograde amnesia, posttraumatic retrograde amnesia, loss of consciousness, dizziness, headache), decreased neurocognitive test score from baseline levels [113], or increased post-concussion symptoms from baseline levels [114]. Controls were recruited from middle and high schools in the greater Pittsburgh area and from the University of Pittsburgh.

Adolescents in both groups were excluded if they had neck pain or injury, an injury with symptoms to the lower body, a history of a musculoskeletal disorder, a history of brain surgery, a history of substance abuse, a history of a major psychiatric or neurological disorder, a history of vestibular disorder, special education, or a history of TBI with a Glasgow Coma Score <13. Adolescents in the control group had met the previous exclusion criteria and did not have a concussion or vestibular/ balance disorder.

The study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh. Adolescents were invited to participate in the study during their visit to the UPMC Sports Concussion clinic. The treating neuropsychologist asked the adolescent and/or his/her guardian if they were interested in participating in the study. If the patient decided that they were interested, one of the study investigators explained the study in greater detail and provided consent forms to be signed by the adolescent and his/her guardian. Adolescents in the control group contacted one of the investigators by phone or email to arrange participation in the study.

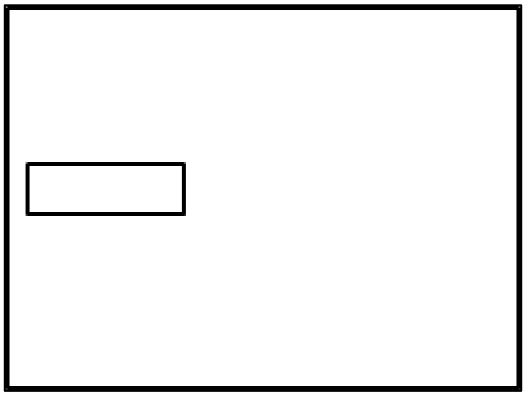
5.3.2 Study design

Sway was measured during the single-task and dual-task conditions while the adolescent was standing on a firm or compliant surface. There were 4 sway assessment trials: 2 surfaces X 2 dual-task tests. The single-task and one of the dual-task tests were performed during the same trial, in a pattern of single-task:dual-task:single-task. The trials started and ended with 20 seconds during which the adolescent was asked to stand quietly while maintaining balance, which was the single-task condition. The dual-task conditions were performed in the middle of the trials for a variable amount of time, depending on the type of cognitive task (Appendix G). Before starting the sway assessment, adolescents were asked to perform a short training of the cognitive tasks. To control for any fatigue effect between the surface conditions, the order of the type of surface was randomized.

5.3.3 Procedures

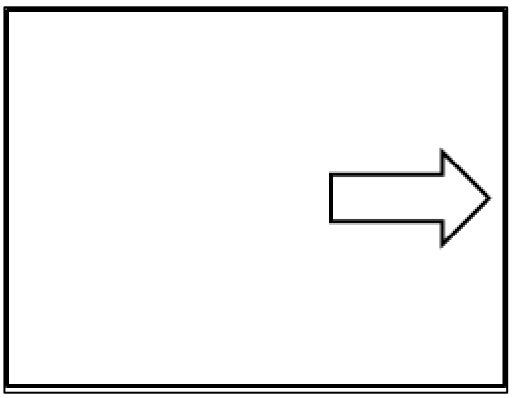
Demographics, medical history, concussion history (Appendix B), and the Post-Concussion Symptom Scale (PCSS) were completed via questionnaire. The PCSS is a 22-item self-reported symptom questionnaire performed as a part of the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) computerized test. The PCSS uses a 7 point Likert scale (range 0 – 6) to assess concussion related symptoms such as headache, vomiting, nausea, dizziness, imbalance, visual problems, fatigue, drowsiness, sleeping disorders, sensitivity to light and noise, emotional symptoms, irritability, nervousness, sadness, numbness, feeling slowed down or foggy, and difficulties with concentrating and remembering. Higher PCSS scores indicate worse symptoms [118]. After completing the questionnaire data collection, the balance test was performed while the adolescent was standing on a force plate and wore a bi-axial accelerometer. The accelerometer was strapped on the adolescents' back at the level of the iliac crest. The dual-task consisted of the subject performing a cognitive task while maintaining balance and the single-task consisted of maintaining standing balance without the cognitive task.

The cognitive task included a subset of the Motor and Perceptual Inhibition Test (MAPIT) [115–117]. First a forced choice spatial discrimination test was performed as a control condition (Figure 5-1). The forced choice spatial discrimination task requires adolescents to operate a thumb activated switch on the right or the left hand in accordance with an on-screen rectangle that appeared to the right or the left of the screen. A total of 20 stimuli were displayed in random order and random timing, with an average inter-stimulus interval of 1.75 seconds (mean total duration 35 seconds ± 1 second). After this priming spatial discrimination task, a forced choice perceptual inhibition task required adolescents to push on the right or the left switch in accordance with the direction of an on-screen arrow that appeared on the right or the left side of the screen. Two types of stimuli were provided during the perceptual inhibition task: congruous (Figure 5-2) and incongruous stimuli (Figure 5-3). For the congruous stimulus, the arrow appeared on the side of the screen that corresponded to the direction of the arrow, while for the incongruous stimulus, the arrow appeared on the side of the screen that was opposite to the direction of the arrow. During the perceptual inhibition task, the adolescent was instructed to respond to the direction of the arrow, not the side of the screen on which the arrow appeared. A total of 40 stimuli (20 congruous and 20 incongruous) were displayed in random order and random timing, with an average inter-stimulus interval of 1.88 seconds (mean total duration 75 seconds ± 3 seconds). The duration of the perceptual inhibition task was approximately twice as long as the spatial discrimination task so that the same number of each stimulus would be displayed. Adolescents were asked to maintain their balance while standing 125 cm away from the MAPIT monitor. The monitor resolution was 1920 X 1080 pixels and the refresh rate was 60Hz. The MAPIT reaction times and accuracy results were not used in the analysis.



Response = left Response = right

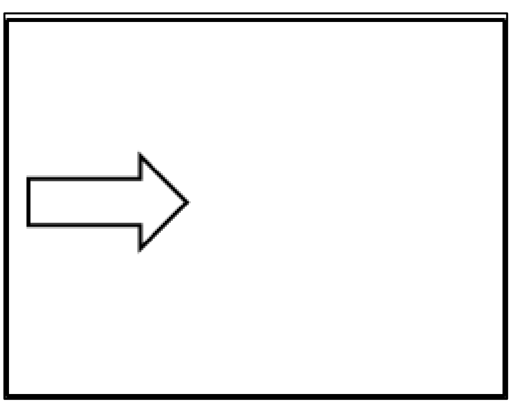
Figure 5-1: Forced choice spatial discrimination task



Response = right Response = left

Congruent stimulus

Figure 5-2: Congruent forced choice perceptual inhibition task



Response = right Response = left

Incongruent stimulus

Figure 5-3: Incongruent forced choice perceptual inhibition task

Body sway was estimated from an accelerometer and a force plate. The accelerometer was developed for the National Institutes of Health (NIH) Toolbox as an inexpensive device designed to quantify sway in clinical settings. The accelerometer was a bi-axial accelerometer that measured acceleration in the anterior-posterior (AP) and medial-lateral (ML) directions. The acceleration was measured in mG at a sampling rate of 100 Hz and transmitted through a Bluetooth connection to a computer (Appendix H). The accelerometer was attached to the back of a gait belt that fit snugly around the participant's waist at the level of the iliac crest, using Velcro. The iliac crest approximates the level of the Center of Mass (COM) (Figure 5-4).

The force plate (BP5050, Bertec, Inc.) contains 4 load cells that measured the vertical ground reaction force and ground reaction moments about the AP and ML axes of the plate, from which the Center of Pressure (COP) was calculated. The force plate was connected to a computer using a USB cable and the ground reaction force and moments were recorded at a sampling rate of 100 Hz (Appendix I). Both the accelerometer and force plate data were collected using a custom made LabVIEW program (National Instruments Corporation). Although the COP and COM are different entities, they were found highly correlated [91,92]. The procedures described above took about 45 minutes to be completed.

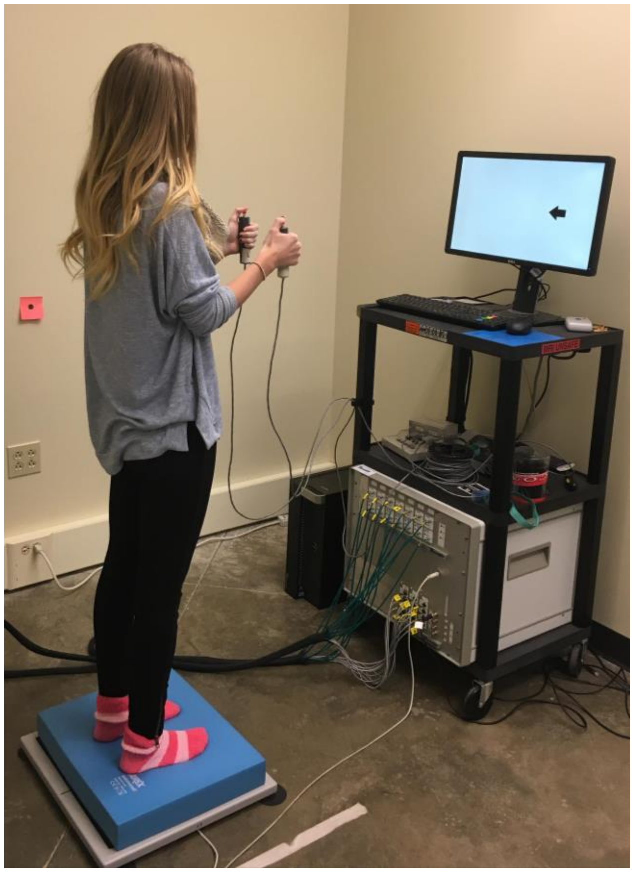


Figure 5-4: Sway measurement setting. Adolescent is standing on force plate with a compliant surface with an accelerometer attached to the participant's lower back using a Velcro belt, while holding two thumb-activated switches to respond to a visual stimulus.

Adolescents in both groups performed additional tests that were not used or reported in this report, including the Balance Error Scoring System (BESS), the Vestibular/Ocular Motor Screening (VOMS), the Video Head Impulse Test (vHIT), and ImPACT. The procedures described above took about 50 minutes to be completed.

5.3.3.1 Data analysis

A considerable number of adolescents did not complete the single task at the end of the trial because they started moving their arms and feet while they should have stood quietly for 20 seconds. Due to the lack of statistically significant difference between the single-task performed before and after the dual-task in valid trials, sway data from the second single-task assessment (post-dual-task) were not used. In cases when the sway data from the first single-task (pre-dual-task) assessment was unable to be analyzed, due to equipment problems or participant's lack of cooperation, sway data from the second single-task (post-dual-task) was used. A detail of the missing sway data during each condition is reported in Appendix J.

Using a custom Matlab program, data from the accelerometer and force plate were processed using a low-pass filter with a frequency cutoff of 2 Hz [135] (Figure 5-5). A frequency analysis of sway showed that a cutoff frequency of 2 Hz retained 97% (range 90% - 99%) of the adolescents' sway. Four measures of sway were computed for both the acceleration and COP: the root mean square (RMS) (Equation 5-1) and the normalized path length (NPL) (Equation 5-2) in the AP and ML directions. The RMS and NPL were defined as:

Equation 5-1

$$RMS = \left[\frac{[\sum_{n=1}^{N-1} Sway[n]^2]}{N}\right]^{\frac{1}{2}}$$

N: $number\ of\ sway\ samples$
Sway $[n]$: $individual\ sway\ sample - the\ mean\ of\ all\ sway\ samples$

Equation 5-2

$$NPL = \left[\sum_{n=1}^{N-1} |Sway[n+1] - Sway[n]|\right] / duration$$

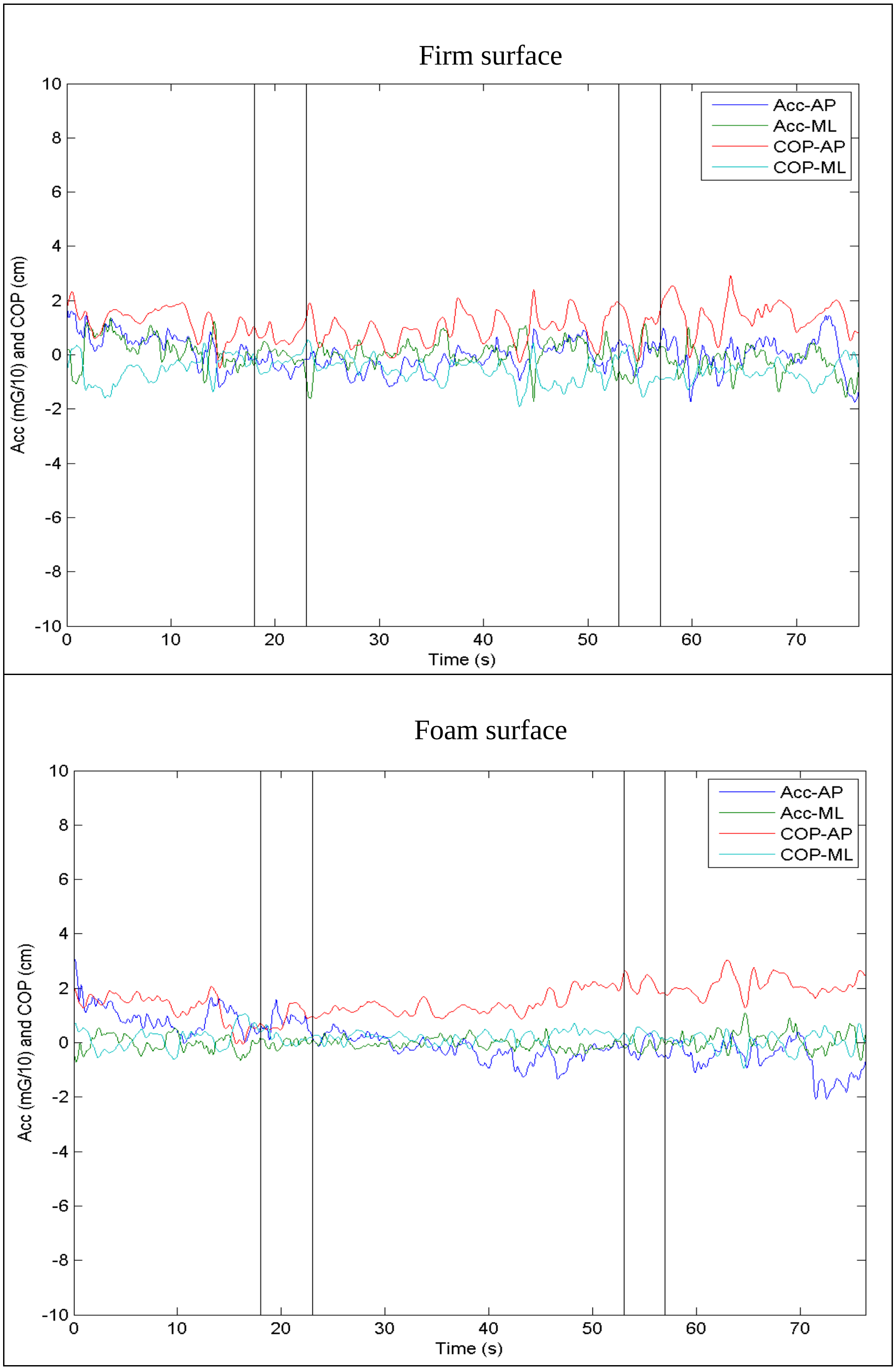


Figure 5-5: Plots of the time series of accelerometer (Acc) and force plate (COP) data processed using a low-pass filter with a frequency cutoff of 2 Hz. Acc: acceleration (mG/10); COP: center of pressure (cm); AP: anterior posterior; ML: medial lateral.

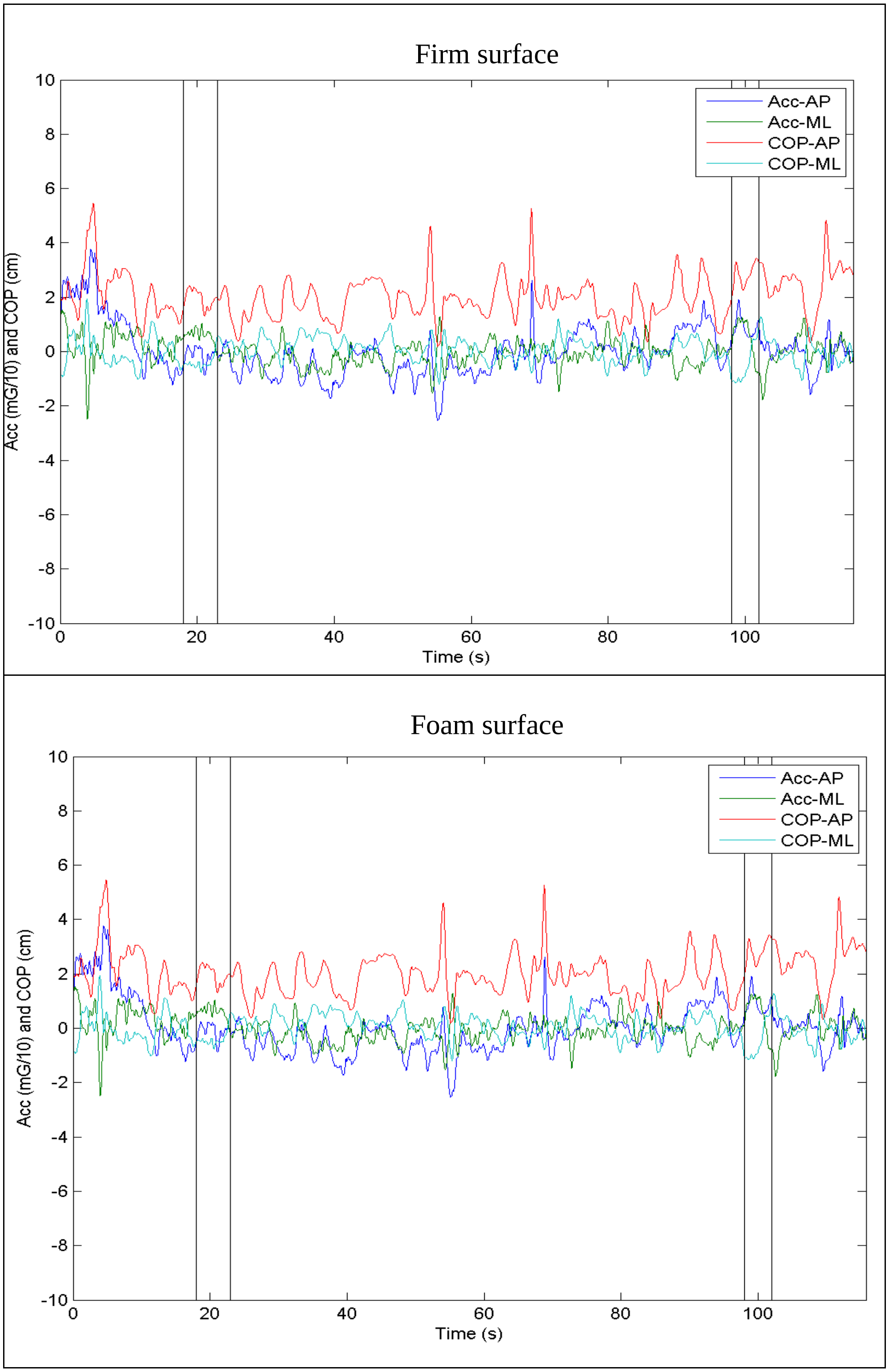


Figure 5-5 (continued)

5.3.4 Statistical analysis

The statistical analysis was conducted using SPSS, with a significance level of $\alpha < 0.05$. Between-group differences in demographic data were tested using independent samples t test for normally distributed data and the Mann-Whitney U test for non-normal data. For dichotomous data, chi square tests were used.

A linear mixed model was performed using a compound symmetry covariance structure to investigate the fixed effects of group (concussion and control), surface (firm and foam), and task (single and dual) as well as the interaction effects of group * surface, and group * task on the magnitude of eight sway measures: the NPL and the RMS of the AP and the ML displacement of COM and COP.

To investigate the effect of cognitive test (spatial discrimination and perceptual inhibition) as well as the interaction effect of group * cognitive test, a separate linear mixed model was performed using a compound symmetry covariance structure. A separate analysis was needed because the design of the dual-task balancing paradigm included performance of the single-task and the dual-task in a continuous manner which resulted in having the single task confounded within each dual-task test. Higher order interactions (3-way and above) were not tested to preserve model simplicity and because we did not have hypotheses of interest for these interactions.

5.4 RESULTS

5.4.1 Participants

Two hundred and seventy-six adolescents visiting the concussion clinic were approached to be recruited in this study. A flow chart (Figure 5-6) shows reasons for exclusion or inability to enroll.

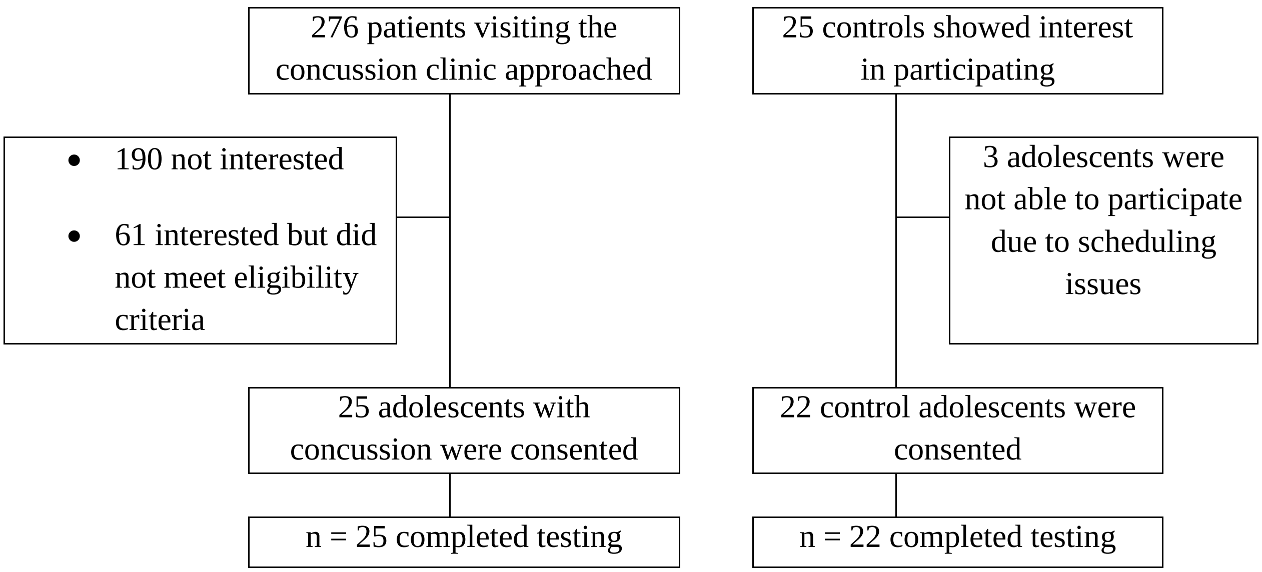


Figure 5-6: Subject enrollment flow chart

Twenty-five (16 male, 9 female) adolescents (9% of 276 patients who were approached) who had a SRC within the past 10 days (mean days since injury 5.8 days, SD 2.7 days, range 0 – 10 days) and aged between 12 to 19 years old (mean age 15.1 years, SD 1.9 years, range 12-19 years) were eligible and agreed to participate in the study. Twenty two (15 male, 7 female) healthy control adolescents (mean age 15.6 years, SD 2.1 years, range 13-20 years) participated. Demographic data are reported in Table 5-1. The sports played during injury were: football (five adolescents); basketball and soccer (three adolescents each); hockey (two adolescents); baseball, cheerleading, diving, softball, volleyball, and wrestling (one adolescent each); recreational activity (six adolescents).

There was not a significant difference in the age, gender, height, weight, and handedness for adolescents with SRC and adolescents without SRC (Table 5-1).

Table 5-1: Demographics and physical characteristics for concussion and control groups

Characteristics	Concussion Group n=25	Control Group n=22	P value
Age, years, mean (SD)	15.1 (1.9)	15.6 (2.1)	0.515^
Gender	9 female	7 female	0.763*
Weight, kg, mean (SD)	64.1 (16.3)	60.0 (8.9)	0.284#
Height, cm, mean (SD)	171.0 (10.7)	168.0 (10.5)	0.346#
Handedness	20 Right	19 Right	1.000*

*: Pearson chi-square; ^: Mann-Whitney U Test; #: independent samples t-test

Adolescents with SRC reported experiencing immediate symptoms at the time of the concussion. All adolescents except one reported dizziness. More than half of the adolescents reported confusion/ disorientation, and amnesia and LOC were reported by 4 and 2 adolescents respectively (Table 5-2).

Table 5-2: Immediate symptoms of concussion

Symptoms n=25	n (%)
Dizziness during injury	24 (96%)
Confusion/disorientation at injury	13 (52%)
Anterograde amnesia at injury	4 (16%)
LOC during injury	2 (8%)
Retrograde amnesia at injury	0

LOC: loss of consciousness

Adolescents with SRC reported more headache, fogginess, and dizziness at the time of recruitment than controls (Table 5-3).

Table 5-3: Symptoms reported at the time of recruitment

Symptoms reported at the time of recruitment	Concussion Group n=25	Control Group n=21	Pearson chi square test p-value
Headache, mean (SD)	2.8 (1.9)	0.6 (1.0)	< 0.001
Fogginess, mean (SD)	1.3 (1.4)	0.1 (0.2)	0.001
Dizziness, mean (SD)	0.6 (1.1)	0.1 (0.3)	0.039
Nausea, mean (SD)	0.3 (0.7)	0.5 (1.2)	0.492

No significant group differences were found for history of attention deficit disorder (ADD), learning disabilities (LD), migraine, or motion sickness between adolescents with and without SRC. None of the adolescents reported any history of LD (Table 5-4).

Table 5-4: Past medical history for concussion and control groups

Characteristics	Concussion n=25 n (%)	Control n=22 n (%)	p value
History of ADD	1 (4%)	1 (5%)	1.000*
History of LD	0	0	N/A
History of migraine	4 (16%)	0	0.112*
History of motion sickness	8 (32%)	4 (18%)	0.242*

*: Pearson chi-square; ADD: attention deficit disorder; LD: learning disabilities; N/A: not applicable (the variable was constant in all subjects)

To further characterize the subject groups, we examined their BESS performance and magnitude of symptoms with the PCSS. Groups BESS scores were not significantly different (p = 0.182). Adolescents with concussion averaged 12 errors (SD = 5) and controls had a mean of 10 errors (SD = 4). Meanwhile, the PCSS was significantly different between groups ($p < 0.001$), as adolescents with concussion had a mean symptom score of 30 (SD = 18) and controls had a mean symptom score of 6 (SD = 14).

5.4.2 Missing sway data

Sway was measured simultaneously using the force plate and the accelerometer. In a few cases, while performing the balance tests, the force plate and/or the accelerometer malfunctioned and data were not recorded. In other cases sway data was not used due to adolescents' failure to follow directions of standing with both feet on force plate and/or keeping both arms in position (mainly distracted by their performance on the cognitive task) while performing the balance test. Furthermore, in a few cases, although adolescents followed instructions and equipment did not show failure, the data output registered outlier sway values in the COM or COP defined as a deviation by more than 3 standard deviations from the mean. In such cases, data were treated as missing data (Appendix J). Seven and six adolescents from the concussion and the control groups, respectively, did not have a complete data set in at least one measure of sway. One adolescent from the concussion group did not have any COP data due to equipment problems.

5.4.3 Center of pressure (COP)

Sway measured using the COP and the COM showed similar results (Appendix K), therefore only COP data are reported. The COP data were mostly normally distributed. The Shapiro-Wilk test of normality showed that only 6 out of 64 measures of the different conditions were not normally distributed ($p < .05$) (Appendix L). The mean and SD of the COP and COM sway values are reported in Appendix M.

Results of the linear mixed model (Table 5-5) showed significant main effects of single vs dual-task, cognitive task, and surface on several of the sway measures, as well as significant interaction effect of group * surface. More details about the nature of the main effects and the interaction effect are discussed in the following paragraphs with visual illustrations.

Table 5-5: Linear mixed model of COP sway for adolescents with SRC (n=25) and controls (n=22)

p value of the effects	NPL		RMS	
	AP	ML	AP	ML
Group	0.817	0.551	0.235	0.127
Single vs dual-task	0.034	<0.001	<0.001	0.864
Cognitive task	0.886	0.714	0.014	<0.001
Surface	<0.001	<0.001	<0.001	<0.001
Group by Single vs dual-task	0.117	0.637	0.965	0.753
Group by Cognitive task	0.909	0.382	0.780	0.728
Group by Surface	0.746	0.011	0.298	0.015

COP: center of pressure; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; SRC: sports-related concussion.

Regarding the main effects, the group effect was not statistically significant in any of the measures of sway. Figure 5-7 shows a minimal group difference in sway values in the control group compared to the concussion group across all measures of sway.

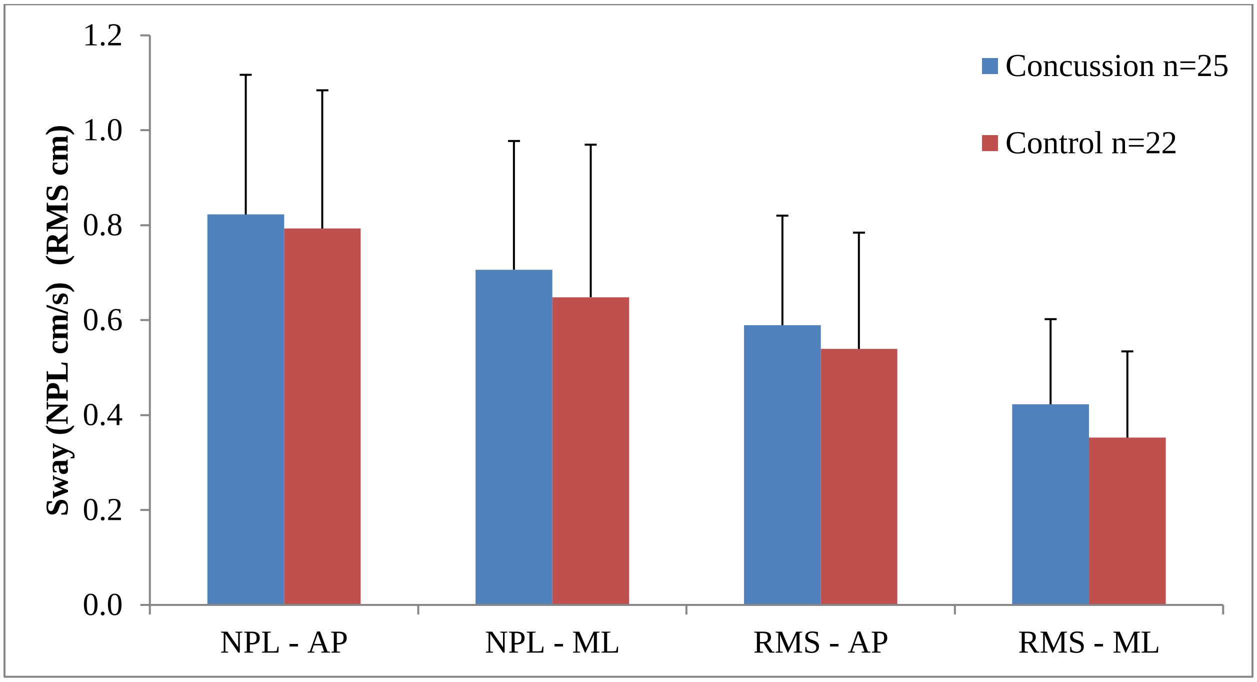


Figure 5-7: Group effect on center of pressure. NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation

The main effect of single vs dual-task was statistically significant, showing decreased NPL sway in the AP and the ML directions during the dual-task compared to the single task, while showing increased RMS sway in the AP direction during the dual-task compared to the single task (Figure 5-8).

