ABSTRACT

TALARICO, MARIA KATHERINE. Static and Dynamic Single Leg Postural Control Performance during Dual-Task Paradigms. (Under the direction of Dr. Jason Mihalik and Dr. Lianne Cartee).

This study examined the differences between static and dynamic single leg postural control performance during single-task and dual-task paradigms. Thirty healthy participants performed a series of single leg stance and single leg squat balance assessments on a force plate during single-task and dual-task paradigms. During dual-tasks, postural control assessments were completed concurrently with 1) a computerized, modified Stroop test and 2) Brooks Spatial Memory Test. Time normalized total center of pressure, anterior-posterior, and medial-lateral excursion, sway area, and anterior-posterior and medial-lateral range analyzed. For all outcome variables, greater values were recorded for the single leg squats assessment compared to the single leg stance assessment during single-task. Significant differences in trial time normalized total center of pressure excursion were found between the single-task paradigm and dual-task paradigms for both static and dynamic postural control assessments. Significant differences between dual-task with Brooks and dual-task with Stroop conditions were found for trial time normalized total and anterior-posterior center of pressure excursion during the static postural control assessment and time normalized medial-lateral center of pressure excursion during the dynamic postural control assessment. Dual-task assessments may be more challenging to the postural control system and should be used more clinically as they may be a better indicator of postural control performance during everyday activity.

Static and Dynamic Single Leg Postural Control Performance during Dual-Task Paradigms

by
Maria Katherine Talarico

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Biomedical Engineering

Raleigh, North Carolina

2015

APPROVED BY:

_____   _____
Jason P. Mihalik   Lianne A. Cartee
Co-Chair of Advisory Committee   Co-Chair of Advisory Committee

_____   _____
Paul S. Weinhold   Darin A. Padua

BIOGRAPHY

Maria Talarico was born on October 11, 1990 to Joe and Nancy Talarico. She has one younger sister. She attended The Ohio State University where she majored in Biomedical Engineering and minored in Exercise Science. She graduated in May 2013 with a B.S. in Biomedical Engineering. She was accepted into the joint graduate program in Biomedical Engineering at North Carolina State University and the University of North Carolina at Chapel Hill.

ACKNOWLEDGMENTS

To my family and friends, thank you for your endless support and love during this process without which nothing would be possible. To my committee members, thank you for your support and praise throughout this process. A special thank you to Rob Lynall and Tim Mauntel for all of your help and guidance with every step of the project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I - INTRODUCTION

1.1. Rationale

Single leg postural control testing plays a crucial role in the evaluation of athletic performance[1] and the assessment of sports-related injuries such as ankle sprains,[2-7] anterior cruciate ligament deficiency,[8-10] and concussions.[11-14] The current approach for balance screening requires athletes to perform a battery of single leg stance balance assessments exclusively.[5,15-19] This approach has been proven successful in identifying abnormal balance or balance deficiencies following injury.[2-14] But, it is possible these single-task, single leg stance balance assessments may not reflect postural control during everyday activity and therefore limited in analyzing performance of the postural control system. Therefore this study examined postural control of healthy individuals while performing static and dynamic balance assessments in single- and dual-task paradigms.

1.2. Introduction

Assessing postural control has been implemented in the sports medicine field to quantify a key aspect of neuromuscular control in athletes, identify athletes at higher risk for injury, improve prevention strategies, and track rehabilitation progress from injury.[20] Maintaining postural control during athletic activities requires a complex interaction of sensory input and motor output[21,22] which should be reflected in dual-task assessments through the use of dynamic balance and cognitive tests.

Although static balance impairment after injury has drawn most of the attention from the scientific community,[2-14,19,23-32] investigation of dynamic postural control deficiencies has only recently made its mark in the literature through the examination of gait stability.[21,33-47]

Dynamic balance is the ability to complete a balance assessment that requires performing some movement or task.[2] Dynamic balance may better represent athletic activity than static balance due to the constant demand for movement during competition.[48] Static balance requires an individual to respond to perturbations while maintaining stability whereas dynamic balance requires an individual to maintain balance while simultaneously executing a functional task; therefore, further research should examine the effects of dynamic balance following injury.

One such dynamic postural control assessment could include the single leg squat. The single leg squat is traditionally used to clinically test hip muscle function during dynamic activity, where those with good hip strength and activation tend to perform the single leg squat very well with minimal loss of balance.[49] The single leg squat assesses postural control of a functionally applicable movement used in dynamic activities.[50] Due to the high proprioceptive demand of the single leg squat on the body,[51] this dynamic assessment may prove effective in assessing postural and neuromuscular control and could help clinicians better and more accurately determine return-to-play status of athletes following injury.

Association between cognitive and motor function have been strengthened through examinations of dual-task performance where dynamic postural control is adversely affected when a secondary cognitive assessment is introduced.[21,39,41-44,52] A dual-task paradigm requires an individual to divide attention while performing two tasks simultaneously. It is suggested that dual-task paradigms should be implemented to concurrently test cognitive,

sensory, and motor systems of an athlete following injury in order to fully assess recovery.[22] Balance assessment under dual-task conditions should be further studied in order to better understand and detect underlying balance and cognitive deficits in dynamic situations.

A dynamic postural control assessment such as the single leg squat, which mimics athletic movement performed concurrently with a cognitive assessment may prove an effective dual-task paradigm for post-injury assessment of athletes. Therefore, preliminary analysis on healthy individuals should be examined to develop a better understanding of dynamic postural control. Thus the purpose of this study was to 1) examine differences between static and dynamic postural control during a single-task paradigm, 2) examine differences between single- and dual-task paradigms during static and dynamic postural control assessments, and 3) examine differences between two dual-task paradigms during static and dynamic postural control assessments.

1.3. Research Questions and Hypotheses

Research Question 1: What are the differences between static and dynamic postural control performance during a single-task paradigm for healthy participants?

> *Hypothesis 1: Participants will display better postural stability (slower total center of pressure, anterior-posterior, and medial-lateral speed, smaller sway area, and smaller anterior-posterior and medial-lateral range) while performing single leg stance compared to single leg squat during single-task.*

Research Question 2: What are the differences between single-task and two dual-task paradigms during static and dynamic postural control performance for healthy participants?

Hypothesis 2A: Participants will display better postural stability (slower total center of pressure, anterior-posterior, and medial-lateral speed, smaller sway area, and smaller anterior-posterior and medial-lateral range) while performing single leg stance during single-task compared to single leg stance during dual-task with the Stroop test and dual-task with the Brooks Spatial Memory Test.

Hypothesis 2B: Participants will display better postural stability (slower total center of pressure, anterior-posterior, and medial-lateral speed, smaller sway area, and smaller anterior-posterior and medial-lateral range) while performing single leg squats during single-task compared to single leg squats during dual-task with the Stroop test and dual-task with the Brooks Spatial Memory Test.

Research Question 3: What are the differences between two dual-task paradigms during static and dynamic postural control performance for healthy participants?

Hypothesis 3: Participants will display better postural stability (slower total center of pressure, anterior-posterior, and medial-lateral speed, smaller sway area, and smaller anterior-posterior and medial-lateral range) while performing both single leg stance and single leg squats during dual-task with the Stroop test compared to dual-task with the Brooks Spatial Memory Test.

1.4. Clinical Significance

Postural control variation between static and dynamic single leg balance assessments in single- and dual-task conditions for healthy participants may provide a more comprehensive foundation to build a better dual-task paradigm platform for postural control assessments in clinical and athletic settings.   Postural control performance evaluation could

evolve from static to dynamic balance assessments, more closely mimicking everyday activity and athletic environment. Also, if there is a difference in postural control between healthy individuals under a single- and dual-task paradigm, a more comprehensive approach to postural control and neurocognitive assessment may be utilized in order to better evaluate multi-system functions. Results from healthy participants can provide information and comparative values for testing and evaluating individuals post-injury.

CHAPTER II – REVIEW OF THE LITERATURE

2.1. Introduction

The need for both static and dynamic postural control is readily apparent in the sport setting due to the constant requirement of athletes to maintain balance during competitive activity for optimal performance.[48] Assessing postural control has been implemented in the sports medicine field to quantify a key aspect of neuromuscular control in athletes, identify athletes at higher risk for injury, improve prevention strategies, and track rehabilitation progress from injury.[20] Although several static assessments have been implemented to evaluate postural control, it is questionable if they effectively assess and challenge the postural control limits of healthy individuals and athletes. Implementing dynamic balance assessments in a dual-task paradigm with a cognitive assessment may better reflect the everyday environment of healthy individuals and competitive environment in which athletes perform to better assess postural control performance.

2.2. Postural Control System and Assessments

Postural control, often identified as balance, is the attempt to counteract unstable equilibrium[53] or the ability of the body to maintain the center of gravity within the limits of stability as determined by the base of support[54] or the dynamics of body posture to prevent falling.[55] Postural control is an essential component to assess the effectiveness of interventions for improving balance.[56]

The postural control system is a complex process involving the coordination of multiple sensory, motor, and biomechanical components.[57] Information obtained from the vestibular, somatosensory, and visual sensors relays commands to the extremity muscles,

which then generates an appropriate contraction to maintain postural control.[58-65] All three sensory systems are vital in maintaining postural control through the integration of information, but information may not be easily integrated following an injury, especially a sports-related concussion, which could affect postural stability.

The visual system is the primary sensory system used in maintaining postural control.[66-68] Visual stimulation of the peripheral visual field decreases postural sway in the direction of the observed visual stimulus to the anterior-posterior direction rather than the medial-lateral direction.[69] Individuals use peripheral vision for visual stabilization of spontaneous or visually induced body sway to control posture.[70] Reliance on vision is dominant among populations younger than 40 years old.[71]

Information from the vestibular system is used in a multitude of ways in order to maintain postural control. Vestibular information helps control eye muscles so that when the head changes position, the eyes can stay fixed to one point.[58] This information is also used to maintain upright posture through the semicircular canal system and the otoliths, which indicate rotational and linear movements, respectively.[58] The vestibular system is primarily involved in stabilizing slow body sway.[63,72-74] The automatic control mechanism, provided by vestibular information, stabilizes the direction of gaze and controls equilibrium when sudden perturbations are induced and sudden body movement or change in head position occurs causing postural instability.[58]

The somatosensory system functions via tactile senses (the mechanoreceptive senses of touch, pressure, and vibration) and the sense of position (proprioception), which

determines the relative positions and rates of movement of parts of the body.[75,76] Muscle

spindles and Golgi tendon sensory receptors provide the nervous system with continuous

feedback about the status of each muscle.[58] Mechanoreceptors send information to the spinal

cord regarding changes in the muscle's length and velocity of contraction, which is then

transferred to motor neurons that carry information back to the muscle fibers and muscle

spindle to contract the muscle to prevent or control postural sway.[74] Information about the

muscle's change in length and velocity of contraction contributes to an individual's ability to

recognize joint movement and sense position of limbs.[77]

2.2.1. Static Postural Control Assessments

Static postural control is the attempt to maintain a position with minimal movement[78]

or balance on a surface without intentionally moving.[2] Static postural control assessments

often used to identify postural control instability following injury are the Sensory

Organization Test (SOT) on the NeuroCom International Smart Balance Master System

(NeuroCom International, Inc., Clackamas, OR), the Balance Error Scoring System

(BESS),[79] and the Clinical Test of Sensory Interaction and Balance (CTSIB).[64,80]

Many studies have used the Sensory Organization Test to assess postural control

following sports-related injuries, more commonly concussions.[12,28,31,81-85] The SOT is a

technical force plate system designed to disrupt the sensory selection process by altering

available information to the somatosensory or visual system while simultaneously measuring

static postural control performance. Three 20-second trials are completed under six testing

conditions which include three visual conditions (eyes open, eyes closed, and sway

referenced) and two surface conditions (fixed and sway referenced). Postural sway and center of pressure date are used to quantify an equilibrium score, which can be objectively used to determine postural control performance. An equilibrium score is calculated by comparing the angular difference between maximum anterior-posterior center of gravity displacement and the theoretical maximum displacement of 12.5 degrees, which is the anterior-posterior sway an average adult can perform without loss of balance. A score of 100% indicates no motion and a score of 0% indicates a fall. The composite score is the equilibrium mean score for all trials across the six conditions.

Along with the composite score, sensory analysis ratios are also calculated. The somatosensory, visual, and vestibular ratios determine the ability of an individual to use the respective system's information to maintain postural control. Sensory ratios close to a value of one reflect greater ability of an individual to rely on that particular sensory system to maintain postural control under conditions in which the vestibular (condition five), visual (condition four), and somatosensory (condition two) systems are required to compensate for altered signals from other systems.[86]

The six sensory conditions are used to test how individuals adapt sensory systems to changing conditions while maintaining postural control. During the first condition, vision, vestibular, and somatosensory signals are all used to maintain postural control (normal vision, fixed support). Conditions two and five remove visual signals and allow individuals to only utilize vestibular and somatosensory signals. Condition two and five have absent vision parameters and fixed support and sway-referenced support, respectively. Conditions

three and six have sway-reference vision parameters and fixed support and sway-reference

support respectively. If an individual is overly reliant on vision to maintain postural control,

then conditions three and six may prove the most challenging because the visual input for

both conditions is sway-referenced. Individuals with vestibular system deficits show

problems in maintaining balance during conditions five and six where visual and

somatosensory inputs are altered and reliance on vestibular information in required.

Individuals can use visual or somatosensory information to compensate for vestibular

feedback deficiency in order to maintain postural control.[87] Those who rely on the

somatosensory system the most to maintain postural control may have the most trouble with

conditions four, five, and six because the base of support is sway-referenced. Condition four

contains parameters of normal vision and sway-reference support.

A clinical balance test also used to evaluate postural control before and after injury is

the BESS,[79] which consists of three stance positions, double-leg stance, single-leg stance, and

tandem stance, performed on two surfaces, a firm and a foam surface. Errors are recorded by

the clinician during a 20-second trial for each of the six conditions. A few of the errors

include lifting hands off hips, stepping, falling out of position, or lifting heel. Described as a

rapid, easy-to-administer, and inexpensive clinical postural control test, the BESS has been

widely accepted by clinicians as a reliable postural control assessment tool due to its high

validity in identifying postural control deficits in concussed populations.[28,31,88-90]

Developed as a clinical version of the SOT to assess sensory contributions to postural

control, the CTSIB attempts to measure how interaction with the vision, vestibular, and

somatosensory systems allows individuals to maintain postural control.[64,80] Six 30-second

trials are completed under three visual conditions (eyes open, eyes closed, visual conflict

dome) and two support-surface conditions (firm and foam). The time that an individual is

able to maintain the starting position for each trial is recorded to quantify postural control

stability and identify any reliance on one or more of the three senses for postural control.

2.2.2. Dynamic Postural Control Assessments

Contrary to static postural control, dynamic postural control is the ability to maintain

a stable base of support while completing a prescribed movement[91] or complete a postural

control assessment that requires performing some movement or task.[2] The fundamental

goals of static and dynamic postural control are one and the same: to maintain balance. The

difference between static and dynamic postural control remains in how this goal is

accomplished. Static postural control aims to maintain postural control during quiet standing

or in response to a sensory perturbation whereas dynamic postural control aims to maintain

postural control while performing a functional movement.