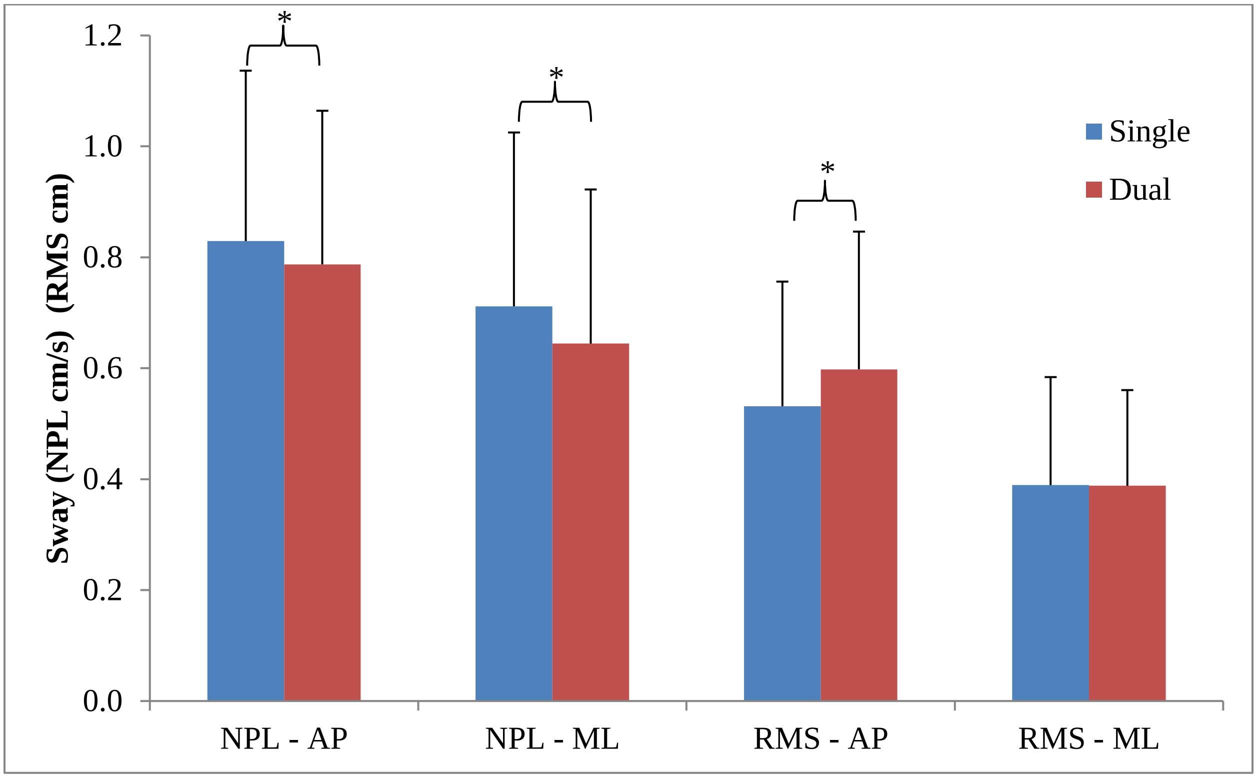


Figure 5-8: Single vs dual-task effect on the center of pressure. NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation. * $p < 0.05$; n=47.

The main effect of cognitive task was statistically significant for the RMS COP showing increased sway values in the AP and the ML directions during the perceptual inhibition task compared to the spatial discrimination task (Figure 5-9). However, the effect of cognitive task on NPL sway was not significant.

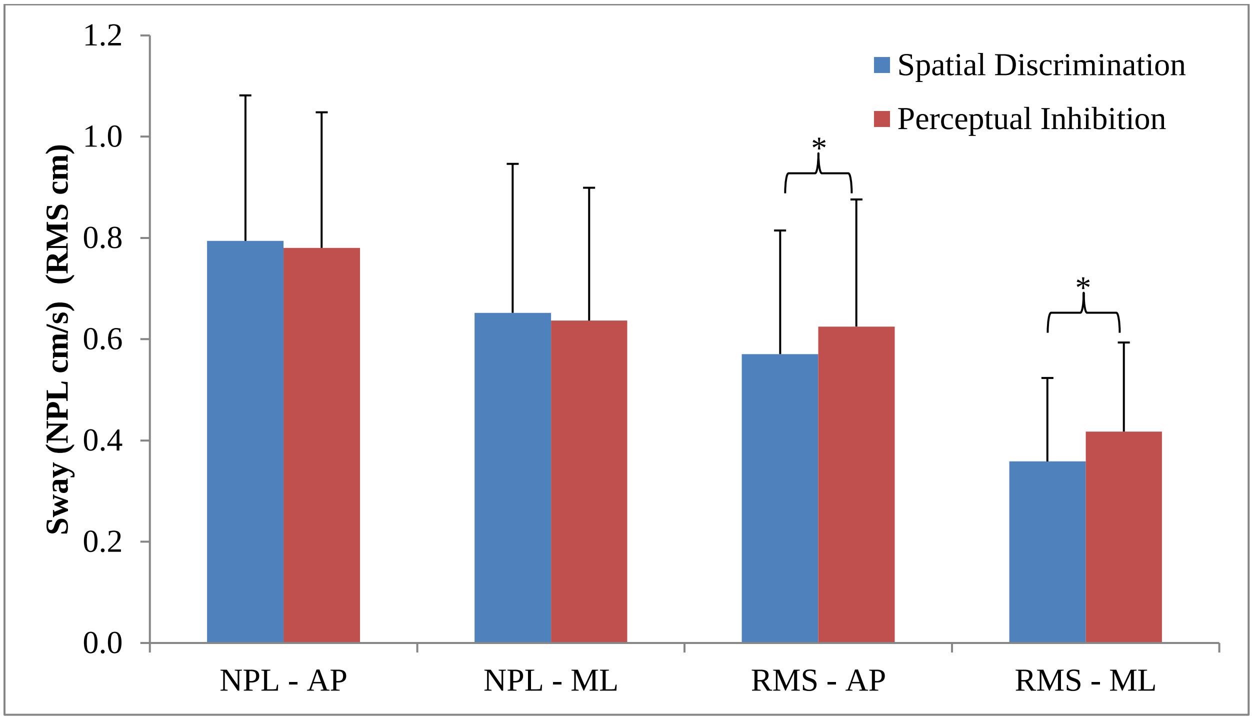


Figure 5-9: Cognitive task effect on center of pressure. NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation. * $p < 0.05$; n=47.

The main effect of surface was statistically significant showing increased sway while standing on a compliant surface compared to the firm surface on all measures of sway (Figure 5-10).

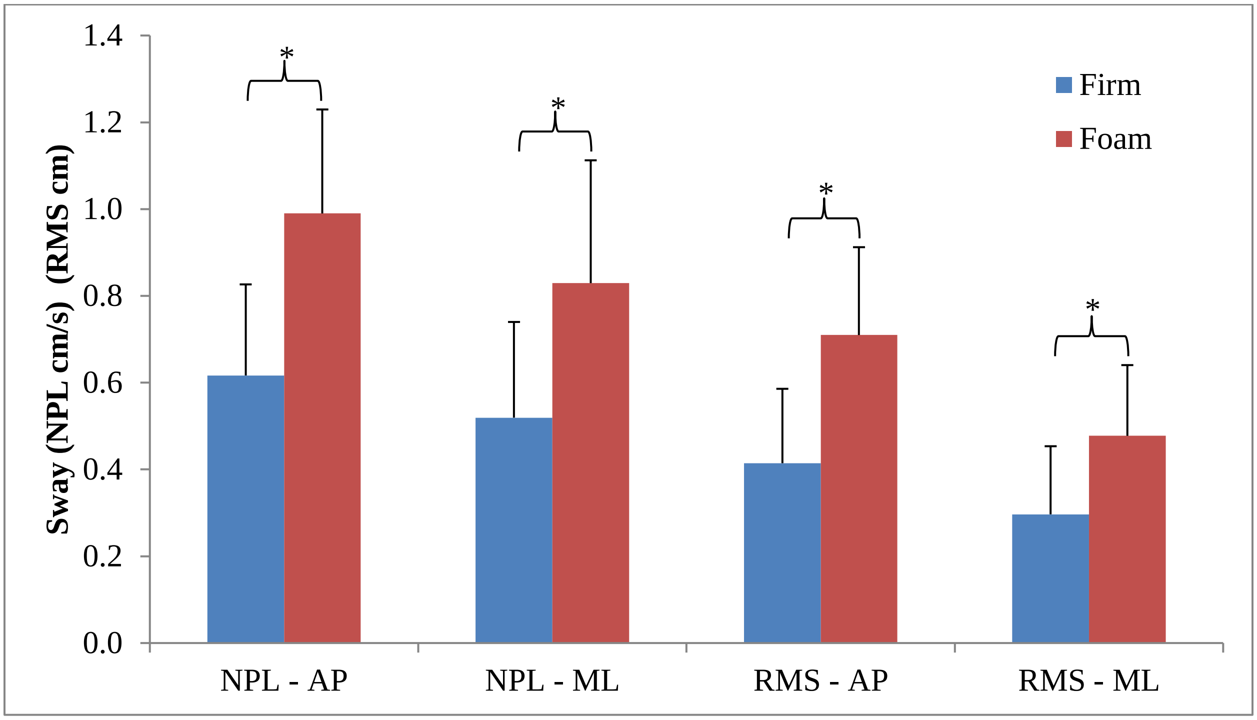


Figure 5-10: Surface effect on the center of pressure. NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation. * p < 0.05; n=47.

A significant interaction effect of group by surface was found on NPL sway ($F(1, 292.99) = 6.58$, $p = .011$) and RMS sway ($F(1, 292.71) = 5.93$, $p = .015$) in the ML direction but not for sway in the AP direction (Figure 5-11). The control group showed lower sway values (NPL = 0.47 cm/s and RMS = 0.25 cm) than the concussion group (NPL = 0.57 cm/s and RMS = 0.35 cm) during the firm surface condition. In the foam surface condition, the control group sway values (NPL = 0.83 cm/s and RMS = 0.46 cm) approximated that of the concussion group (NPL = 0.83 cm/s and RMS = 0.49 cm). Because the control group had lower sway than the concussion group on the firm surface, but nearly equal sway on the foam surface, the control group had greater difference between firm and foam conditions than the concussion group, which resulted in the significant interactions. No other significant interactions between the group and experimental conditions were found (Appendix N).

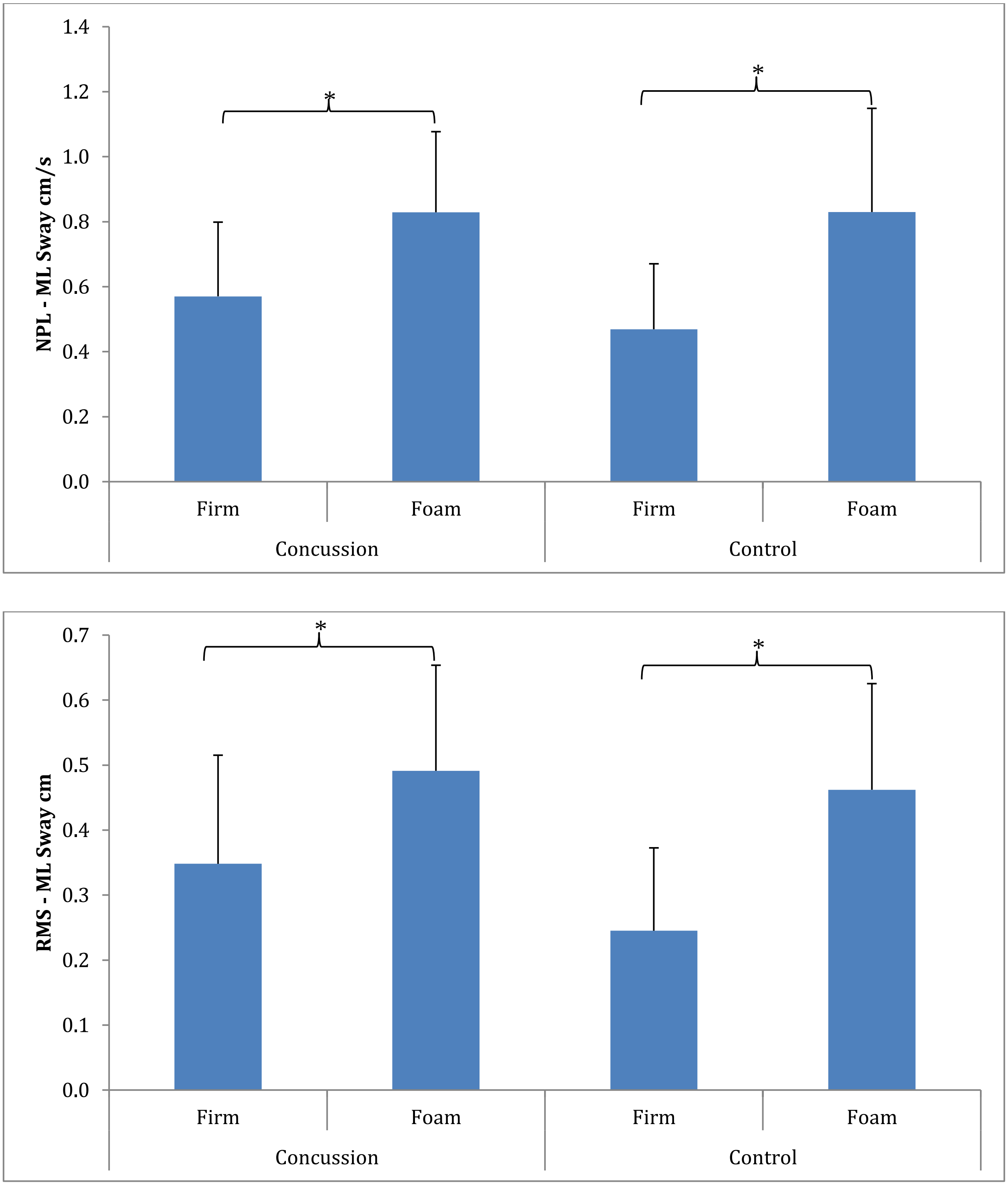


Figure 5-11: Group by surface interaction on center of pressure. NPL: normalized path length; RMS: root mean square; ML: medial-lateral; Error bars: standard deviation; significant interaction of group * surface on NPL and RMS sway in the ML direction $p < 0.05$; * $p < 0.05$; n=47.

5.5 DISCUSSION

The aim of this study was to investigate postural sway changes in adolescents after a SRC and controls matched for age and sex during single and dual-task balance tests. The main findings were: 1) no difference in sway between the concussion and control groups; 2) a dual-task effect that produced reduced NPL sway and greater RMS sway compared with the single task; 3) increased RMS sway during the perceptual inhibition task compared with the spatial discrimination task; and 4) increased sway during the foam surface condition compared with firm surface; also, the control group had significantly less sway than the SRC group on the firm surface, but about the same amount of sway on the foam surface.

We hypothesized that adolescents with SRC would have greater sway across all conditions compared with controls. However, we found no difference in sway measures between the two groups. Similar results of no sway differences between adolescents with SRC (within 14 days of injury, mean days between concussion and balance testing = 8 SD 3.2 days) and controls were reported by Furman et al. (2013). The balance test was performed during six standing conditions: standing with eyes open and closed while feet are side by side on firm and foam surfaces and feet in tandem stance. Our findings are in contrast with several other studies [12,16,30,93]. Dorman et al. found a difference in postural sway between adolescents with concussion within 10 days of injury who had a complicated concussion who had performed concussion-related testing at least four times in the clinic over the course of their recovery, and controls. They tested postural sway with eyes open and closed during single and dual-task (reciting months of the year backwards while balancing) while the participants stood feet apart on firm surface with hands on their hips. Their results demonstrated higher sway values of COP (95% ellipse area (cm^2) and velocity (cm/s)) in adolescents with concussion during eyes open and eyes closed conditions of the single and dual-task balance tests [30]. A possible reason for contradicting results between our study and Dorman's is that they reported that their inclusion criteria may have resulted in the inclusion of a subset of participants with concussion who had a complicated concussion injury. Furthermore, the balance conditions and the type of cognitive task were different between the two studies.

Guskiewicz et al. reported a difference in force plate sway measures during quiet sway between adolescents with and without sports-related mild head injury, showing an increase of sway in adolescents with injury one and three days after injury [12,93] and five days after injury [93]. Guskiewicz et al. (2001) tested postural sway of 36 collegiate athletes with a SRC concussion and 36 matched controls using the NeuroCom Smart Balance Master (NeuroCom International, Inc., Clackamas, OR) during the Sensory Organization Test (SOT) that generated an Equilibrium Score (ES). The ES is the percentage of a person's unused limits of stability in the anterior–posterior direction. Therefore, a higher ES represents less sway and greater postural stability (Equitest System Data Interpretation Manual, NeuroCom International, Inc., Clackamas, OR) [93]. Guskiewicz et al. (1996) tested postural sway of 10 collegiate athletes with a SRC concussion and 10 matched controls using a force plate during 9 testing conditions (eyes open, blindfolded, and visual-conflict dome) with a firm stable platform, foam surface stable platform, and firm dynamic platform [12]. It has also been reported that balance impairment after concussion injury resolved in 3 to 5 days when assessed using the BESS [41,89,93]. In the current study the majority (64%) of the adolescents with concussion were assessed more than 5 days after their concussive injury. Therefore the amount of time between the concussion and assessment may be a critical factor for demonstrating balance deficits.

Regarding dual versus single-task conditions, our results indicated decreased NPL sway (i.e. less distance traveled by the COP) during the dual-task compared with the single task balance test, which is typically interpreted as an improvement in balance control [14,136–139]. Furthermore our results indicated increased RMS sway (i.e. greater variability of the COP) during the dual-task compared to the single task, which is usually interpreted as a worsening postural control [136].

The reduction in NPL sway that we observed in the dual-task condition is consistent with multiple studies of healthy young adults (mean age range 20 - 22 years old) that reported smaller postural sway during the dual-task test compared with the single-task test [137–140]. These studies tested their participants' postural sway using the NeuroCom Smart Balance Master (NeuroCom International, Inc., Clackamas, OR). The balance test conditions, the type of cognitive task, the length of the dual-task test, and the number of trials varied between the studies. Two studies computed the ES for the four eyes-open SOT conditions and found an increase in ES during the dual-task in SOT 1 (fixed surface/ eyes open) and SOT 2 (fixed surface/ eyes closed) [140] as well as SOT 4 (sway surface/ eyes open) [137,140]. The other two studies computed the ES for all six SOT conditions and found an increase in ES during dual-task test in SOT conditions 1 and 3 (fixed surface/ stable and sway-referenced vision) [138] as well as the composite ES from all SOT conditions [139]. The cognitive task in the Broglio et al. (2005) study was a visual processing task in which a letter-digit pair was visually presented in a 2 by 2 table on a computer monitor and the participant responded if the number was odd or even when the letter–digit pair was shown in the top row of the table, and responded if the letter was a vowel or consonant when the letter–digit pair was shown in the bottom row of the table. The participant responded by depressing a computer mouse key [140]. The cognitive task in the Teel et al. (2013) study was an incongruent Stroop test that displayed a color name in a colored font and if the name of the color and the color of the font disagreed, the participant was instructed to respond by pressing a hand held clicker. If they matched, the participant was instructed not to respond [137]. The cognitive task in Resch et al. (2011) study was an auditory stimulus of computer-generated letters and numbers displayed to a headphone. Using a hand held mouse, the participant pressed the left button when they heard an even number or a vowel and pressed the right button when they heard an odd number or a consonant [138]. The cognitive task in Ross et al. (2011) study was to respond to a visually displayed number using a handheld computer mouse by pressing the right button if the displayed number was 2 or 3 or pressing the left button if the displayed number was 4 or 5, during SOT 1, 3, 4, and 6. Meanwhile, during SOT 2 and 5 the cognitive task was to verbally respond by saying “right” when they heard the numbers 2 or 3, and by saying “left” when they heard the numbers 4 or 5 [139]. All of these cognitive tasks involved visual processing to some degree and thus it appears that such a cognitive dual-task serves to reduce the magnitude of sway.

Contrary to the previous dual-task studies, Pellecchia (2003) reported increased path length of COP and increased sway variability (i.e. standard deviation of the COP) in the AP direction during the dual-task compared with the single task balance test [136]. They assessed postural sway in 20 healthy adults aged 18 to 30 years while standing on a force plate with foam surface during single-task (quiet standing) and 3 dual-task conditions. The cognitive tasks were to verbally respond to a pre-recorded audiotape of digit pairs by reversing the numbers (first cognitive task) and by classifying a 2-digit numbers as less than or greater than 50, and odd or even (second cognitive task); the third task was counting backward by 3’s. These tasks primarily engaged auditory processing and working memory, so one possible explanation for the disparate results reported compared with visual cognitive tasks is that attention directed to different sensory modalities affects postural control in different ways.

Furthermore, our COP data demonstrated decreased NPL but increased RMS during the dual-task compared with the single task, which at first glance appears to be contradictory. However, the NPL and RMS are measuring different aspects of sway and using both measures may give more insight into sway. The RMS sway reflects the variability in deviation from the center point of sway, whereas the NPL sway may represent higher frequency sway adjustments. During the single balance task, participants may focus on consciously controlling their balance by trying to minimize the variation in deviation of sway magnitude by using higher frequency adjustments, resulting in decreased RMS and increased NPL compared with the dual-task condition. Conversely, during the dual-task condition, by directing attention to the visually-based MAPIT task, more automatic postural control strategies may occur, which could result in larger sway deviations. Maintaining standing posture is normally achieved automatically and without conscious control, while during balance testing (especially when balance is the only test being performed), adolescents may focus on consciously controlling their balance which would interfere with the automatic motor control processes that normally regulate balance and result in less efficient postural control [141]. Adding a visual task to a balance test, although requiring more attention than balance in isolation of other tasks, has shown to improve postural stability (decreased sway path length) during saccadic and smooth pursuit eye movements compared with visual fixation [142].

Performance of a more complex perceptual inhibition task while balancing produced higher RMS sway compared to the performance of a simpler spatial discrimination task. However, the NPL was unchanged, implying that the frequency characteristics of the postural adjustments didn't change while the magnitude of the variability did. These results are consistent with results of Pellecchia, (2003), who found that performing verbal tasks of different difficulties while balancing resulted in increased sway variability (i.e. standard deviation of the COP) in the AP direction as the task difficulty increased [136].

Despite the fact that the dual-task testing included a cognitive component (i.e. the perceptual task) and a sensorimotor component (i.e. the balance task), the results showed that they are not independent, generating increased sway as the difficulty of the cognitive task increased. A substantial impact of attention on sensorimotor performance in which the cognitive and the motor tasks are performed as a single higher order skill was shown. Although Pellecchia suggested that COP path length was more sensitive to the effect of task difficulty than sway variability [136], our results didn't show a significant effect of cognitive task on the NPL sway. While task difficulty may have a specific influence on postural control, others have examined the relationship between MAPIT task performance and postural sway. In a study of young and older healthy adults, Redfern et al. (2009) investigated the effect of MAPIT subtests (perceptual inhibition and motor inhibition) on sway. The perceptual inhibition (but not the motor inhibition) was positively correlated with sway (longer reaction time correlated with higher sway amplitude) in the older healthy group (but not the younger healthy group) when standing on a sway-referenced floor [116]. This finding can be interpreted that as more attentional interference occurs (specifically perceptual inhibition), less attention can be devoted to the regulation of balance and thus produce greater sway.

Interference of somatosensation can be introduced by standing on a compliant surface [143]. As expected, results showed a significant increase of sway during the foam surface balance test compared to the firm surface balance test. This is consistent with the results of several reports of the effect of foam and firm surfaces on postural sway as well as BESS performance [14,144–146]. In adolescents with concussion and healthy adolescents, Furman et al. found that the magnitude of the NPL sway, assessed using a bi-axial accelerometer, and the BESS increased (worsened) during the foam surface compared with the firm surface balance tests [14]. Hammami et al. assessed postural sway from 24 healthy elite athletes (mean age 22 years SD 3) using a force plate and found increases in sway speed (equivalent to NPL) during the foam surface compared to the firm surface balance [144]. Similarly, in healthy adults (mean age 26.9 SD 5.5) Lin et al. found increased postural sway (the RMS sway and the NPL sway) assessed using a bi-axial accelerometer during the foam surface compared with the firm surface balance tests [145]. Using force plate sway assessment, Patel et al. reported greater postural instability when standing on a foam surface compared to a firm surface in healthy adults (mean age 23 SD 6) [146] Therefore, our result confirms the significant contribution of somatosensory input in maintaining postural stability in adolescents with and without SRC. These results support using the modified BESS (firm surface only as in SCAT2 and SCAT3) rather than the original BESS that included firm and foam surfaces [12,86,93].

The group by surface interaction showed a greater increase of sway in the control group than the concussion group with the introduction of the compliant surface. The control group had lower sway values than the concussion group during the firm surface condition and during the foam surface condition the sway value between groups was comparable. Contrary to our result of group by surface interaction, other studies of postural sway in different populations had found differences between groups on a foam surface, but not firm surface [89,147,148]. Cohen et al. (2014) found increased postural sway in 90 patients with vestibular impairments (age range 21 – 79 years) compared with 156 controls (age range 23 – 90 years) during the foam surface but not the firm surface [147]. Kang et al. (2016) found significantly increased postural sway in 30 healthy young adults, 29 healthy older adults, and 27 older adults with impaired balance during the foam surface but not with the firm surface [148]. Riemann et al. compared the performance of sixteen adolescents with concussion (mean age 19 years SD 2 years) with matched controls using the BESS. They found a significant difference between groups on firm and foam surface conditions of BESS in day 1 after concussion while on day 3 after concussion group difference was significant during foam BESS only [89].

The foam surface may be equally challenging for adolescents with and without concussion to such a degree that group differences are minimized. The foam surface introduces disturbances to the proprioception feedback from the lower limbs [143]. While it is not expected that the concussion injury would affect the proprioceptive sensation from the lower limbs, it is not expected that changes to the proprioception feedback would be different between adolescents with and without SRC. In addition, this challenging condition also produces greater variability among the subjects, which makes it more difficult to detect differences between groups. Firm surface balance testing during the modified BESS showed significant differences between male and female school athletes (9^{th} grade – 12^{th} grade) showing significantly better balance in male athletes compared with female athletes as well as significantly better balance in grades 10^{th} – 12^{th} compared with 9^{th} grade [149].

Contrary to our hypothesis, there was not a significant interaction of group by single vs dual-task or group by cognitive task. Our results are also in contrast to Dorman et al. (2015) who reported a significant group difference on sway during dual-task (reciting months of the year backwards) that was not significant during single-task. The groups were eighteen adolescents with concussion (mean age 17 years SD 2 years) and twenty-six healthy adolescents (mean age 17 years SD 3 years) [30]. Another group assessed gait spatial and temporal measurements as well as whole-body COM of fourteen young adults with concussion (mean age 22 years SD 5 years) and fourteen matched controls while performing a single-task (walking only) and dual-task (walking with cognitive task). They found that the concussion group performed worse than the control group in all measures. Also they found that both groups performed worse during the dual-task condition compared to the single-task condition but no group by task interaction was found [37]. There were two cognitive tasks: 1) A reaction time task (simple cognitive task) as the participant held a switch and was required to push the switch to a cued sound; and 2) A question and answer task (complex cognitive task) that required spelling a common word in reverse, continuous subtraction by a certain number, and backward reciting of the months of the year. Based on these other reports, we expected that the addition of a cognitive task, or performance of a more difficult cognitive task, would require greater attentional resources, and thus greater sway, in the concussion group than the control group. However, this was not observed.

5.6 LIMITATIONS

Due to the design of the MAPIT test, the two types of the cognitive tasks used in this study did not have an equal task duration. Using a comparable duration of balance test may improve the validity of the comparison between the types of cognitive task.

Although simple instructions of maintaining the standing position while performing the balance tests were given to the adolescents, it was noted that adolescents were distracted from maintaining the position during the single-task conditions. Providing a continuous reminder of maintaining the standing position such as having the instruction in front of the adolescent while he/she is performing the single balance testing may have reduced distractions.

5.7 CONCLUSION

No differences in sway were noted between adolescents with a SRC within 10 days of injury and injury free controls. Several factors affected the amount of sway in adolescents with and without SRC including the type of surface (firm or foam), performing balance test in isolation or accompanying cognitive task, and the complexity of the cognitive task.

5.8 CLINICAL RELEVANCE

The dual-task paradigm that we used in this study showed interference with balancing; however, it did not improve the ability of the balance test to distinguish between adolescents with and without sports-related concussion (SRC). Furthermore, our dual-task paradigm may not be suitable to be used in clinical setting, as it is time and labor consuming and requires extensive instrumentation. A dual-task paradigm that does not require instrumentation to assess balance and/or to provide the cognitive task may be more suitable for clinical use.

6.0 ASSESSMENT OF SINGLE-TASK AND DUAL-TASK BALANCE IN ADOLESCENTS DURING RECOVERY FROM A SPORTS-RELATED CONCUSSION

6.1 INTRODUCTION

The Consensus Statement on Concussion in Sport (2012) defined concussion as "a complex pathophysiological process affecting the brain, induced by biomechanical forces"[1]. Concussion is considered the most common acquired neurologic disorder in children and young adults [122]. It has been estimated that 44 million children and adolescents participate in organized sports in the United States each year [2]. In 2006, it was estimated that 1.6 - 3.8 million sports related concussions occurred annually in the United States across all age groups [3]. Emergency department visits due to concussion showed an increase of 62% between 2001 and 2009 [4]. In a report to the Congress it was estimated that concussion costs the United States of America nearly $17 billion each year [123].

Concussion is one of the most complex injuries in sports medicine to diagnose, assess, and manage [1]. Concussion assessment requires a multimodal investigation of symptoms, neuropsychological testing, and balance testing [1,5]. It has been reported by many groups that cognitive function and postural stability decline after concussion injury [10–14,16]. Balance problems are commonly reported and assessed after concussion [10,12,13,16]. Consensus guidelines and concussion panels recommend the assessment of the cognitive functioning as well as postural stability after concussion [1,8]. Returning to normal activity without full recovery from concussion appears to make the athlete with concussion more susceptible to a second more severe concussion [5].

Balance testing has been used in diagnosing and managing concussion, especially Sports-Related Concussion (SRC) [5]. The Balance Error Scoring System (BESS) is a widely used balance assessment tool for concussion assessment [16]. In a study comparing BESS scores between 94 collegiate athletes with concussion and 56 matched controls, differences were found between groups on the total BESS score at the time of concussion that resolved within 3 to 5 days post-concussion [41]. King et al. found superiority of using the BESS along with an accelerometer compared to the BESS alone in identifying children with concussion [83]. Lab-based balance assessment tools incorporate sway measurements to infer postural stability. Body sway can be assessed by measuring movement of the body or parts of the body or by recording forces between the body and the base of support. Powers et al. measured Center of Pressure (COP) using a force plate on 9 athletes with concussion and 9 healthy athletes to investigate the effect of concussion on sway. They found greater sway in the concussion group compared to the healthy group. The elevated sway was significant even after return to play clearance, which was based on reported symptoms and other gross balance and motor control assessments [42]

Sports activities require high performance on cognitive tasks and balance function simultaneously. In individuals with concussion, postural instability and imbalance typically return to normal levels within 7-10 days of injury [1,5,8,28]. However, when postural and gait control tests are performed in conjunction with cognitive tasks (i.e. dual-task), postural instability and imbalance in individuals with concussion have persisted for more than 7 days after the injury.[29–32,35,38] Furthermore some studies reported balance deficits months after injury when patients were tested using dual-task paradigms [31–34]. In sports, especially contact sports, balance is maintained while the athlete’s attention is challenged by focusing on other goals than maintaining balance. Therefore, inclusion of an attention demanding task when balancing may imitate sport situations and reveal hidden balance impairments that may exist for longer time periods in individuals with concussion [30]. Furthermore, while evidence suggests there are age-related differences (high school age vs college age) in postural stability and reported symptoms in individuals with concussion [28], few longitudinal studies have focused on adolescents with concussion.