Dynamic postural control assessments are used in the athletic setting in an attempt to

quantify functional postural control performance through the Star Excursion Balance Test

(SEBT), the Lower Quarter Y-Balance Test (YBT), and gait stability.[21,33-44,92-98] The SEBT

and YBT have helped identify lower extremity musculoskeletal injury risk and balance

deficits of athletes by measuring single leg stance postural control while executing multi-

directional reaches with the non-stance leg[17,92,99-102] while gait analysis has helped identify

more conservative gait strategies[34,35,39,40,103-105] and postural control deficits of individuals following concussion.[21,34,103,104]

The YBT assesses dynamic postural control performance of single leg stance while simultaneously reaching the non-stance limb in three of the six directions used in the SEBT: anterior, posteromedial, and posterolateral.[17,93,94] Due to redundancy found in the SEBT, the YBT was developed to improve reliability and standardize performance of a modified SEBT.[94] Deficits in single leg stance excursions, or YBT reach distances, have been found in those with a history of lower extremity injury, including ankle sprains, chronic ankle instability, and anterior knee pain.[106-109] A recent study found that athletes with an anterior asymmetry (absolute difference between legs in anterior reach performance) greater or equal to four centimeters have significantly greater odds of injury compared with those with less than four centimeters anterior asymmetry, suggesting that an imbalance with anterior reach during single leg stance identifies elevated risk for injury of athletes across multiple sports may be a useful measurement to identify risk of future injury.[110]

It is becoming more evident that maintenance of postural control during locomotion or sport activities requires a complex interaction of sensory input and motor output[21,22] which should be reflected in post-injury dynamic postural control assessments.

2.3. Single Leg Squats

Athletes are required throughout physical activity to rely on a single leg base of support, therefore, the use of single leg tests to measure dynamic postural stability in a clinical or research settings is both logical and warranted.[111] Since single leg tests have already been implemented in clinical and research settings to assess performance following

lower extremity injury, similar unilateral leg assessments should be considered for examining dynamic balance following injury. The use of a biomechanically comparable movement to the anterior reach of the YBT, such as the single leg squat, may prove equally challenging to an athlete's dynamic postural control and thus an effective measurement of dynamic postural control performance following injury.

The single leg squat is traditionally used to clinically assess dynamic postural control[50,112] and test hip muscle function during dynamic activity, where those with good hip strength and activation tend to perform the single leg squat very well with minimal decrease of postural control.[49] Clinicians apply the single leg squat as a tool to help identify faulty lower extremity biomechanics,[113] which ultimately could increase musculoskeletal injury risk. Similar to the single leg stance, which is applied in static postural control assessment, the single leg squat challenges postural control ability due to a reduced base of stability.[50] But, unlike static single leg stance, the single leg squat assesses postural control of a functionally applicable movement used in dynamic activities.[50] Individuals with hip chondropathy demonstrate reduced postural control performance compared to healthy controls while completing the single leg squat as measured by greater coronal plane sway.[114] This indicates the effective, clinical use of the single leg squat in evaluating dynamic postural control of injured individuals.

Assessments that are more complex and require more processing, such as the single leg squat, have been demonstrated to result in greater interference with postural control than simpler assessments, like the single leg stance.[115,116] Even though clinical dynamic postural

control assessments, such as the single leg squat, have not been traditionally introduced in assessing balance performance of concussed individuals, many clinicians practice and are familiar with using the single leg squat as a lower extremity injury tool. Therefore, single leg squat could be readily transitioned into effect as a dynamic postural control post-injury assessment tool and assist with return-to-play evaluation.

2.4. Dual-Task Paradigm

Single-task paradigms effectively measure either cognitive function or postural control, but these paradigms may be limited as they only evaluate domains in isolation and not the interaction of these domains across concurrent assessments.[117] Therefore, a dual-task paradigm may be more suitable in assessing cognitive and postural control deficits since performance in sport requires simultaneous processing of information across multiple cognitive domains.[22] Furthermore, it has been shown that sports-related head injuries reduce attentional resources and consequentially affects the ability to perform simultaneous assessments and results in decreased ability to successfully perform in dual-task paradigms.[32] A dual-task paradigm requires a person to perform two different assessments concurrently and is thought to address cognitive, postural control, and or visual deficits following sports injuries.[118-121] Executing multiple assessments simultaneously in dual-task can be accomplished if there is adequate processing capacity, but if capacity is exceeded by the undertaking of concurrent assessments, performance in one or all assessments is compromised.[32,39-41,117,120,122,123] Assessments that are more complex and require more processing have been demonstrated to result in greater postural instability than simpler

assessments, thus as dual-task demands increase in difficulty postural control performance suffers and simultaneously decreases.[115,116,124]

Dual-task paradigms using dynamic postural control in conjunction with a cognitive assessment have been proposed as a method for assessing deficits following injury rather than the traditional use of single-task paradigms.[39,40,125] Dynamic postural control methods currently used in post-concussion dual-task paradigms include gait stability with neurocognitive tests.[21,33-44] Because performance in sport requires simultaneous processing of cognitive, sensory, and motor information,[22] it is suggested that dual-task paradigms provide a better representation of sport, where cognitive function and postural control must be simultaneously processed and attention must be divided, compared to single-task paradigms.[21,22,42,44,117,126]

2.4.1. Dual-Task Deficits of Healthy Individuals

Under static dual-task conditions, studies have reported contradictory results with some individuals exhibiting increased coronal plane sway[30] while others exhibit decreased coronal plane sway.[59] These discrepancies may be due to different postural control methodologies where the former uses a modified SOT and the latter uses a tandem stance similar to that used in the BESS. Healthy individuals also have slower sway velocity in dual-task than in single-task.[30]

In dynamic dual-task conditions, healthy individuals demonstrate greater whole-body sway[36] and slower whole-body sway velocity during gait.[30] Non-injured individuals adopt strategies to better maintain stable postural control during gait in dual-task when compared to

single-task, such as shorter stride length,[21,34] longer stride time,[21,34,40] and slower gait speed.[21,34,39,40,44]

Along with spatial-temporal gait deficiencies, healthy individuals also experience dynamic instability under dual-task settings. Decreased sagittal plane sway[21,34,39,40] is consistently reported for healthy individuals in dynamic dual-task, but some inconsistencies exist in the results regarding sagittal and coronal plane sway velocities. Some studies report that in dual-task, non-injured individuals display slower sagittal plane sway velocity[21,34,39] while one study reports them to demonstrate faster sagittal plane sway velocity compared to single-task.[41] In similar form, a few studies report healthy individuals having faster coronal plane sway velocity[34,44] whereas one study reports contradictory findings in that healthy individuals display slower coronal plane sway velocity.[21] Differences in these results are likely due to inconsistent methodology carried out between the studies. In regards to neurocognitive performance, non-injured individuals have slower reaction times under dual-task conditions compared to single-task conditions.[22,117]

2.5. Deficits and Assessments Following Concussion

Concussion, often causing impairment in balance and cognitive performance, is a complex pathophysiological process affecting the brain and induced by traumatic biomechanical forces.[127] Sports-related concussion is a growing national concern for athletes of all ages in all sports. The Centers for Disease Control and Prevention estimates that there are approximately 1.6 to 3.8 million sports-related concussions each year in the United States.[128] Over a 10 year span, high school concussion incidence rates for multiple sports have more than quadrupled.[129] The NCAA Injury Surveillance System showed an average

annual concussion incidence rate increase of 7% over 16 years for all sports.[130] It was originally anticipated that this study examine changes in postural control of athletes following a sports-related concussion. Due to limited subject availability and time constraints, adjustments were made and the study currently is examining the effects of dynamic postural control assessments in dual-task paradigms in healthy, active participants. Initial findings from this study are anticipated to encourage future studies to examine dynamic postural control assessments for both healthy and post-injury athletes to improve return-to-play conclusions.

Sports-related concussion is commonly assessed using a battery of tests that evaluate neurocognitive function, postural control, and self-reported symptoms.[90] Each assessment measure adds additional information on the status of concussed athletes by independently evaluating differing aspects of cerebral function.[90] Evaluating information from each assessment may be used to help in the return-to-play decision by examining the progression of recovery from lingering symptoms, postural control deficiencies, and neurocognitive deficits.

2.5.1. Symptomology

The most commonly and consistently reported symptoms following a sports-related concussion include headaches, dizziness, mental clouding, difficulty concentrating, and confusion.[131-144] Other symptoms reported that may not be present immediately after concussion are sleep disturbance,[131] visual problems, fatigue, and nausea.[132,135,137,139] Symptomology is often assessed using rating scales and questionnaires that can be

administered quickly by a clinician following concussion. The Sideline Concussion Assessment Tool 3rd Edition (SCAT3),[145] the Post-Concussion Scale,[146] and the Concussion Symptom Inventory (CSI),[147] are just a few tools used to evaluate symptoms immediately post-concussion and throughout the recovery stage. The majority of symptoms experienced by athletes recede over 7 to 10 days following concussion.[18,21-25] It has been reported, though, that some athletes may have a brief period of symptoms immediately after concussion followed by a short disappearance, only to have the symptoms return anywhere from several hours to a few days later.[127,148,149]

2.5.2. Neurocognition

Athletes may also experience neurocognitive impairment following concussion which could include deficiencies in attention, memory, concentration, and information processing.[25,150-160] Neurocognitive assessments evaluate brain function by quantifying multiple cognitive domains such as memory, attention, information processing, planning, and reaction time[90] which can help identify underlying deficiencies following concussion.[23-30,32] It has been suggested that neurocognitive evaluations provide the greatest amount of information post-concussion and thus are often used by clinicians as the primary source of information in determining return-to-play status.[161-163] While the use of neurocognitive evaluation has recently been advocated as the "cornerstone" of proper concussion management,[164] it should be noted that all domains that may be impacted by brain injury are not assessed by this method. Neurocognitive performance is often assessed using the Standard Assessment of Concussion (SAC),[159] the Automated Neuropsychological

Assessment Metrics (ANAM, (US Army Medical Research and Material Command; Fort

Detrick, MD),[165] or the Immediate Postconcussion and Cognitive Test (ImPACT, ImPACT

Applications, Pittsburgh, PA) following concussion.

Concussed athletes score poorly on neurocognitive tests when compared with their

own pre-concussion baseline scores, normative data, and with uninjured matched control

athletes.[151,155,157,166-169] Some variation is evident in reports as to when neurocognitive

deficits subside following concussion, but the majority of those injured return to normal

cognitive performance within 7 to 10 days.[89,170-172] High school athletes have been found to

demonstrate significant memory impairment one to two weeks[171,173] and reaction time

impairments up to two to three weeks following concussion.[171,174] For college athletes,

neurocognitive impairment in auditory attention and visuomotor processing speed is found to

be resolved within five days of concussion.[157]

2.5.3. Static Postural Control Post-Concussion

Areas of the brain disrupted as a result of concussion have been reported to be

responsible for the maintenance of postural stability[19,31,82,175-184] thus postural control

impairment is often seen post-concussion.[19,21,31,34,82,103,104,175-190] Overall postural stability

deficit can best be explained by a sensory interaction problem that prevents concussed

athletes from accurately using the exchanging sensory information from the visual,

vestibular, and somatosensory systems.[28] Concussion adversely affects both static and

dynamic postural control. Following concussion, postural sway measures are significantly

increased compared to pre-concussion measures, indicating postural control deficiencies as a result of brain injury.[19,28,31]

Following concussion, individuals demonstrate decreased postural stability, indicated by the SOT composite score, on day one post-concussion in comparison with their baseline performance as well as in relation to healthy individuals' postural stability day three post-concussion.[28,31] It has also been reported that the composite SOT score is significantly less for up to 10 days following a concussion compared to that of healthy individuals.[84] After further evaluation, researchers determine that the vestibular system is the most disrupted following concussion with deficits lasting three to five days post-concussion.[28,84]

Injured individuals have been found to have decreased postural stability on day one post-concussion in comparison with baseline and day three post-concussion scores as well as the healthy individuals' post-concussion day one, three, and five BESS scores.[28] Concussed individuals also have higher BESS error scores in comparison with healthy individuals on day one post-concussion on firm surface and on days one and three post-concussion on foam surface.[31]

Concussed athletes have been found to have decreased postural stability compared with their own baseline scores and to their matched control following CTSIB assessment within three days post-concussion.[19] The degree of postural control impairment in concussed athletes is found to increase with increasing task demands, such as altering sensory feedback during CTSIB testing.[19]

Similar to symptoms and neurocognitive function, overall postural stability usually recovers within 7 to 10 days following concussion,[89,170-172] but may reports indicate that, specifically, postural sway returns to baseline around three days post-concussion.[19,28,31,79] As measured by the SOT, concussed athletes return to normal postural control within three to five days following concussion.[28,31,82-84] Participants with a mild traumatic brain injury demonstrate impaired postural stability during quiet standing or during standing with altered sensory inputs for one to three days following concussion.[19]

2.5.4. Dynamic Postural Control Post-Concussion

Many studies that have examined postural control deficiencies post-concussion have exclusively assessed static postural control, which has drawn most of the attention from the scientific community.[19,23-32] The investigation of dynamic postural control deficiencies has only recently made its mark in sports-related concussion literature through the examination of gait stability.[21,33-44] The general consensus among these researchers is that following concussion, individuals display increased caution during gait as demonstrated by slower gait speed[34,35,39,40,103,104] and shorter stride length.[34,103-105] Previously concussed individuals also adopted more conservative gait strategies by reducing the time spent in less stable positions, such as single-leg stance.[35] Postural sway during gait is also affected by concussion. Following concussion, athletes exhibit greater whole-body sway and sway velocity.[21,34,103,104] When broken down, athletes also demonstrate greater sway[40,41] and sway velocity[40,44] in the medial-lateral direction as well as smaller sway[41,103,104] and sway velocity[39-41,103,104] in the anterior-posterior direction during gait following concussion. It has been suggested that

individuals with concussion may maintain postural control throughout gait progression by reducing center of mass forward momentum, as indicated through smaller sagittal plane movement, in order to compensate for increased coronal plane movement.[21,34,36,39,40,125,191,192]

Through the use of gait, some studies have found that dynamic postural instability is maintained for up to 28 days following concussion,[21,34] which is more than two weeks longer than static postural control and neurocognitive deficits persist. Previous research on concussed athletes has shown though that complex motor functions require a longer recovery period than cognitive assessments,[21,34,193] which may explain the prolonged gait stability deficits compared to neurocognitive deficits Other studies have found that gait parameters return to that of healthy normal controls within the first six to seven days following concussion.[21,33,34,36,39-41,125,194,195] One longitudinal study found that individuals reporting a history of concussion over six years prior to participation continued to show significant differences in gait patterns compared to healthy controls.[35]

With the recent introduction of gait postural control studies there is expected to be some discrepancies in findings, but this should be addressed with further research. Despite the overwhelming evidence for dynamic postural control deficits following concussion taking longer to recover than traditional static postural control measures, currently there are no standard methods to assess dynamic postural control deficits, hence future studies should further examine dynamic postural control assessments.

2.5.5. Dual-Task Paradigm Testing Post-Concussion

Similar to healthy individuals, those with concussion show similar gait, dynamic postural control, and neurocognitive performance deficits in dual-task conditions. It is widely reported that concussion adversely affects dual-task performance as demonstrated by instability and decreased motor function.[39,40,44,196-202] Immediately following concussion, individuals display a more distinct inability to appropriately control posture during dual-task revealed through greater sway and sway velocity compared to healthy individuals.[21,33,34,36,39-42,125,195] In general, following concussion, individuals walk slower in dual-task than in single-task[21,34,36,39,40,44] when compared with healthy individuals.[34,39,40] One potential reason for this slower gait speed exhibited by concussed individuals during dual-task conditions is that concussed individuals demonstrate shorter stride length compared to healthy individuals[34] and compared to single-task performance.[21,34] Concussed individuals also exhibit shorter stride length in dual-task when compared to that of healthy individuals.[21,34,40] A gait conservation method adopted by concussed individuals in dual-task is spending more time in double-support stance and shorter time in single-leg stance throughout the progression of gait.[35]

In conjunction with spatial-temporal gait deficits, individuals also exhibit reduced dynamic postural control following concussion. Compared to non-injured individuals and in single-task paradigm, concussed individuals perform gait assessments with greater whole-body sway.[34,36,39] Similar to findings with a healthy population, concussed individuals walk in dual-task with greater coronal plane sway[21,40,44] and sway velocity[34,36,44] as well as less

sagittal plane sway[21,34,39,40,125] and sway velocity.[21,34,39,44,125] Concussed individuals also have slower reaction times during gait in dual-task conditions where a more cautious gait strategy is utilized.[21,34,39-41] There is some inconsistency in the reporting of how long dual-task deficits linger, but many studies report the deficits last up to one month following concussion.[33,34,36,41,125,194] Some studies even report that individuals about six years post-concussion still are found to have divided attention deficits.[35,42,203] Initial findings of dual-task effects persisting almost three times as long as single-task effects suggests the necessity of implementing dual-task paradigms in post-concussion assessment to better determine return-to-play status.