6.2 PURPOSE

The main purpose of this study is to assess if there are changes on clinical balance tests and lab-based sway assessment tools over time in adolescents with SRC. Also, this study will assist in understanding the effect of dual-tasking and compliant surfaces on sway in this population.

We hypothesized that balance improvement will be seen over time. Furthermore, less balance improvement will be seen during balance tests with the more attention-demanding perceptual inhibition dual-task compared with the single balance test or the spatial discrimination dual-task. In addition, we hypothesized that less improvement will be observed during the foam surface condition compared with firm surface condition, because the foam surface condition presents a greater balance challenge.

6.3 METHODS

6.3.1 Participants

Twenty-five symptomatic male and female adolescents aged 12 to 19 years with a recent (within 10 days) SRC were assessed. Adolescents were recruited by neuropsychologists who made the diagnosis of concussion after an extensive history, interview, survey of symptoms, and computerized neurocognitive testing exam were performed. The following criteria were used to make a concussion diagnosis: presence of signs or symptoms at the time of injury (posttraumatic anterograde amnesia, posttraumatic retrograde amnesia, loss of consciousness, dizziness, headache), decreased neurocognitive test score from baseline levels [113], or increase post-concussion symptoms from baseline levels [114].

Inclusion criteria were: males and females aged 12 to 20 years old currently symptomatic with a diagnosed SRC within the past 10 days. Adolescents were excluded if they had neck pain or injury, an injury with symptoms to the lower body, a history of a musculoskeletal disorder, a history of brain surgery, a history of substance abuse, a history of a major psychiatric or neurological disorder, preexisting (prior to their current concussion) vestibular disorder, special education, or a history of TBI with a Glasgow Coma Score <13.

The study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh. Adolescents were invited to participate in the study during their visit to the UPMC Sports Concussion clinic. The treating neuropsychologist asked the adolescent and/or his/her guardian if they were interested in participating in the study. If the patient decided that they were interested, one of the study co-authors explained the study in greater detail and provided consent forms to be signed by the adolescent and his/her guardian.

6.3.2 Study design

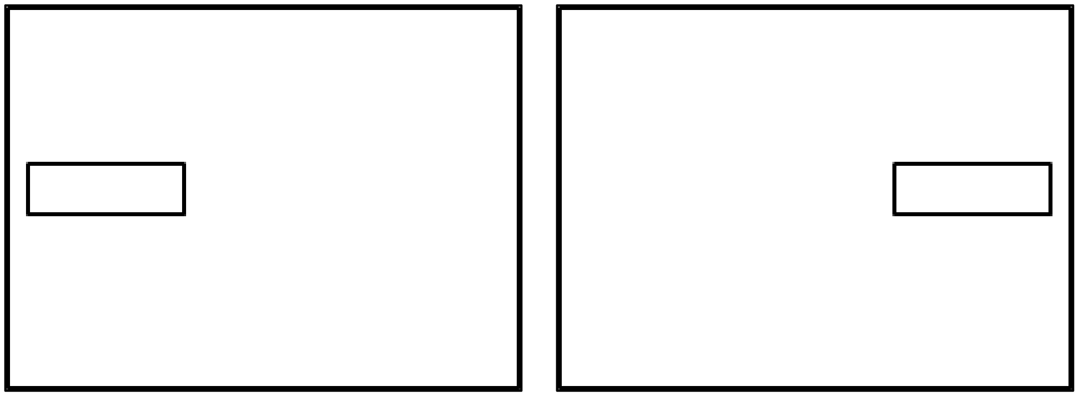
Adolescents had 3 visits, the first visit was within 10 days of the concussion injury, the second visit was performed according to the participant's availability within seventeen days after the first visit (range 4 – 17 days after first visit), and the third visit was at the time of clearance as decided by the treating physician.

Sway was measured during the single-task and dual-task conditions while the adolescent was standing on firm and compliant surfaces (Appendix A). There were 4 sway assessment trials: 2 surfaces X 2 dual-task conditions. The single-task and one of the dual-task conditions were performed during the same trial, in a pattern of single-task:dual-task:single-task. The trials started and ended with 20 seconds during which the adolescent was asked to stand quietly while maintaining balance, which was the single-task condition. The dual-task conditions were performed in the middle of the trials for a variable amount of time, depending on the type of cognitive task (Appendix G). Before starting the sway assessment, the adolescent was asked to perform the cognitive tasks. To control for any fatigue effect between the sway conditions, the order of the type of surface was randomized.

6.3.3 Procedures

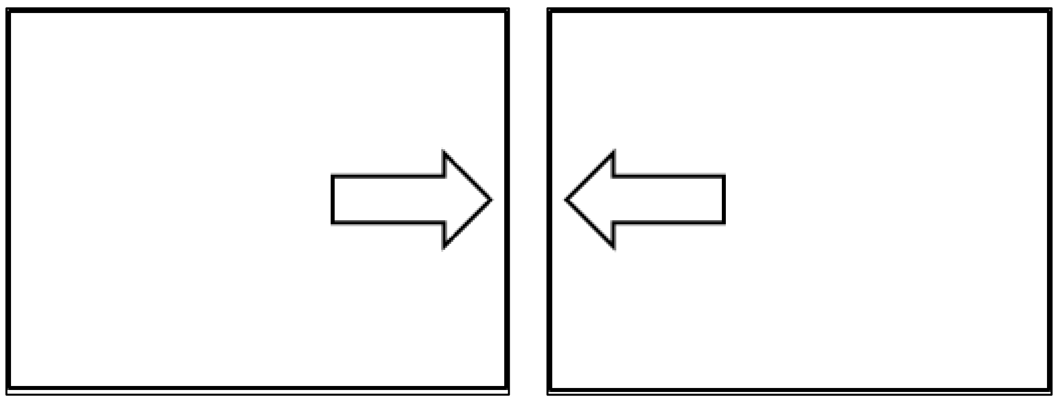
Demographics, medical history, and concussion history were completed via questionnaire (Appendix B). After completing the demographic data collection, the balance test was performed while the adolescent was standing on a force plate and wore an accelerometer. The accelerometer was strapped on the adolescents' back at the level of the iliac crest. The dual-task consisted of the subject performing a cognitive task while maintaining balance and the single-task consisted of maintaining standing balance without the cognitive task.

The cognitive task included a subset of the Motor and Perceptual Inhibition Test (MAPIT) [115–117]. First a forced choice spatial discrimination test was performed as a control condition (Figure 6-1). The spatial discrimination task required the adolescent to operate a thumb activated switch in the right or the left hand in accordance with an on-screen rectangle that appeared to the right or the left of the screen. A total of 20 stimuli were displayed in random order and random timing, with an average inter-stimulus interval of 1.75 seconds (mean total duration 35 seconds ± 1 second). After this priming spatial discrimination task, a perceptual inhibition task required the adolescent to push the switch in the right or the left hand in accordance with the direction of an on-screen arrow that appeared on the right or the left side of the screen. Two types of stimuli were provided during the perceptual inhibition task: congruous (Figure 6-2) and incongruous stimuli (Figure 6-3). For the congruous stimulus, the arrow appeared on the side of the screen that corresponded to the direction of the arrow, while for the incongruous stimulus, the arrow appeared on the side of the screen that was opposite to the direction of the arrow. During the perceptual inhibition task, the adolescent was instructed to respond to the direction of the arrow, not the side of the screen on which the arrow appeared. A total of 40 stimuli were displayed in random order and random timing, with an average inter-stimulus interval of 1.88 seconds (mean total duration 75 seconds ± 3 seconds). The duration of the perceptual inhibition task was approximately twice as long as the spatial discrimination task so that the same number of each stimulus would be displayed. The adolescent was asked to maintain their balance while standing 125 cm away from the MAPIT monitor. The monitor resolution was 1920 X 1080 pixels and the refresh rate was 60Hz.



Response = left　　　　　　　　Response = right

Figure 6-1: Forced choice spatial discrimination task



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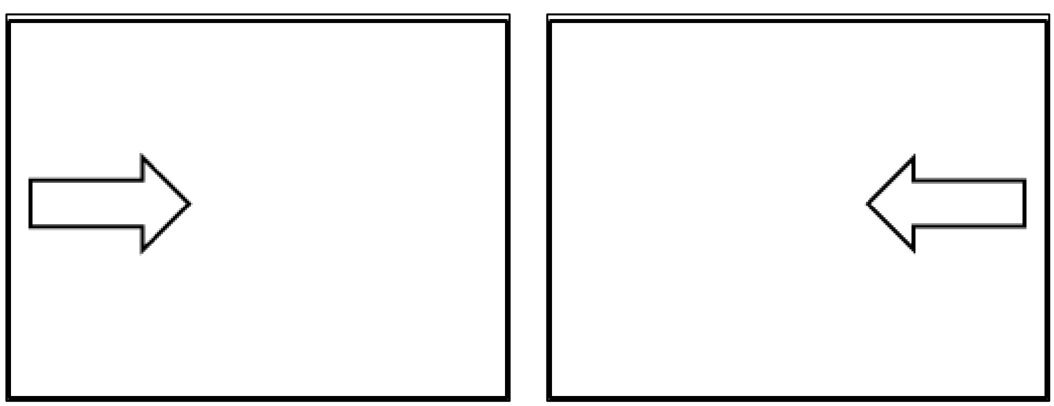
Congruent stimulus

Figure 6-2: Congruent forced choice perceptual inhibition task



Response = right　　　　　　　　Response = left

Incongruent stimulus

Figure 6-3: Incongruent forced choice perceptual inhibition task

Body sway was estimated from the accelerometer and a force plate. The accelerometer was developed for the National Institutes of Health (NIH) Toolbox as an inexpensive tool designed to quantify sway in clinical settings [92]. The accelerometer was a bi-axial accelerometer that measured acceleration in the anterior-posterior (AP) and medial-lateral (ML) directions. The acceleration was measured in mG at a sampling rate of 100 Hz and transmitted through a Bluetooth connection to a computer (Appendix H). The accelerometer was attached to the back of a gait belt that fit snugly around the participant's waist at the level of the iliac crest, using Velcro. The iliac crest approximates the level of the Center of Mass (COM) (Figure 6-4).

The force plate (BP5050, Bertec, Inc.) contains 4 load cells that measured the vertical ground reaction force and ground reaction moments about the AP and ML axes of the plate, from which the COP was calculated. The force plate was connected to a computer using a USB cable and the ground reaction force and moments were recorded at a sampling rate of 100 Hz (Appendix I). Both the accelerometer and force plate data were collected using a custom made LabVIEW program (National Instruments Corporation). Although the COP and COM are different entities, they were found highly correlated [91,92].

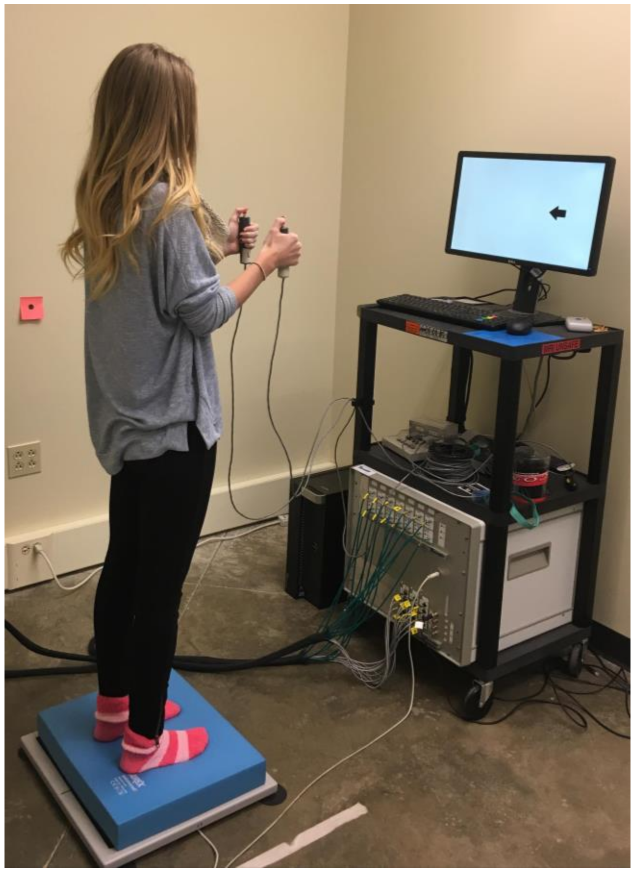


Figure 6-4: Sway measurement setting. Adolescent is standing on force plate with a compliant surface with an accelerometer attached to the participant's lower back using a Velcro belt, while holding two thumb-activated switches to respond to a visual stimulus.

The BESS [89] consists of 6 tasks, each tested barefoot with eyes closed and hands on hips for 20 seconds (Appendix E). There are 3 stance tasks: double leg stance (standing with feet together), single leg stance (standing on the non-dominant foot), and tandem stance (standing with on foot front of the other with non-dominant foot in back). Each stance task is performed on a level surface and on an Airex® foam pad (Appendix A). Timing starts when the adolescent assumes the position and closes their eyes. A hand held stopwatch is used to time each task. Tasks are scored by counting the number of times the adolescent moves out of the position.

The Post-Concussion Symptom Scale (PCSS) is a 22-item self-reported symptom questionnaire performed as a part of the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) computerized test. The PCSS uses a 7 point Likert scale (range 0 – 6) to assess concussion related symptoms such as headache, vomiting, nausea, dizziness, imbalance, visual problems, fatigue, drowsiness, sleeping disorders, sensitivity to light and noise, emotional symptoms, irritability, nervousness, sadness, numbness, feeling slowed down or foggy, and difficulties with concentrating and remembering. Higher PCSS scores indicate worse symptoms [118]. The procedures described above took about 50 minutes to be completed.

6.3.3.1 Data analysis

Sway Assessment

A considerable number of adolescents did not complete the single-task at the end of the trial because they started moving their arms and feet while they were instructed to stand quietly for 20 seconds. Due to the lack of statistically significant difference between the single-task performed before and after the dual-task in valid trials, sway data from the second single-task assessment (post-dual-task) was not used. In cases when the sway data from the first single-task (pre-dual-task) assessment was unable to be analyzed, due to equipment problems or participant’s lack of cooperation, sway data from the second single-task (post-dual-task) was used. Details of the missing sway data during each condition are reported in Appendix O.

Using a custom Matlab program, data from the accelerometer and force plate were processed using a low-pass filter with a frequency cutoff of 2 Hz [135]. A frequency analysis of sway showed that a cutoff frequency of 2 Hz retained 97% (range 90% - 99%) of the adolescents’ sway. Four measures of sway were computed for both the acceleration and COP: the root mean square

(RMS) (Equation 6-1) and the normalized path length (NPL) (Equation 6-2) in the AP and ML directions. The RMS and NPL were defined as:

Equation 6-1

$$RMS = \left[\frac{[\sum_{n=1}^{N-1} Sway[n]^2]}{N}\right]^{\frac{1}{2}}$$

N: $number\ of\ sway\ samples$
Sway $[n]$: $individual\ sway\ sample - the\ mean\ of\ all\ sway\ samples$

Equation 6-2

$$NPL = \left[\sum_{n=1}^{N-1} |Sway[n+1] - Sway[n]|\right] / duration$$

Balance Error Scoring System (BESS)

The BESS is scored by counting the number of errors committed during each of the six 20 second testing periods. Errors include opening eyes, taking hands off hips, raising heel or forefoot, step, stumble or fall, abduction or flexion of the hip more than 30°, or remaining out of the testing position for more than 5 seconds. Multiple errors occurring at the same time are counted as one error. The maximum number of errors for each task is 10 with a total of 60 for the whole test. A higher score indicates worse performance on the test [89]. The number of errors committed while performing each of the balance tests was summed. A total BESS score was calculated by summing the number of errors in all 6 balancing conditions. A total firm BESS and a total foam BESS were calculated by summing the 3 firm surface conditions and the 3 foam pad conditions, respectively.

6.3.4 Statistical analysis

Statistical analysis was conducted using SPSS with a significance level of $p < 0.05$. An intention-to-treat analysis using a last observation carry-forward approach was adopted. A linear mixed model was performed using a compound symmetry covariance structure to investigate the effect of visit, surface, and task as well as the interaction effect of visit * surface, and visit * task on the magnitude of eight sway measures: the NPL and the RMS of the AP and the ML displacement of COM and COP. As fixed effects, we entered visit (initial, second, and clearance visits), surface (firm and foam), and task (single and dual) as well as the interaction terms visit * surface and visit * task.

To investigate the effect of cognitive test as well as the interaction effect of visit * cognitive test, a separate linear mixed model was performed using a compound symmetry covariance structure. As fixed effects, we entered visit, surface, and cognitive test (spatial discrimination and perceptual inhibition), as well as the interaction terms visit * surface and visit * cognitive test were entered into the model. A separate analysis was needed because the design of the dual-task balancing paradigm included performance of the single-task and the dual-task in a continuous manner which resulted in having the single task confounded within each dual-task test. Higher order interactions (3-way and above) were not tested to preserve model simplicity and because we did not have hypotheses of interest for these interactions.

A non-parametric Friedman's analysis was conducted to compare the effect of visit on BESS and PCSS scores during the initial, second, and clearance visits. A post-hoc test was performed using the Wilcoxon matched-pair signed rank test to investigate the between- visit difference. Post-hoc results were adjusted using Bonferroni correction to control for multiple comparisons.

Statistical analysis was conducted using other models to confirm robustness of results. A per protocol approach and an intention to treat approach resulted in similar results. Repeated measures ANOVA analysis using subjects who had complete data sets resulted in similar results of the linear mixed model. To assess the effect of the drop out from the clearance visit, an analysis of the data using first and second visits, which had 23 adolescents, showed similar results to the analysis of the three visits (14 adolescents completed the third visit) (Appendix P).

6.4 RESULTS

6.4.1 Participants

Two hundred and seventy-six adolescents visiting the concussion clinic were approached to be recruited in this study. A flow chart (Figure 6-5) shows number of adolescents in each visit.

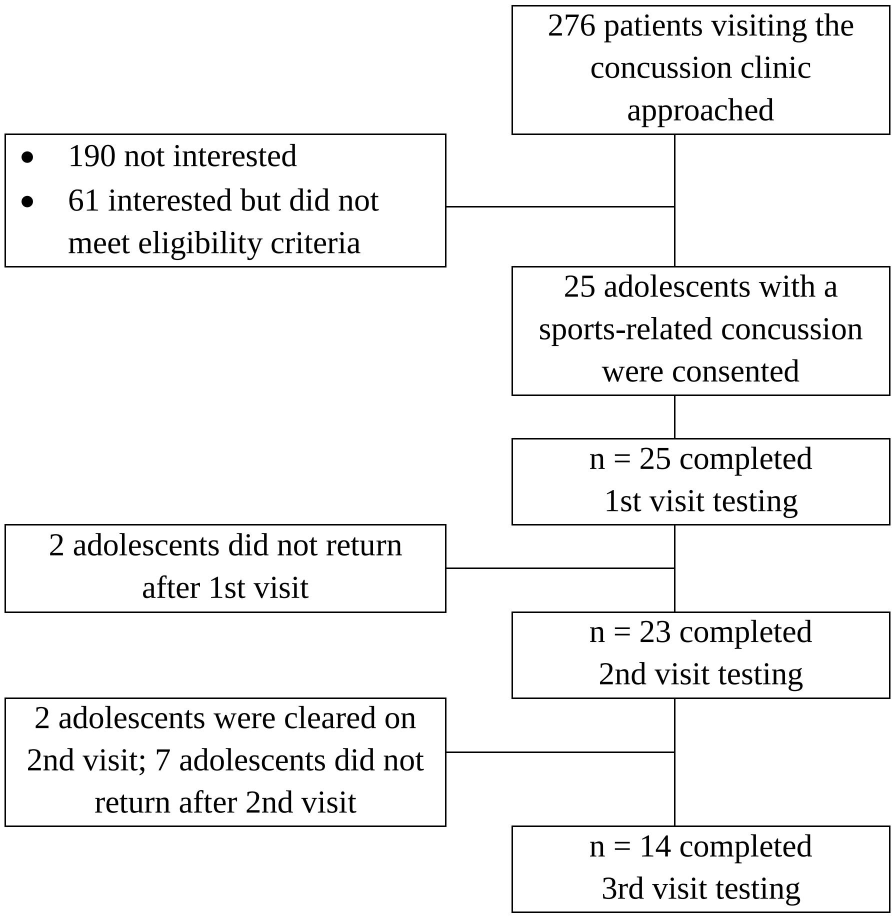


Figure 6-5: Subject enrollment flow chart

Twenty-five (16 male, 9 female) adolescents (9% of 276 patients who were approached) who had a SRC within the past 10 days (mean days since injury 5.8 days, SD 2.7 days, range 0 – 10 days) and aged between 12 to 19 years old (mean age 15.1 years, SD 1.9 years, range 12-19 years) were deemed eligible and agreed to participate in the study (Table 6-1).

Table 6-1: Demographics and physical characteristics for adolescents with concussion

Characteristics	**n = 25**
Age, years mean (SD)	15.1 (1.9)
Height, cm mean (SD)	171.0 (10.7)
Weight, kg mean (SD)	64.1 (16.3)
Gender	9 female, 16 male
Handedness	21 Right, 4 left
Sport during injury	n (%)
Recreational Activity	6 (24%)
Football	5 (20 %)
Basketball	3 (12%)
Soccer	3 (12%)
Hockey	2 (8%)
Baseball	1 (4%)
Cheerleading	1 (4%)
Diving	1 (4%)
Softball	1 (4%)
Volleyball	1 (4%)
Wrestling	1 (4%)

Although it was the intent of the investigators to assess adolescents on the second visit ten days after the first visit, due to scheduling issues adolescents were allowed to complete the second visit within 4 to 17 days from the first visit. Furthermore, the third visit was performed within 0 to 36 days after the clearance from concussion. Table 6-2 shows length of time between injury onset and visits as well as clearance from injury.

Table 6-2: Length of time between onset of concussion and visits and clearance

Visit	N	Days since onset of concussion median (range)	Days since last visit median (range)
Visit 1	25	6 (0 – 10)	---
Visit 2	23	13 (8 – 25)	7 (4 – 17)
Visit 3 (after clearance)	14	30 (16 – 188)	17 (2 – 178)
Length of recovery	21	22 (12 – 193)	---

Adolescents reported experiencing immediate symptoms at the time of the concussion. All adolescents except one adolescent reported dizziness, and more than half of the adolescents reported confusion/ disorientation (12 males and 1 female). Amnesia was reported by four adolescents (2 males and 2 females) and two male adolescents reported loss of consciousness (LOC) along with dizziness and confusion (Table 6-3).

Table 6-3: Immediate symptoms of concussion

Symptoms n=25	n (%)
Dizziness during injury	24 (96%)
Confusion/disorientation at injury	13 (52%)
Anterograde amnesia at injury	4 (16%)
LOC during injury	2 (8%)
Retrograde amnesia at injury	0

LOC: loss of consciousness

Subjects were asked about past medical history including history of motion sickness, previous concussion, migraine, ADD, and LD (Table 6-4). Fourteen adolescents reported at least one existing medical history item with four adolescents reporting two medical history items. Eight adolescents (32%) (5 females) reported a history of motion sickness. Five adolescents (20%) reported having a concussion within the last year. Migraine was reported by four adolescents (3 males and 1 female) and one adolescent reported ADD plus motion sickness

Table 6-4: Past medical history for adolescents with concussion

Characteristics n=25	n (%)
History of motion sickness	8 (32%)
History of concussion within the last year	5 (20%)
History of migraine	4 (16%)
History of ADD	1 (4%)
History of LD	0

ADD: attention deficit disorder; LD: learning disorder

6.4.2 Missing sway data

Sway was measured simultaneously using the force plate and the accelerometer. In a few cases, while performing the balance tests, the force plate and/or the accelerometer were disconnected or were unable to connect to the computer and data where not recorded. In other cases, sway data was not used due to adolescents' failure to follow directions of standing with both feet on force plate and/or keeping both arms in position (mainly distracted by their performance on the cognitive task) while performing the balance test. Furthermore, in a few cases, although adolescents followed instructions and the equipment didn't show any disruptions, data output registered outlier values in the COM or COP defined as a deviation of more than three standard deviations from the mean. In such cases, data were treated as missing data (Appendix N). In the first visit, seven adolescents did not have a complete data set in at least one measure of sway. On the second visit, two adolescents had incomplete data sets. On the clearance visit four adolescents had incomplete data sets. One adolescent did not have any COP data during the first visit due to an equipment problem; also that adolescent did not return for any of the follow-up testing. Comparisons between adolescents who completed the clearance visit with the adolescents who did not complete it showed no significant differences between them on age, sex, injury onset, LD, ADD, migraine, immediate symptoms of concussion, BESS, or PCSS (Table 6-5).

Table 6-5: Comparison between adolescents with SRC who did/ did not complete all visits

Characteristics n=25	Completers n=14	Non-completers n=11	p value
Age in years, mean (SD)	16 (2)	15 (2)	0.257#
Sex	6 females	3 females	0.667*
Injury onset in days, mean (SD)	6 (3)	6 (3)	0.912#
History of ADD	1	0	1.000*
History of LD	0	0	N/A
History of Migraine	3	1	0.604*
Immediate symptoms of concussion			
Anterograde amnesia at injury	1	3	0.288*
Confusion/disorientation at injury	6	7	0.428*
Dizziness during injury	13	11	1.000*
LOC during injury	2	0	0.487*
Retrograde amnesia at injury	0	0	N/A
Firm BESS errors, mean (SD)	4 (3)	4 (2)	0.745#
Foam BESS errors, mean (SD)	9 (4)	9 (3)	0.875#
Total BESS errors, mean (SD)	12 (6)	13 (4)	0.948#
PCSS symptoms, mean (SD)	35 (18)	25 (18)	0.218#

#: Independent samples t-test; *: Pearson chi-square; ADD: attention deficit disorder; LD: learning disabilities; N/A: not applicable (the variable was constant in all subjects); PCSS: post-concussion symptom scale; BESS: balance error scoring system.

6.4.3 Center of pressure (COP)

Sway measured using the COP and the COM showed similar results (Appendix P), therefore only COP data are reported in this section (Table 6-6). Furthermore, per-protocol and ITT analysis of sway data rendered the same results; therefore only ITT analysis results will be reported. We had COP sway data available from twenty-three adolescents with SRC. The COP data were mostly normally distributed. The Shapiro-Wilk test of normality showed that 32 out of 96 measures of the different conditions were not normally distributed ($p < .05$) (Appendix Q). Mean and SD of sway values are reported in Appendix R.

Results of the linear mixed model (Table 6-6) showed a significant effect of visit for RMS sway in the AP and the ML directions, a single vs dual-task effect for NPL sway in the ML direction and the RMS sway in the AP direction, a cognitive task effect for RMS sway in the AP and the ML directions, and a surface effect for all of the sway measures. In addition, there was a significant interaction effect of visit * surface for NPL sway in the AP direction. More details about the main and interaction effects are discussed in the following paragraphs.

Table 6-6: Linear mixed model analysis of COP sway for adolescents with concussion

p value of the effects	NPL		RMS	
	AP	ML	AP	ML
Visit	0.147	0.338	0.042	0.033
Single vs Dual-task	0.227	<0.001	<0.001	0.302
Cognitive task	0.919	0.911	0.006	<0.001
Surface	<0.001	<0.001	<0.001	<0.001
Visit by Single vs Dual-task	0.287	0.393	0.658	0.526
Visit by Cognitive task	0.748	0.928	0.905	0.938
Visit by Surface	0.024	0.054	0.090	0.225

COP: center of pressure; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior direction; ML: medial-lateral direction; n=23.

Regarding the main effects, the visit effect was statistically significant, showing a significant difference between visits on the RMS sway in the AP and ML directions ($p = 0.042$ and $p = 0.033$, respectively). However, the effect of visit on the NPL sway was not significant. Pairwise comparisons using Sidak adjustment for multiple comparisons showed a significant increase of RMS sway in the AP and ML directions ($p = 0.036$ and $p = 0.028$, respectively) during the second visit compared with the first visit, and no other significant differences were found (Figure 6-6).

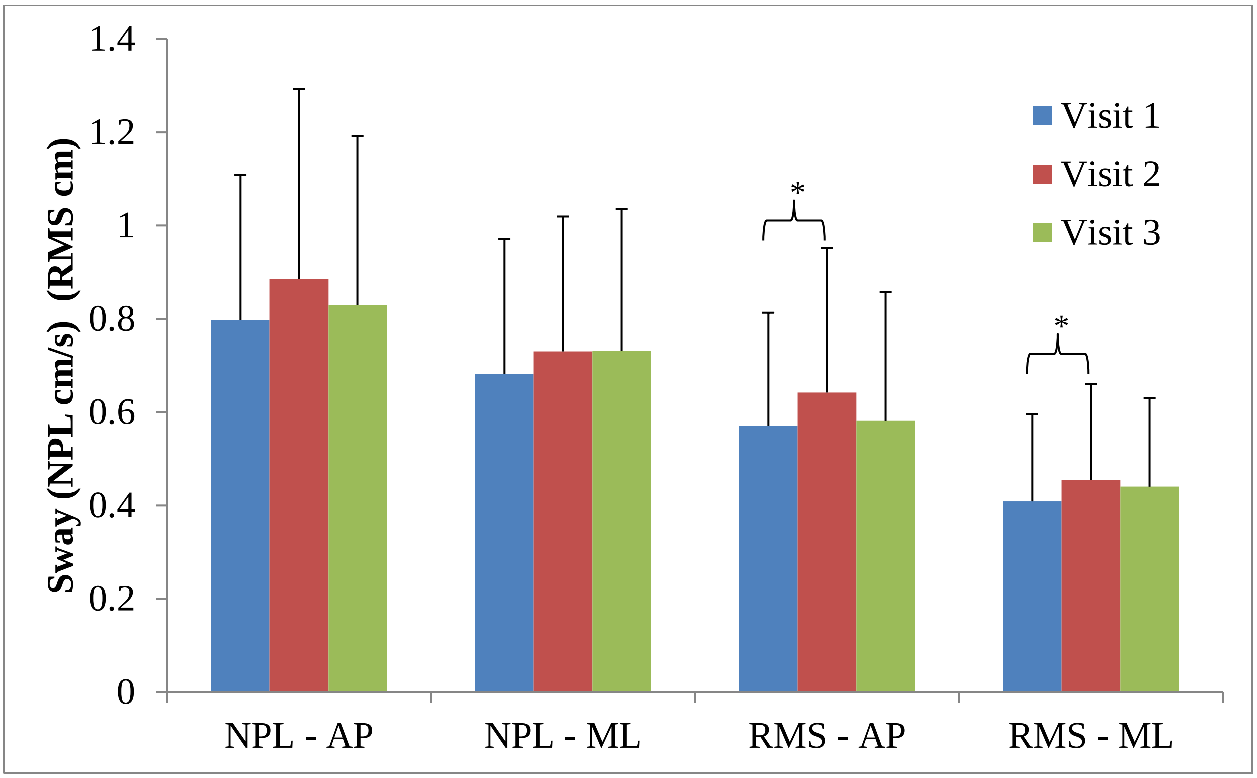


Figure 6-6: Visit effect – mean center of pressure for adolescents with concussion. NPL: normalized path length (cm/s); RMS: root mean square (cm); AP: anterior-posterior; ML: medial-lateral. Error bars: standard deviation; * p < 0.05; n=23.