2.6. Rationale for Study

Assessing cognitive and motor performance following injury is critical in determining responsible return-to-play status. Static postural control assessments in single-task paradigms are readily employed and have proven effective in the athletic setting as post-injury evaluations, but dynamic postural control dual-task paradigms assessments may better represent athletic activity due to the constant demand for movement and integration of multiple sensory systems during competition. Studies examining the use of a secondary task during dynamic postural control for an injured population is limited in scope, pertaining largely only to gait. Prevalent athletic movements, such as the single leg squat, could be used to evaluate dynamic postural control in healthy and injured individuals. Assessments such as the single leg squat, already used by many clinicians in the evaluation of recovery from lower extremity injury, may be more feasible for clinicians to apply as a part of a thorough return-to-play assessment.

Exploring the effects of dynamic balance assessments in dual-task paradigms is critical in the athletic post-injury population, but preliminary examination should be completed with an active, healthy population. Comprehensive information obtained from healthy participants could be used to create a platform for further pre- and post-injury testing in the athletic setting.

If changes in postural control can be identified between a dynamic balance test, single leg squat, and a static balance test, single leg stance, within a healthy population, then dynamic postural control could be used as a measure to better test return-to-play status of athletes and provide a better understanding of the effects of injury on dynamic postural control. Therefore the purpose of this study was to 1) examine differences between static and dynamic postural control during a single-task paradigm, 2) examine differences between single- and dual-task paradigms during static and dynamic postural control assessments, and 3) examine differences between two dual-task paradigms during static and dynamic postural control assessments.

CHAPTER III - METHODOLOGY

3.1. Participants

The cross-sectional study design included 30 healthy college students (female = 22, male = 8; age = 20.83±1.64 years, height = 157.88±13.04 cm, mass = 67.79±20.64 kg) who volunteered to participate in this study. All participants had 1) no previous history of a concussion within the past two years, 2) full medical clearance for physical activity, 3) no history of surgical procedure to the lower extremities or low back, 4) no injury to the lower extremities or low back within the past six months that resulted in an inability to participate in physical activity for three consecutive days, 5) no color blindness, and 6) no known vestibular or balance disorders. Participants signed an informed consent approved by the University of North Carolina's Institutional Review Board prior to participation in the study.

3.2. Instrumentation

3.2.1. Force Plate

For all trials, participants stood on a tri-axial force plate (Model #4060-NC Bertec Co., Columbus, OH) embedded in a raised wooden platform on level floor that measured translational forces and moments about three axes. Center of pressure values were calculated using custom Matlab (MathWorks, Inc., Natick, MA, USA) programs.

3.2.2. Electromagnetic Tracking Sensor

An electromagnetic motion tracking sensor (TrakStar, Ascension Technology Corp., Burlington, VT) was used for kinematic analysis during testing. Using double-sided tape, the 6-degrees-of-freedom sensor was placed on the sacral body of the participant. The world and sensor axis system were established and designed as the positive x-axis facing the same

direction as the participant, positive y-axis to the left of the participant, and positive z-axis superiorly to the participant. Sacral displacement in the z-axis was used to determine vertical displacement during testing.

3.3. Procedure

All participants reported for one testing session that lasted approximately 75 minutes. Before testing, participants were asked to complete a health history questionnaire. Following the questionnaire, height and mass were measured and recorded. Participants wore their own athletic shorts and a shirt and were barefoot throughout testing. Prior to testing, participants were instructed to warm-up on a stationary bike for five minutes at a self-selected pace followed by self-directed stretches.

Following warm-up, participants completed three trials each of two cognitive baseline assessments, the Brooks Spatial Memory Test that uses visuospatial working memory[204] and a modified computerized Stroop test. Baseline testing for both cognitive assessments were completed while in double-limb stance. The order of baseline testing between the two neurocognitive assessments was randomized for each participant. Following the baseline neurocognitive assessments, postural control assessments under six conditions were then completed. In order to minimize the effect of fatigue, a maximum of 30 seconds were given for all participants to rest between trials unless a participant verbally indicated they were ready to begin the next trial before the end of 30 seconds. The postural control conditions included: 1) single leg stance, 2) single leg squats, 3) single leg stance during dual-task with the Brooks Spatial Memory Test, 4) single leg squats during dual-task with the Brooks Spatial Memory Test, 5) single leg stance during dual-task with the Stroop test, and 6) single

leg squats during dual-task with the Stroop test. Table 1 describes the six test conditions completed by all participants. Each participant performed all six postural control conditions on both their dominant (the leg the participant would use to kick a soccer ball for maximum distance) and non-dominant limb. The order of testing for the 12 assessments (6 postural control conditions on both limbs) were randomized for each participant. Participants completed one trial for each of the 12 assessments and then repeated the same order of testing two more times for a total of three trials for each of the 12 postural control assessments. Trials were discarded and repeated if the non-weight bearing foot touched the floor or force plate. The researcher manually marked each trial, within the computer software, to indicate the start and stop of a trial. For all assessments, participants were instructed to face forward throughout testing and reduce head and eye movement as best as possible. During performance of the Stroop test, participants were instructed to look at the computer screen throughout testing. These instructions were given in order to minimize the effect of voluntary head and eye movement which may affect postural control performance.

3.3.1. Cognitive Assessments

For the Brooks Spatial Memory test, participants were shown a card with unique locations of eight numbers, listed as 1-8 in numerical order and placed in a 4x4 grid. Figure 4 shows an example card. When the presentation of numbers was completed, lasting no more than one minute, the participant verbally recalled the position of each digit at a self-selected pace while standing on the testing limb. Total time to complete the Brooks test varied for each participant. A total of 30 unique cards were used throughout the study and no card was

repeated during any one participant's testing session. All participants were allowed one practice trial in order to familiarize themselves with the test before baseline assessments.

Participants completed a computerized, modified Stroop test utilizing CNS Vital Signs (CNS Vital Signs, LLC, Morrisville, NC). During the Stroop test, a series of color names (red, yellow, blue, and green) in color fonts (red, yellow, blue, and green) were displayed on the computer screen in a random order. If the color name and color font did not match, the participant was instructed to press the trigger. If the color name and color font matched, the participant was instructed to take no action. The laptop on which the Stroop test was performed was placed at eye level approximately one meter away directly in front of the participant. The Stroop test lasted for 20 seconds. Participants used a hand-held trigger to respond as quickly as possible to the computerized Stroop test. The hand-held trigger was held in the participant's dominant hand (defined as the hand the participant uses for writing) and held at the ipsilateral hip with the other hand placed on its respective hip. This position was identical to the hand positions during single-task postural control assessments. All participants were allowed one practice trial of the Stroop test in order to familiarize themselves with the test prior to baseline assessments.

3.3.2. Postural Control Assessments

For the single leg stance postural control assessment, participants were asked to stand on the limb to be tested with their toes facing forward (positive x axis) and centered on the force plate. Participants were instructed to maintain the non-stance limb in 20°-30° of hip flexion and 40°-50° of knee flexion with hands placed on the hips and head and eyes facing

forward. Participants were instructed to remain as motionless as possible with eyes open during testing. A trial was considered incomplete if the participant could not sustain the stance position for longer than 5 seconds. Participants were provided with a minimum of 1 practice trial on each limb lasting 7 seconds to familiarize themselves with the assessment.

During the single leg squat postural control assessment, participants were asked to stand on the limb to be tested on the force plate, toes facing forward, and heel on the ground. Participants were instructed to flex the non-stance leg to 90° of hip flexion and 90° of knee flexion and to place the hands on the hips with head and eyes facing forward. Participants were instructed to flex the stance knee as deep as comfortably possible and to repeat the same squat depth to the best of their ability throughout testing. Following a squat, participants were instructed to return to the upright position in a fluid motion. Additionally, participants were instructed to (a) maintain proper testing position throughout the entire motion, (b) not touch down with the non-stance limb, (c) maintain heel contact of the stance limb with the ground, and (d) complete the assessment in a fluid motion while maintaining balance. No additional feedback or instruction was given to the participants regarding technique. Participants were allowed a minimum of one practice trial of five consecutive squats, to familiarize themselves with the assessment.

3.3.3. Single-Task Paradigm

During single leg stance, participants were instructed to maintain balance for 20 seconds following the single leg stance procedure previously described. For single leg squats, participants completed five consecutive squats at a self-selected pace and squat depth following the single leg squats procedure previously described.

3.3.4. Dual-Task Paradigms

For dual-task paradigms, participants concurrently performed a cognitive and postural control assessment. Instructions were not given to focus attention on either task, but rather to maintain postural stability while completing the cognitive task as best as possible. Performing the single leg stance during dual-task with Stroop lasted 20 seconds for all participants. Total trial time varied while performing the single leg stance during dual-task with the Brooks assessment, depending on the time it took the participant to repeat the number positions. When completing the single leg squats, participants were instructed to continuously squat throughout the entire cognitive assessment performance, which was defined as the start of the cognitive assessment through the end of the cognitive assessment. The total number of squats completed during the dual-task assessments varied depending on the amount of time it took each participant to complete the cognitive assessment.

3.4. Data Reduction

The three trials performed on the dominant and non-dominant limbs were averaged for separate dominant and non-dominant means for all outcome variables. The first and last single leg squats were excluded from single leg squat trials during data analysis. The

remaining single leg squats within each trial were then used to calculate all outcome variables.

Kinetic and kinematic data were synchronized using the Motion Monitor motion capture system (Innovative Sports Training, Chicago, IL). Although previous research reports a sampling frequency of around 100 Hz for kinetic data,[56,111,205,206] we used a sampling rate of 1400 Hz. Kinematic data were collected at 140 Hz. All data were low-pass filtered at 14 Hz (fourth-order zero-phase lag Butterworth). Kinetic data were smoothed with a 10 ms sliding window average. Figures 1 and 2 shows a comparison of stabilograms using raw and smooth data to trace the total center of pressure path. Custom Matlab programs were used to calculate the primary outcome variables to quantify postural control: total center of pressure speed (CPspeed), anterior-posterior center of pressure speed (APspeed), medial-lateral center of pressure speed (MLspeed), 95% elliptical sway area (CParea), anterior-posterior center of pressure range (APrange), and medial-lateral center of pressure range (MLrange). Definitions and explanations of postural control variables are shown in Table 2. Traditionally, trial time normalized excursion is identified as speed and was labeled as such for this study. Center of pressure data were only analyzed for the active squat movement (full extension, to maximum flexion, to full extension) for all single leg squat trials. The method used to identify single leg squats is shown in Figure 3.

Kinematic variables and trial times were calculated as secondary outcome variables to help further explain postural control performance. Vertical displacement of the sacrum was calculated for each trial in order to determine sacrum range and sacrum speed along the z-

axis. For single leg stance postural control conditions, total trial time was measured as the time, in seconds, between the start and end of a trial as manually recorded by the researcher. For single leg squat postural control conditions, total squat trial time was measured as the sum of the times to complete the individual squats in a trial. Definitions and formulas for kinematic variables can be found in Table 3.   Kinematic variables and trial times were analyzed via custom Matlab programs. Kinematic variables were only of interest for the dynamic postural control assessments, therefore kinematic variables were not reported for the static postural control assessments.

3.5. Statistical Analyses

Paired t-tests were used to compare dominant and non-dominant means for all outcome variables. No significant differences were found, therefore dominant and non-dominant means were averaged for a combined test condition mean for all outcome variables. A 2 (balance assessment: stance vs. squat) x 2 (test condition: single- vs. dual-task) within-subjects analysis of variance (ANOVA) was used for each postural control variable. The alpha level was set a prior at 0.05 for ANOVA analyses. If the omnibus ANOVA models were significant, Bonferroni post hoc paired t-tests were employed to explore interactions of clinical interest with an adjusted p value of 0.00714 (adjusted for 7 post hoc analyses). Individual paired t-tests were used to compare means for sacrum range and sacrum speed variables during dynamic postural control performance conditions for three interactions of interest: 1) single-task vs. dual-task with Brooks, 2) single-task vs. dual-task with Stroop, and 3) dual-task with Brooks vs. dual-task with Stroop. The alpha level was set a prior at 0.05

for kinematic independent paired t-test comparisons. All analyses were performed using

Statistical Package for the Social Sciences version 21 (SPSS Inc, Chicago, IL).

CHAPTER IV - MANUSCRIPT

4.1. Introduction

       Single leg postural control assessments are critical in the evaluation of athletic

performance[1] and the assessment of sports-related injuries including ankle sprains,[2-7] anterior

cruciate ligament deficiency,[8-10] and concussions.[11-14] Sports medicine clinicians assess

postural control to quantify a key aspect of neuromuscular control in athletes, identify

athletes at higher risk for injury, improve injury prevention strategies, and as a progressive

marker for rehabilitation following injury.[20] The current standard for postural control

assessments requires athletes to perform a battery of static, single leg and double leg stance

assessments.[5,15-19] While this approach is successful in identifying abnormal postural control

or postural control deficiencies following injury,[2-14] it may not be sensitive enough to fully

identify all postural control deficiencies.

       Dynamic postural control may better represent the physical and cognitive demands of

athletic activity than static postural control due to the constant demand for movement during

competition.[48] Dynamic postural control requires an individual to maintain balance while

simultaneously executing a functional assessment.[2] Recently, dynamic postural control

deficiencies have been identified through the examination of gait stability following

injury.[21,33-47] These studies identified postural control deficiencies that were not identified

through traditional static postural control assessments.

       The single leg squat may be a comparable dynamic postural control assessment. The

single leg squat is traditionally used to clinically assess lower extremity movement patterns.[49]

The single leg squat can also be used to assess postural control of a functional movement.[50]

Due to the high proprioceptive demand of the single leg squat on the body,[51] this dynamic

assessment may prove effective in assessing postural and neuromuscular control and could

help clinicians better and more accurately identify postural control deficiencies.

Postural control during athletic activity requires a complex interaction of sensory

input and motor output.[21,22] Therefore, postural control assessments should reflect the

environment in which athletes participate. This can be accomplished through dual-task

paradigms and with the use of dynamic postural control assessments. A dual-task paradigm

requires a person to perform two different assessments concurrently, typically a motor and a

cognitive assessment, and is thought to address cognitive, postural control, and or visual

deficits following an injury.[118-121] Associations between cognitive and motor function have

been strengthened through examinations of dual-task performance where dynamic postural

control is adversely affected when a secondary cognitive assessment is introduced.[21,39,41-44,52]

Dual-task paradigms may better represent the physical and cognitive demands of athletic

activity than single-task postural control due to the constant demand for movement during

competition.[48]

A dynamic postural control assessment which mimics athletic movement (i.e., single

leg squat) performed concurrently with a cognitive assessment may prove an effective dual-

task paradigm for postural control assessments of athletes. This dynamic dual-task paradigm

may be a better representative of postural control for physically active individuals than

traditional static, single-task assessments. Thus the purpose of this study was threefold: 1)

examine differences between static and dynamic postural control during a single-task

paradigm, 2) examine differences between single-task and dual-task paradigms during static and dynamic postural control assessments, and 3) examine differences between two dual-task paradigms during static and dynamic postural control assessments. We hypothesize that there will be poorer postural stability during the dynamic assessment compared to the static assessment during single-task. We also believe that individuals will display poorer postural stability during dual-task paradigms compared to single-task paradigms for both static and dynamic postural control assessments. Comparing postural control performance between dual-tasks, we hypothesize that poorer postural stability will be seen under the dual-task with Brooks condition compared to the dual-task with Stroop condition.

4.2. Methods

4.2.1. Participants

The cross-sectional study design included 30 healthy college students (female = 22, male = 8; age = 20.83 ± 1.64 years, height = 157.88 ± 13.04 cm, mass = 67.79 ± 20.64 kg) who volunteered to participate in this study. All participants had 1) no previous history of a concussion within the past two years, 2) full medical clearance for physical activity, 3) no history of surgical procedure to the lower extremities or low back, 4) no injury to the lower extremities or low back within the past six months that resulted in an inability to participate in physical activity for three consecutive days, 5) no color blindness, and 6) no known vestibular or balance disorders.

4.2.2. Instrumentation

4.2.2.1. Force Plate

For all trials, participants stood on a tri-axial force plate (Model #4060-NC Bertec Co., Columbus, OH) embedded in a raised wooden platform on level floor that measured translational forces and moments about three axes. Center of pressure values were calculated using custom Matlab (MathWorks, Inc., Natick, MA, USA) programs.

4.2.2.2. Electromagnetic Tracking Sensor

An electromagnetic motion tracking sensor (TrakStar, Ascension Technology Corp., Burlington, VT) was used for kinematic analysis during testing. Using double-sided tape, the 6-degrees-of-freedom sensor was placed on the sacral body of the participant. The world and sensor axis system were established and designed as the positive x-axis facing the same direction as the participant, positive y-axis to the left of the participant, and positive z-axis superiorly to the participant. Sacral displacement in the z-axis was used to determine vertical displacement during testing.

4.3. Procedure

All participants reported for one testing session that lasted approximately 75 minutes. Before testing, participants were asked to complete a health history questionnaire. Following the questionnaire, height and mass were measured and recorded. Participants wore their own athletic shorts and a shirt and were barefoot throughout testing. Prior to testing, participants were instructed to warm-up on a stationary bike for five minutes at a self-selected pace followed by self-directed stretches.

Following warm-up, participants completed three trials each of two cognitive baseline

assessments, the Brooks Spatial Memory Test that uses visuospatial working memory[204] and

a modified computerized Stroop test. Baseline testing for both cognitive assessments were

completed while in double-limb stance. The order of baseline testing between the two

neurocognitive assessments was randomized for each participant. Following the baseline

neurocognitive assessments, postural control assessments under six conditions were then

completed. In order to minimize the effect of fatigue, a maximum of 30 seconds were given

for all participants to rest between trials unless a participant verbally indicated they were

ready to begin the next trial before the end of 30 seconds. The postural control conditions

included: 1) single leg stance, 2) single leg squats, 3) single leg stance during dual-task with

the Brooks Spatial Memory Test, 4) single leg squats during dual-task with the Brooks

Spatial Memory Test, 5) single leg stance during dual-task with the Stroop test, and 6) single

leg squats during dual-task with the Stroop test. Table 1 describes the six test conditions

completed by all participants. Each participant performed all six postural control conditions

on both their dominant (the leg the participant would use to kick a soccer ball for maximum

distance) and non-dominant limb. The order of testing for the 12 assessments (6 postural

control conditions on both limbs) were randomized for each participant. Participants

completed one trial for each of the 12 assessments and then repeated the same order of

testing two more times for a total of three trials for each of the 12 postural control

assessments. Trials were discarded and repeated if the non-weight bearing foot touched the

floor or force plate. The researcher manually marked each trial, within the computer

software, to indicate the start and stop of a trial. For all assessments, participants were

instructed to face forward throughout testing and reduce head and eye movement as best as

possible. During performance of the Stroop test, participants were instructed to look at the

computer screen throughout testing. These instructions were given in order to minimize the

effect of voluntary head and eye movement which may affect postural control performance.

4.3.1. Cognitive Assessments

For the Brooks Spatial Memory test, participants were shown a card with unique

locations of eight numbers, listed as 1-8 in numerical order and placed in a 4x4 grid. Figure 4

shows an example card. When the presentation of numbers was completed, lasting no more

than one minute, the participant verbally recalled the position of each digit at a self-selected

pace while standing on the testing limb. Total time to complete the Brooks test varied for

each participant. A total of 30 unique cards were used throughout the study and no card was

repeated during any one participant's testing session. All participants were allowed one

practice trial in order to familiarize themselves with the test before baseline assessments.

Participants completed a computerized, modified Stroop test utilizing CNS Vital

Signs (CNS Vital Signs, LLC, Morrisville, NC). During the Stroop test, a series of color

names (red, yellow, blue, and green) in color fonts (red, yellow, blue, and green) were

displayed on the computer screen in a random order. If the color name and color font did not

match, the participant was instructed to press the trigger. If the color name and color font

matched, the participant was instructed to take no action. The laptop on which the Stroop

test was performed was placed at eye level approximately one meter away directly in front of

the participant. The Stroop test lasted for 20 seconds. Participants used a hand-held trigger to respond as quickly as possible to the computerized Stroop test. The hand-held trigger was held in the participant's dominant hand (defined as the hand the participant uses for writing) and held at the ipsilateral hip with the other hand placed on its respective hip. This position was identical to the hand positions during single-task postural control assessments. All participants were allowed one practice trial of the Stroop test in order to familiarize themselves with the test prior to baseline assessments.

4.3.2. Postural Control Assessments

For the single leg stance postural control assessment, participants were asked to stand on the limb to be tested with their toes facing forward (positive x axis) and centered on the force plate. Participants were instructed to maintain the non-stance limb in 20°-30° of hip flexion and 40°-50° of knee flexion with hands placed on the hips and head and eyes facing forward. Participants were instructed to remain as motionless as possible with eyes open during testing. A trial was considered incomplete if the participant could not sustain the stance position for longer than 5 seconds. Participants were provided with a minimum of 1 practice trial on each limb lasting 7 seconds to familiarize themselves with the assessment.

During the single leg squat postural control assessment, participants were asked to stand on the limb to be tested on the force plate, toes facing forward, and heel on the ground. Participants were instructed to flex the non-stance leg to 90° of hip flexion and 90° of knee flexion and to place the hands on the hips with head and eyes facing forward. Participants were instructed to flex the stance knee as deep as comfortably possible and to repeat the same

squat depth to the best of their ability throughout testing. Following a squat, participants were instructed to return to the upright position in a fluid motion. Additionally, participants were instructed to (a) maintain proper testing position throughout the entire motion, (b) not touch down with the non-stance limb, (c) maintain heel contact of the stance limb with the ground, and (d) complete the assessment in a fluid motion while maintaining balance. No additional feedback or instruction was given to the participants regarding technique. Participants were allowed a minimum of one practice trial of five consecutive squats, to familiarize themselves with the assessment.

4.3.3. Single-Task Paradigm

During single leg stance, participants were instructed to maintain balance for 20 seconds following the single leg stance procedure previously described. For single leg squats, participants completed five consecutive squats at a self-selected pace and squat depth following the single leg squats procedure previously described.

4.3.4. Dual-Task Paradigm

For dual-task paradigms, participants concurrently performed a cognitive and postural control assessment. Instructions were not given to focus attention on either task, but rather to maintain postural stability while completing the cognitive task as best as possible. Performing the single leg stance during dual-task with Stroop lasted 20 seconds for all participants. Total trial time varied while performing the single leg stance during dual-task with the Brooks assessment, depending on the time it took the participant to repeat the number positions. When completing the single leg squats, participants were instructed to

continuously squat throughout the entire cognitive assessment performance, which was defined as the start of the cognitive assessment through the end of the cognitive assessment. The total number of squats completed during the dual-task assessments varied depending on the amount of time it took each participant to complete the cognitive assessment.

4.4. Data Reduction

The three trials performed on the dominant and non-dominant limbs were averaged for separate dominant and non-dominant means for all outcome variables. The first and last single leg squats were excluded from single leg squat trials during data analysis. The remaining single leg squats within each trial were then used to calculate all outcome variables.

Kinetic and kinematic data were synchronized using the Motion Monitor motion capture system (Innovative Sports Training, Chicago, IL). Although previous research reports a sampling frequency of around 100 Hz for kinetic data,[56,111,205,206] we used a sampling rate of 1400 Hz. Kinematic data were collected at 140 Hz. All data were low-pass filtered at 14 Hz (fourth-order zero-phase lag Butterworth). Kinetic data were smoothed with a 10 ms sliding window average. Figures 1 and 2 shows a comparison of stabilograms using raw and smooth data to trace the total center of pressure path. Custom Matlab programs were used to calculate the primary outcome variables to quantify postural control: total center of pressure speed (CPspeed), anterior-posterior center of pressure speed (APspeed), medial-lateral center of pressure speed (MLspeed), 95% elliptical sway area (CParea), anterior-posterior center of pressure range (APrange), and medial-lateral center of pressure range (MLrange). Definitions and explanations of postural control variables are shown in Table 2.

Traditionally, trial time normalized excursion is identified as speed and was labeled as such for this study. Center of pressure data were only analyzed for the active squat movement (full extension, to maximum flexion, to full extension) for all single leg squat trials. The method used to identify single leg squats is shown in Figure 3.

Kinematic variables were calculated as secondary outcome variables to help further explain postural control performance. Vertical displacement of the sacrum was calculated for each trial in order to determine sacrum range and sacrum speed along the z-axis. Definitions and formulas for kinematic variables can be found in Table 3. Kinematic variables were analyzed via custom Matlab programs. Kinematic variables were only of interest for the dynamic postural control assessments, therefore kinematic variables were not reported for the static postural control assessments.

4.5. Statistical Analyses

Paired t-tests were used to compare dominant and non-dominant means for all outcome variables. No significant differences were found, therefore dominant and non-dominant means were averaged for a combined test condition mean for all outcome variables. A 2 (balance: single leg stance and single leg squats) x 3 (cognitive: none, Brooks, Stroop) within-subjects analysis of variance (ANOVA) was used to analyze each center of pressure postural control variable. Bonferroni corrections were employed to explore interactions of clinical interest with an adjusted p value of 0.00714 (adjusted for 7 post hoc analyses). A one-way ANOVA was used to compare means for sacrum range and sacrum speed between cognitive conditions for the squat balance conditions only. Bonferroni corrections were employed to explore interactions of clinical interest with an adjusted p value of 0.017

(adjusted for 3 post hoc analyses). The alpha level was set a prior at p<0.05 for ANOVA

analyses. All analyses were performed using Statistical Package for the Social Sciences

version 21 (SPSS Inc, Chicago, IL).

4.6. Results

4.6.1. Total Center of Pressure Speed

There was a significant interaction for total CPspeed ($F_{2,58}$=11.58, p<0.001). Post-

hoc pairwise comparisons revealed significantly faster CPspeed during dual-task with Brooks

(4.88±0.74 cm/s) as compared to single-task (4.62±0.76 cm/s; p<0.001) and dual-task with

Stroop (4.44±0.77 cm/s; p<0.001) during single leg stance balance. Significantly slower

CPspeed was observed during dual-task with Stroop as compared to single-task (p<0.001)

during single leg stance balance. Significantly slower CPspeed was observed during dual-

task with Brooks (10.99± 2.48 cm/s; p=0.006) and dual-task with Stroop (10.95±2.61 cm/s;

p<0.001) as compared to single-task (11.74±2.84 cm/s) during single leg squats balance.

CPspeed means and standard deviations can be found in Table 4.

4.6.2. A/P Center of Pressure Speed

There was a significant interaction for APspeed ($F_{2,58}$=8.72, p=0.002). Post-hoc

pairwise comparisons revealed significantly slower APspeed during dual-task with Stroop

(3.04±0.49 cm/s) as compared to both the dual-task with Brooks (3.26±0.46 cm/s; p<0.001)

and the single-task conditions (3.19±0.47 cm/s; p<0.001) during single leg stance balance.

Significantly slower APspeed was observed during dual-task with Brooks (8.96±2.52 cm/s;

p=0.006) and dual-task with Stroop (9.07±2.57 cm/s; p=0.001) as compared to single-task

(9.68±2.79 cm/s) during single leg squats balance. APspeed means and standard deviations can be found in Table 4.

4.6.3. M/L Center of Pressure Speed

There was a significant interaction for total MLspeed ($F_{2,58}$=11.87, p<0.001). Post-hoc pairwise comparisons revealed significantly faster MLspeed during dual-task with Brooks (2.96±0.53 cm/s) as compared to dual-task with Stroop (2.60±0.53 cm/s; p<0.001) and single-task (2.71±0.53 cm/s; p<0.001) during single leg stance balance. During single leg squats balance, significantly slower MLspeed was observed during dual-task with Stroop (4.45±0.82 cm/s) as compared to both the dual-task with Brooks (4.67±0.78 cm/s; p=0.003) and single-task (4.84±0.88 cm/s; p<0.001) conditions. MLspeed means and standard deviations can be found in Table 4.

4.6.4. Sway Area

No significant interaction was observed for CParea ($F_{2,58}$=0.55, p=0.582). A main effect for balance condition was observed ($F_{1,29}$=166.41, p<0.001) such that single leg squats balance (25.17±1.71 cm^2) had significantly greater CParea than single leg stance balance (6.81±0.52 cm^2). CParea means and standard deviations can be found in Table 4.

4.6.5. A/P Center of Pressure Range

No significant interaction was observed for APrange ($F_{2,58}$=0.75, p=0.476). A main effect for balance condition was observed ($F_{1,29}$=24.85, p<0.001) such that single leg squats balance (4.89±0.29 cm) had significantly greater APrange than single leg stance balance (3.61±0.13 cm). A main effect for cognitive condition was observed ($F_{2,58}$=7.48, p=0.001)

such that no cognitive condition (4.49±0.019 cm) had significantly greater APrange than the Brooks condition (4.15±0.22 cm, p=0.026) and the Stroop condition (4.11±3.77 cm, p<0.001). APrange means and standard deviations can be found in Table 4.

4.6.6. M/L Center of Pressure Range

No significant interaction was observed for MLrange ($F_{2,58}$=1.41, p=0.251). A main effect for balance condition was observed ($F_{1,29}$=59.07, p<0.001) such that single leg stance condition (2.56±0.11 cm) had significantly greater MLrange than single leg squats condition (1.75±0.05 cm). A main effect for cognitive condition was observed ($F_{2,58}$=4.32, p=0.034) such that no cognitive condition (2.21±0.06 cm) had significantly greater MLrange than the Stroop condition (2.03±0.06 cm, p=0.001). MLrange means and standard deviations can be found in Table 4.

4.6.7. Sacrum Vertical Displacement Range

There was a significant difference between sacrum range for single leg squats conditions ($F_{2,58}$=46.58, p<0.001). Post-hoc pairwise comparisons revealed significantly less squat depth during dual-task with Brooks (12.00±3.01 cm, p<0.001) and dual-task with Stroop (12.69±3.41 cm, p<0.001) as compared to single-task (14.57±3.59 cm). Significantly less squat depth was observed during dual-task with Brooks as compared to dual-task with Stroop (p=0.001). Sacrum Range means and standard deviations can be found in Table 5.

4.6.8. Sacrum Vertical Speed

There was a significant difference between sacrum speed for single leg squats conditions ($F_{2,58}$=28.55, p<0.001). Post-hoc pairwise comparisons revealed significantly

faster squats during single-task (19.64±5.53 cm/s) as compared to the dual-task with Brooks (16.15±4.53 cm/s; p<0.001) and dual-task with Stroop (16.90±4.65 cm/s; p<0.001) conditions. Sacrum Speed means and standard deviations can be found in Table 5.