The main effect of single vs dual-task was statistically significant, showing decreased NPL sway in the ML direction during the dual-task compared to the single task ($p < 0.001$), while showing increased RMS sway in the AP direction during the dual-task compared to the single task ($p < 0.001$) (Figure 6-7).

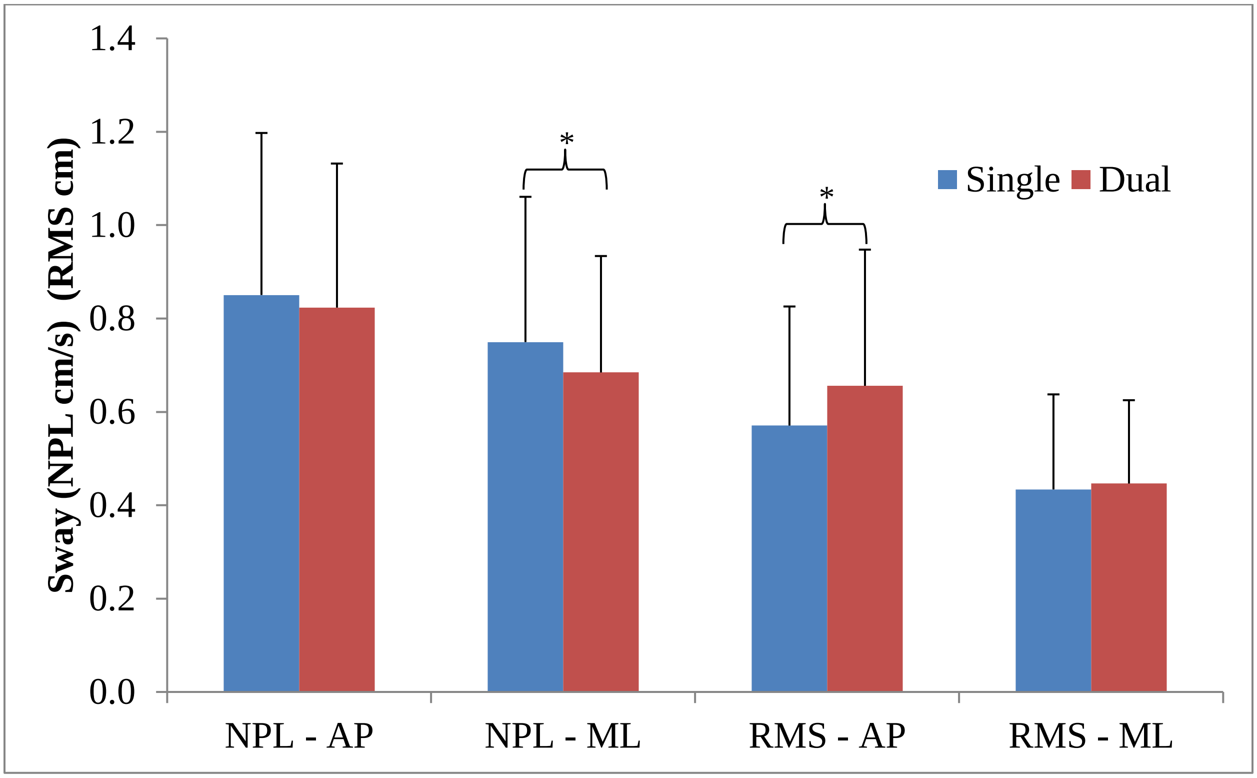


Figure 6-7: Single vs dual-task effect – mean center of pressure for adolescents with concussion. NPL: normalized path length (cm/s); RMS: root mean square (cm); AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation; * p < 0.05; n=23.

The main effect of cognitive task was statistically significant, showing increased RMS sway in the AP and ML directions ($p = 0.006$ and $p < 0.001$, respectively) during the perceptual inhibition task compared to the spatial discrimination task (Figure 6-8). However, the effect of cognitive task on NPL sway was not significant.

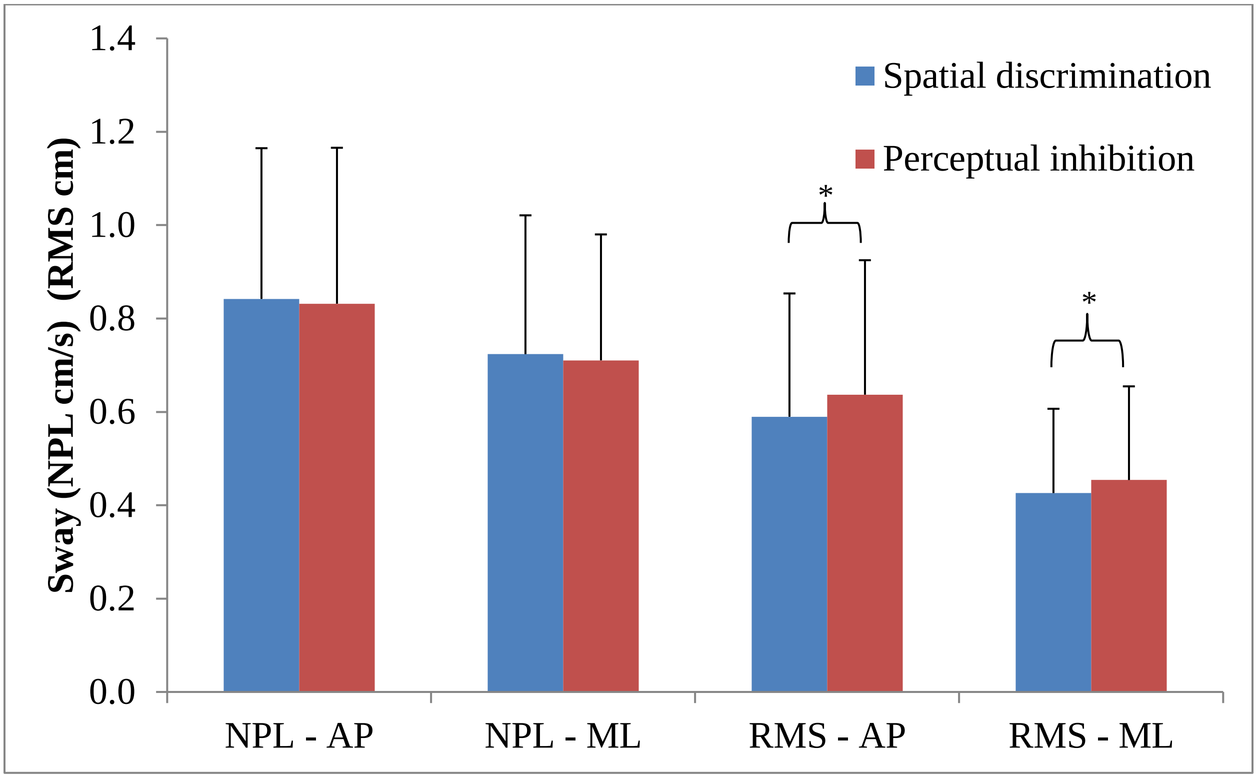


Figure 6-8: Cognitive test effect – mean center of pressure for adolescents with concussion. NPL: normalized path length (cm/s); RMS: root mean square (cm); AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation; * p < 0.05; n=23.

The main effect of surface was statistically significant ($p < 0.001$) showing increased sway while standing on a compliant surface compared to firm surface on all measures of sway (Figure 6-9).

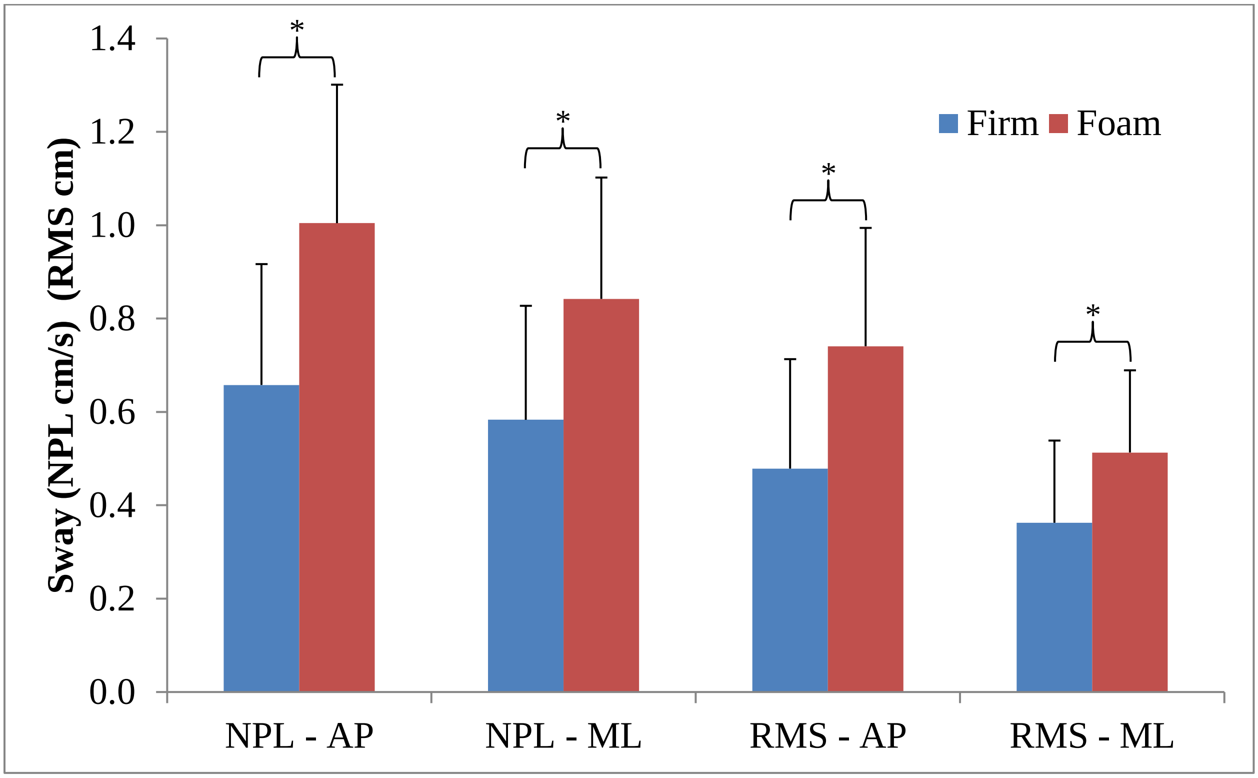


Figure 6-9: Surface effect – mean center of pressure for adolescents with concussion. NPL: normalized path length (cm/s); RMS: root mean square (cm); AP: anterior-posterior; ML: medial-lateral; Error bars: standard deviation; * $p < 0.05$; n=23.

The interaction effect of visit by surface was significant on the NPL sway in the ML direction (p = 0.024) (Figure 6-10). Standing on the foam surface resulted in increased sway which was more pronounced in the first visit (0.25 cm/s) and the second visit (0.29 cm/s) compared to the clearance visit (0.20 cm/s). It appears that the NPL sway in the AP direction on the firm surface was increasing from visit 1 to visit 3, which explains the reduced difference between the firm and the foam surfaces on the clearance visit. No other significant interactions between visits and experimental conditions were found (Appendix S).

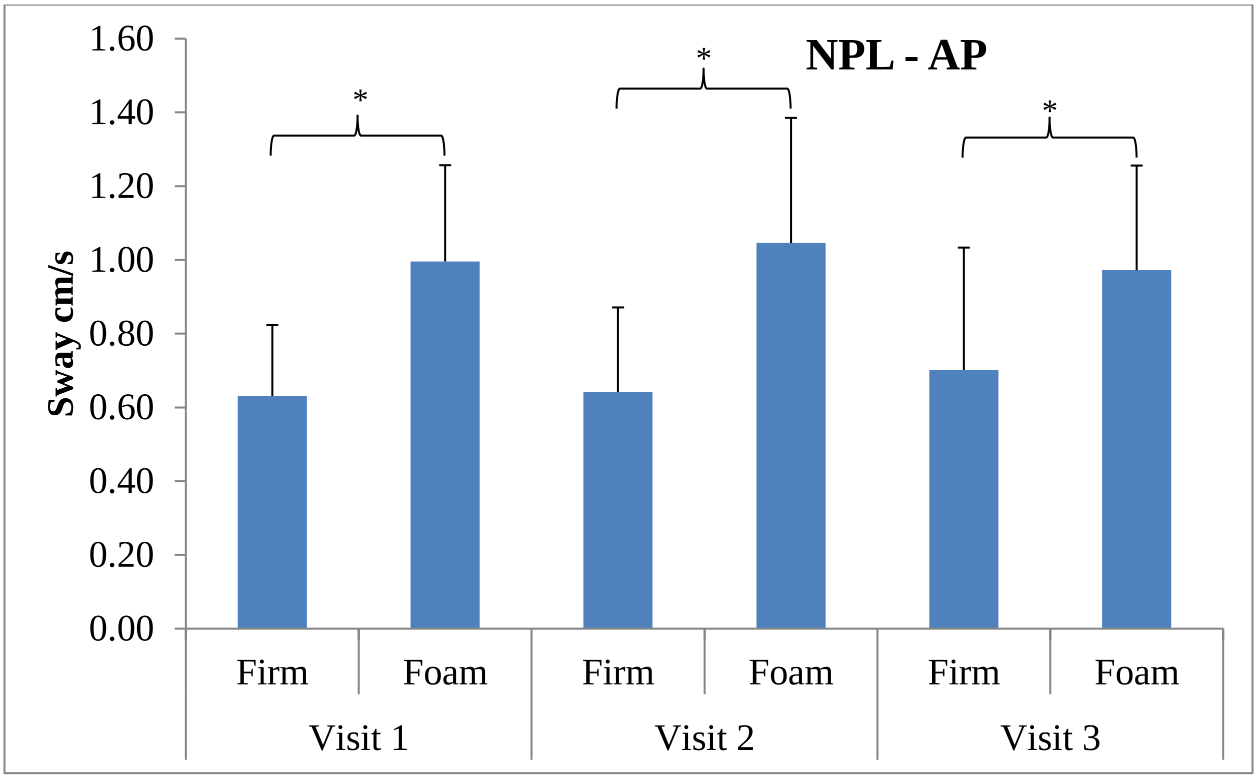


Figure 6-10: Visit by surface interaction – mean center of pressure for adolescents with concussion. NPL: normalized path length; ML: medial-lateral; Error bars: standard deviation; * p < 0.05; n=23.

6.4.4 Balance error scoring system (BESS)

Per-protocol and ITT analysis of BESS scores produced the same results. Therefore only the ITT analysis results are reported. A Shapiro-Wilk test of normality showed that total BESS and foam pad BESS were normally distributed in all visits, whereas the normality assumptions for firm BESS were violated in all visits ($p < 0.05$) (Appendix T).

A Friedman test was conducted to evaluate differences of the total BESS, foam BESS, and firm BESS scores among the three visits. The firm BESS rendered a significant difference among first visit (Median = 3.5), second visit (Median = 3.0), and third visit (Median = 2.0) (Friedman's test statistic = 10.32, p = .006) (Figure 6-11). Follow-up pairwise comparisons were conducted using a Wilcoxon test and controlling for the Type I errors across theses comparisons at the .05 level using the Bonferroni correction. The first visit firm BESS median score was significantly greater than the last visit firm BESS median score, p = .042. No other comparisons were significant.

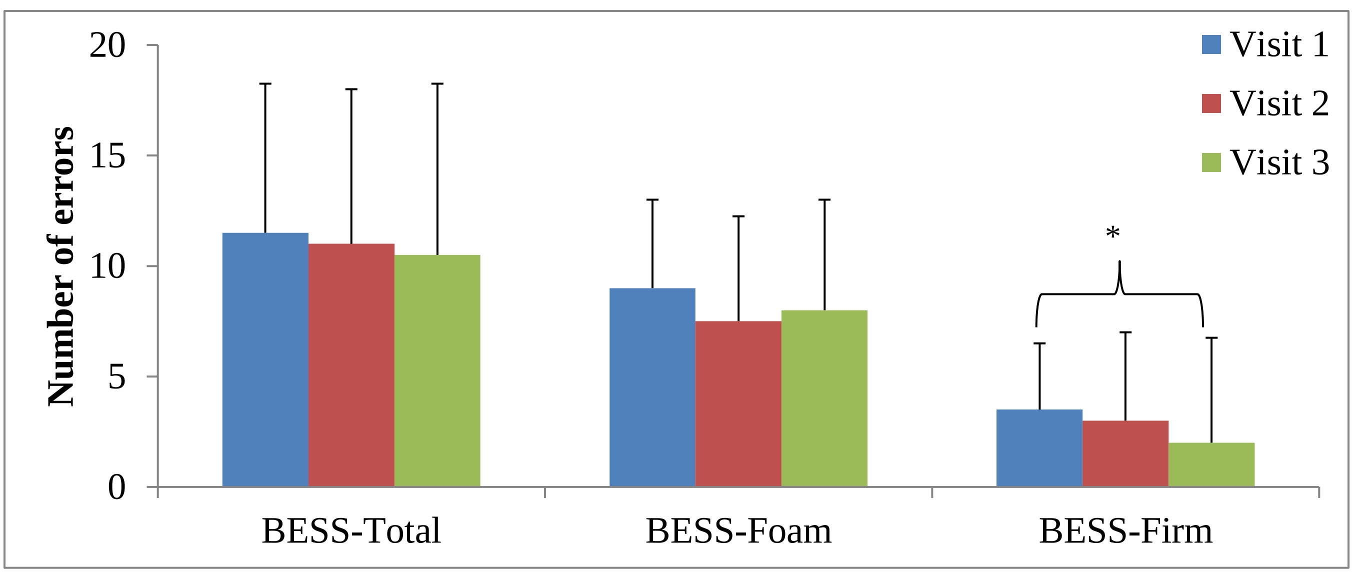


Figure 6-11: BESS median and interquartile range of number of errors for adolescents with concussion. BESS: balance error scoring system; Error bars: interquartile range. * p < 0.05; n=25.

6.4.5 Post-Concussion Symptom Scale (PCSS)

Per-protocol and ITT analysis of PCSS showed the same results; therefore only ITT analysis results will be reported. A Shapiro-Wilk test of normality showed that PCSS was normally distributed in the first visit, where the normality assumptions during the second and clearance visits were violated ($p < 0.05$) (Appendix U).

A Friedman test was conducted to evaluate differences of PCSS among the three visits. There was a significant difference on PCSS among first visit (Median = 28), second visit (Median = 8), and third visit (Median = 1) (Friedman's test statistic = 15.32, $p < 0.001$) (Figure 6-12). Follow-up pairwise comparisons conducted using a Wilcoxon test demonstrated that the first visit PCSS median score was significantly greater than the clearance visit PCSS median score, p = .001. No other comparisons were significant.

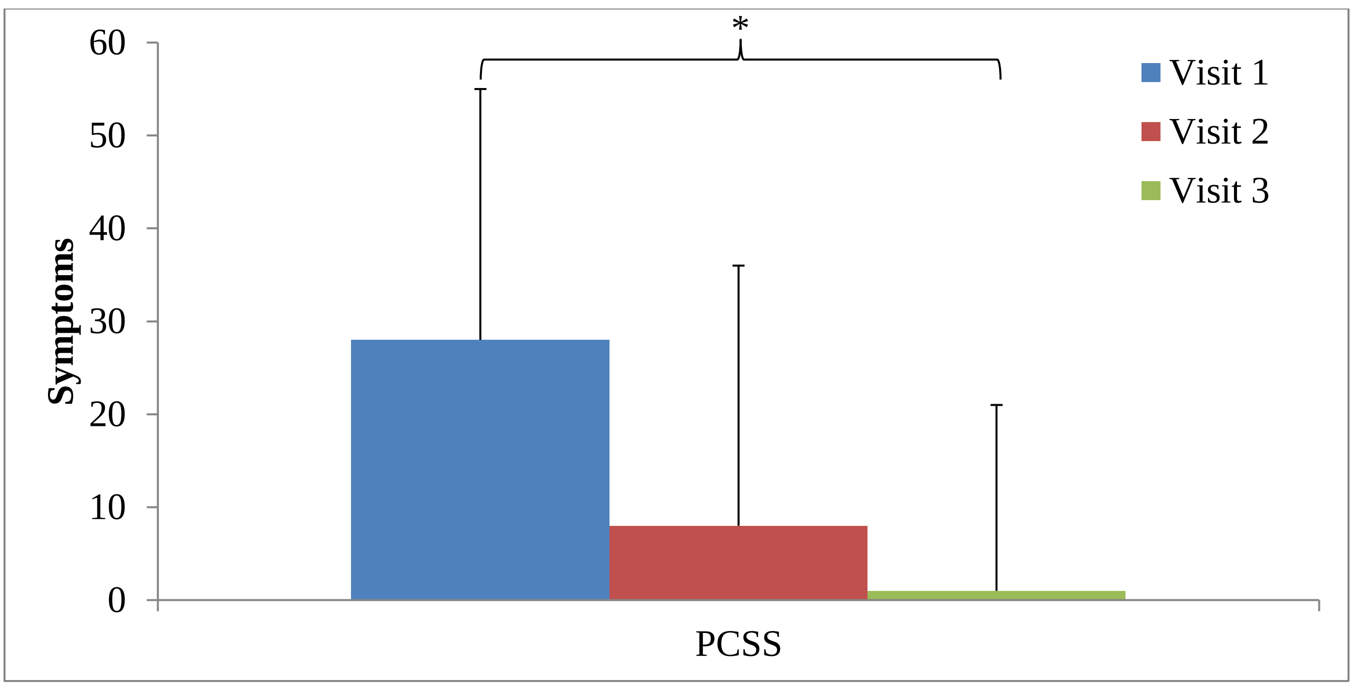


Figure 6-12: PCSS median and interquartile range of symptoms for adolescents with concussion. PCSS: post-concussion symptom scale; Error bars: interquartile range; * p < 0.05; n=25.

6.5 DISCUSSION

The aim of this study was to investigate changes on a clinical balance test and lab-based postural sway in single and dual-task conditions in adolescents after a SRC, over the course of three visits. We hypothesized that adolescents would show balance improvement over visits assessed using BESS and sway measures. Furthermore, less balance improvement would be seen during dual-tasking and during conditions when the balance challenge is greater. The main findings were: 1) improvement on firm BESS over visits; 2) an increase in RMS sway during visit 2; 3) a dual-task effect that produced reduced NPL sway but greater RMS sway compared with the single task; 4) increased RMS sway during the perceptual inhibition task compared with the spatial discrimination task; and 5) increased sway during the foam conditions compared with firm surface, which was dependent on the visits.

We found an improvement of balance from the first to the clearance visit during the firm surface condition of the BESS (modified BESS). This effect was not seen during the foam surface BESS or the total BESS scores, which suggests a benefit of testing balance on a firm surface rather than compliant surface to detect improvement over time of balance in adolescents with a SRC. These results support using the modified BESS (firm surface only as in SCAT2 and SCAT3) rather than the original BESS that included firm and foam surfaces [12,86,93]. It is possible that the foam portion of the BESS test is very challenging for both controls and individuals with SRC, such that group differences are difficult to detect because of the high variability. Furthermore, our results of the BESS during the first visit (mean BESS 12.4) was comparable to those reported by Sufrinko et al. (mean BESS 12.7) of adolescents with recent SRC (mean days since injury 5.2 days) [150]. The practice effect of BESS has been considered an important factor to be acknowledged when administering the BESS to track recovery in athletes. Valovich et al. tested thirty-two healthy adolescents using the BESS over 4 visits (day 1, 3, 5, 7, and 30) and found improvements on the total BESS on days 5 and 7 compared with day 1 and found improvement of the foam BESS condition on day 7 compared with day 1, while no effect of visit was seen during firm BESS [90]. Therefore, it does not appear that the change in BESS score that we observed over time can be explained by a practice effect.

We noted improvements of symptom scores on the PCSS over visits, showing less symptoms on the last visit compared with the first visit. Our result is consistent with several reports of adolescents with concussion [28,30,151]. Henry et al. assessed 66 adolescents within 7 days of SRC (mean age 17 years SD 2 years; PCSS mean 31 SD 20) and followed them weekly for 3 weeks. There was a decrease of symptoms over time [151]. Field et al. assessed baseline symptoms of injury-free 183 high school athletes and 371 college athletes. Nineteen high school athletes and 35 college athletes with acquired SRC were included in the study and age-matched with controls. They assessed the PCSS at five time points: pre-injury, within 24 hours of injury, 3, 5, and 7 days post-injury. They found progressive decrease of the PCSS on each visit [28]. Dorman et al. assessed concussion symptoms of 18 adolescents (mean age 17 years SD 2 years) within 10 days of concussion injury using the PCSS on four follow-up visits over the course of about 3 months, when the participants had appointments with the examining physician. They found a progressive decrease of PCSS symptoms between each 2 consecutive visits [30].

Although our results supported the hypothesis that sway would change over visits, the nature of the change in sway over visits was contrary to our expectation and to the literature, [12,30,31,93,94,152]. Contrary to the BESS and PCSS scores, our lab-based postural sway assessment results showed a significant increase of the RMS sway during the second visit compared with the first visit.

An explanation for the unexpected direction of the visit effect may be due to the time of recruitment, because the previous studies of postural sway that showed linear improvement over visits tested their participants acutely after injury (day 1 after concussion) and followed them a few days after the injury [12,93,152]. These studies showed the largest improvement in balance as assessed with postural sway measures between days 1 and 3 and showed no significant change of postural sway between day 3 and the rest of the visits. The time frame of resolution of imbalance is shorter than the mean length of time for the first visit in our study. The Dorman et al. study included adolescents within 10 days of concussion injury, but their participants had an important difference compared with ours because they limited participation to those who had unresolved concussion symptoms over an extended period of time. In our study more than 80% of adolescents were enrolled 6 to 10 days after the injury and the inclusion was not restricted to length of recovery time. Furthermore, the p-value of the significant relationship of the RMS sway in the AP direction was near the borderline of significance ($p = 0.042$), while the significant relationship of the RMS sway in the ML direction appeared to be driven by sway data of one subject who had very low sway values during the first visit. The exclusion of that subject resulted in a non-significant effect of visit on RMS way in the ML direction.

Our results supported the hypothesis that introducing a second task while balancing affects balance. Our results indicated decreased NPL sway in the ML direction (i.e. less distance traveled by the COP) and increased RMS sway in the AP direction (i.e. greater variability of the COP) during the dual-task compared to the single task.

At first glance the result appears to be contradicting. However, the NPL and RMS are measuring different aspects of sway and using both measures may give more insight into sway. The RMS sway reflects the variability in deviation from the center point of sway, whereas the NPL sway can represent the frequency and/or the magnitude of the sway adjustments. During the single task test, adolescents may focus on consciously controlling their balance by trying to minimize the variation in deviation of sway magnitude by using higher frequency adjustments, resulting in decreased RMS and increased NPL compared with the dual-task condition. On the other hand, during the dual-task condition, by directing attention to the visually-based MAPIT task, more automatic postural control strategies may occur, which could result in larger sway deviations. Maintaining standing posture is normally achieved automatically and without conscious control, while during balance testing (especially when balance is the only test being performed), adolescents may focus on consciously controlling their balance which would interfere with the automatic motor control processes that normally regulate balance and result in less efficient postural control [141]. Adding a visual task to a balance test, although requiring more attention than balance in isolation of other tasks, has shown to improve postural stability (decreased sway path length) during saccadic and smooth pursuit eye movements compared with visual fixation [142].

Consistent with our finding of increased RMS sway in the AP direction during the dual-task, Pellecchia (2003) reported increased path length of COP and increased sway variability (i.e. standard deviation of the COP) in the AP direction during the dual-task compared with the single task balance test [136]. They assessed postural sway in 20 healthy adults aged 18 to 30 years while standing on a force plate with foam surface during single-task (quiet standing) and 3 dual-task conditions; each testing trial lasted for 30 seconds. The cognitive tasks were to verbally respond to a pre-recorded audiotape of digit pairs by reversing the numbers (first cognitive task); by classifying a 2-digit number as less than or greater than 50, and odd or even (second cognitive task); the third task was counting backward by 3s. Thus the attention directed to the cognitive-task may serve to promote the automatic control strategies.

The reduction in NPL sway that we observed in the dual-task condition is consistent with multiple studies of healthy young adults (mean age range 20 - 22 years old) that reported less postural sway in the AP direction during the dual-task test compared with the single-task test [137–140]. These studies tested their participants' postural sway using the NeuroCom Smart Balance Master (NeuroCom International, Inc., Clackamas, OR). The balance test conditions, the type of cognitive task, the length of the dual-task test, and the number of trials varied between the studies. Two studies computed the Equilibrium Score (ES) in the AP plane for the four eyes-open SOT conditions and found an increase in ES during the dual-task in SOT 1 (fixed surface/ eyes open) and SOT 2 (fixed surface/ eyes closed) [140] as well as SOT 4 (sway surface/ eyes open) [137,140]. The other two studies computed the ES for all six SOT conditions and found an increase in ES dual-task during SOT 1 and SOT 3 (fixed surface/ stable and sway-referenced vision) [138] as well as the composite ES from all SOT conditions [139]. The cognitive task in the Broglio et al. (2005) study was a visual processing task in which a letter-digit pair was visually presented in a 2 by 2 table on a computer monitor and the participant responded if the number was odd or even when the letter–digit pair was shown in the top row of the table, and responded if the letter was a vowel or consonant when the letter–digit pair was shown in the bottom row of the table. The participant responded by pressing a computer mouse key [140]. The cognitive task in the Teel et al. (2013) study was an incongruent Stroop test that displayed a color name in a colored font and if the name of the color and the color of the font disagreed, the participant was instructed to respond by pressing a hand held clicker. If they matched, the participant was instructed not to respond [137]. The cognitive task in Resch et al. (2011) study was an auditory stimulus of computer-generated letters and numbers displayed to a headphone. Using a hand held mouse, the participant pressed the left button when they heard an even number or a vowel and pressed the right button when they heard an odd number or a consonant [138]. The cognitive task in Ross et al. (2011) study was to respond to a visually displayed number using a handheld computer mouse by pressing the right button if the displayed number was 2 or 3 or pressing the left button if the displayed number was 4 or 5, during SOT 1, 3, 4, and 6. Meanwhile, during SOT 2 and 5 the cognitive task was to verbally respond by saying "right" when they heard the numbers 2 or 3, and by saying "left" when they heard the numbers 4 or 5 [139]. The reports of increased sway measures in some studies and decreased measures in other studies demonstrate the complex nature of postural sway interactions with cognitive dual-tasks.

Our results supported the hypothesis that balance would be affected by the complexity of the dual-task [94,136]. Performance of a more complex perceptual inhibition task while balancing produced higher RMS sway compared to the performance of a simpler spatial discrimination task. However, NPL was unchanged, implying that the average velocity of the postural adjustments didn't change while the magnitude of the variability did. These results are consistent with results of Pellecchia, (2003), who found that performing verbal tasks of different difficulties while balancing resulted in increased sway variability (i.e. standard deviation of the COP) in the AP direction as the task difficulty increased [136]. Despite the fact that the dual-task testing included a cognitive component (i.e. the perceptual task) and a sensorimotor component (i.e. the balance task), the results showed that they are not independent, generating increased sway as the difficulty of the cognitive task increased. The result shows a substantial impact of attention on sensorimotor performance in which the cognitive and the motor tasks are performed as a single higher order skill.

Although Pellecchia suggested that COP path length was more sensitive to the effect of task difficulty than sway variability [136], our results didn't show an effect of cognitive task on the

NPL sway. While task difficulty may have a specific influence on postural control, others have examined the relationship between MAPIT task performance and postural sway. In a study of young and older healthy adults, Redfern et al. investigated the effect of MAPIT subtests (perceptual inhibition and motor inhibition) on sway. They found that the perceptual inhibition (but not the motor inhibition) to be positively correlated with sway (longer reaction time correlated with higher sway amplitude) in the older healthy group (but not the younger healthy group) when standing on sway-referenced floor [116]. This finding can be interpreted that as more attentional interference occurs (specifically perceptual inhibition), less attention can be devoted to the regulation of balance and thus produce greater sway.

Interference of somatosensation can be introduced by standing on a compliant surface [143]. As expected, results showed an increase of sway during the foam surface balance test compared to the firm surface balance test. This is consistent with the results of several reports of effect of foam and firm surfaces on postural sway as well as BESS performance [14,144–146]. In adolescents with concussion and healthy adolescents, Furman et al. found that the magnitude of the NPL sway, assessed using a bi-axial accelerometer, and the BESS increased (worsened) during the foam surface condition compared with the firm surface balance tests [14]. Hammami et al. assessed postural sway from 24 healthy elite athletes using a force plate and found an increase in sway speed (equivalent to NPL) during the foam surface condition compared to the firm surface condition [144]. Similarly, in healthy young adults Lin et al. found increased postural sway (the RMS sway and the NPL sway) assessed using a bi-axial accelerometer, during the foam surface condition compared with the firm surface balance tests [145]. Using force plate sway assessment, Patel et al. reported greater postural instability when standing on foam surface compared to firm surface in healthy young adults [146]. Therefore, our result confirms the significant contribution of somatosensory input in maintaining postural stability in adolescents with and without SRC.

The visit by surface interaction showed a smaller difference in NPL sway in the AP direction between the firm and the foam surface conditions over time. The primary reason for the smaller difference was an increase in NPL sway in the AP direction on firm surface from visit 1 to visit 3. It is unclear why there was an increase in NPL sway in the AP direction across the visits.

Contrary to our hypothesis and to findings of Howell et al. (2013) and Parker et al. (2006), the amount of change in balance measures did not depend on the presence or difficulty of the cognitive dual-task. Howell et al. (2013) assessed gait stability using motion analysis of 20 adolescents (mean age 15 years SD 1 year) within 3 days of a SRC, while walking during single-task and dual-task conditions. The dual-task was walking while performing an auditory Stroop task in which subjects verbally indicated a high or low pitch of 2 congruent and 2 incongruent computer played words “high” or “low”. This procedure was repeated on 4 follow-up visits (1 week, 2 weeks, 1 month, and 2 months after SRC). They found a significant interaction of visit by single vs dual-task on the peak anterior COM velocity showing higher values during the single-task testing in the 2-month follow-up compared with all other visits and showing lesser values during the dual-task testing in the 3-day visit compared with all other visits [31]. Parker et al. (2006) assessed gait stability using a motion analysis of 15 adolescents within 2 days of concussion injury, while walking during single-task and dual-task conditions. The dual-task was a question and answer task that included backward spelling, subtracting by 7s, and backward reciting of the months of the year. This procedure was repeated on 3 follow-up visits: 5, 14, 28 days after injury. They found an interaction of visit by single vs dual-task on the ML displacement showing more stable gait in the single-task compared with dual-task during the initial visit and the 2-weeks follow-up [153].

Howell et al. (2014) followed up their previous study by assessing the gait of 15 adolescents (mean age 15 years SD 1 year) within 3 days of a SRC, while walking under 4 cognitive-task conditions (no task, single auditory Stroop, multiple auditory Stroop, and question and answer task). This procedure was repeated on 4 follow-up visits (1 week, 2 weeks, 1 month, and 2 months after SRC). The auditory Stroop task was to verbally indicate a high or low pitch of a congruent or incongruent computer played word “high” or “low”. The single auditory Stroop was to respond to one stimulus per trial while the multiple Stroop was to respond to four stimuli per trial. The question and answer task included (backward spelling, subtracting by 6s or 7s, backward reciting of the months of the year). They found an interaction of visit by cognitive-task on the peak anterior COM velocity (higher velocity is interpreted as better gait stability), showing improved gait stability during the follow-up visits compared with the first visit on the 3 dual-task conditions. However, the question and answer task showed lower values during weeks 1 and 2 compared with months 1 and 2 [94]. These findings were interpreted that subjects with SRC improved more on the single-task compared with the dual-task. Important differences exist between our study and Howell et al.’s and Parkers et al.’s. First their participants were more acute with means of 2 days and 40 hours from the concussion, respectively, while our adolescents had a mean of 6 days from concussion; secondly they assessed gait stability while we assessed static postural sway.

6.6 LIMITATIONS

The BESS was scored onsite by trained athletic trainers. Although it may represent the real situation in sport settings, filming the adolescent while performing the test may allow for better inter-rater reliability of the test and more balance errors can be noticed [14].

Although simple instructions of standing steady and quietly while performing the balance tests were given to the adolescents, it was noted that adolescents were distracted from maintaining a steady standing position. Providing a continuous reminder of maintaining a steady posture such as having the instruction in front of the adolescent while performing testing may reduce such distraction.

Although the sample size was powered to capture a visit effect, 11 (44%) adolescents did not complete all three visits. Furthermore two (8%) of the adolescents were cleared before the second visit. The completers and the non-completers did not differ on any of the outcomes. Furthermore, analyzing the data using the first two visits showed similar results compared with the three visits. These findings give us confidence that the dropouts did not affect our results.

6.7 CLINICAL RELEVANCE

Based on our results we recommend using the firm surface conditions of the Balance Error Scoring System (BESS) rather than the complete BESS when tracking recovery in adolescents with sports-related concussion (SRC). Unlike the firm BESS, the dual-task paradigm that we used in this study was not able to show sway improvement over visits in adolescents with SRC. Our dual-task paradigm may not be suitable to be used in a clinical setting; a dual-task paradigm that would not require instrumentation may be more suitable for clinical use and may be able to track sway improvement in adolescents with SRC.

7.0 DISCUSSION

The primary motivation for performing this study is the high prevalence of dizziness and balance problems after concussion [18,19,22,23]. In addition, consensus panels and concussion guidelines have recommended the assessment of both balance and cognitive function after concussion [1,8]. Therefore, the purpose of this dissertation was to investigate balance performance differences during a dual-task balance-testing paradigm between adolescents with and without a Sports-related Concussion (SRC) injury and to track the performance of adolescents with SRC injury during the dual-task balance-testing paradigm throughout the course of recovery. Additionally, a goal was to determine the prevalence of reduced Vestibulo-Ocular Reflex (VOR) function assessed using the Video Head Impulse Test (vHIT) in adolescents with and without SRC injury. Although evidence suggests a relationship between head injuries and vestibular impairments, few studies have focused on children and adolescents with concussion. Furthermore, the prevalence of peripheral vestibular disorders in adolescents after Sports-Related Concussion (SRC) is unknown.

In the first aim, we wanted to explore peripheral vestibular function in adolescents with SRC because although others have studied the prevalence of peripheral vestibular disorders after concussion in adults and children, no one has examined head impulse test abnormalities [9,10]. The prevalence of peripheral vestibular disorders in general, and specifically head impulse test abnormalities after SRC in adolescents is unknown. Furthermore, in individuals with concussion, it is not clear if abnormalities in head impulse testing relates to clinical signs and symptoms of dizziness and imbalance. As a result we tested vHIT, BESS, VOMS, and PCSS in adolescents with SRC and controls. The main finding of this aim was that reduced VOR function was not found in any of the adolescents with SRC. Furthermore, the gain of the head impulse test was not related to clinical signs and symptoms of concussion on BESS, VOMS, and PCSS in adolescents with SRC. Therefore, it does not appear that peripheral vestibular impairments assessed using the vHIT are common in adolescents with SRC. This finding may indicate that assessing peripheral vestibular function after SRC is not important unless more definitive signs of peripheral vestibular injury, (such as spontaneous nystagmus, vertigo, hearing changes) are present. Alternatively, another assessment method of peripheral vestibular function such as the caloric test should be used to assess peripheral vestibular injuries after concussion.

The second aim was to investigate balance performance differences during a dual-task balance-testing paradigm between adolescents with and without a Sports-Related Concussion (SRC) injury. Balance is an intrinsic function of maintaining posture that normally does not require much cognition or attention. Assessing balance in isolation of other attention-demand tasks may conceal existing balance deficits in individuals with concussion. However, inclusion of an attention-demanding task when balancing may challenge the postural control system and reveal hidden balance impairment in individuals with concussion [30]. Dual-task balance assessment after concussion has been examined in gait studies [136,138,139] but, to the knowledge of the author, dual-task balance assessment using cognitive tasks of different difficulties has not been examined in standing balance studies. In order to address this gap in the literature, we tested standing balance performance during single and dual-task conditions as well as during different levels of cognitive-task difficulty and different surfaces. The main findings of the dual-task balance paradigm were that no difference in sway between the groups was observed, but that differences in sway were dependent on the different balance conditions. For instance, dual-task balance performance produced lesser COP NPL sway but greater RMS COP sway compared with single-task performance. Also, a perceptual inhibition task resulted in greater RMS COP sway than the spatial discrimination task. The lack of a difference between the individuals with SRC and controls was counter to our main hypothesis, which could be due to when we performed the balance testing; in our case it was on an average of 6 days after concussion. Several other studies have shown that balance changes during single-task balance tests usually resolve within 3 days [41,57]. However, we hypothesized that the dual-task would elicit changes for a longer period of time. Nonetheless, it does not appear that this type of dual-task balance testing can help distinguish balance performance between adolescents with SRC and controls when assessed approximately a week after the SRC. It is possible that other dual-task paradigms performed in standing, and also during walking, could demonstrate these changes.

The final aim was to track the performance of adolescents with SRC injury during the dual-task balance-testing paradigm throughout the course of recovery. Returning to normal activity without full recovery from concussion appears to make the athlete with concussion more susceptible to a second more severe concussion [5]. Balance assessment should be used as a part of assessment and return-to-play decisions after concussion [1]. Dual-task balance assessment may provide a more valid test of the ability of individuals with SRC to perform higher-level activities. Studies found greater sway in individuals with concussion compared to controls that was statistically significant even at the time of return to play clearance (mean number of days at clearance 26 days), which was based on reported symptoms and other gross balance and motor control assessments [42]. Performing a cognitive task and balancing simultaneously will stress attention resources and may be a reasonable method to test balance after SRC [29]. Therefore, it may be valuable to use dual-task balance tests as part of the determination of return to play. We tested balance performance during single and dual-task conditions in adolescents with SRC within 10 days of injury and followed them for three visits throughout the course of recovery. The main finding was that we did not see improvement in performance of single or dual-task balance measures over visits, which may be related to the time duration between the injury and performing the testing. As a result, the dual-task balance-testing paradigm used in our study does not appear to be useful in monitoring concussion injury and a different approach (i.e. alternate dual-task or walking dual-task) may be used. On the other hand, we did observe a significant decrease in errors during the firm condition of the BESS, but not the foam condition, which may indicate that if tasks are too difficult, the increased variability may mask differences in performance.

8.0 LIMITATIONS

Contrary to our hypothesis, we did not find a difference in sway between groups. One of the possible reasons for this lack of an effect is that adolescents with SRC injury were within 10 days of their injury which is considered a wide range as other studies found resolution of reported symptoms as well as resolution of balance impairment (assessed using BESS) within 3 to 7 days after SRC injury [41,57]. Recruiting adolescents within the first 3 days of injury may have revealed balance impairments and allowed investigators to detect a change over time as well as a between groups changes of balance.

Our results supported our hypothesis that there will be a difference between the spatial discrimination and the perceptual inhibition cognitive-tests. It can be argued that one of the reasons that we found a difference is that the perceptual inhibition test was longer and adolescents may become fatigued and showed different performance than during the spatial discrimination test. Due to the design of the MAPIT test, the two types of the cognitive-tests used in this study did not have an equal balance testing duration. Using a comparable duration of balance test may improve the validity of the comparison between the types of cognitive-tests.

Contrary to our hypothesis, we did not find a visit effect on sway. A possible reason for this lack of visit effect may be because a significant number of adolescents did not complete all the visits, and we used an Intention-to-Treat analysis which carried values forward. Eleven (44%) adolescents did not complete all three visits and two (8%) of the adolescents were cleared before the second visit. The completers and the non-completers did not differ on any of the outcomes. However, analyzing the data using the first two visits, which included 23 completers, showed similar results compared with the three visits. These findings give us confidence that the dropouts did not affect our results. However, it may have decreased the statistical power of the data to show significant effect of visit.

The Balance Error Scoring System (BESS) was scored onsite by trained athletic trainers. Although it may represent the real situation in sport setting, filming the adolescent while performing the BESS may allow for better inter-rater reliability of the test and more balance errors can be noticed [14].

We did not find any differences between groups on the Video Head Impulse Test (vHIT). A main limitation of the vHIT study is its lack of a gold standard comparison test of vestibular function such as caloric testing. Inclusion of such a test would help in confirming vestibular system involvement. Furthermore, the vHIT is testing only the horizontal canal while there are four other structures of the peripheral vestibular system that can be involved including the posterior canal, the anterior canal, the utricle, and the saccule. Testing these other structures may provide a more thorough assessment of the peripheral vestibular system. Also the vHIT is testing only the high frequency response of the VOR function. Testing the VOR at different frequencies such as using the caloric test, a very low frequency test of the VOR, and the rotational chair test that assesses functional frequencies of VOR may reveal abnormalities not found using the vHIT.

9.0 FUTURE DIRECTIONS

Although we did not find any vHIT abnormalities among adolescents, nor differences in vHIT gain between groups, more investigations of vHIT abnormalities after sport related concussion should be performed using more acute adolescents with SRC, as well as testing more structures of the peripheral vestibular system such as the anterior and the posterior canals. We found that the VOMS was able to show a difference between adolescents with SRC and controls. The VOMS is a short test that did not require any special equipment and should be incorporated in assessing and tracking concussion injury.

We found that the dual-task balance paradigm was able to produce balance changes during the different conditions. Performing dual-task balance testing should be further investigated in adolescents with more acute SRC. In addition, we assessed one version of a dual-task that assessed perceptual inhibition using a computerized test. It would be interesting to evaluate other types of dual-tasks, especially ones that can be performed without the need of additional equipment.

Vestibular function testing including diagnostic tests such as vHIT and functional tests such as VOMS, as well as dual-task balance testing should be incorporated with other neurocognitive tests such as ImPACT to improve return to play decisions.

10.0 CONCLUSION

The purpose was to investigate balance performance differences during a dual-task balance testing paradigm between adolescents with and without a Sports-related Concussion (SRC) injury and to track the performance of adolescents with SRC injury during the dual-task balance testing paradigm through the course of recovery from the SRC injury. Another purpose of this dissertation was to assess the prevalence of reduced Vestibulo-Ocular Reflex (VOR) function assessed using the Video Head Impulse Test (vHIT) in adolescents with and without SRC injury. We also compared the Balance Error Scoring System (BESS) performance, the Vestibular/Ocular Motor Symptoms (VOMS) symptom provocation, and the Post-Concussion Symptom Scale (PCSS) in adolescents with and without SRC.

Dual-task balance tests did not improve the ability to distinguish between groups or demonstrate recovery. No differences of sway were found between adolescents with a Sports-Related Concussion (SRC) within 10 days of injury and injury free controls. Balance conditions including the type of surface (firm or foam), performing balance tests in isolation or accompanying cognitive task, and the complexity of the cognitive task affected the amount of sway in adolescents with and without SRC injury.

Multiple assessment tools of concussion exist such as the Balance Error Scoring System (BESS), the Vestibular/Ocular Motor Screening (VOMS), the Post-Concussion Symptom Scale (PCSS), and the Video Head Impulse Test (vHIT) that may be sensitive to the onset of the injury, the reported symptoms, and the involved structures. When managing patients with a concussion injury, choosing the right assessment tools that are more relevant to the patient's condition and presentation may improve injury management and reduce patient and therapist load by reducing the number of tools used in managing the injury and use the relevant tools only which would improve the efficiency and quality of the care. While the total BESS was not able to show a difference between the groups, the firm BESS showed improvement of balance over time. The vHIT as a test of reduced VOR function did not find any differences between groups as well as did not indicate any abnormal findings in any of the adolescents in both groups. The VOMS and the PCSS found significant difference between groups.

Our study showed that unlike the single and dual-task balance paradigm and the vHIT, which involved objective testing of sway and VOR gain, the functional balance test (i.e. BESS) and the self-reporting symptom assessment (i.e. VOMS and PCSS) were able to show differences between adolescents with SRC and controls as well as capturing improvement over visits in adolescents with SRC.

11.0 ACKNOWLEDGMENTS

This research was supported in part by a grant to the University of Pittsburgh from the National Institute on Deafness and Other Communication Disorders (1K01DC012332-01A1) to Dr. Kontos.

APPENDIX A

FOAM PAD

https://www.my-airex.com

APPENDIX B

DEMOGRAPHICS, MEDICAL HISTORY, AND CONCUSSION HISTORY

Concussion History	Yes	No
A concussion within the last year	☐1	☐0
Number of times subject had been diagnosed with a concussion in the past (not including current concussion):	___ times	
Residual symptoms or deficits related to a previous concussion	☐1	☐0
Current or history of motion sickness, space-motion discomfort, dizziness, etc.	☐1	☐0
Demographic Data		
Age: _____ years Gender: ☐ 1 Male ☐ 2 Female Height: ______inches Weight: ______pounds Racial Category: ☐1 White ☐2 African-American ☐3 Pacific Islander or Native Hawaiian ☐4 Asian ☐5 African ☐6 American Indian or Alaskan Native ☐7 Other, Specify: ______________ Subject's Ethnicity is Hispanic/Latino? ☐ 1 Yes ☐ 0 No		

Medical History Does the subject have a history of, or currently have the following conditions?	Yes	No
Learning Disorder	☐1	☐0
Attention Deficit Disorder ADD	☐1	☐0
Migraine	☐1	☐0
Concussion Event Details		

1. Concussion Event Date/ Time: ________________________

2. Sport or activity during concussion:_______________________________

3. Type of injury: ☐1 Direct impact ☐2 Indirect impact

If direct impact, specify impact location: ☐1 Front ☐2 Top ☐3 Back

☐4 Left ☐5 Right ☐6Unknown

If indirect impact, specify type: ☐1 Acceleration ☐2 Deceleration

☐3 Rotational ☐4 Unknown

4. Symptoms at time of injury:

Loss of consciousness? ☐1 Yes ☐ 0 No

If 'Yes', how long was the subject unconscious? ______

Dizziness? ☐1 Yes ☐ 0 No

Retrograde Amnesia? ☐1 Yes ☐ 0 No

Anterograde Amnesia? ☐1 Yes ☐ 0 No

Confusion / Disorientation? ☐1 Yes ☐ 0 No

APPENDIX C

VIDEO HEAD IMPULSE TEST (VHIT)

http://www.interacoustics.com/images/products/eyeseecam/goggleTop2.png

APPENDIX D

VESTIBULAR/OCULAR MOTOR SCREENING (VOMS)

Vestibular/Ocular Motor Test:	Not Tested	Headache 0-10	Dizziness 0-10	Nausea 0-10	Fogginess 0-10	Comments
BASELINE SYMPTOMS:	N/A					
Smooth Pursuits						
Saccades – Horizontal						
Saccades – Vertical						
Convergence (Near Point)						(Near Point in cm): Measure 1: ______ Measure 2:______ Measure 3:______
VOR – Horizontal						
VOR – Vertical						
Visual Motion Sensitivity Test						

Instructions:

Interpretation: This test is designed for use with subjects ages 9-40. When used with patients outside this age range, interpretation may vary. Abnormal findings or provocation of symptoms with any test may indicate dysfunction – and should trigger a referral to the appropriate health care professional for more detailed assessment and management.
Equipment: Tape measure (cm); Metronome; Target w/ 14 point font print.

Baseline Symptoms – Record: Headache, Dizziness, Nausea & Fogginess on 0-10 scale prior to beginning screening

- **Smooth Pursuits** - Test the ability to follow a slowly moving target. The patient and the examiner are seated. The examiner holds a fingertip at a distance of 3 ft. from the patient. The patient is instructed to maintain focus on the target as the examiner moves the target smoothly in the horizontal direction 1.5 ft. to the right and 1.5 ft. to the left of midline. One repetition is complete when the target moves back and forth to the starting position, and 2 repetitions are performed. The target should be moved at a rate requiring approximately 2 seconds to go fully from left to right and 2 seconds to go fully from right to left. The test is repeated with the examiner moving the target smoothly and slowly in the vertical direction 1.5 ft. above and 1.5 ft. below midline for 2 complete repetitions up and down. Again, the target should be moved at a rate requiring approximately 2 seconds to move the eyes fully upward and 2 seconds to move fully downward. Record: Headache, Dizziness, Nausea & Fogginess ratings after the test. (Figure 1)

- **Saccades** – Test the ability of the eyes to move quickly between targets. The patient and the examiner are seated.
  - **Horizontal Saccades**: The examiner holds two single points (fingertips) horizontally at a distance of 3 ft. from the patient, and 1.5 ft. to the right and 1.5 ft. to the left of midline so that the patient must gaze 30 degrees to left and 30 degrees to the right. Instruct the patient to move their eyes as quickly as possible from point to point. One repetition is complete when the eyes move back and forth to the starting position, and 10 repetitions are performed. Record: Headache, Dizziness, Nausea & Fogginess ratings after the test. (Figure 2)

Reprinted from Mucha et al. (2014) [26]

- **Vertical Saccades**: Repeat the test with 2 points held vertically at a distance of 3 ft. from the patient, and 1.5 feet above and 1.5 feet below midline so that the patient must gaze 30 degrees upward and 30 degrees downward. Instruct the patient to move their eyes as quickly as possible from point to point. One repetition is complete when the eyes move up and down to the starting position, and 10 repetitions are performed. Record: Headache, Dizziness, Nausea & Fogginess ratings after the test. (Figure 3)

- **Convergence** – Measure the ability to view a near target without double vision. The patient is seated and wearing corrective lenses (if needed). The examiner is seated front of the patient and observes their eye movement during this test. The patient focuses on a small target (approximately 14 point font size) at arm's length and slowly brings it toward the tip of their nose. The patient is instructed to stop moving the target when they see two distinct images or when the examiner observes an outward deviation of one eye. Blurring of the image is ignored. The distance in cm. between target and the tip of nose is measured and recorded. This is repeated a total of 3 times with measures recorded each time. Record: Headache, Dizziness, Nausea & Fogginess ratings after the test. Abnormal: Near Point of convergence ≥ 6 cm from the tip of the nose. (Figure 4)

- **Vestibular-Ocular Reflex (VOR) Test** – Assess the ability to stabilize vision as the head moves. The patient and the examiner are seated. The examiner holds a target of approximately 14 point font size in front of the patient in midline at a distance of 3 ft.
  - **Horizontal VOR Test**: The patient is asked to rotate their head horizontally while maintaining focus on the target. The head is moved at an amplitude of 20 degrees to each side and a metronome is used to ensure the speed of rotation is maintained at 180 beats/minute (one beat in each direction). One repetition is complete when the head moves back and forth to the starting position, and 10 repetitions are performed. Record: Headache, Dizziness, Nausea and Fogginess ratings 10 sec after the test is completed. (Figure 5)
  - **Vertical VOR Test**: The test is repeated with the patient moving their head vertically. The head is moved in an amplitude of 20 degrees up and 20 degrees down and a metronome is used to ensure the speed of movement is maintained at 180 beats/minute (one beat in each direction). One repetition is complete when the head moves up and down to the starting position, and 10 repetitions are performed. Record: Headache, Dizziness, Nausea and Fogginess ratings after the test. (Figure 6)

- **Visual Motion Sensitivity (VMS) Test** – Test visual motion sensitivity and the ability to inhibit vestibular-induced eye movements using vision. The patient stands with feet shoulder width apart, facing a busy area of the clinic. The examiner stands next to and slightly behind the patient, so that the patient is guarded but the movement can be performed freely. The patient holds arm outstretched and focuses on their thumb. Maintaining focus on their thumb, the patient rotates, together as a unit, their head, eyes and trunk at an amplitude of 80 degrees to the right and 80 degrees to the left. A metronome is used to ensure the speed of rotation is maintained at 50 beats/min (one beat in each direction). One repetition is complete when the trunk rotates back and forth to the starting position, and 5 repetitions are performed. Record: Headache, Dizziness, Nausea & Fogginess ratings after the test. (Figure 7)

Reprinted from Mucha et al. (2014) [26]

Figure 1. Smooth pursuits.

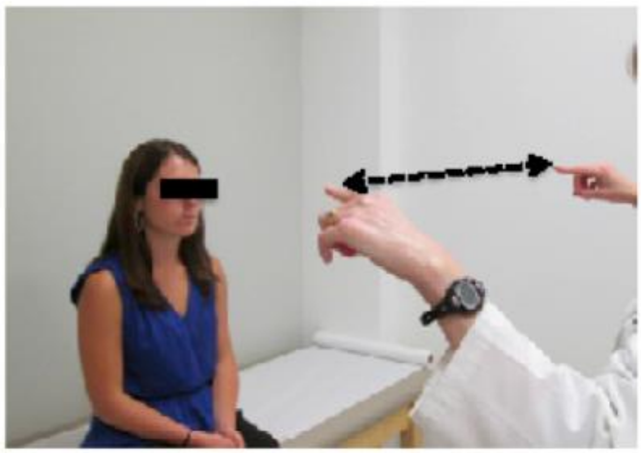


Figure 2. Horizontal saccades.

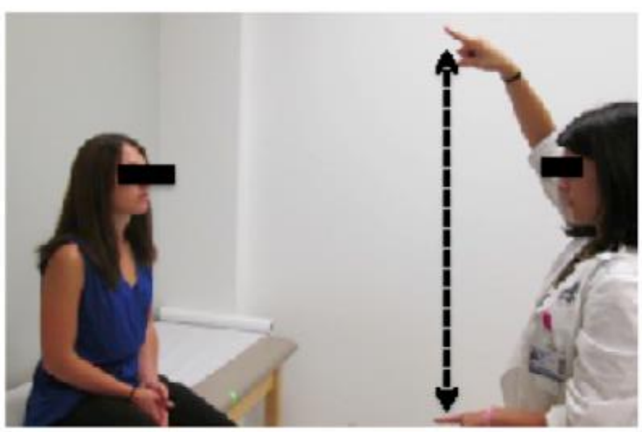


Figure 3. Vertical saccades.

Reprinted from Mucha et al. (2014) [26]

Figure 4. Convergence

Figure 5. Horizontal VOR.

Figure 6. Vertical VOR.

Figure 7. VMS.

Reprinted from Mucha et al. (2014) [26]

APPENDIX E

BALANCE ERROR SCORING SYSTEM (BESS)

		
Double Leg Stance Firm Surface	Single Leg Stance Firm Surface	Tandem Stance Firm Surface
		
Double Leg Stance Foam Surface	Single Leg Stance Foam Surface	Tandem Stance Foam Surface

APPENDIX F

NORMALITY TEST OF BALANCE ERROR SCORING SYSTEM (BESS)

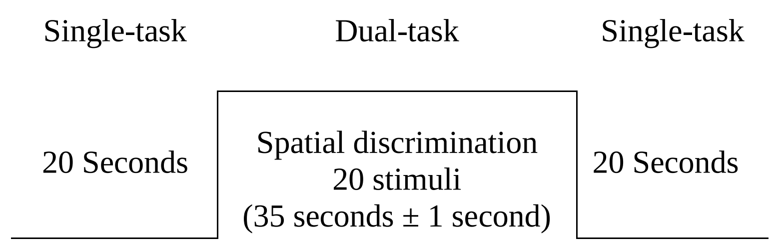
Shapiro-Wilk test	Concussion n=24			Control n=22		
	Statistic	df	P value	Statistic	df	P value
Firm BESS	.891	24	.014	.902	22	.032
Foam BESS	.971	24	.686	.970	22	.712
Total BESS	.930	24	.097	.974	22	.799

BESS: balance error scoring system; df: degrees of freedom.

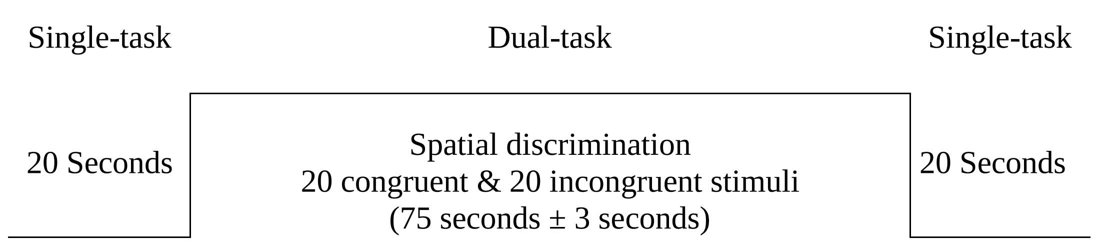
APPENDIX G

SEQUENCE OF PERFORMING SINGLE AND DUAL-TASKS

G.1 FORCED CHOICE SPATIAL DISCRIMINATION



G.2 FORCED CHOICE PERCEPTUAL INHIBITION



APPENDIX H

ACCELEROMETER

APPENDIX I

FORCE PLATE

http://bertec.com/

APPENDIX J

NUMBER OF PARTICIPANTS WITH MISSING SWAY DATA IN EACH BALANCE CONDITION

<table>
<tr><th rowspan="2">Group</th><th rowspan="2">Cognitive task</th><th rowspan="2">Surface</th><th rowspan="2">Task</th><th colspan="2">NPL</th><th colspan="2">RMS</th></tr>
<tr><th>AP</th><th>ML</th><th>AP</th><th>ML</th></tr>
<tr><td rowspan="8">Concussion n=25</td><td rowspan="4">Spatial discrimination</td><td rowspan="2">Firm</td><td>Single</td><td>3</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td>Dual</td><td>3</td><td>4</td><td>2</td><td>3</td></tr>
<tr><td rowspan="2">Foam</td><td>Single</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Dual</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">Perceptual inhibition</td><td rowspan="2">Firm</td><td>Single</td><td>2</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td>Dual</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td rowspan="2">Foam</td><td>Single</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Dual</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="8">Control n=22</td><td rowspan="4">Spatial discrimination</td><td rowspan="2">Firm</td><td>Single</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Dual</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><td rowspan="2">Foam</td><td>Single</td><td>1</td><td>1</td><td>1</td><td>2</td></tr>
<tr><td>Dual</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">Perceptual inhibition</td><td rowspan="2">Firm</td><td>Single</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Dual</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td rowspan="2">Foam</td><td>Single</td><td>2</td><td>2</td><td>3</td><td>2</td></tr>
<tr><td>Dual</td><td>2</td><td>2</td><td>1</td><td>2</td></tr>
</table>

Two adolescents from the concussion group (not included in the table) did not have any COP data due to equipment problem in one adolescent and due to excessive noise in the sway data in the other participant; Center of pressure data; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral

APPENDIX K

LINEAR MIXED MODEL

Effect n=45	NPL				RMS			
	COM		COP		COM		COP	
	AP	ML	AP	ML	AP	ML	AP	ML
Group	.491	.642	.826	.830	.542	.499	.534	.268
single vs dual-task	<.001	<.001	.033	<.001	.009	.326	<.001	.914
cognitive task	.971	.132	.934	.752	.018	.003	.012	<.001
Surface	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Group by single vs dual-task	.077	.706	.114	.733	.171	.989	.948	.804
Group by cognitive task	.212	.642	.958	.351	.693	.159	.794	.729
Group by Surface	.555	.128	.566	.005	.952	.272	.199	.008

COM: center of mass; COP: center of pressure; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral.