4.7. Discussion

The aim of this study was to determine if changes in postural control performance existed under static and dynamic postural control assessments during dual-task paradigms. We hypothesized that greater postural stability would be seen during the static postural control assessment compared to the dynamic postural control assessment. We also hypothesized that poorer postural stability would be seen during the dual-task paradigms compared to the single-task paradigm and poorer stability would be seen during dual-task with the Brooks Spatial Memory Test compared to the Stroop test. The most important finding of this study is that not all dual-task paradigms have the same effect on postural stability. Attention is finite and can only accommodate as much as the limited capacity allows.[123] If capacity is exceeded by one assessment in a dual-task paradigm that requires more attentional capacity than the other assessment, performance on the latter assessment will be impaired which is reflected in our findings and other relevant studies.[21] Surprisingly, the effect of concurrently performing Brooks while maintaining balance was not consistent between static and dynamic postural control assessments and could be attributed to compensation in biomechanical performance during the single leg squats.

4.7.1. Postural Control Assessment Differences

Performance of a dynamic postural control assessment resulted in significantly poorer postural stability compared to performance of a static postural control assessment in single-task. These findings reveal that a dynamic postural control assessment challenges the postural control system more than a static postural control assessment, which supports our hypothesis and previous research examining a similar population and postural control assessments.[207] Significantly faster sway speed and a larger sway area may indicate greater postural instability during single leg squats.[115,116] These findings may be misleading interpretations of postural control performance due to the biomechanical differences that naturally exist between single leg squats and single leg stance. A significantly greater anterior-posterior sway can be supported by the displacement of the center of pressure primarily in these directions during knee flexion and extension.[208] With additional flexion of the ankle and knee joints during single leg squatting compared to single leg stance, the displacement of the center of pressure is favored in the anterior-posterior directions to prevent the body from falling and support the change in weight distribution, which likely contributes to significantly increased whole-body sway and thus an increase in center of pressure parameters.[208] Although our results reveal significantly poorer postural stability during single leg squats via kinetic analysis, kinematic variables should be considered in order to better represent dynamic postural control performance. A comparison between the results of our study to previous literature is somewhat limited as there are only a few studies that have captured the same static and dynamic measures of postural stability for a healthy

population within one study.[114,209] This warrants further investigation into comparing

postural control performance of similar dynamic and static postural control assessments used

in this study.

4.7.2. Static Postural Control Performance

Employing the dual-task paradigm with Brooks resulted in poorer postural stability

compared to the single-task paradigm; whereas, employing the dual-task paradigm with

Stroop resulted in improved postural stability compared to the single-task paradigm.

Previous research reported significantly decreased postural stability during a dual-task

paradigm compared to single-task, which supports our findings for postural control

performance during dual-task with Brooks.[120,210] It should be noted that these studies used

tandem stance instead of single leg stance for the static postural control assessment. Our

findings for postural control performance during dual-task with Stroop are similar to the

findings of previous studies, where improved postural stability was seen during a dual-task

paradigm with a static postural control assessment.[22,30,59,211] These studies also did not use

single leg stance as the static postural control assessment, but rather the tandem[59] and

Sensory Organization Test (SOT)[22,30,211] instead.

Our hypothesis was static postural stability would decrease with the concurrent

performance of a cognitive assessment compared to single-task and to our surprise, this was

only confirmed for the Brooks test and not the Stroop test. A central pattern generator (CPG)

may govern single leg stance and maintenance of static postural control as it reflects a similar

movement pattern as the stance phase of gait where one pathway of the gait CPG may be

used to regulate the stance phase by exciting the CPG extensor half-canter.[212] Based on this theory, a more difficult cognitive assessment may compromise postural control due to increased attentional demand of the postural control system as observed in our findings with Brooks. If no other activity is required of an individual except maintaining postural control, increased attention on single leg stance may increase muscle tension and in turn cause greater postural instability[59] where a CPG may not require as much attention given. This observation was seen in our findings where improved postural stability occurred with Stroop. The Stroop test may not be as challenging of a cognitive assessment and by taking focus off of a task that does not require attention, like the single leg stance, concurrent performance of the simple Stroop may in turn improve stability.

4.7.3. Dynamic Postural Control Performance

The Star Excursion Balance Test (SEBT) is a valid and reliable outcome measure of dynamic balance[95] used to identify injury risk and serve as a measure of unilateral balance and neuromuscular control.[17] The previously validated and reliable anterior reach component of the SEBT shares similar movement patterns as the single leg squat[92] which was implemented in the procedures of the current study. Another favorable quality of single leg squats to support their use as a dynamic postural control assessment is that they are already used clinically to assess functional postural control.[213] A dynamic assessment that combines functional and postural control performance to assess dynamic postural stability may prove to be a comparable postural control assessment in the clinical and athletic settings compared with previously validated assessments.[214]

Significantly slower sway was observed in postural control performance during both dual-tasks compared to single-task, which indicates improved postural stability while concurrently performing single leg squats and a cognitive assessment. These findings support previous research on gait performance[40,4121,39,44] and may suggest other factors contribute to postural control performance during dynamic dual-task paradigms.

Sacrum displacement and sacrum speed may help explain how the postural control system performs during dual-task paradigms compared to single-task. Participants displayed significantly less squat depth and significantly slower squat speeds during dual-task conditions compared to single-task which may indicate that the concurrent performance of a cognitive assessment compromised squat performance. Based on these findings, we believe that the mental focus was shifted to performance on the cognitive assessment rather than the squat performance because the cognitive assessment was more challenging than the squatting assessment. The compensation in motor task performance may contribute to improved postural stability during dual-task where slower sway would help support these findings. Compensatory dynamic motor performance of healthy individuals during dual-task testing has been published through studies examining gait analysis which supports findings from our study examining single leg squats.[21,34,36,39,40,44] Reduced knee and hip flexion, as suggested by significantly less squat depth, reduces anterior-posterior sway and significantly slower squats could explain postural control performance that reflects improved stability and postural control. Kinematic variables were analyzed in order to better understand how the

postural control system performs under single- and dual-task conditions and should be further investigated in future studies.

4.7.4. Dual-Task Difficulty

The findings from this study indicate that there is a difference in level of difficulty between the cognitive assessments. This can be explained by the difference in postural control and dynamic motor performance between the concurrent performance of the Brooks and Stroop tests while maintaining static and dynamic postural stability. We hypothesized that postural stability would be less with the concurrent performance of Brooks compared to Stroop, which was confirmed through our findings for both static and dynamic postural control.

During static and dynamic postural control assessments, employing the dual-task with Brooks resulted in faster sway compared to dual-task with Stroop. In the current study, the level of difficulty of dual-task paradigms was compared and determined by the impact each cognitive assessment had on measures of postural control and squat performance. Conceptually, the Brooks test, which assesses visuo-spatial memeory, is more difficult than the Stroop test, which measures reaction time. Compared to the simple Stroop test, the more mentally challenging Brooks test worsened static and dynamic postural stability. The attentional demands of a visuo-spatial memory assessment show that it requires more focus than a reaction-time assessment while concurrently maintaining postural control.

Tasks that are more complex and require more processing and attention have been demonstrated to result in greater interference with postural control than simpler

tasks,[115,116,120,215] which supports our findings with Brooks being the more complex task and Stroop the simpler task. As suggested by Hunter and Hoffman,[59] it is possible that the simpler Stroop test decreased muscle activation, due to decreased attentional demand, leading to reduced sway while maintaining postural control. A familiar reaction-time assessment that more directly reflects everyday scenarios may elicit reduced stress on the postural control system compared to a complex assessment that is mentally taxing.

Kinematic analysis helped support the findings that a difference in dynamic stability exists between concurrent performance of Brooks and Stroop tests while maintain postural control. Compared to the dual-task with Stroop condition, participants did not squat as deep and squatted more slowly during the dual-task with Brooks condition. These findings suggest that individuals squatted in a more conservative manner and modified dynamic motor output to accommodate for a more challenging cognitive assessment while concurrently maintaining postural control.

4.7.5. Limitations

Trial time was not controlled for across all postural control assessment conditions. Dual-task with Stroop conditions and the single leg stance during single-task condition were 20 second assessments; whereas, dual-task with Brooks conditions and single leg squats during single-task condition varied in trial time depending on participant performance. We only normalized center of pressure speed variables by trial time because we felt sway area and center of pressure ranges would not have been well represented if normalized to time. We recognize this may not have been the best methodology to carry out in testing and

analysis. Future research should not modify performance of cognitive assessments as these have already been standardized, but analysis of all trials should be consistent by examining data within the same amount of time even if it's less than the total trial time. The number of squats completed between conditions was also not controlled for. For single-task, participants completed five squats. For the dual-task paradigms, participants were instructed to repeatedly squat throughout the entire trial while completing the neurocognitive assessment. We recognize this may introduce such factors as fatigue which could affect postural control and kinematic performance, but believe that the methodology employed in this study best reflects a dual-task paradigm where balance and cognitive assessments were completed concurrently. Future studies should analyze the same number of squats for all trials. We only studied a college-aged, healthy cohort. It is unclear from our findings how other cohorts, such as elderly and injured, will respond to different dynamic and dual-task postural control paradigms. A key component missing to our study is that we did not account for cognitive assessment performance. Future research should account for errors in the cognitive assessment as well as measuring motor assessment performance. Employing this methodology will help researchers understand assessment priority and limits of attentional capacity. Further analyses into cognitive assessment performance will also provide more insight into differences in task difficulty between the Brooks and Stroop tests and how cognitive performance is influenced by postural control performance.

4.7.6. Future Work

Based on our findings, a reaction time assessment may more closely reflect everyday activity and athletic competition than a visuo-spatial memorization assessment, although postural stability varied based on the different assessments. Future studies should consider employing a dual-task paradigm that mimics the environment in which the tested population is most exposed to. One of the major limitations to our study was not controlling for trial time between test conditions. Future studies should implement a procedure which maintains the same trial time across all test conditions. Postural control performance during single leg squats is limited in the literature and therefore should be further assessed to better understand how maintaining balance changes while performing a dynamic single leg postural control assessment. Establishing reliability of single leg squat postural control measures during both single-task and dual-task conditions will be addressed in the future to determine if this dynamic assessment is more sensitive in identifying between group differences compared to the single leg stance or other static assessments.

4.8. Conclusion

Findings from this study demonstrate that differences in postural control performance exist between static and dynamic single leg postural control assessments and between single- and dual-task paradigms. Compared to single-task, healthy individuals display poorer static postural stability while performing the Brooks test and improved static postural stability while performing the Stroop test. Healthy individuals compensated squat performance under dual-task conditions in order to maintain postural control. Postural control and kinematic measurements suggest that the Brooks test may be more challenging than the Stroop test.

Dynamic postural control assessments and dual-task paradigms may better reflect the athletic

environment and everyday activity of healthy individuals and should therefore be used in

postural control assessment to better reflect the postural control system. Our study

highlighted the importance of dual-task difficulty while assessing postural control

performance. To understand the effects of cognitive performance on posture, the degree of

attentional demand required by the concurrent task should be considered in addition to the