APPENDIX L

NORMALITY TEST OF SWAY MEASURES

Shapiro-Wilk tests of normality p-value n=45				Spatial discrimination				Perceptual inhibition			
				Firm surface		Foam surface		Firm surface		Foam surface	
				Injured	Control	Injured	Control	Injured	Control	Injured	Control
COP	Single	NPL	AP	0.170	0.136	0.900	0.823	0.698	0.351	0.144	0.144
			ML	0.326	0.269	0.354	0.885	0.609	0.002	0.146	0.066
		RMS	AP	0.660	0.013	0.579	0.162	0.943	0.402	0.658	0.327
			ML	0.064	0.214	0.177	0.068	0.720	0.053	0.414	0.129
	Dual	NPL	AP	0.410	0.338	0.437	0.142	0.136	0.629	0.929	0.209
			ML	0.848	0.052	0.533	0.813	0.670	0.173	0.912	0.647
		RMS	AP	0.028	0.556	0.171	0.033	0.322	0.092	0.031	0.031
			ML	0.843	0.070	0.236	0.558	0.343	0.059	0.945	0.369
COM	Single	NPL	AP	0.125	0.007	0.100	0.386	0.066	0.151	0.151	0.005
			ML	0.760	0.012	0.914	0.055	0.379	0.007	0.143	0.274
		RMS	AP	0.041	0.020	0.005	0.571	0.910	0.041	0.024	0.121
			ML	0.092	0.007	0.059	0.203	0.487	0.01	0.799	0.013
	Dual	NPL	AP	0.138	<0.001	0.100	0.673	0.031	0.001	0.741	0.002
			ML	0.023	0.079	0.128	0.003	0.229	0.079	0.899	0.002
		RMS	AP	0.076	0.017	0.037	0.001	0.004	0.018	0.080	0.010
			ML	0.002	0.001	0.047	0.032	0.630	0.009	0.697	0.041

Violations of normality for 6/64 COP data and 30/64 COM data; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral; COM: center of mass in mG; COP: center of pressure in centimeters.

APPENDIX M

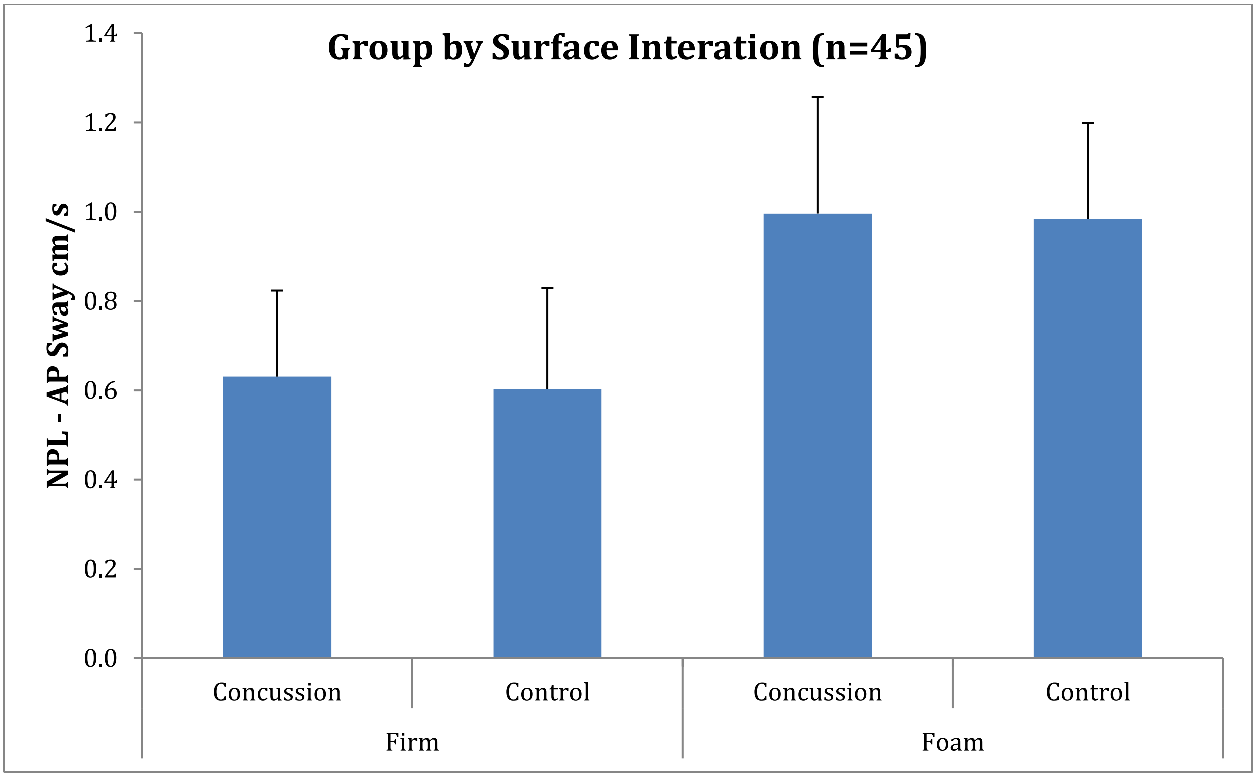
MEAN AND (SD) OF SWAY

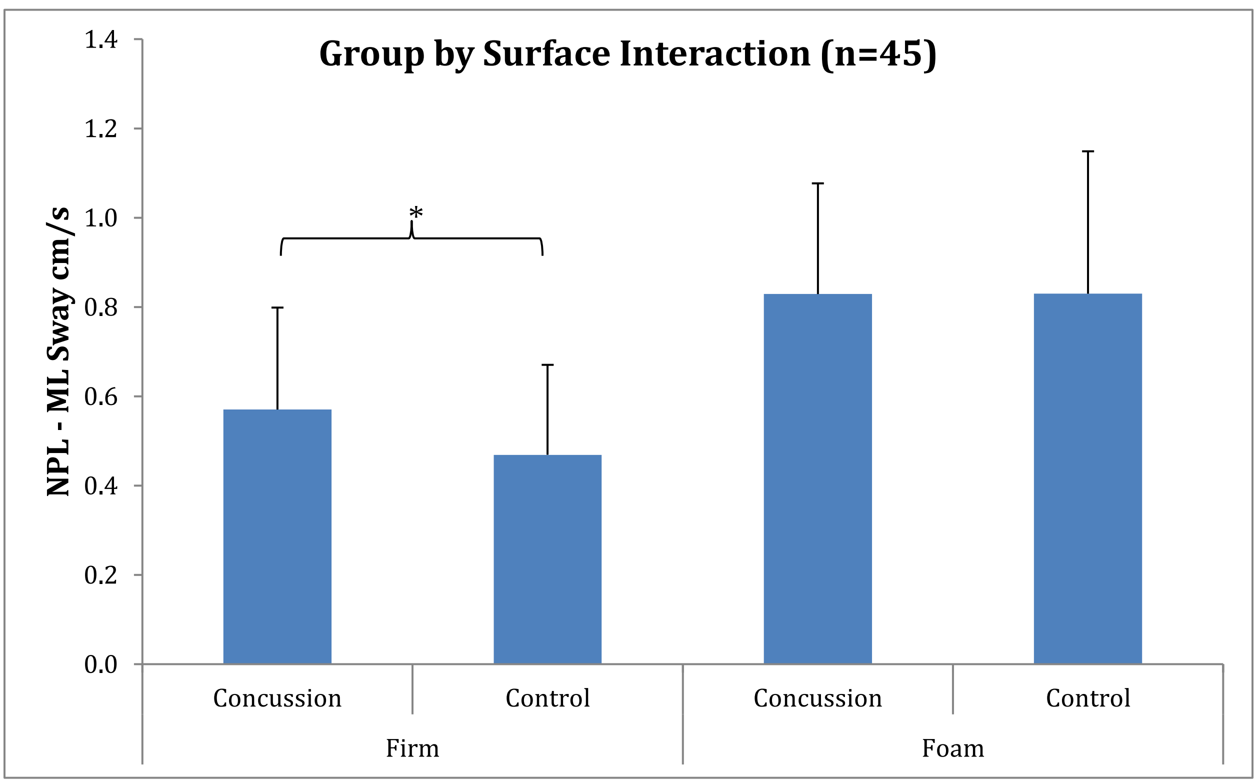
n=45				Spatial discrimination								Perceptual inhibition							
				Firm surface				Foam surface				Firm surface				Foam surface			
				Injured		Control		Injured		Control		Injured		Control		Injured		Control	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
COP (mG)	Single-task	NPL	AP	0.63	0.18	0.62	0.24	1.05	0.31	0.99	0.26	0.69	0.21	0.62	0.22	1.01	0.30	0.97	0.24
			ML	0.61	0.26	0.50	0.20	0.86	0.28	0.91	0.45	0.64	0.27	0.48	0.20	0.85	0.22	0.82	0.23
		RMS	AP	0.40	0.11	0.40	0.19	0.68	0.22	0.67	0.24	0.41	0.14	0.35	0.13	0.71	0.19	0.61	0.15
			ML	0.35	0.19	0.26	0.14	0.48	0.13	0.46	0.17	0.34	0.18	0.22	0.12	0.52	0.23	0.46	0.17
	Dual-task	NPL	AP	0.60	0.20	0.55	0.17	0.96	0.23	1.01	0.20	0.59	0.18	0.61	0.27	0.96	0.18	0.95	0.16
			ML	0.48	0.15	0.46	0.24	0.81	0.26	0.81	0.29	0.53	0.18	0.44	0.17	0.80	0.23	0.77	0.27
		RMS	AP	0.49	0.26	0.34	0.12	0.69	0.15	0.73	0.20	0.49	0.15	0.43	0.18	0.80	0.20	0.78	0.22
			ML	0.31	0.11	0.22	0.12	0.46	0.15	0.43	0.16	0.39	0.18	0.28	0.12	0.50	0.14	0.50	0.16
COM (cm)	Single-task	NPL	AP	11.6	3.04	12.3	5.32	17.6	6.87	14.7	4.13	13.9	5.31	12.2	4.97	16.4	5.31	15.2	5.24
			ML	9.92	3.05	9.23	4.04	16.3	6.71	16.0	8.75	11.1	3.72	8.99	2.89	15.4	4.69	14.7	5.68
		RMS	AP	6.35	1.98	6.95	3.42	8.81	2.43	8.69	3.76	6.91	3.19	5.54	1.98	10.1	3.76	8.19	3.45
			ML	3.48	1.51	2.78	1.54	6.69	3.05	6.61	3.77	3.48	1.79	2.79	1.22	6.37	2.61	5.72	2.64
	Dual-task	NPL	AP	11.3	3.64	10.2	3.97	15.0	5.30	14.6	6.29	11.1	3.75	9.34	2.66	13.9	3.56	15.2	7.21
			ML	8.09	2.44	7.04	2.60	13.7	5.31	13.5	6.52	9.20	3.16	7.48	2.86	14.0	5.08	14.8	9.01
		RMS	AP	6.41	1.79	6.20	3.08	9.50	3.59	10.2	4.22	7.80	2.33	7.80	4.96	10.1	3.12	9.94	3.23
			ML	3.45	1.94	2.61	1.63	6.57	3.05	5.79	3.41	3.82	1.98	2.83	1.44	6.94	2.91	7.56	3.90

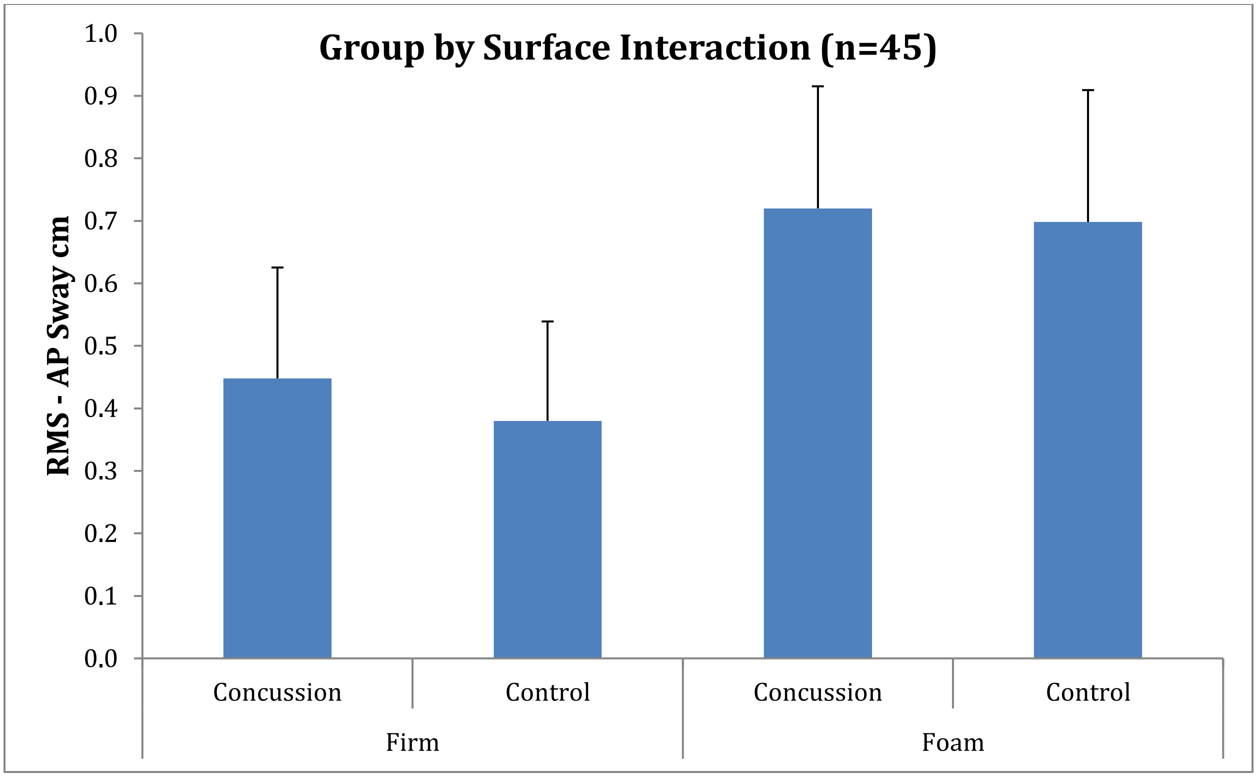
NPL: normalized path length; RMS: root mean square; COM: center of mass in mG; COP: center of pressure in centimeters; AP: anterior-posterior direction; ML: medial-lateral direction.

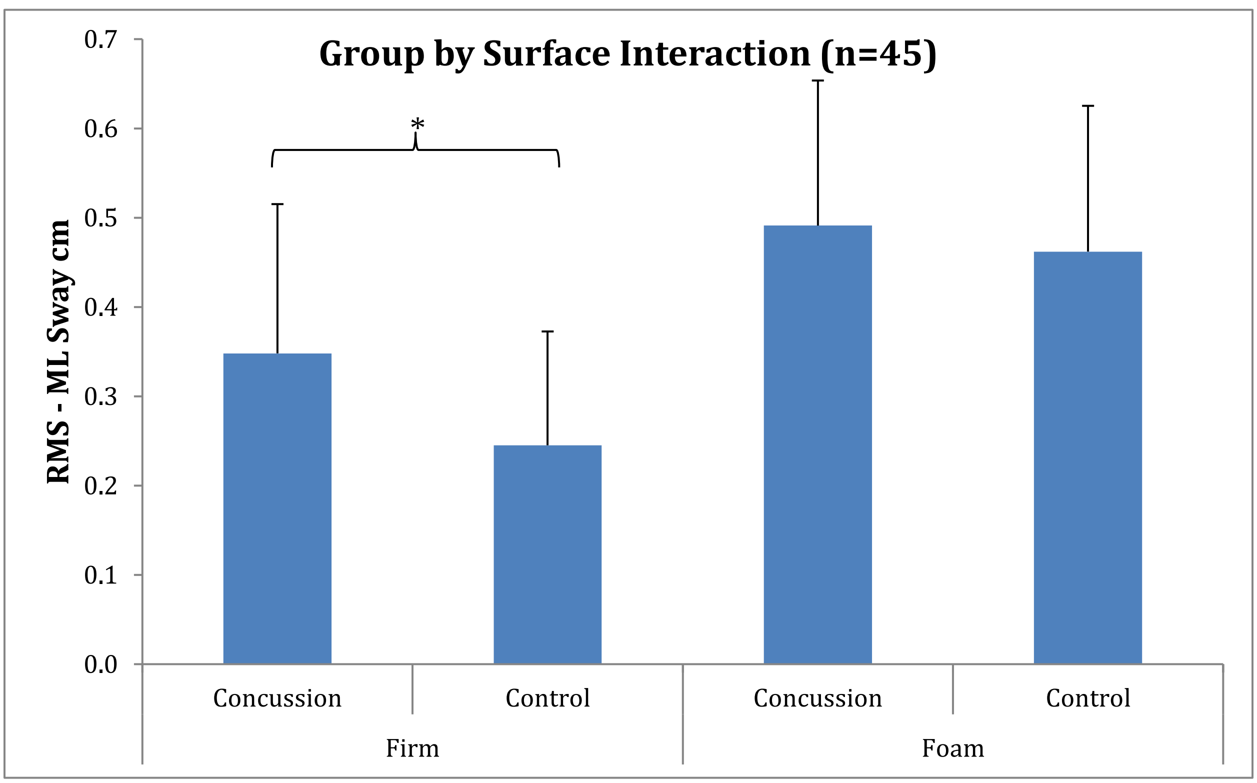
APPENDIX N

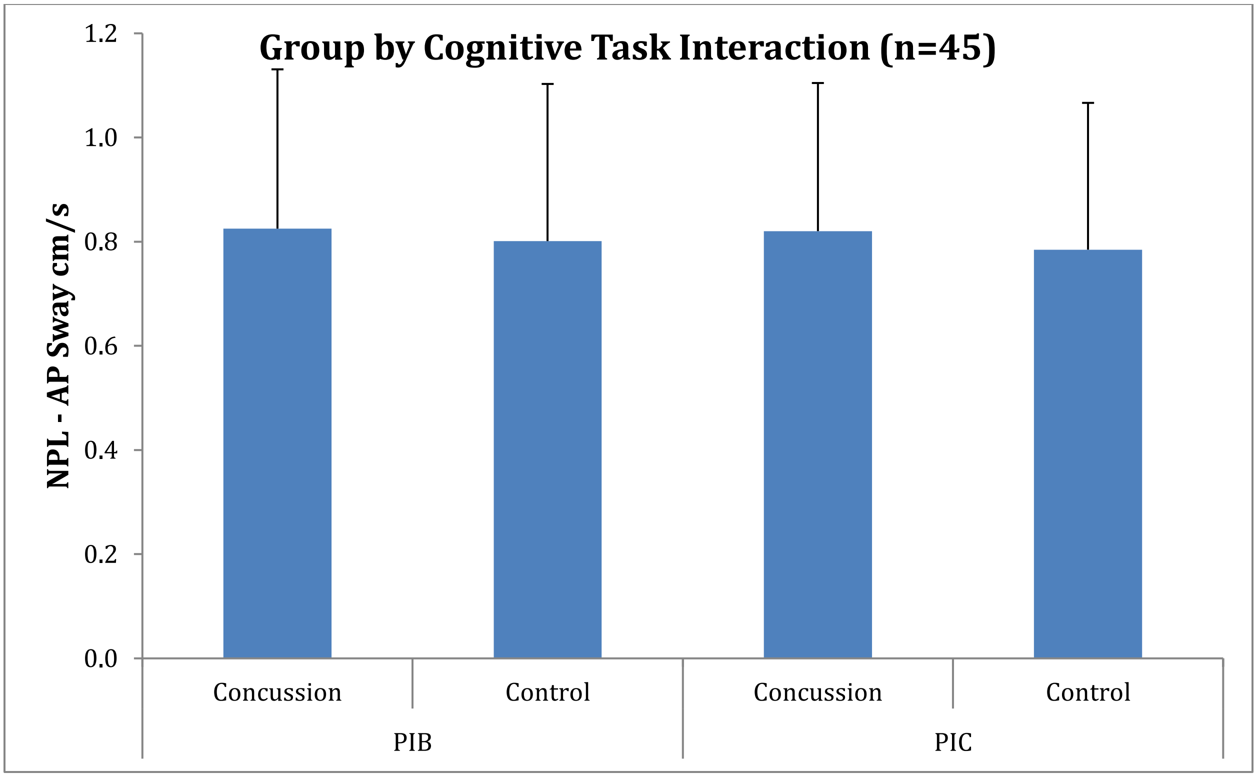
INTERACTION EFFECT OF GROUP BY SURFACE, COGNITIVE TEST, AND SINGLE AND DUAL-TASKS

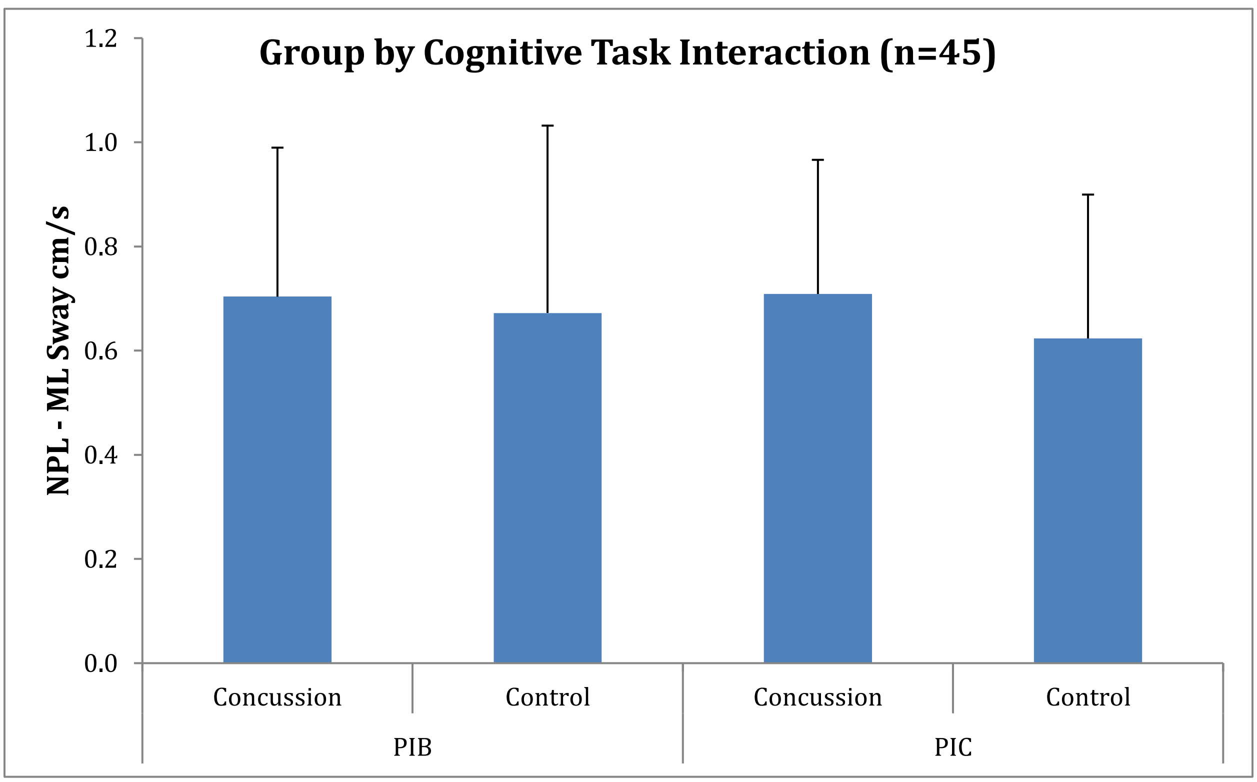

Group by Surface Interation (n=45)
NPL - AP Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Concussion
Control
Concussion
Control
Firm
Foam


Group by Surface Interaction (n=45)
NPL - ML Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
*
Concussion
Control
Concussion
Control
Firm
Foam

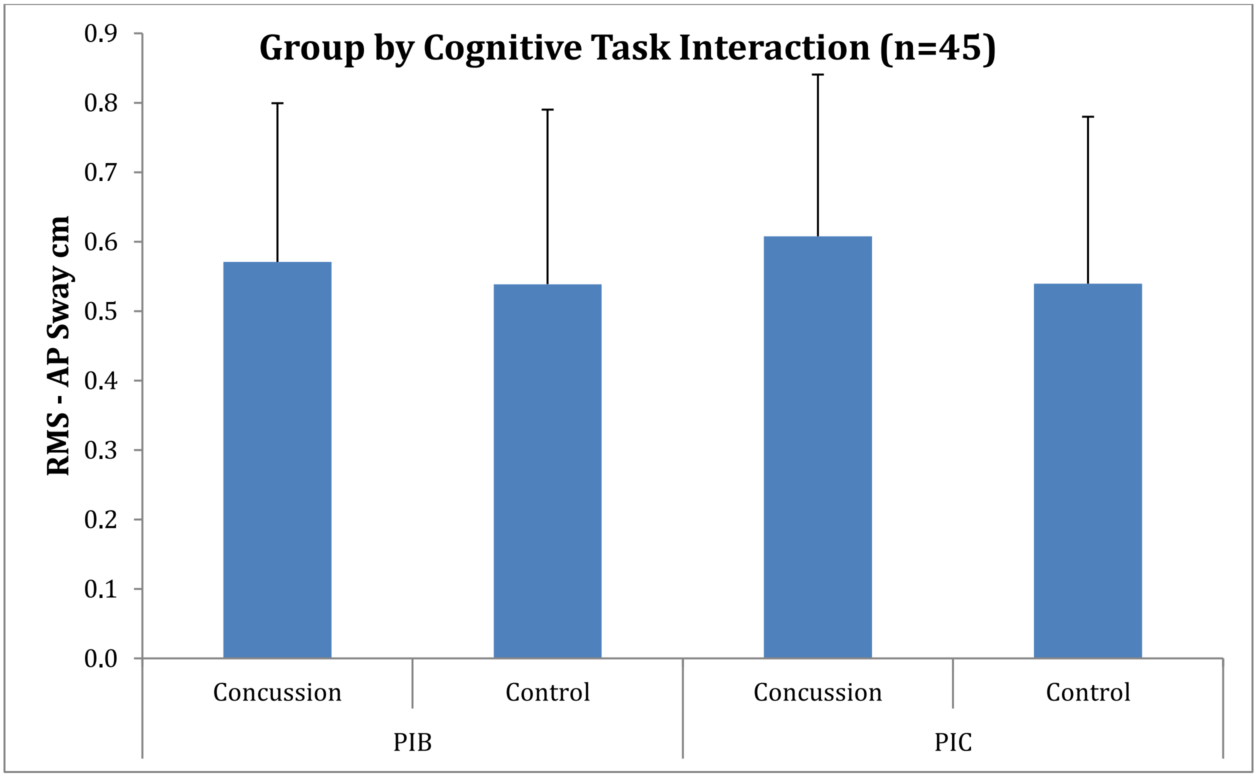

Group by Surface Interaction (n=45)
RMS - AP Sway cm
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Concussion
Control
Concussion
Control
Firm
Foam

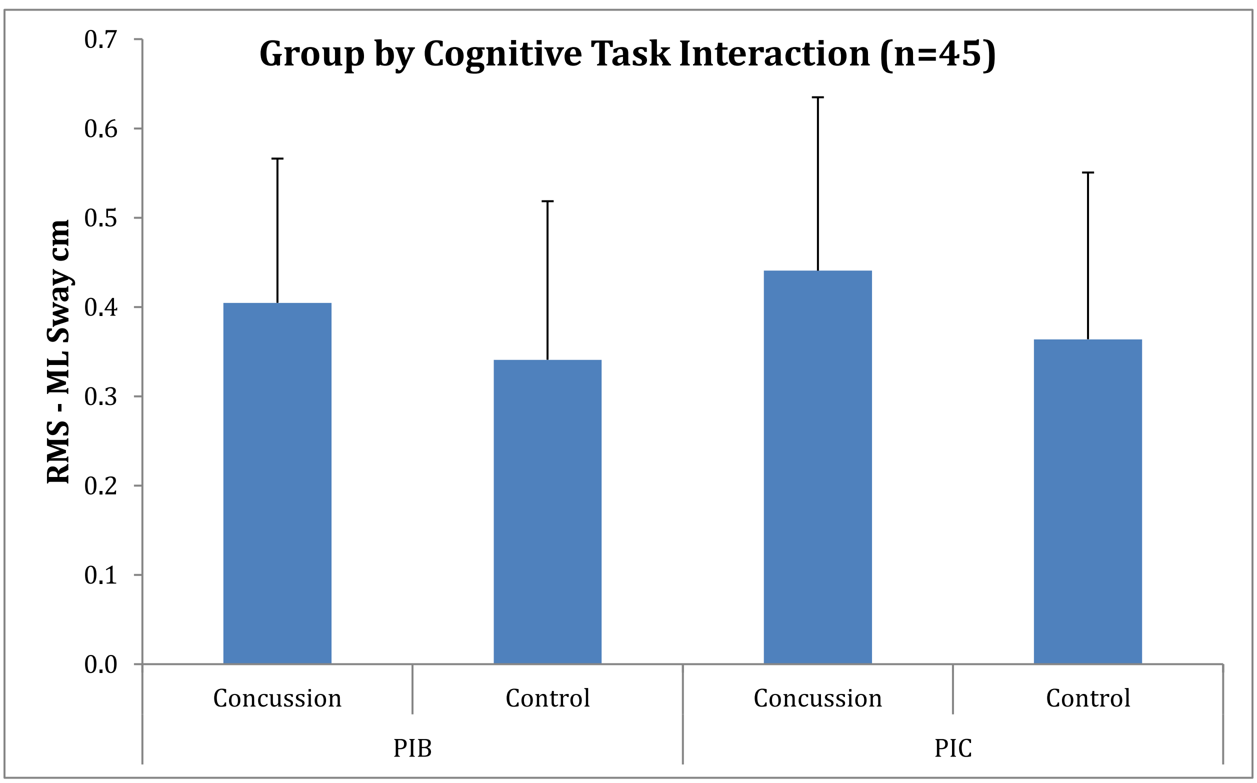

Group by Surface Interaction (n=45)
RMS - ML Sway cm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
*
Concussion
Control
Concussion
Control
Firm
Foam



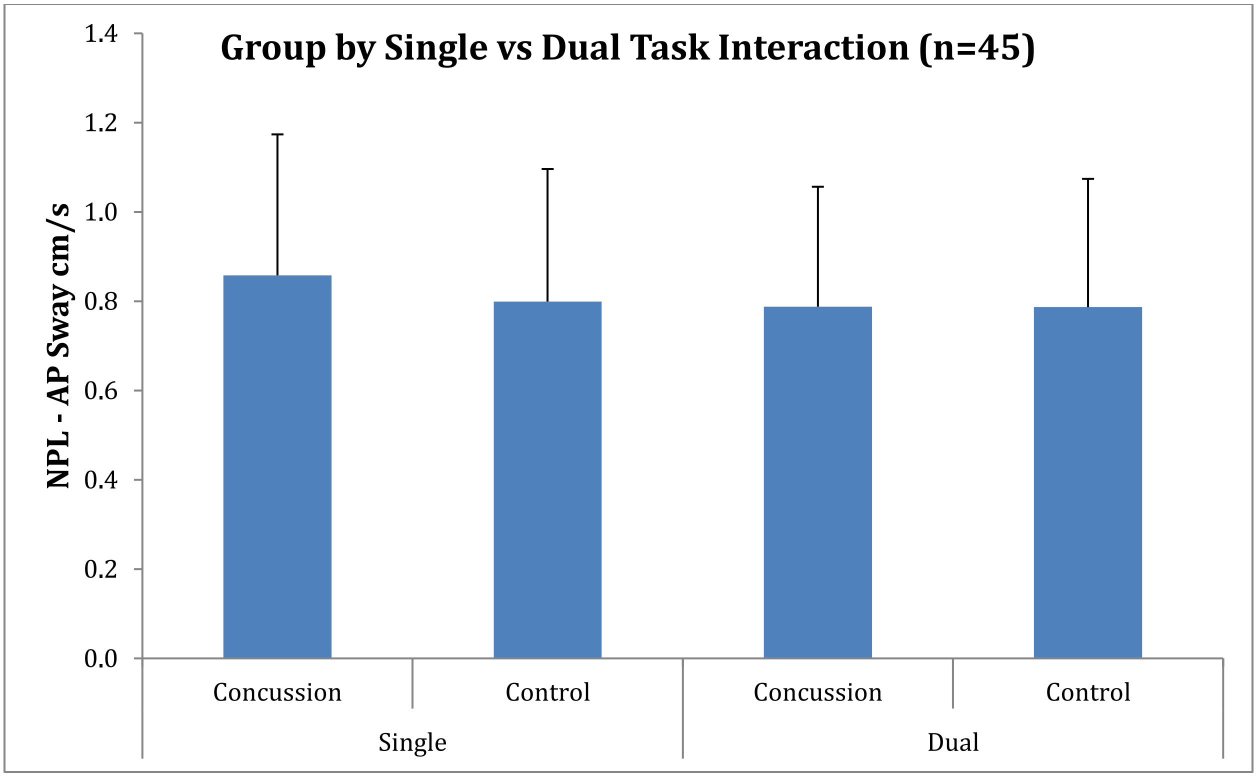


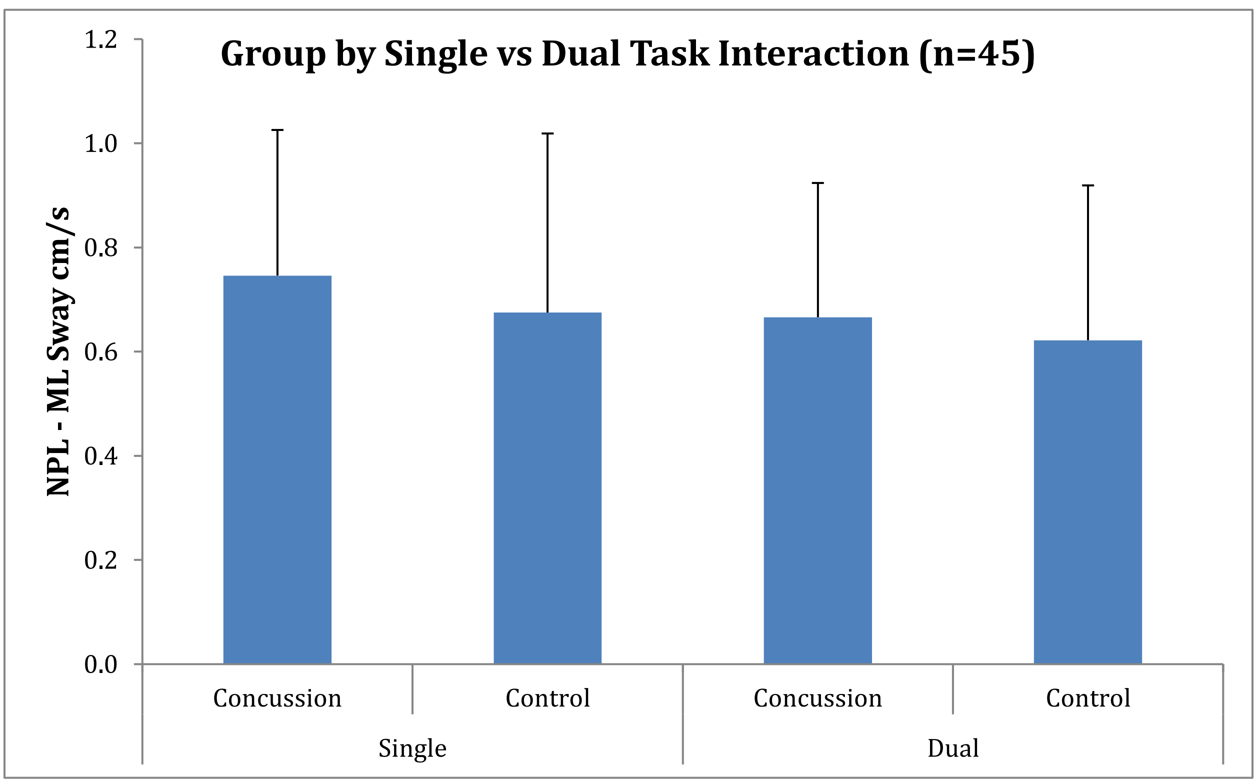
PIB: spatial discrimination; PIC: perceptual inhibition.

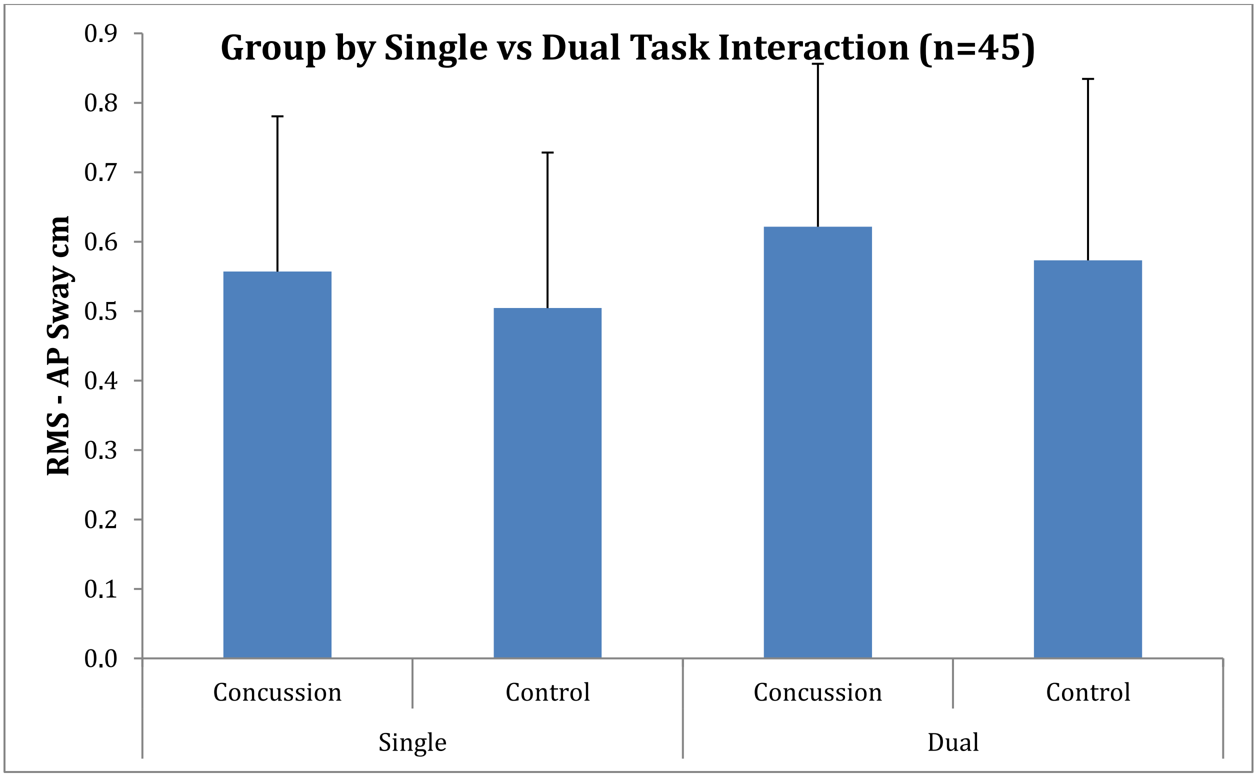


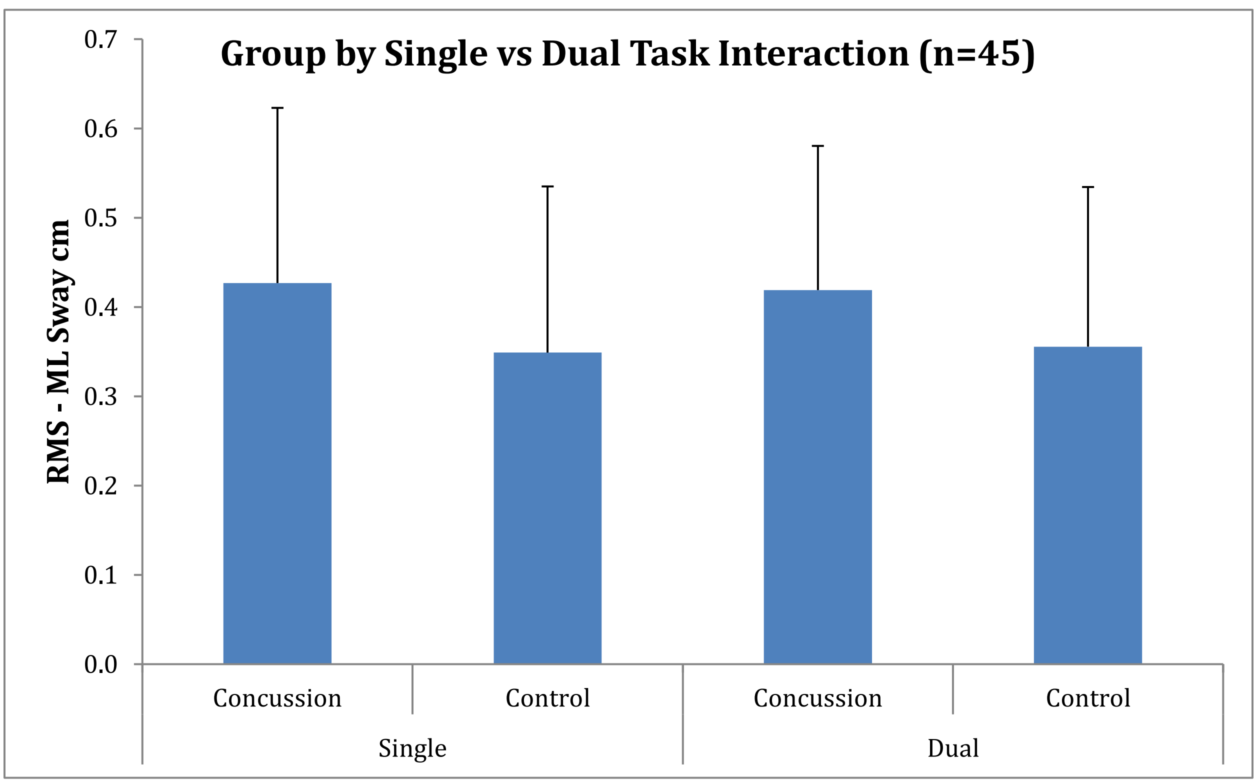


PIB: spatial discrimination; PIC: perceptual inhibition.


Group by Single vs Dual Task Interaction (n=45)
NPL - AP Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Concussion
Control
Concussion
Control
Single
Dual


Group by Single vs Dual Task Interaction (n=45)
NPL - ML Sway cm/s
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Concussion
Control
Concussion
Control
Single
Dual


Group by Single vs Dual Task Interaction (n=45)
RMS - AP Sway cm
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Concussion
Control
Concussion
Control
Single
Dual


Group by Single vs Dual Task Interaction (n=45)
RMS - ML Sway cm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Concussion
Control
Concussion
Control
Single
Dual

APPENDIX O

NUMBER OF MISSING SWAY DATA IN EACH BALANCE CONDITION

Visit	Cognitive task	Surface	Task	NPL		RMS	
				AP	ML	AP	ML
First visit n=25	Spatial discrimination	Firm	Single	3	2	2	2
			Dual	3	4	2	3
		Foam	Single	0	0	0	0
			Dual	0	0	0	0
	Perceptual inhibition	Firm	Single	2	2	2	2
			Dual	1	1	1	1
		Foam	Single	0	0	0	0
			Dual	0	0	0	0
Second visit n=23	Spatial discrimination	Firm	Single	2	2	2	2
			Dual	2	2	2	2
		Foam	Single	1	1	1	1
			Dual	1	1	1	1
	Perceptual inhibition	Firm	Single	2	2	2	2
			Dual	1	1	1	1
		Foam	Single	1	1	1	1
			Dual	1	1	1	1
Third visit n=14	Spatial discrimination	Firm	Single	3	3	3	3
			Dual	3	3	3	3
		Foam	Single	1	1	1	1
			Dual	1	1	1	1
	Perceptual inhibition	Firm	Single	2	2	2	2
			Dual	1	1	1	1
		Foam	Single	1	1	1	1
			Dual	1	1	1	1

One adolescent (not included in the table) did not have any sway data due to equipment problem; Center of pressure data; NPL: normalized path length; RMS: root mean square; AP: anterior-posterior; ML: medial-lateral

APPENDIX P

ANALYSIS OF CENTER OF PRESSURE SWAY DATA FOR ADOLESCENTS WITH CONCUSSION USING DIFFERENT MODELS

LMM (per protocol analysis) n=14	NPL		RMS	
	AP	ML	AP	ML
visit	0.479	0.275	0.104	0.029
single vs dual-task	0.035	<0.001	0.017	0.663
cognitive task	0.709	0.203	<0.001	<0.001
surface	<0.001	<0.001	<0.001	<0.001
visit by single vs dual-task	0.474	0.354	0.821	0.309
visit by cognitive task	0.65	0.878	0.984	0.941
visit by surface	0.006	0.016	0.015	0.119
LMM (first and second visits) n=23	**NPL**		**RMS**	
	AP	**ML**	**AP**	**ML**
visit	0.106	0.124	0.018	0.013
single vs dual-task	0.075	0.01	<0.001	0.475
cognitive task	0.652	0.951	0.037	0.004
surface	<0.001	<0.001	<0.001	<0.001
visit by single vs dual-task	0.327	0.221	0.587	0.290
visit by cognitive task	0.857	0.682	0.739	0.761
visit by surface	0.457	0.186	0.517	0.294
ANOVA	**NPL**		**RMS**	
	AP n=14	**ML n=14**	**AP n=16**	**ML n=15**
visit	0.220	0.463	0.256	0.334
single vs dual-task	0.129	0.001	0.018	0.705
cognitive task	0.888	0.392	0.022	0.002
surface	<0.001	<0.001	<0.001	<0.001
visit by single vs dual-task	0.886	0.303	0.716	0.704
visit by cognitive task	0.410	0.957	0.856	0.904
visit by surface	0.053	0.189	0.057	0.241

NPL: normalized path length; RMS: root mean square; AP: anterior-posterior direction; ML: medial-lateral direction

APPENDIX Q

LINEAR MIXED MODEL

Linear mixed model p value of the effects	Sway n=25							
	NPL				RMS			
	COM		COP		COM		COP	
	AP	ML	AP	ML	AP	ML	AP	ML
visit	0.539	0.560	0.147	0.338	0.455	0.505	0.042	0.033
single vs dual-task	<0.001	<0.001	0.227	<0.001	0.017	0.235	<0.001	0.302
cognitive task	0.890	0.074	0.919	0.911	0.001	<0.001	0.006	<0.001
surface	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
visit by single vs dual-task	.046	0.103	0.287	0.393	0.003	0.030	0.658	0.526
visit by cognitive task	0.651	0.970	0.748	0.928	0.975	0.246	0.905	0.938
visit by Surface	0.490	0.448	0.024	0.054	0.827	0.243	0.090	0.225

NPL: normalized path length; RMS: root mean square; COM: center of mass; COP: center of pressure; AP: anterior-posterior direction; ML: medial-lateral direction.

APPENDIX R

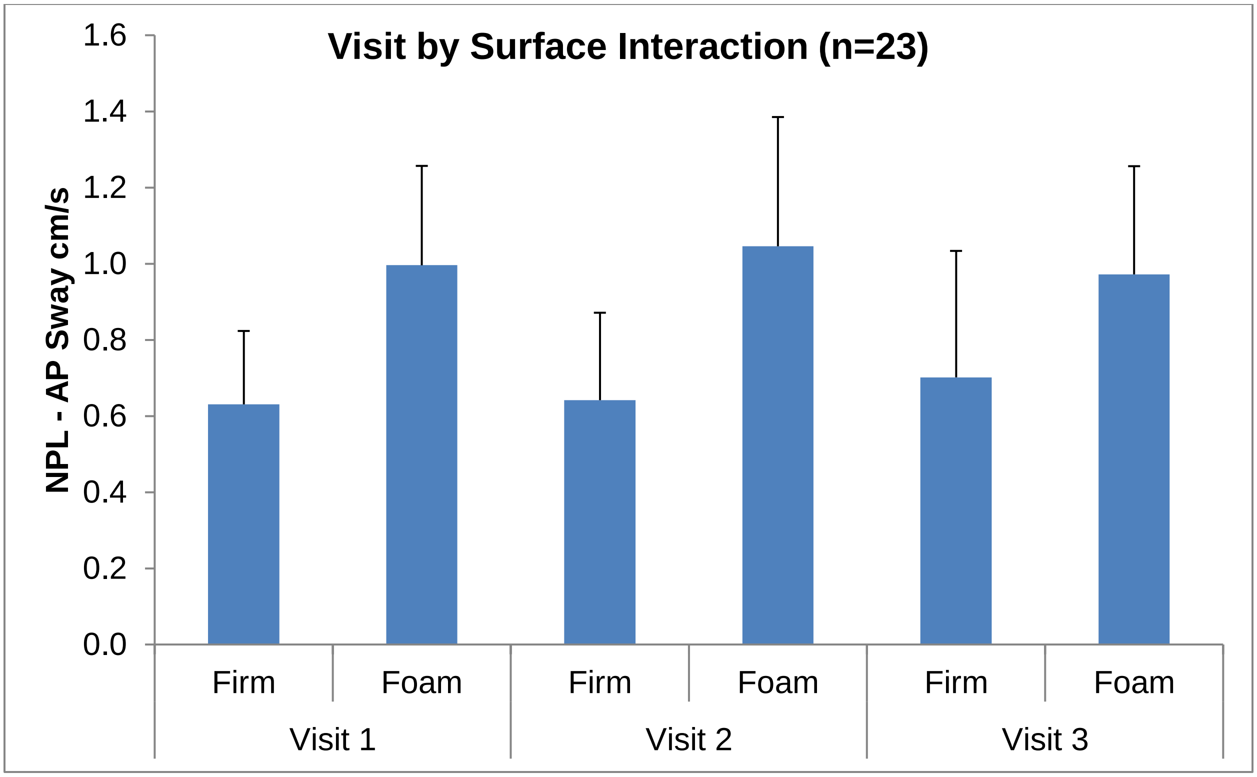
NORMALITY TEST OF SWAY MEASURES

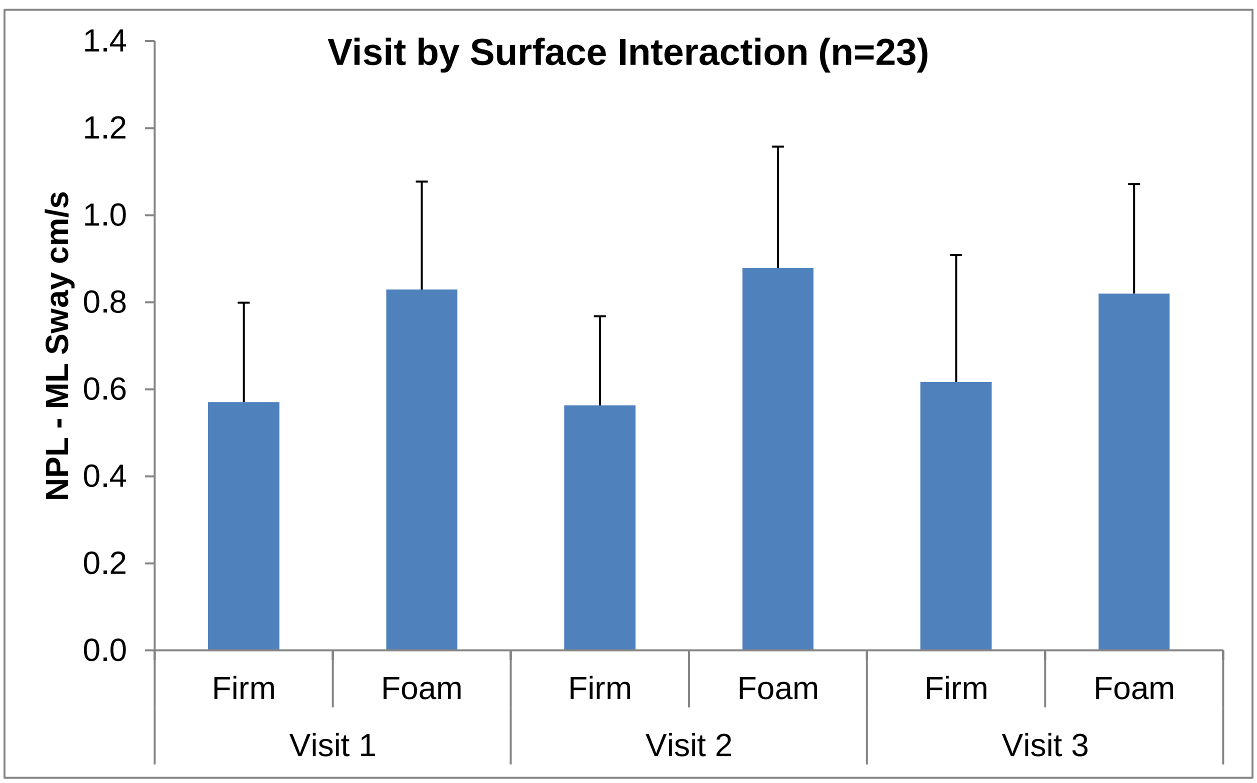
Shapiro-Wilk tests of normality n=25				Spatial discrimination				Perceptual inhibition			
				Firm surface		Foam surface		Firm surface		Foam surface	
				Single	Dual	Single	Dual	Single	Dual	Single	Dual
COP	Initial visit	NPL	AP	0.948	0.973	0.970	0.962	0.977	0.961	0.943*	0.976
			ML	0.945*	0.960	0.894*	0.988	0.962	0.974	0.941*	0.983
		RMS	AP	0.916*	0.867*	0.975	0.953	0.958	0.954	0.969	0.919*
			ML	0.920*	0.972	0.981	0.992	0.922*	0.942*	0.951	0.984
	Second visit	NPL	AP	0.914	0.864*	0.902*	0.945	0.761*	0.627*	0.794*	0.949
			ML	0.943	0.887*	0.912*	0.987	0.955	0.951	0.831*	0.971
		RMS	AP	0.905*	0.695*	0.938	0.874*	0.891*	0.891*	0.892*	0.930
			ML	0.943	0.927	0.923	0.928	0.943	0.779*	0.841*	0.913*
	Clearance visit	NPL	AP	0.927	0.956	0.887	0.915	0.930	0.650*	0.947	0.968
			ML	0.824*	0.972	0.906	0.930	0.963	0.969	0.960	0.959
		RMS	AP	0.753*	0.854*	0.943	0.892	0.860*	0.901	0.904	0.946
			ML	0.924	0.928	0.902	0.889	0.937	0.967	0.967	0.930
COM	Initial visit	NPL	AP	0.888*	0.893*	0.913*	0.885*	0.955	0.937*	0.923*	0.876*
			ML	0.936*	0.925*	0.925*	0.953	0.959	0.904*	0.973	0.891*
		RMS	AP	0.892*	0.926*	0.955	0.883*	0.900*	0.843*	0.948*	0.924*
			ML	0.915*	0.848*	0.928*	0.941*	0.917*	0.907*	0.957	0.939*
	Second visit	NPL	AP	0.880*	0.866*	0.960	0.989	0.856*	0.773*	0.738*	0.976
			ML	0.951	0.885*	0.941	0.961	0.948	0.945	0.906*	0.931
		RMS	AP	0.889*	0.882*	0.924	0.981	0.905*	0.899*	0.902*	0.941
			ML	0.936	0.920	0.924	0.929	0.950	0.605*	0.921	0.953
	Clearance visit	NPL	AP	0.897	0.944	0.923	0.927	0.913	0.718*	0.853*	0.853*
			ML	0.900	0.946	0.944	0.932	0.884	0.911	0.965	0.971
		RMS	AP	0.854*	0.874	0.904	0.886	0.962	0.824*	0.859*	0.927
			ML	0.892	0.934	0.960	0.843*	0.882	0.931	0.920	0.951

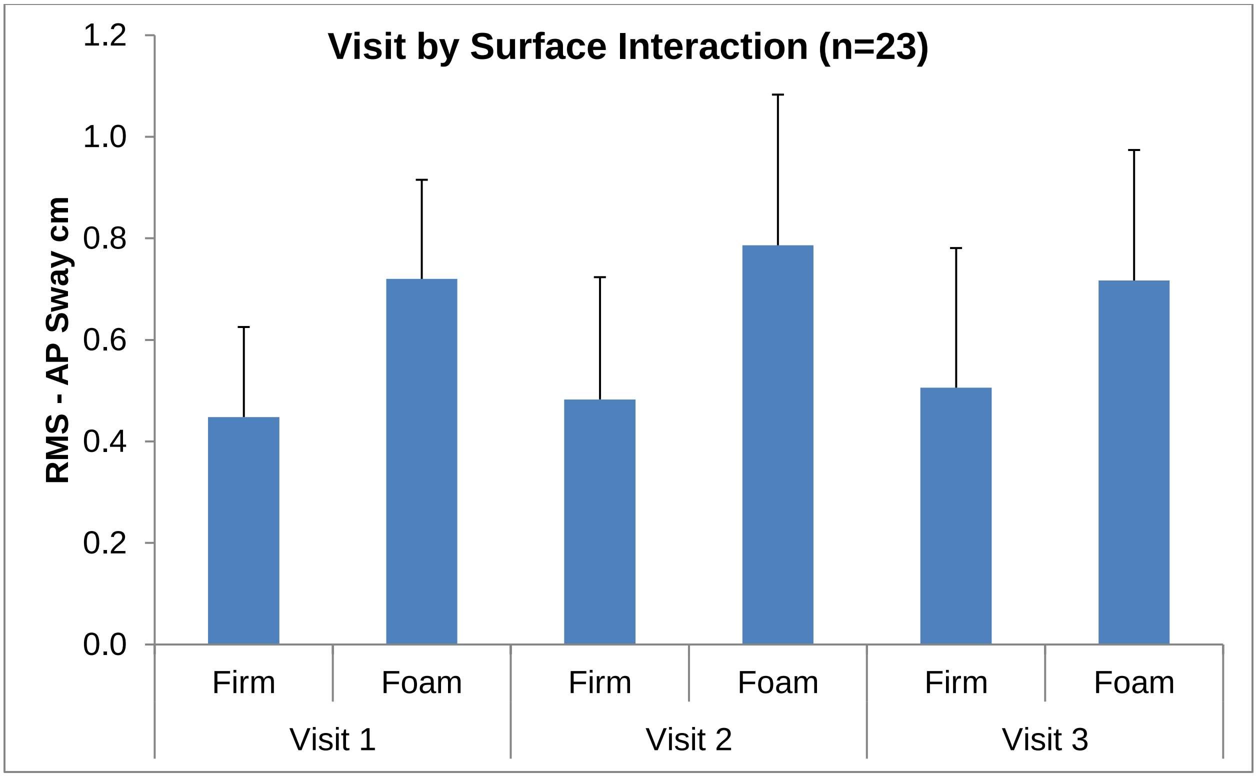
Violations of normality for 32/96 COP data and 46/96 COM data; * Assumption of normality violated ($P < 0.05$); NPL: normalized path length; RMS: root mean square; AP: anterior posterior; ML: medial-lateral.