various postural strategies.
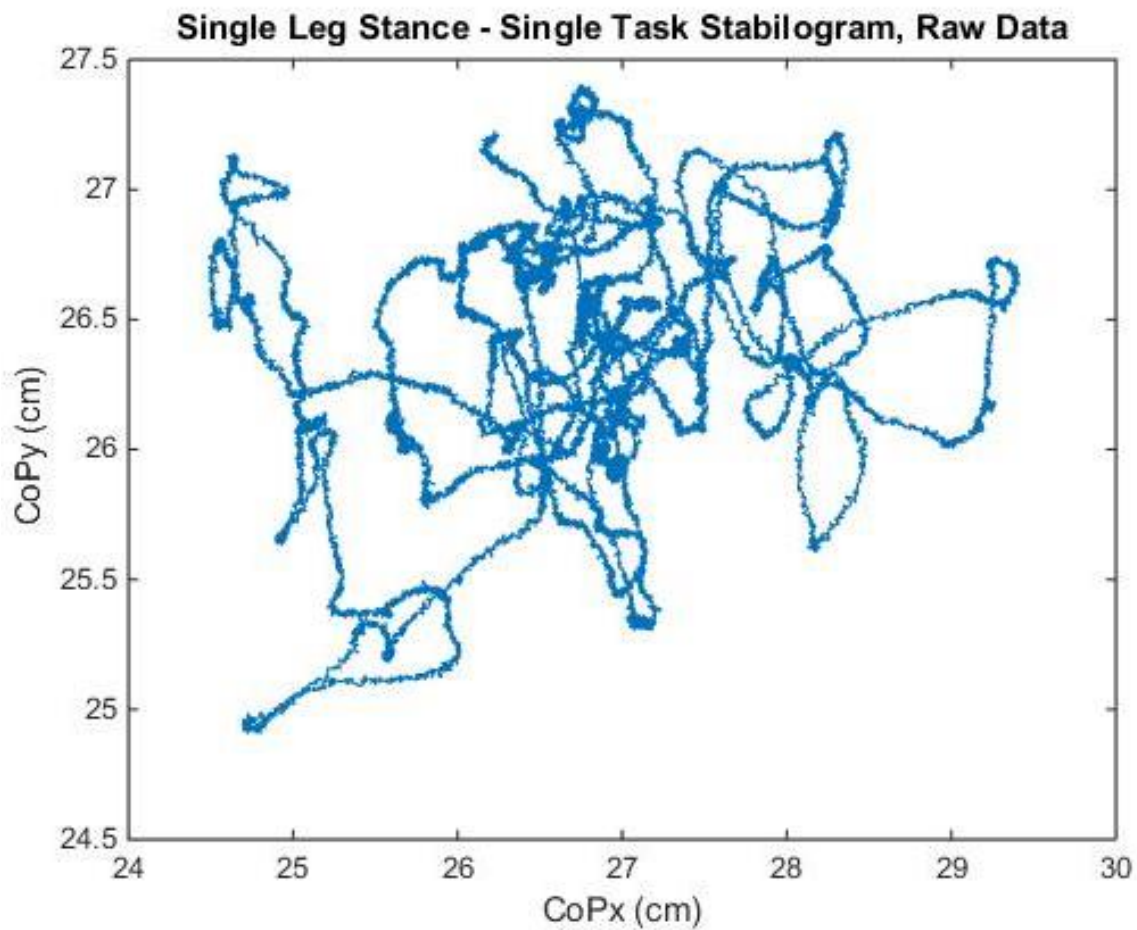
Figure 1: A stabilogram plotting center of pressure excursion during one trial of the test condition single leg stance during single-task for one subject. Raw center of pressure data was used for this plot, where no smoothing technique was applied.
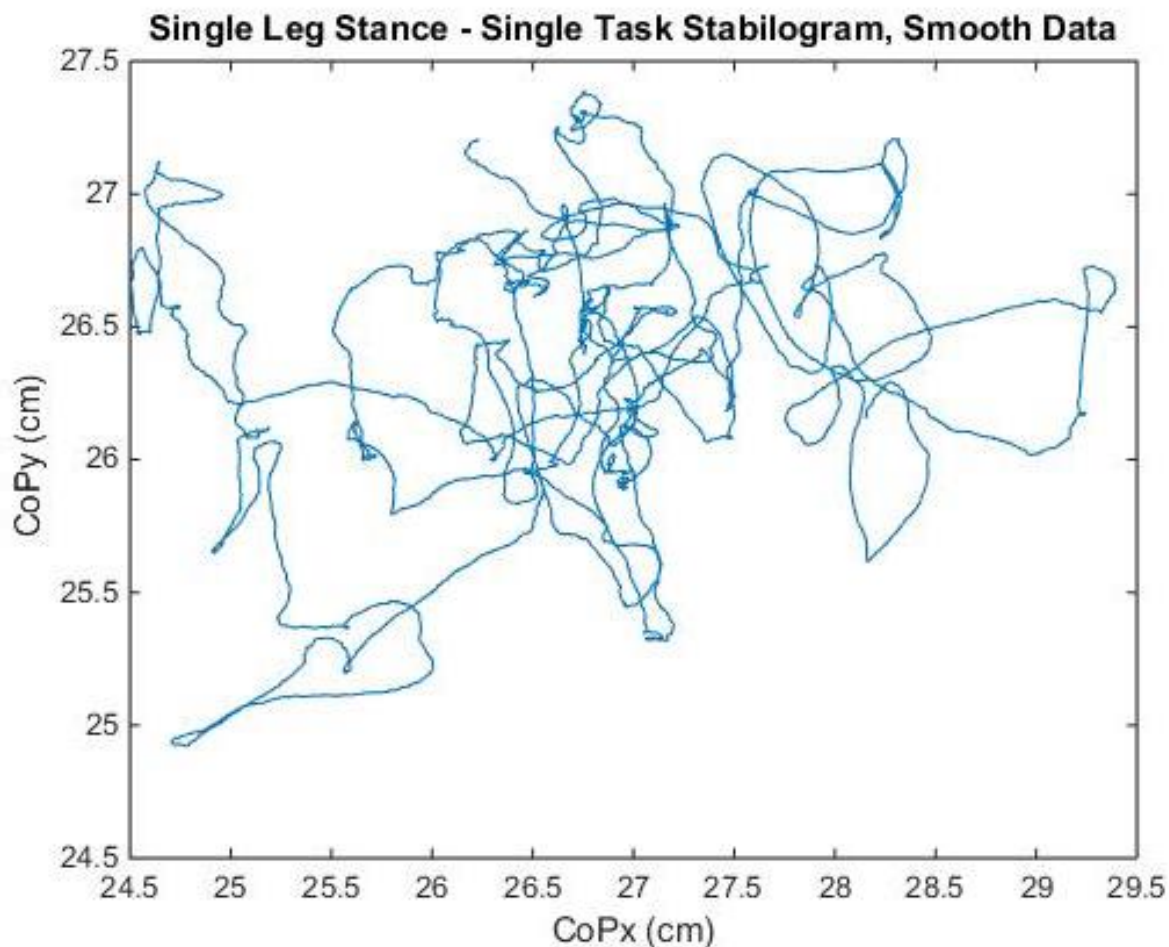
Figure 2: A stabilogram plotting center of pressure excursion during one trial of the test condition single leg stance during single-task for one subject. Smoothed center of pressure data was used for this plot, where a 10 ms sliding window average was used to smooth raw center of pressure data collected at 1400 Hz.
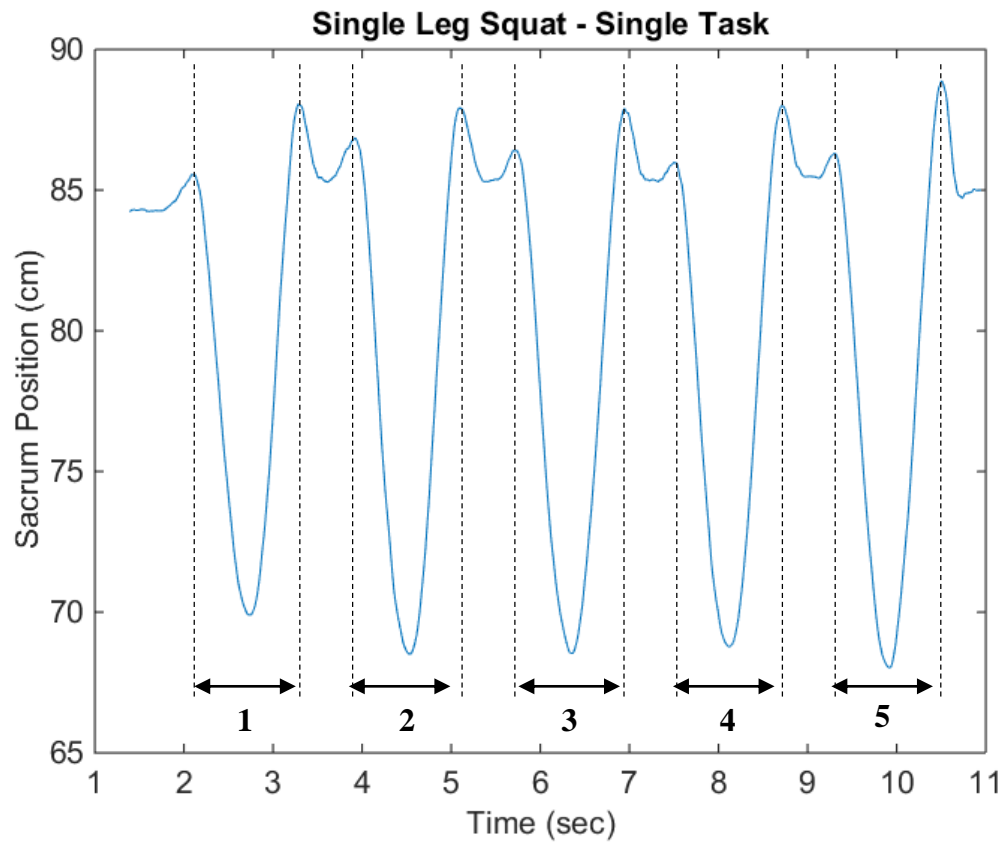
Figure 3: A single squat was identified as the combined descension and ascension phase of a squat indicated by the sacrum vertical displacement between maximum positions in the z-axis. All complete squats were identified in each trial.

1	2		8
	3	6	7
	4	5	

Figure 4: Sample Brooks Spatial Memory Test card. Participants would memorize the grid position of each number and recall these positions in numerical order starting with 1 and ending with 8.

Table 1: Six test conditions completed by all participants to test postural control performance. Balance and cognitive assessments for each condition were performed concurrently during testing.

Condition	Balance Assessment	Cognitive Assessment
1	single leg stance (static)	none
2	single leg squats (dynamic)	none
3	single leg stance (static)	Brooks Spatial Memory Test
4	single leg squats (dynamic)	Brooks Spatial Memory Test
5	single leg stance (static)	Stroop Test
6	single leg squats (dynamic)	Stroop Test

Table 2: Definitions and formulae of postural control outcome variables.

Variable	Unit	Definition	Formula
CPspeed	cm/s	time normalized distance of center of pressure path in the combined x and y axes	$\dfrac{\sum \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2}}{time}$
APspeed	cm/s	time normalized distance of center of pressure path in the x axis (sagittal plane)	$\dfrac{\sum \lvert x_{n+1} - x_n \rvert}{time}$
MLspeed	cm/s	time normalized distance of center of pressure path in the y axis (coronal plane)	$\dfrac{\sum \lvert y_{n+1} - y_n \rvert}{time}$
CParea	cm²	statistically based estimate of a confidence ellipse that encloses approximately 95% of the points of the center of pressure trajectory *Single Leg Squats: center of pressure data was combined for all squats in a trial to calculate sway area*	$2\pi F_{.05[2,N-2]}\sqrt{s_{AP}{}^2 s_{ML}{}^2 - s_{APML}{}^2}$ s_{AP} and s_{ML} are the standard deviations of the AP and ML time series s_{APML} represents their covariance
APrange	cm	distance between maximum and minimum center of pressure position in the x-axis (sagittal plane)	$x_{max} - x_{min}$
MLrange	cm	distance between maximum and minimum center of pressure position in the y-axis (coronal plane)	$y_{max} - y_{min}$

Table 3: Definition and formulae of kinetic outcome variables.

Variable	Unit	Definition	Formula
Sacrum Range	**cm**	Difference between maximum and minimum sacral position in the z-axis during a trial	$\max(z) - \min(z)$ *Squats: Calculated for each individual squat in a trial then averaged across all squats in a trial*
Sacrum Speed	**cm/s**	Sacrum vertical distance normalized to time	*z=sacrum position in the z-axis* *Single Leg Stance* $$\frac{\sum|z_{n+1} - z_n|}{\text{total trial time}}$$ *Single Leg Squats* $$\frac{\sum|z_{n+1} - z_n|}{\text{squat time}}$$ *Sacrum vertical distance calculated for individual squat, not entire trial*

Table 4: Mean values ± standard deviations of postural control variables for all conditions. ANOVA statistical significance indicated by: a, interaction effect (p<0.05); b, effect for balance condition (p<0.05); c, main effect for cognitive condition (p<0.05). Post hoc pairwise statistical significance indicated by: d, different from single-task (p<0.00714); e, different from dual-task with Brooks (p<0.00714); f, different from both single-task and dual-task with Brooks (p<0.00714).

	Single Leg Stance			Single Leg Squats		
	Single-Task	Dual-Task with Brooks	Dual-Task with Stroop	Single-Task	Dual-Task with Brooks	Dual-Task with Stroop
CPspeed[a] (cm/s)	4.64 ± 0.76	4.88 ± 0.74[d]	4.44 ± 0.77[f]	11.74 ± 2.84	10.99 ± 2.48[d]	10.95 ± 2.61[d]
APspeed[a] (cm/s)	3.19 ± 0.47	3.26 ± 0.46	3.04 ± 0.49[f]	9.68 ± 2.79	8.96 ± 2.52[d]	9.07 ± 2.57[d]
MLspeed[a] (cm/s)	2.71 ± 0.53	2.96 ± 0.53[d]	2.60 ± 0.53[e]	4.84 ± 0.88	4.67 ± 0.78	4.45 ± 0.82[f]
CParea[b] (cm^2)	7.16 ± 3.06	7.35 ± 5.03	5.97 ± 2.74	25.19 ± 8.30	25.13 ± 11.02	25.19 ± 10.98
APrange[b,c] (cm)	3.82 ± 0.79	3.60 ± 1.20	3.41 ± 0.61	5.16 ± 1.70	4.71 ± 1.72	4.81 ± 1.55
MLrange[b,c] (cm)	2.58 ± 0.53	2.70 ± 0.20	2.40 ± 0.45	1.84 ± 0.31	1.74 ± 0.30	1.66 ± 0.31

Table 5: Mean values ± standard deviations of kinematic variables for dynamic postural control conditions. Post hoc pairwise statistical significance indicated by: *, different from single-task (p<0.017); ‡, different from both single-task and dual-task with Brooks (p<0.017).

	Single-Task	Dual-Task with Brooks	Dual-Task with Stroop
Sacrum Range (cm)	14.57 ± 3.59	12.00 ± 3.01*	12.69 ± 3.41‡
Sacrum Speed (cm/s)	19.64 ± 5.53	16.15 ± 4.53*	16.90 ± 4.65*

REFERENCES

1. Hrysomallis C. Balance ability and athletic performance. *Sports Med.* 2011;41(3):221-232.

2. Arnold BL, De La Motte S, Linens S, Ross SE. Ankle instability is associated with balance impairments: a meta-analysis. *Med Sci Sports Exerc.* 2009;41(5):1048-1062.

3. Hertel J, Denegar CR, Buckley WE, Sharkey NA, Stokes WL. Effect of rearfoot orthotics on postural sway after lateral ankle sprain. *Arch Phys Med Rehabil.* 2001;82(7):1000-1003.

4. Perrin PP, Béné MC, Perrin CA, Durupt D. Ankle trauma significantly impairs posture control--a study in basketball players and controls. *Int J Sports Med.* 1997;18(5):387-392.

5. Chen C-Y, Hsu A-T, Guo L-Y, Lin C-F, Chen Y-A. Postural Control and Lower Extremity Contribution During Star Excursion Balance Test in Athletes with Chronic Ankle Instability. 2011;36(4):263-273.

6. Ross SE, Guskiewicz KM, Gross MT, Yu B. Balance measures for discriminating between functionally unstable and stable ankles. *Med Sci Sports Exerc.* 2009;41(2):399-407.

7. Witchalls JB, Newman P, Waddington G, Adams R, Blanch P. Functional performance deficits associated with ligamentous instability at the ankle. *J Sci Med Sport.* 2013;16(2):89-93.

8. Lysholm M, Ledin T, Odkvist LM, Good L. Postural control--a comparison between patients with chronic anterior cruciate ligament insufficiency and healthy individuals. *Scand J Med Sci Sports.* 1998;8(6):432-438.

9. Shiraishi M, Mizuta H, Kubota K, Otsuka Y, Nagamoto N, Takagi K. Stabilometric assessment in the anterior cruciate ligament-reconstructed knee. *Clin J Sport Med.* 1996;6(1):32-39.

10. Negahban H, Mazaheri M, Kingma I, van Dieen JH. A systematic review of postural control during single-leg stance in patients with untreated anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc.* 2014;22(7):1491-1504.

11. Broglio SP, Sosnoff JJ, Ferrara MS. The relationship of athlete-reported concussion symptoms and objective measures of neurocognitive function and postural control. *Clin J Sport Med.* 2009;19(5):377-382.

12. Cavanaugh J, Guskiewicz K, Giuliani C, Marshall S, Mercer V, Stergiou N. Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *Br J Sports Med.* 2005;39(11):805-811.

13. Guskiewicz KM. Assessment of postural stability following sport-related concussion. *Curr Sports Med Rep.* 2003;2(1):24-30.

14. Schmidt JD, Register-Mihalik JK, Mihalik JP, Kerr ZY, Guskiewicz KM. Identifying Impairments after concussion: normative data versus individualized baselines. *Med Sci Sports Exerc.* 2012;44(9):1621-1628.

15. Baier M, Hopf T. Ankle orthoses effect on single-limb standing balance in athletes with functional ankle instability. *Arch Phys Med Rehabil.* 1998;79(8):939-944.

16. Ekdahl C, Jarnlo GB, Andersson SI. Standing balance in healthy subjects. Evaluation of a quantitative test battery on a force platform. *Scand J Rehabil Med.* 1989;21(4):187-195.

17. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train.* 2012;47(3):339-357.

18. McGuine TA, Greene JJ, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clin J Sport Med.* 2000;10(4):239-244.

19. Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. *J Athl Train.* 1996;31(4):300-306.

20. Rogind H, Simonsen H, Era P, Bliddal H. Comparison of Kistler 9861A force platform and Chattecx Balance System for measurement of postural sway: correlation and test-retest reliability. *Scand J Med Sci Sports.* 2003;13(2):106-114.

21. Parker TM, Osternig LR, Lee H-J, Donkelaar Pv, Chou L-S. The effect of divided attention on gait stability following concussion. *Clin Biomech (Bristol, Avon).* 2005;20(4):389-395.

22. Broglio SP, Tomporowski PD, Ferrara MS. Balance performance with a cognitive task: a dual-task testing paradigm. *Med Sci Sports Exerc.* 2005;37(4):689-695.

23. Collie A, Makdissi M, Maruff P, Bennell K, McCrory P. Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of neurology, neurosurgery, and psychiatry.* 2006;77(2):241-245.

24. Covassin T, Schatz P, Swanik CB. Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery.* 2007;61(2):345-350; discussion 350-351.

25. Echemendia RJ, Putukian M, Mackin RS, Julian L, Shoss N. Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. *Clin J Sport Med.* 2001;11(1):23-31.

26. Eckner JT, Kutcher JS, Richardson JK. Effect of concussion on clinically measured reaction time in 9 NCAA division I collegiate athletes: a preliminary study. *PM R.* 2011;3(3):212-218.

27. Fazio VC, Lovell MR, Pardini JE, Collins MW. The relation between post concussion symptoms and neurocognitive performance in concussed athletes. *NeuroRehabilitation.* 2007;22(3):207-216.

28. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train.* 2001;36(3):263-273.