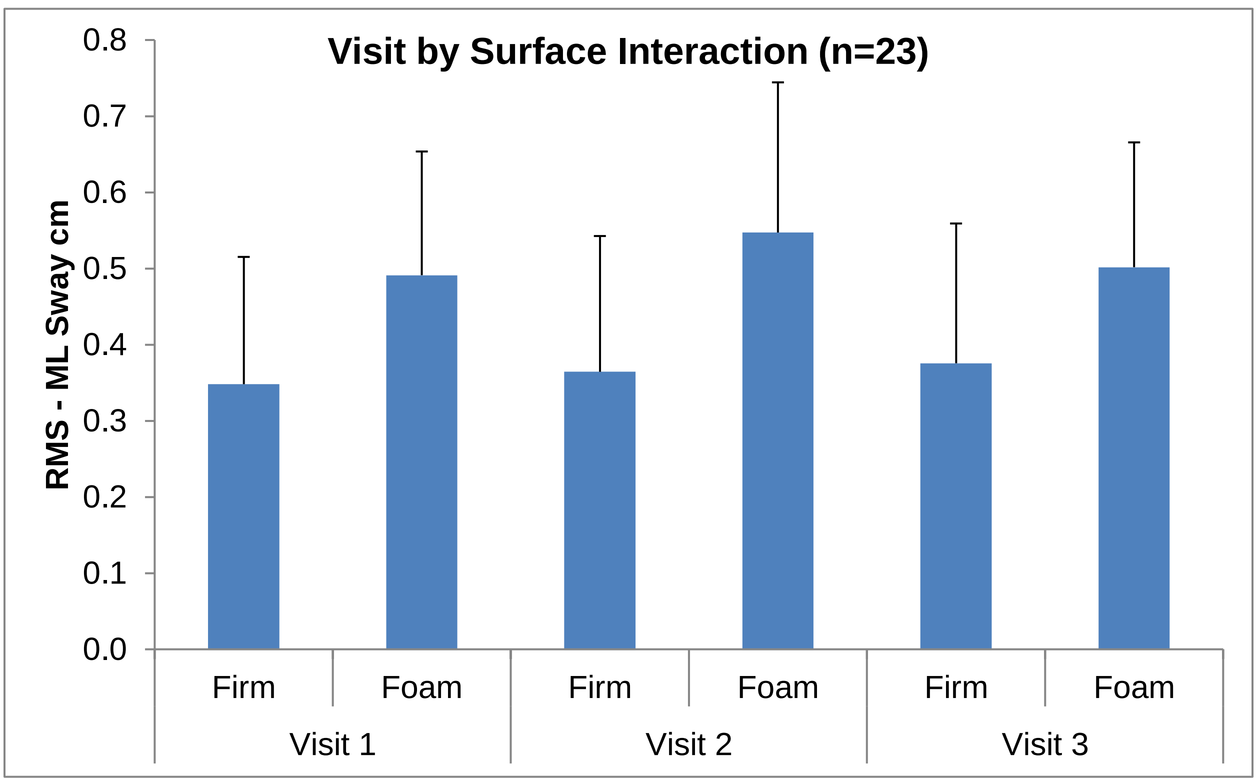
APPENDIX S

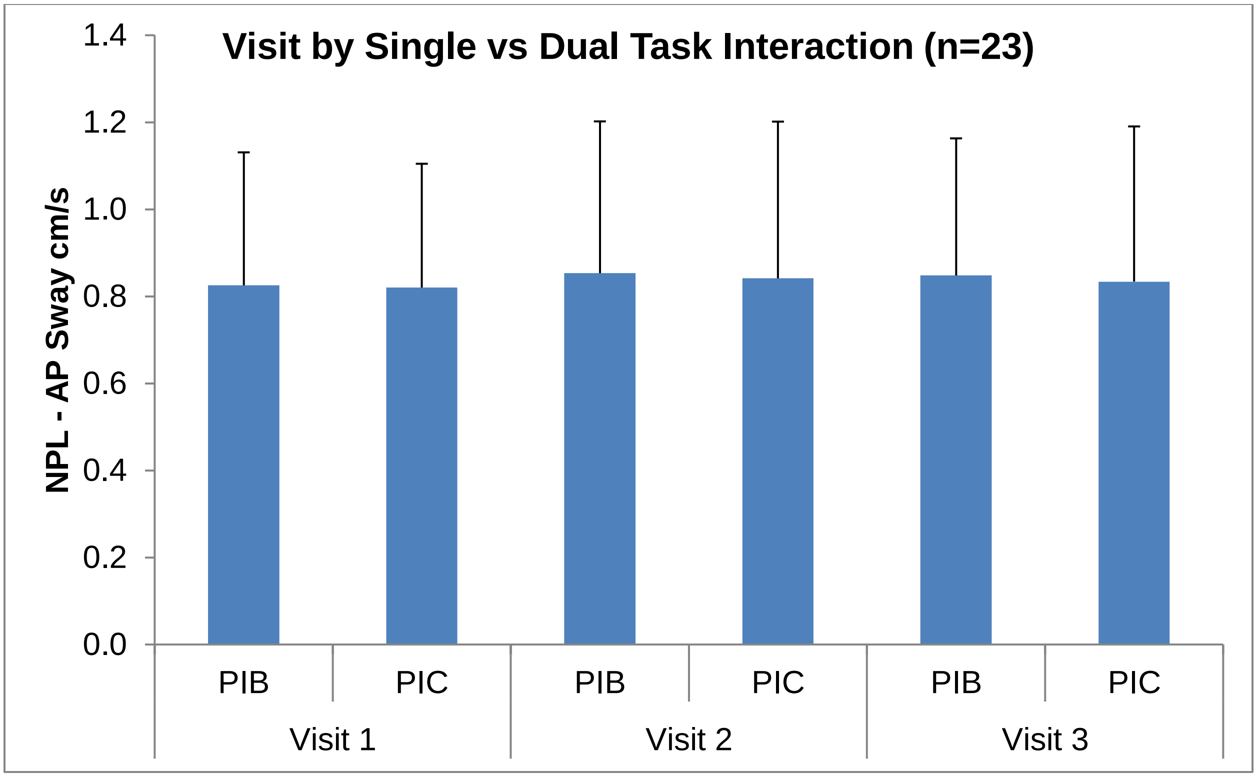
INTERACTION EFFECT OF VISIT BY SURFACE, COGNITIVE TEST, AND SINGLE AND DUAL-TASKS

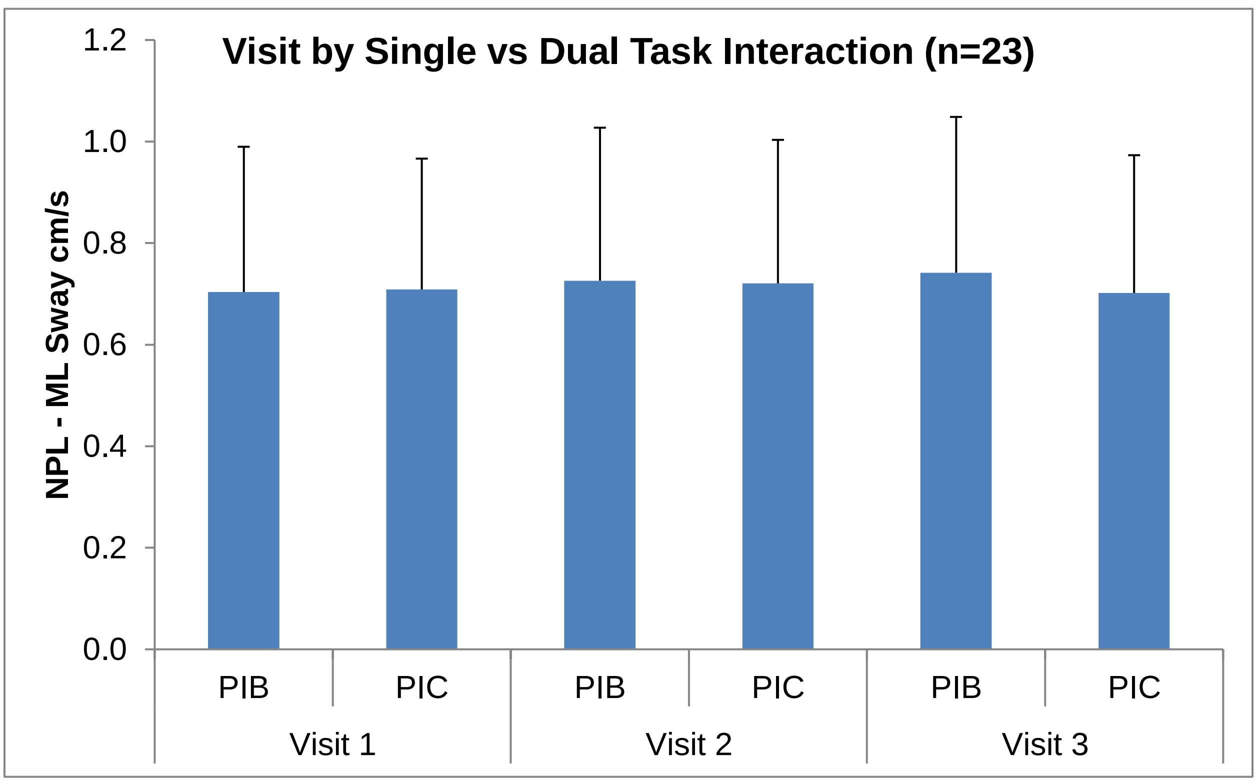

Visit by Surface Interaction (n=23)
NPL - AP Sway cm/s
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Firm
Foam
Firm
Foam
Firm
Foam
Visit 1
Visit 2
Visit 3

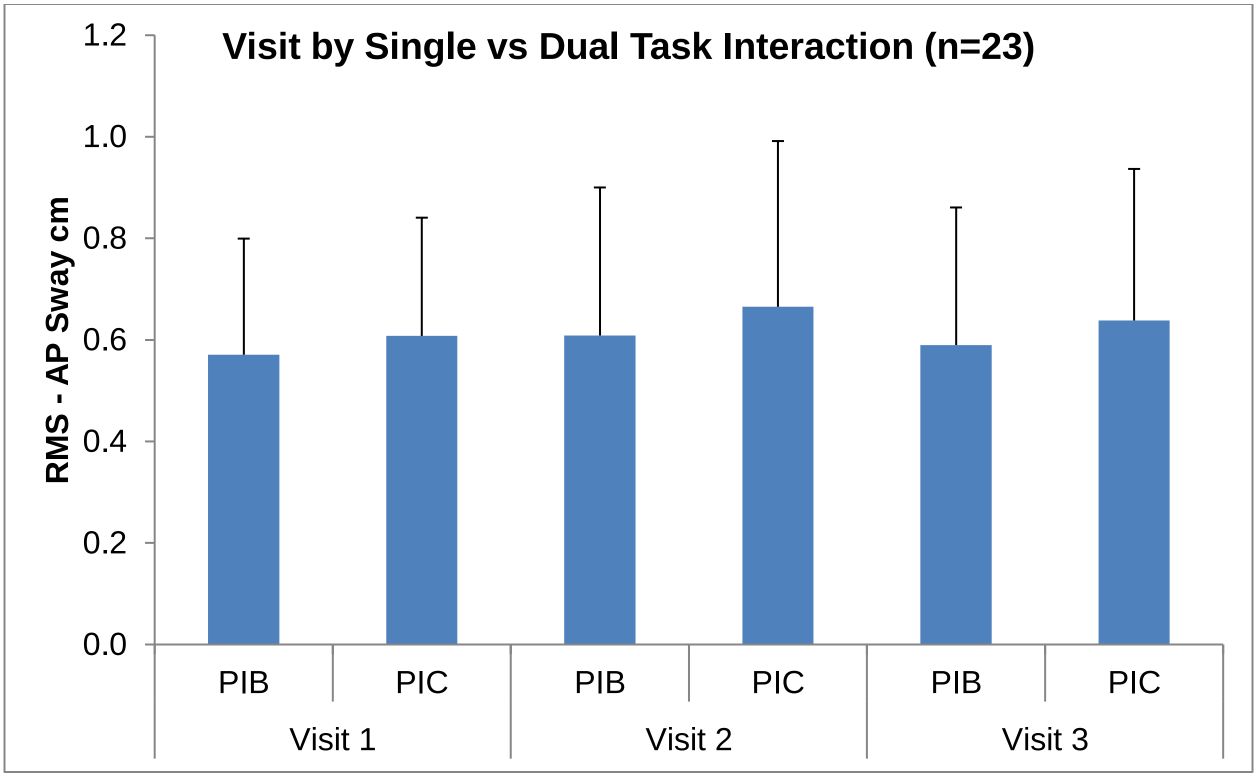

Visit by Surface Interaction (n=23)
NPL - ML Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Firm
Foam
Firm
Foam
Firm
Foam
Visit 1
Visit 2
Visit 3

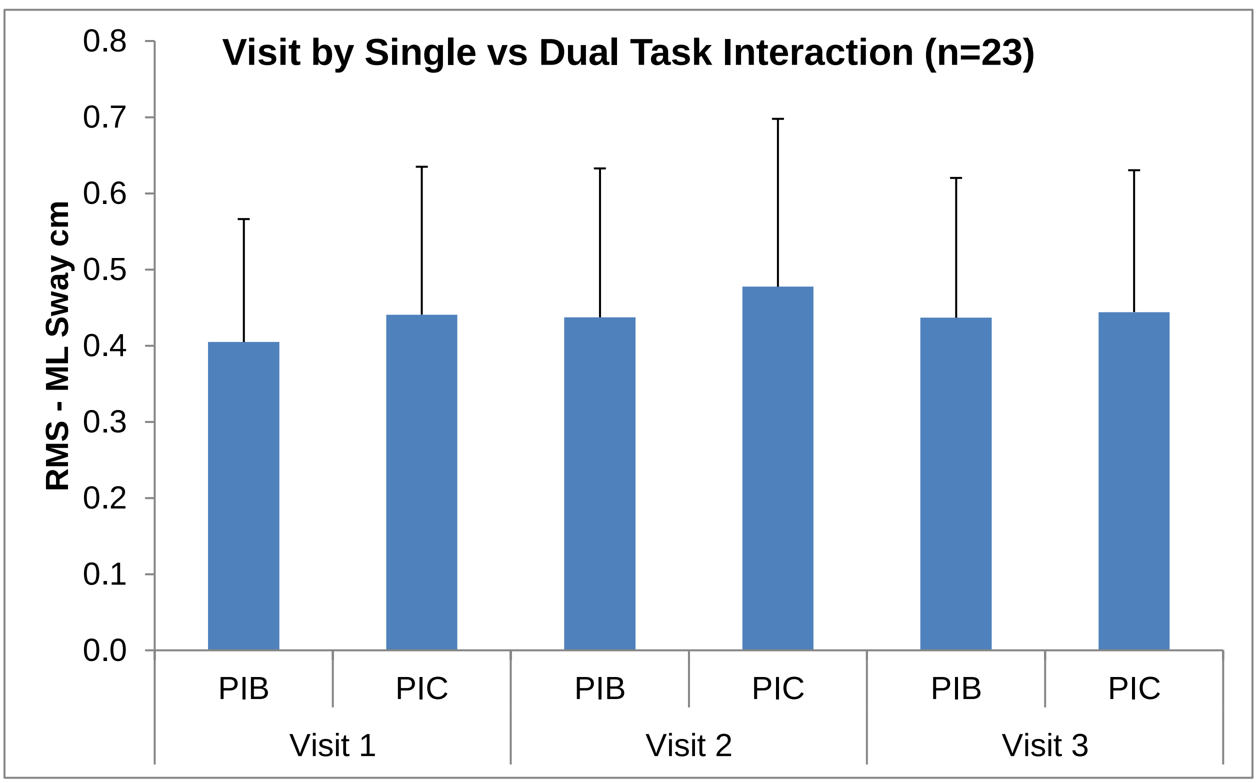

Visit by Surface Interaction (n=23)
RMS - AP Sway cm
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Firm
Foam
Firm
Foam
Firm
Foam
Visit 1
Visit 2
Visit 3

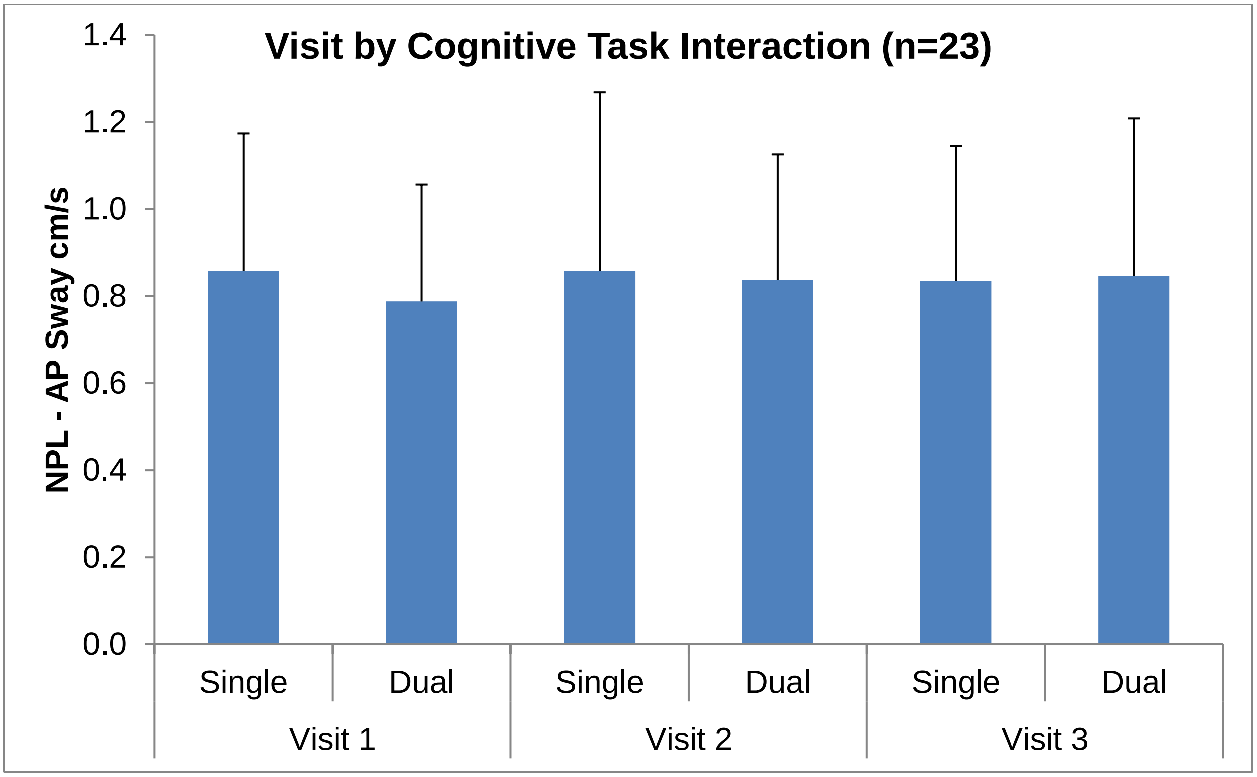

Visit by Surface Interaction (n=23)
RMS - ML Sway cm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Firm
Foam
Firm
Foam
Firm
Foam
Visit 1
Visit 2
Visit 3

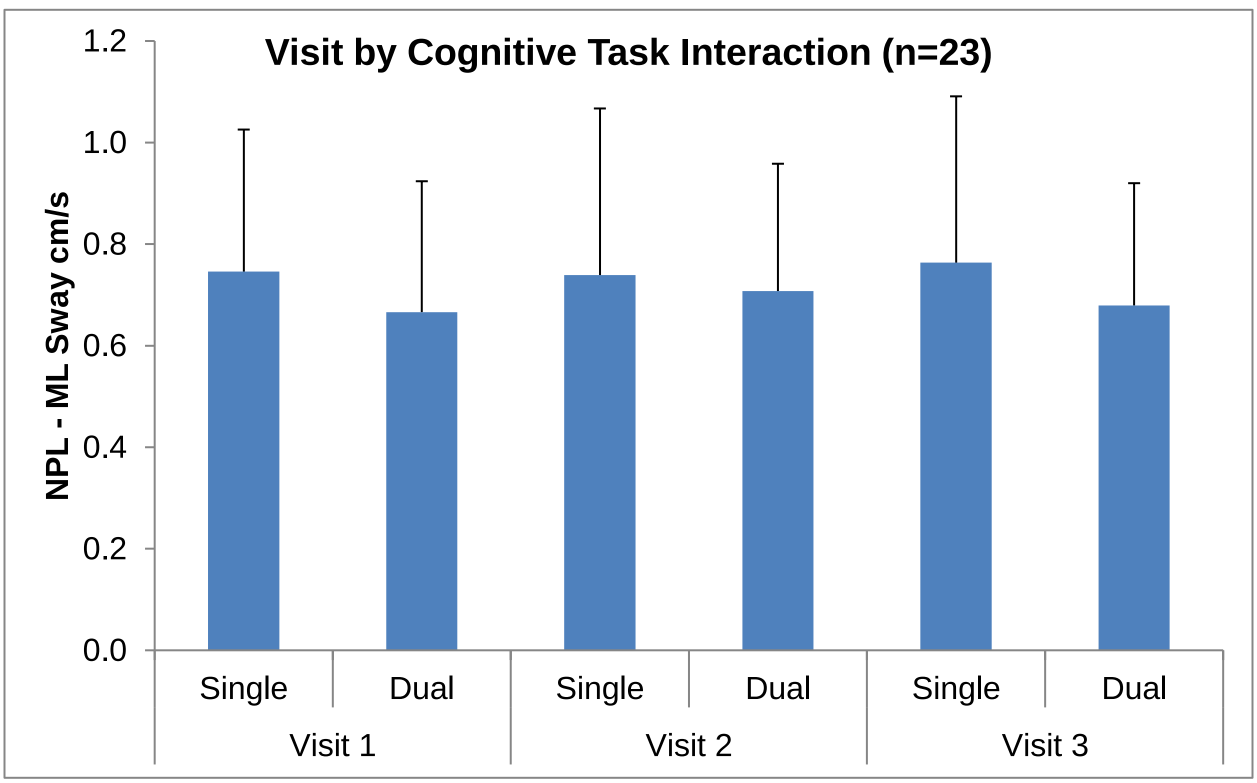

Visit by Single vs Dual Task Interaction (n=23)
NPL - AP Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
PIB
PIC
PIB
PIC
PIB
PIC
Visit 1
Visit 2
Visit 3

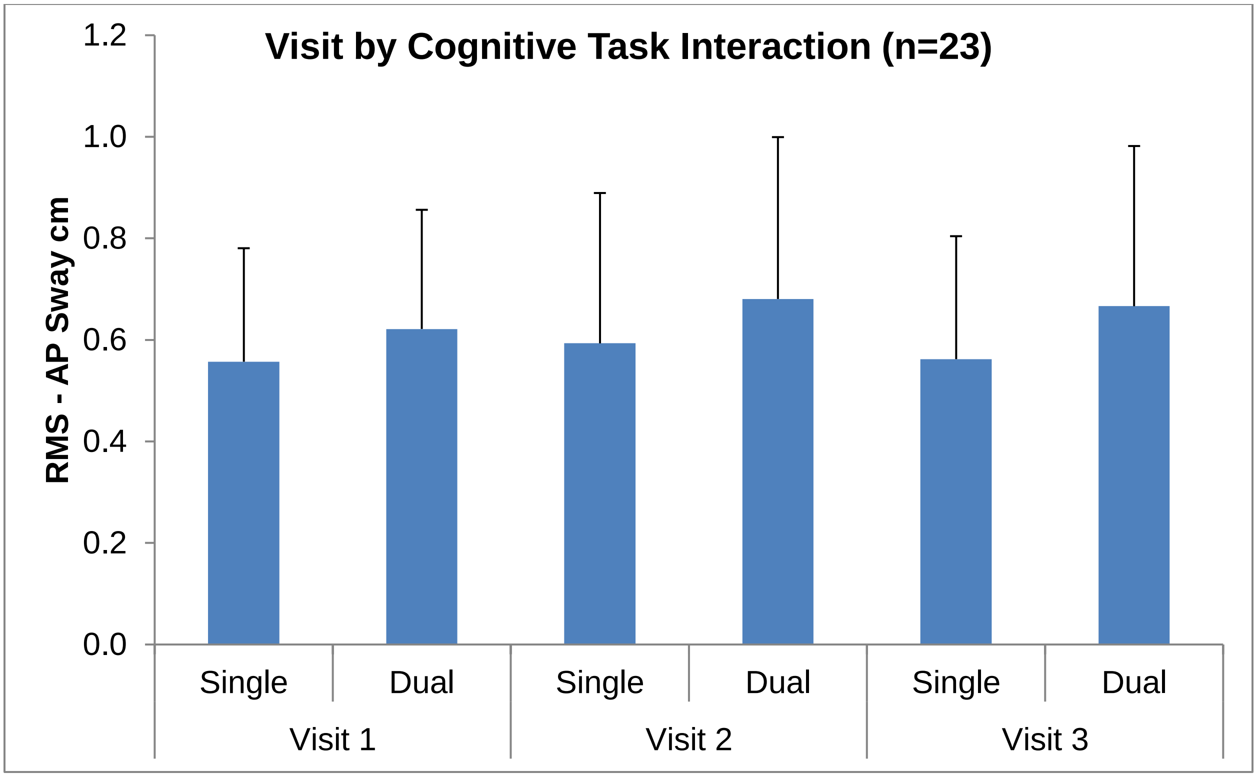

Visit by Single vs Dual Task Interaction (n=23)
NPL - ML Sway cm/s
1.2
1.0
0.8
0.6
0.4
0.2
0.0
PIB
PIC
PIB
PIC
PIB
PIC
Visit 1
Visit 2
Visit 3

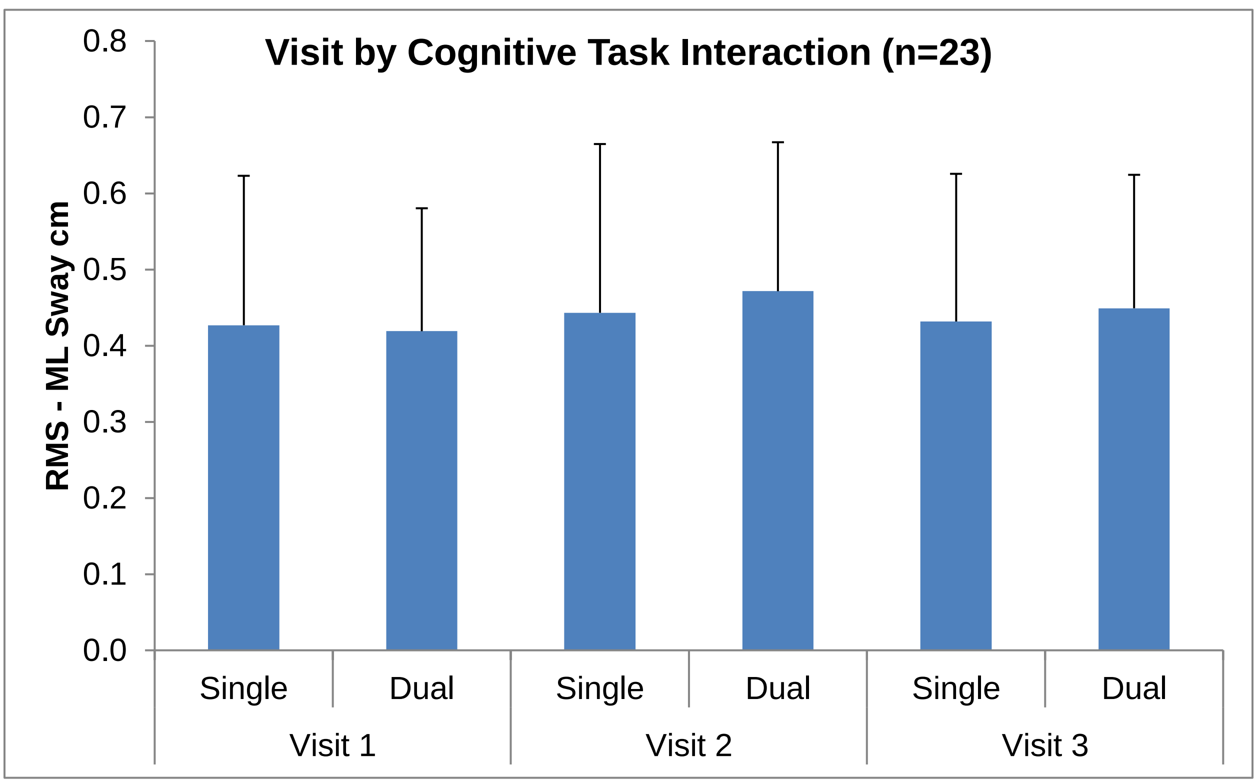

Visit by Single vs Dual Task Interaction (n=23)
RMS - AP Sway cm
1.2
1.0
0.8
0.6
0.4
0.2
0.0
PIB
PIC
PIB
PIC
PIB
PIC
Visit 1
Visit 2
Visit 3


Visit by Single vs Dual Task Interaction (n=23)
RMS - ML Sway cm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
PIB
PIC
PIB
PIC
PIB
PIC
Visit 1
Visit 2
Visit 3


Visit by Cognitive Task Interaction (n=23)
NPL - AP Sway cm/s
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Single
Dual
Single
Dual
Single
Dual
Visit 1
Visit 2
Visit 3


Visit by Cognitive Task Interaction (n=23)
NPL - ML Sway cm/s
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Single
Dual
Single
Dual
Single
Dual
Visit 1
Visit 2
Visit 3


Visit by Cognitive Task Interaction (n=23)
RMS - AP Sway cm
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Single
Dual
Single
Dual
Single
Dual
Visit 1
Visit 2
Visit 3


Visit by Cognitive Task Interaction (n=23)
RMS - ML Sway cm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Single
Dual
Single
Dual
Single
Dual
Visit 1
Visit 2
Visit 3

APPENDIX T

MEAN AND (SD) OF SWAY

Mean and (SD) of sway n=25				Spatial discrimination								Perceptual inhibition							
				Firm surface				Foam surface				Firm surface				Foam surface			
				Single		Dual		Single		Dual		Single		Dual		Single		Dual	
				M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
COP	Initial visit	NPL	AP	0.6	0.2	0.6	0.2	1.0	0.3	1.0	0.2	0.7	0.2	0.6	0.2	1.0	0.3	1.0	0.2
			ML	0.6	0.3	0.5	0.2	0.9	0.3	0.8	0.3	0.6	0.3	0.5	0.2	0.8	0.2	0.8	0.2
		RMS	AP	0.4	0.1	0.5	0.3	0.7	0.2	0.7	0.2	0.4	0.1	0.5	0.2	0.7	0.2	0.8	0.2
			ML	0.3	0.2	0.3	0.1	0.5	0.1	0.5	0.1	0.3	0.2	0.4	0.2	0.5	0.2	0.5	0.1
	Second visit	NPL	AP	0.6	0.2	0.7	0.2	1.1	0.4	1.0	0.2	0.7	0.2	0.6	0.2	1.1	0.5	1.0	0.2
			ML	0.5	0.2	0.6	0.2	0.9	0.3	0.8	0.2	0.6	0.2	0.6	0.2	0.9	0.3	0.8	0.2
		RMS	AP	0.4	0.1	0.5	0.3	0.7	0.3	0.8	0.2	0.5	0.2	0.5	0.3	0.7	0.3	0.9	0.3
			ML	0.3	0.1	0.4	0.1	0.6	0.2	0.5	0.1	0.4	0.2	0.4	0.2	0.5	0.2	0.6	0.2
	Clearance visit	NPL	AP	0.7	0.3	0.7	0.3	1.0	0.3	1.0	0.3	0.7	0.2	0.7	0.5	0.9	0.3	1.0	0.3
			ML	0.7	0.4	0.6	0.2	0.9	0.3	0.8	0.2	0.6	0.3	0.6	0.2	0.8	0.3	0.8	0.2
		RMS	AP	0.4	0.2	0.5	0.3	0.6	0.2	0.7	0.3	0.5	0.2	0.6	0.3	0.7	0.2	0.8	0.3
			ML	0.4	0.2	0.3	0.1	0.5	0.2	0.5	0.1	0.4	0.2	0.4	0.2	0.5	0.2	0.6	0.2
COM	Initial visit	NPL	AP	11.6	3.0	11.3	3.6	17.6	6.9	15.0	5.3	13.9	5.3	11.1	3.7	16.4	5.3	13.9	3.6
			ML	9.9	3.1	8.1	2.4	16.2	6.7	13.7	5.3	11.1	3.7	9.2	3.2	15.4	4.7	14.0	5.1
		RMS	AP	6.3	2.0	6.4	1.8	8.8	2.4	9.5	3.6	6.9	3.2	7.8	2.3	10.1	3.8	10.1	3.1
			ML	3.5	1.5	3.4	1.9	6.7	3.1	6.6	3.0	3.5	1.8	3.8	2.0	6.4	2.6	6.9	2.9
	Second visit	NPL	AP	12.0	3.4	12.4	4.7	18.7	6.3	15.6	4.5	13.0	4.6	12.1	3.9	18.2	8.1	15.9	4.1
			ML	9.9	2.8	10.0	3.7	17.7	7.2	14.0	4.5	10.5	3.6	9.9	3.6	16.8	7.1	15.2	5.1
		RMS	AP	7.5	3.6	7.4	3.3	9.9	4.1	10.3	3.5	7.5	2.8	8.6	3.6	11.1	4.9	10.9	3.6
			ML	3.5	1.2	4.0	1.7	7.4	3.5	6.5	2.7	4.0	1.7	4.9	3.6	6.7	3.1	7.7	3.0
	Clearance visit	NPL	AP	14.0	5.1	12.8	4.1	18.1	6.2	15.7	5.1	13.2	3.9	13.4	6.3	17.3	5.8	14.9	4.2
			ML	11.8	5.4	10.1	3.6	17.3	6.9	12.8	4.6	10.7	4.9	10.0	4.4	16.0	6.3	13.7	4.9
		RMS	AP	8.3	4.2	8.3	3.7	9.5	4.4	9.4	3.5	8.2	2.6	9.0	4.9	9.5	3.8	10.9	3.3
			ML	4.5	2.4	3.8	1.6	6.7	2.7	5.9	2.4	4.1	2.3	4.3	2.1	6.3	2.4	6.9	2.6

M: mean; NPL: normalized path length; RMS: root mean square; COM: center of mass in mG; COP: center of pressure in centimeters; AP: anterior-posterior direction; ML: medial-lateral direction; NPL-COP unit (cm/second); NPL-COM unit (mG/second); RMS-COP unit (cm); RMS-COM unit (mG).

APPENDIX U

NORMALITY TEST OF BALANCE ERROR SCORING SYSTEM (BESS)

Shapiro-Wilk test	**Visit 1 n=24**	**Visit 2 n=23**	**Visit 3 n=14**
Firm	0.891*	0.899*	0.870*
Foam pad	0.971	0.934	0.937
Total BESS	0.930	0.918	0.927

*: normality assumption violated $p < .05$; BESS: balance error scoring system.

APPENDIX V

NORMALITY TEST OF POST-CONCUSSION SYMPTOM SCALE (PCSS)

Shapiro-Wilk test	**Visit 1 N=25**	**Visit 2 N=23**	**Visit 3 N=14**
PCSS	0.931	0.704*	0.364*

*: normality assumption violated $p < .05$; PCSS: post-concussion symptom scale.

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