29. Majerske CW, Mihalik JP, Ren D, et al. Concussion in sports: postconcussive activity levels, symptoms, and neurocognitive performance. *J Athl Train.* 2008;43(3):265-274.

30. Resch JE, May B, Tomporowski PD, Ferrara MS. Balance Performance With a Cognitive Task: A Continuation of the Dual-Task Testing Paradigm. *J Athl Train.* 2011;46(2):170-175.

31. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train.* 2000;35(1):19-25.

32. Sosnoff JJ, Broglio SP, Ferrara MS. Cognitive and motor function are associated following mild traumatic brain injury. *Exp Brain Res.* 2008;187(4):563-571.

33. Parker TM, Osternig LR, van Donkelaar P, Chou L-S. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med.* 2007;41(12):868-873; discussion 873.

34. Parker TM, Osternig LR, Van Donkelaar P, Chou L-S. Gait stability following concussion. *Med Sci Sports Exerc.* 2006;38(6):1032-1040.

35. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil.* 2011;92(4):585-589.

36. Parker TM, Osternig LR, van Donkelaar P, Chou L-S. Balance control during gait in athletes and non-athletes following concussion. *Med Eng Phys.* 2008;30(8):959-967.

37. Fait P, McFadyen BJ, Swaine B, Cantin JF. Alterations to locomotor navigation in a complex environment at 7 and 30 days following a concussion in an elite athlete. *Brain Inj.* 2009;23(4):362-369.

38. Cantin J-F, McFadyen BJ, Doyon J, Swaine B, Dumas D, Vallée M. Can measures of cognitive function predict locomotor behaviour in complex environments following a traumatic brain injury? *Brain Inj.* 2007;21(3):327-334.

39. Catena RD, van Donkelaar P, Chou L-S. Altered balance control following concussion is better detected with an attention test during gait. *Gait & Posture.* 2007;25(3):406-411.

40. Catena RD, van Donkelaar P, Chou L-S. Cognitive task effects on gait stability following concussion. *Exp Brain Res.* 2007;176(1):23-31.

41. Catena RD, van Donkelaar P, Chou LS. The effects of attention capacity on dynamic balance control following concussion. *J Neuroeng Rehabil.* 2011;8:8.

42. Fait P, Swaine B, Cantin J-F, Leblond J, McFadyen BJ. Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: a preliminary study. *J Head Trauma Rehabil.* 2013;28(4):293-301.

43. Howell DR, Osternig LR, Koester MC, Chou L-S. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res.* 2014.

44. Howell DR, Osternig LR, Chou L-S. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil.* 2013;94(8):1513-1520.

45. Paterno MV, Hewett TE. Biomechanics of Multi-ligament Knee Injuries (MLKI) and Effects on Gait. *North American Journal of Sports Physical Therapy : NAJSPT.* 2008;3(4):234-241.

46. McKeon PO, Paolini G, Ingersoll CD, et al. Effects of balance training on gait parameters in patients with chronic ankle instability: a randomized controlled trial. *Clinical rehabilitation.* 2009;23(7):609-621.

47. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Balance failure in single limb stance due to ankle sprain injury: An analysis of center of pressure using the fractal dimension method. *Gait & Posture.* 2014;40(1):172-176.

48. Rogers ME, Fernandez JE, Bohlken RM. Training to reduce postural sway and increase functional reach in the elderly. *J Occup Rehabil.* 2001;11(4):291-298.

49. Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med.* 2011;39(4):866-873.

50. Boyd Y. Integrating Corrective Exercise with Traditional Athletic Trainer Evaluations. 2011; http://www.glata.org/documents/filelibrary/glata_2013_presentations/Integrating_CEx_with_Traditional_At_0AE7CD76F6648.pdf.

51. Patel B. The Single Leg Squat. 2014; http://www.bsmpg.com/the-single-leg-squat/.

52. Kerr B, Condon SM, McDonald LA. Cognitive spatial processing and the regulation of posture. *Journal of experimental psychology. Human perception and performance.* 1985;11(5):617-622.

53. Horak FB. Clinical measurement of postural control in adults. *Phys Ther.* 1987;67(12):1881-1885.

54. Horak FB. Clinical assessment of balance disorders. *Gait & Posture.* 1997;6(1):76-84.

55. Winter DA. Human balance and posture control during standing and walking. *Gait & Posture.* 1995;3(4):193-214.

56. Chaudhry H, Findley T, Quigley KS, et al. Measures of postural stability. *J Rehabil Res Dev.* 2004;41(5):713-720.

57. Nashner L. Practical biomechanics and physiology of balance. In: Jacobson G, Newman C, Kartush J, eds. *Handbook of Baalnce Function and Testing*. St. Louis, MO: Mosby Year Book; 1993:261-279.

58. Guskiewicz KM, Perrin DH. Research and Clinical Applications of Assessing Balance. *JSR.* 1996;5:45-63.

59. Hunter MC, Hoffman MA. Postural control: visual and cognitive manipulations. *Gait Posture.* 2001;13(1):41-48.

60. Vuillerme N, Nougier V. Attentional demand for regulating postural sway: the effect of expertise in gymnastics. *Brain research bulletin.* 2004;63(2):161-165.

61. Hellebrandt FA, Braun GL. The influence of sex and age on the postural sway of man. *American Journal of Physical Anthropology.* 1939;24(3):347-360.

62. Jansen EC, Larsen RE, Olesen MB. Quantitative Romberg's test. Measurement and computer calculation of postural stability. *Acta neurologica Scandinavica.* 1982;66(1):93-99.

63. Nashner LM. Adaptation of human movement to altered environments. *Trends in Neurosciences.* 1982;5(0):358-361.

64. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction of balance. Suggestion from the field. *Phys Ther.* 1986;66(10):1548-1550.

65. Sugano H, Takeya T. Measurement of body movement and its clinical application. *The Japanese journal of physiology.* 1970;20(3):296-308.

66. Merla JL, Spaulding SJ. The Balance System: Implications for Occupational Therapy Intervention. *Physical & Occupational Therapy in Geriatrics.* 1997;15(1):21-36.

67. Poole JL. Age Related Changes in Sensory System Dynamics Related to Balance. *Physical & Occupational Therapy in Geriatrics.* 1992;10(2):55-66.

68. Uchiyama M, Demura S. The role of eye movement in upright postural control. *Sport Sci Health.* 2009;5(1):21-27.

69. Berencsi A, Ishihara M, Imanaka K. The functional role of central and peripheral vision in the control of posture. *Human movement science.* 2005;24(5-6):689-709.

70. Guerraz M, Bronstein AM. Ocular versus extraocular control of posture and equilibrium. *Neurophysiologie clinique = Clinical neurophysiology.* 2008;38(6):391-398.

71. Cohen H, Heaton LG, Congdon SL, Jenkins HA. Changes in sensory organization test scores with age. *Age and ageing.* 1996;25(1):39-44.

72. Nashner LM, Black FO, Wall C, 3rd. Adaptation to altered support and visual conditions during stance: patients with vestibular deficits. *The Journal of neuroscience : the official journal of the Society for Neuroscience.* 1982;2(5):536-544.

73. Horstmann GA, Dietz V. The contribution of vestibular input to the stabilization of human posture: a new experimental approach. *Neuroscience letters.* 1988;95(1-3):179-184.

74. Dietz V, Horstmann GA, Berger W. Significance of proprioceptive mechanisms in the regulation of stance. *Progress in brain research.* 1989;80:419-423; discussion 395-417.

75. Guyton A. *Textbook of Medical Physiology.* 7th ed. Philadelphia, PA: Saunders; 1986.

76. Vander A, Sherman J, Luciano D. *Human Physiology: The Mechanisms of Body Function.* 5th ed. New York: McGraw-Hill; 1990.

77. Shaffer SW, Harrison AL. Aging of the somatosensory system: a translational perspective. *Phys Ther.* 2007;87(2):193-207.

78. Kivlan BR, Martin RL. Functional performance testing of the hip in athletes: a systematic review for reliability and validity. *Int J Sports Phys Ther.* 2012;7(4):402-412.

79. Riemann BL, Guskiewicz KM, Shields EW. Relationship Between Clinical and Forceplate Measures of Postural Stability. *JSR.* 1999;8(2):71-82.

80. Ingersoll CD, Armstrong CW. The effects of closed-head injury on postural sway. *Med Sci Sports Exerc.* 1992;24(7):739-743.

81. Cavanaugh JT, Guskiewicz KM, Stergiou N. A nonlinear dynamic approach for evaluating postural control: new directions for the management of sport-related cerebral concussion. *Sports Med.* 2005;35(11):935-950.

82. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc.* 1997;29(7 Suppl):S213-221.

83. Mrazik M, Ferrara MS, Peterson CL, et al. Injury severity and neuropsychological and balance outcomes of four college athletes. *Brain Inj.* 2000;14(10):921-931.

84. Peterson CL, Ferrara MS, Mrazik M, Piland S, Elliott R. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. *Clin J Sport Med.* 2003;13(4):230-237.

85. Register-Mihalik JK, Mihalik JP, Guskiewicz KM. Balance deficits after sports-related concussion in individuals reporting posttraumatic headache. *Neurosurgery.* 2008;63(1):76-80; discussion 80-72.

86. Nashner LM. Computerized dynamic posturography. In: Jacobson GP, Newman CW, Kartush JM, eds. *Handbook of balance function and testing*. St. Louis, MO: Mosby Year Book; 1997:261-307.

87. Black FO, Shupert CL, Horak FB, Nashner LM. Abnormal postural control associated with peripheral vestibular disorders. *Progress in brain research.* 1988;76:263-275.

88. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc.* 2005;11(1):58-69.

89. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA : the journal of the American Medical Association.* 2003;290(19):2556-2563.

90. Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control : a meta-analysis. *Sports Med.* 2008;38(1):53-67.

91. Gribble PA, Hertel J. Considerations for Normalizing Measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science.* 2003;7(2):89-100.

92. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* 2006;36(12):911-919.

93. Teyhen DS, Shaffer SW, Lorenson CL, et al. Clinical measures associated with dynamic balance and functional movement. *J Strength Cond Res.* 2014;28(5):1272-1283.

94. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* 2009;4(2):92-99.

95. Gray GW. *Lower Extremity Functional Profile.* wynn Marketing, Incorporated; 1995.

96. Sato K, Mokha M. Does core strength training influence running kinetics, lower-extremity stability, and 5000-M performance in runners? *J Strength Cond Res.* 2009;23(1):133-140.

97. Batson G. Validating a dance-specific screening test for balance: preliminary results from multisite testing. *Medical problems of performing artists.* 2010;25(3):110-115.

98. Coughlan GF, Fullam K, Delahunt E, Gissane C, Caulfield BM. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. *J Athl Train.* 2012;47(4):366-371.

99. Overmoyer GV, Reiser RF, 2nd. Relationships between asymmetries in functional movements and the star excursion balance test. *J Strength Cond Res.* 2013;27(7):2013-2024.

100. Trojian TH, McKeag DB. Single leg balance test to identify risk of ankle sprains. *Br J Sports Med.* 2006;40(7):610-613.

101. Sefton JM, Hicks-Little CA, Hubbard TJ, et al. Sensorimotor function as a predictor of chronic ankle instability. *Clin Biomech (Bristol, Avon).* 2009;24(5):451-458.

102. Herrington L, Hatcher J, Hatcher A, McNicholas M. A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *The Knee.* 2009;16(2):149-152.

103. Basford JR, Chou LS, Kaufman KR, et al. An assessment of gait and balance deficits after traumatic brain injury. *Arch Phys Med Rehabil.* 2003;84(3):343-349.

104. Chou LS, Kaufman KR, Walker-Rabatin AE, Brey RH, Basford JR. Dynamic instability during obstacle crossing following traumatic brain injury. *Gait Posture.* 2004;20(3):245-254.

105. McFadyen BJ, Swaine B, Dumas D, Durand A. Residual effects of a traumatic brain injury on locomotor capacity: a first study of spatiotemporal patterns during unobstructed and obstructed walking. *J Head Trauma Rehabil.* 2003;18(6):512-525.

106. Akbari M, Karimi H, Farahini H, Faghihzadeh S. Balance problems after unilateral lateral ankle sprains. *J Rehabil Res Dev.* 2006;43(7):819-824.

107. Aminaka N, Gribble PA. Patellar taping, patellofemoral pain syndrome, lower extremity kinematics, and dynamic postural control. *J Athl Train.* 2008;43(1):21-28.

108. Gribble PA, Hertel J, Denegar CR. Chronic ankle instability and fatigue create proximal joint alterations during performance of the Star Excursion Balance Test. *Int J Sports Med.* 2007;28(3):236-242.

109. Gribble PA, Hertel J, Denegar CR, Buckley WE. The Effects of Fatigue and Chronic Ankle Instability on Dynamic Postural Control. *J Athl Train.* 2004;39(4):321-329.

110. Smith CA, Chimera NJ, Warren M. Association of Y Balance Test Reach Asymmetry and Injury in Division I Athletes. *Med Sci Sports Exerc.* 2014.

111. Riemann BL, Schmitz R. The Relationship Between Various Modes of Single Leg Postural Control Assessment. *Int J Sports Phys Ther.* 2012;7(3):257-266.

112. Stone J. Functional Anatomy and Movement Assessment. http://goeata.org/protected/EATACD12/downloads/PDF/presentation-jostone4.pdf.

113. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech.* 2006;22(1):41-50.

114. Hatton AL, Kemp JL, Brauer SG, Clark RA, Crossley KM. Impairment of dynamic single-leg balance performance in individuals with hip chondropathy. *Arthritis care & research.* 2014;66(5):709-716.

115. Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. *Exp Brain Res.* 1993;97(1):139-144.

116. Teasdale N, Bard C, LaRue J, Fleury M. On the cognitive penetrability of posture control. *Experimental aging research.* 1993;19(1):1-13.

117. Teel EF, Register-Mihalik JK, Blackburn T, Guskiewicz KM. Balance and cognitive performance during a dual-task: preliminary implications for use in concussion assessment. *J Sci Med Sport.* 2013;16(3):190-194.

118. Lee H, Sullivan SJ, Schneiders AG. The use of the dual-task paradigm in detecting gait performance deficits following a sports-related concussion: a systematic review and meta-analysis. *J Sci Med Sport.* 2013;16(1):2-7.

119. Ingriselli JM, Register-Mihalik JK, Schmidt JD, Mihalik JP, Goerger BM, Guskiewicz KM. Outcomes, utility, and feasibility of single task and dual task intervention programs: Preliminary implications for post-concussion rehabilitation. *J Sci Med Sport.* 2013.

120. Brauer SG, Broome A, Stone C, Clewett S, Herzig P. Simplest tasks have greatest dual task interference with balance in brain injured adults. *Human movement science.* 2004;23(3-4):489-502.

121. Register-Mihalik JK, Littleton AC, Guskiewicz KM. Are Divided Attention Tasks Useful in the Assessment and Management of Sport-Related Concussion? *Neuropsychol Rev.* 2013.

122. Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. *Movement disorders : official journal of the Movement Disorder Society.* 2008;23(3):329-342; quiz 472.

123. Weerdesteyn V, Schillings AM, van Galen GP, Duysens J. Distraction affects the performance of obstacle avoidance during walking. *Journal of motor behavior.* 2003;35(1):53-63.

124. Brown LA, Shumway-Cook A, Woollacott MH. Attentional demands and postural recovery: the effects of aging. *J Gerontol A Biol Sci Med Sci.* 1999;54(4):M165-171.

125. Catena RD, van Donkelaar P, Chou L-S. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *J Neuroeng Rehabil.* 2009;6.

126. McCulloch KL, Buxton E, Hackney J, Lowers S. Balance, attention, and dual-task performance during walking after brain injury: associations with falls history. *J Head Trauma Rehabil.* 2010;25(3):155-163.

127. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport: the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *J Athl Train.* 2009;44(4):434-448.

128. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* 2006;21(5):375-378.

129. Lincoln AE, Caswell SV, Almquist JL, Dunn RE, Norris JB, Hinton RY. Trends in concussion incidence in high school sports: a prospective 11-year study. *Am J Sports Med.* 2011;39(5):958-963.

130. Daneshvar DH, Nowinski CJ, McKee AC, Cantu RC. The epidemiology of sport-related concussion. *Clin Sports Med.* 2011;30(1):1-17, vii.

131. McCrory P, Meeuwisse W, Aubry M, et al. Consensus statement on concussion in sport--the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Clin J Sport Med.* 2013;23(2):89-117.

132. Benson BW, Meeuwisse WH, Rizos J, Kang J, Burke CJ. A prospective study of concussions among National Hockey League players during regular season games: the NHL-NHLPA Concussion Program. *CMAJ : Canadian Medical Association journal = journal de l'Association medicale canadienne.* 2011;183(8):905-911.

133. Pellman EJ, Powell JW, Viano DC, et al. Concussion in professional football: epidemiological features of game injuries and review of the literature--part 3. *Neurosurgery.* 2004;54(1):81-94; discussion 94-86.

134. Duhaime A-C, Beckwith JG, Maerlender AC, et al. Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets: clinical article. *J. Neurosurg.* 2012;117(6):1092-1099.

135. Lau BC, Kontos AP, Collins MW, Mucha A, Lovell MR. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? *Am J Sports Med.* 2011;39(11):2311-2318.

136. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA : the journal of the American Medical Association.* 2003;290(19):2549-2555.

137. Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med.* 1995;5(1):32-35.

138. McCrory PR, Ariens T, Berkovic SF. The nature and duration of acute concussive symptoms in Australian football. *Clin J Sport Med.* 2000;10(4):235-238.

139. Meehan WP, 3rd, d'Hemecourt P, Collins CL, Comstock RD. Assessment and management of sport-related concussions in United States high schools. *Am J Sports Med.* 2011;39(11):2304-2310.

140. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE, Jr. Epidemiology of concussion in collegiate and high school football players. *The American journal of sports medicine.* 2000;28(5):643-650.

141. Kaut KP, DePompei R, Kerr J, Congeni J. Reports of head injury and symptom knowledge among college athletes: implications for assessment and educational intervention. *Clin J Sport Med.* 2003;13(4):213-221.

142. Broshek DK, Kaushik T, Freeman JR, Erlanger D, Webbe F, Barth JT. Sex differences in outcome following sports-related concussion. *J Neurosurg.* 2005;102(5):856-863.

143. Collins M, Stump J, Lovell MR. New developments in the management of sports concussion. *Current Opinion in Orthopaedics.* 2004;15(2):100-107.

144. Viano DC, Casson IR, Pellman EJ. Concussion in professional football: biomechanics of the struck player--part 14. *Neurosurgery.* 2007;61(2):313-327; discussion 327-328.

145. SCAT3. *Br J Sports Med.* 2013;47(5):259.

146. Lovell MR, Collins MW. Neuropsychological assessment of the college football player. *J Head Trauma Rehabil.* 1998;13(2):9-26.

147. Randolph C, Millis S, Barr WB, et al. Concussion symptom inventory: an empirically derived scale for monitoring resolution of symptoms following sport-related concussion. *Arch Clin Neuropsychol.* 2009;24(3):219-229.

148. Khurana VG, Kaye AH. An overview of concussion in sport. *Journal of clinical neuroscience : official journal of the Neurosurgical Society of Australasia.* 2012;19(1):1-11.

149. Lovell MR, Collins MW, Iverson GL, Johnston KM, Bradley JP. Grade 1 or "ding" concussions in high school athletes. *Am J Sports Med.* 2004;32(1):47-54.

150. Barth J, Alves W, Ryan T, al. e. Mild head injury in sports: neuropsychological sequela and recovery of function. In: Levin H, Eisenberg H, Benton A, eds. *Mild Head Injury*. New York: Oxford University Press; 1989:257-275.

151. Collins MW, Grindel SH, Lovell MR, et al. Relationship between concussion and neuropsychological performance in college football players. *JAMA : the journal of the American Medical Association.* 1999;282(10):964-970.

152. Gentilini M, Nichelli P, Schoenhuber R, et al. Neuropsychological evaluation of mild head injury. *Journal of Neurology, Neurosurgery & Psychiatry.* 1985;48(2):137-140.

153. Gronwall D, Wrightson P. Delayed recovery of intellectual function after minor head injury. *Lancet.* 1974;2(7881):605-609.

154. Gronwall D, Wrightson P. Cumulative effect of concussion. *Lancet.* 1975;2(7943):995-997.

155. Leininger BE, Gramling SE, Farrell AD, Kreutzer JS, Peck EA, 3rd. Neuropsychological deficits in symptomatic minor head injury patients after concussion and mild concussion. *Journal of neurology, neurosurgery, and psychiatry.* 1990;53(4):293-296.

156. Levin HS, Williams DH, Eisenberg HM, High WM, Jr., Guinto FC, Jr. Serial MRI and neurobehavioural findings after mild to moderate closed head injury. *Journal of neurology, neurosurgery, and psychiatry.* 1992;55(4):255-262.

157. Macciocchi SN, Barth JT, Alves W, Rimel RW, Jane JA. Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurgery.* 1996;39(3):510-514.

158. McCrea M, Kelly JP, Kluge J, Ackley B, Randolph C. Standardized assessment of concussion in football players. *Neurology.* 1997;48(3):586-588.

159. McCrea M, Kelly JP, Randolph C, et al. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil.* 1998;13(2):27-35.

160. Rimel RW, Giordani B, Barth JT, Boll TJ, Jane JA. Disability caused by minor head injury. *Neurosurgery.* 1981;9(3):221-228.

161. Collie A, Darby D, Maruff P. Computerised cognitive assessment of athletes with sports related head injury. *Br J Sports Med.* 2001;35(5):297-302.

162. Grindel SH, Lovell MR, Collins MW. The assessment of sport-related concussion: the evidence behind neuropsychological testing and management. *Clin J Sport Med.* 2001;11(3):134-143.

163. McCrory P, Johnston K, Meeuwisse W, et al. Summary and agreement statement of the second international conference on concussion in sport, prague 2004. *The Physician and sportsmedicine.* 2005;33(4):29-44.

164. Guskiewicz KM, Bruce SL, Cantu RC, et al. National Athletic Trainers' Association Position Statement: Management of Sport-Related Concussion. *J Athl Train.* 2004;39(3):280-297.

165. Reeves DL, Winter KP, Bleiberg J, Kane RL. ANAM genogram: historical perspectives, description, and current endeavors. *Arch Clin Neuropsychol.* 2007;22 Suppl 1:S15-37.

166. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol.* 2006;21(1):91-99.

167. McCrea M, Kelly JP, Randolph C, Cisler R, Berger L. Immediate neurocognitive effects of concussion. *Neurosurgery.* 2002;50(5):1032-1040; discussion 1040-1032.

168. Barr WB, McCrea M. Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion. *J Int Neuropsychol Soc.* 2001;7(6):693-702.

169. Erlanger D, Feldman D, Kutner K, et al. Development and validation of a web-based neuropsychological test protocol for sports-related return-to-play decision-making. *Arch Clin Neuropsychol.* 2003;18(3):293-316.

170. Lovell MR, Collins MW, Iverson GL, et al. Recovery from mild concussion in high school athletes. *J Neurosurg.* 2003;98(2):296-301.

171. McClincy MP, Lovell MR, Pardini J, Collins MW, Spore MK. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj.* 2006;20(1):33-39.

172. Bleiberg J, Cernich AN, Cameron K, et al. Duration of cognitive impairment after sports concussion. *Neurosurgery.* 2004;54(5):1073-1078; discussion 1078-1080.

173. Field M, Collins MW, Lovell MR, Maroon J. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *The Journal of pediatrics.* 2003;142(5):546-553.

174. Covassin T, Elbin RJ, Nakayama Y. Tracking neurocognitive performance following concussion in high school athletes. *The Physician and sportsmedicine.* 2010;38(4):87-93.

175. Adams J. The neuropathology of head injuries. In: Vinken P, Bruyn G, eds. *Handbook of Clinical Neurology: Injuries of the Brail and Skukll*. Amsterdam, Netherlands: North-Holland Publishing Co; 1975:35-65.

176. Arcan M, Brull MA, Najenson T, Solzi P. FGP assessment of postural disorders during the process of rehabilitation. *Scand J Rehabil Med.* 1977;9(4):165-168.

177. Geurts AC, Ribbers GM, Knoop JA, van Limbeek J. Identification of static and dynamic postural instability following traumatic brain injury. *Arch Phys Med Rehabil.* 1996;77(7):639-644.

178. Lehmann JF, Boswell S, Price R, et al. Quantitative evaluation of sway as an indicator of functional balance in post-traumatic brain injury. *Arch Phys Med Rehabil.* 1990;71(12):955-962.

179. Mauritz KH, Dichgans J, Hufschmidt A. Quantitative analysis of stance in late cortical cerebellar atrophy of the anterior lobe and other forms of cerebellar ataxia. *Brain.* 1979;102(3):461-482.

180. McIntosh T, Vink R. Biomechanical and pathophysiologic mechanisms in experimental mild to moderate traumatic brain injury. In: Hoff J, Anderson T, Cole T, eds. *Mild to Moderate Head Injury*. Boston, MA: Blackwell Scientific Publications; 1989:135-145.

181. Mitchell DE, Adams JH. Primary focal impact damage to the brainstem in blunt head injuries. Does it exist? *Lancet.* 1973;2(7823):215-218.

182. Rubin AM, Woolley SM, Dailey VM, Goebel JA. Postural stability following mild head or whiplash injuries. *The American journal of otology.* 1995;16(2):216-221.

183. Shumway-Cook A, Olmscheid R. A systems analysis of postural dyscontrol in traumatically brain-injured patients. *J Head Trauma Rehabil.* 1990;5(4):51-62.

184. Wober C, Oder W, Kollegger H, et al. Posturographic measurement of body sway in survivors of severe closed head injury. *Arch Phys Med Rehabil.* 1993;74(11):1151-1156.

185. Mallinson AI, Longridge NS. Dizziness from whiplash and head injury: differences between whiplash and head injury. *The American journal of otology.* 1998;19(6):814-818.

186. Greenwald BD, Cifu DX, Marwitz JH, et al. Factors associated with balance deficits on admission to rehabilitation after traumatic brain injury: a multicenter analysis. *J Head Trauma Rehabil.* 2001;16(3):238-252.

187. Rinne MB, Pasanen ME, Vartiainen MV, Lehto TM, Sarajuuri JM, Alaranta HT. Motor performance in physically well-recovered men with traumatic brain injury. *Journal of rehabilitation medicine.* 2006;38(4):224-229.

188. Kaufman KR, Brey RH, Chou LS, Rabatin A, Brown AW, Basford JR. Comparison of subjective and objective measurements of balance disorders following traumatic brain injury. *Med Eng Phys.* 2006;28(3):234-239.

189. Campbell M, Parry A. Balance disorder and traumatic brain injury: preliminary findings of a multi-factorial observational study. *Brain Inj.* 2005;19(13):1095-1104.

190. Gagnon I, Forget R, Sullivan SJ, Friedman D. Motor performance following a mild traumatic brain injury in children: an exploratory study. *Brain Inj.* 1998;12(10):843-853.

191. Kaya BK, Krebs DE, Riley PO. Dynamic stability in elders: momentum control in locomotor ADL. *J Gerontol A Biol Sci Med Sci.* 1998;53(2):M126-134.

192. Hahn ME, Chou LS. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *J Biomech.* 2004;37(6):837-844.

193. Notebaert AJ, Guskiewicz KM. Current trends in athletic training practice for concussion assessment and management. *J Athl Train.* 2005;40(4):320-325.

194. Catena RD, van Donkelaar P, Halterman CI, Chou L-S. Spatial orientation of attention and obstacle avoidance following concussion. *Exp Brain Res.* 2009;194(1):67-77.

195. Chiu S-L, Osternig L, Chou L-S. Concussion induces gait inter-joint coordination variability under conditions of divided attention and obstacle crossing. *Gait & Posture.* 2013;38(4):717-722.

196. Camicioli R, Howieson D, Lehman S, Kaye J. Talking while walking: the effect of a dual task in aging and Alzheimer's disease. *Neurology.* 1997;48(4):955-958.

197. Brauer SG, Woollacott M, Shumway-Cook A. The interacting effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *J Gerontol A Biol Sci Med Sci.* 2001;56(8):M489-496.

198. Brauer SG, Woollacott M, Shumway-Cook A. The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait Posture.* 2002;15(1):83-93.

199. Shumway-Cook A, Woollacott M. Attentional demands and postural control: the effect of sensory context. *J Gerontol A Biol Sci Med Sci.* 2000;55(1):M10-16.

200. Holtzer R, Friedman R, Lipton RB, Katz M, Xue X, Verghese J. The relationship between specific cognitive functions and falls in aging. *Neuropsychology.* 2007;21(5):540-548.

201. Li S, Aggen SH, Nesselroade JR, Baltes PB. Short-term fluctuations in elderly people's sensorimotor functioning predict text and spatial memory performance: The Macarthur Successful Aging Studies. *Gerontology.* 2001;47(2):100-116.

202. Nesselroade JR, Salthouse TA. Methodological and theoretical implications of intraindividual variability in perceptual-motor performance. *The journals of gerontology. Series B, Psychological sciences and social sciences.* 2004;59(2):P49-55.

203. Kleffelgaard I, Roe C, Soberg HL, Bergland A. Associations among self-reported balance problems, post-concussion symptoms and performance-based tests: a longitudinal follow-up study. *Disabil Rehabil.* 2012;34(9):788-794.

204. Brooks LR. The suppression of visualization by reading. *The Quarterly journal of experimental psychology.* 1967;19(4):289-299.

205. Strang A, Haworth J, Hieronymus M, Walsh M, Smart LJ, Jr. Structural changes in postural sway lend insight into effects of balance training, vision, and support surface on postural control in a healthy population. *European journal of applied physiology.* 2011;111(7):1485-1495.

206. Dorman JC, Valentine VD, Munce TA, Tjarks BJ, Thompson PA, Bergeron MF. Tracking postural stability of young concussion patients using dual-task interference. *J Sci Med Sport.* 2013.

207. Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport.* 2012;13(2):80-86.

208. Dionisio VC, Almeida GL, Duarte M, Hirata RP. Kinematic, kinetic and EMG patterns during downward squatting. *J Electromyogr Kinesiol.* 2008;18(1):134-143.

209. Hoffman MA, Koceja DM. Dynamic balance testing with electrically evoked perturbation: a test of reliability. *Arch Phys Med Rehabil.* 1997;78(3):290-293.

210. Swan L, Otani H, Loubert PV. Reducing postural sway by manipulating the difficulty levels of a cognitive task and a balance task. *Gait Posture.* 2007;26(3):470-474.

211. Ross LM, Register-Mihalik JK, Mihalik JP, et al. Effects of a single-task versus a dual-task paradigm on cognition and balance in healthy subjects. *JSR.* 2011;20(3):296-310.

212. Pearson KG. Common principles of motor control in vertebrates and invertebrates. *Annual review of neuroscience.* 1993;16:265-297.

213. Oliver GD, Di Brezzo R. Functional balance training in collegiate women athletes. *J Strength Cond Res.* 2009;23(7):2124-2129.

214. Mauntel TC, Frank BS, Begalle RL, Blackburn JT, Padua DA. Kinematic differences between those with and without medial knee displacement during a single-leg squat. *J Appl Biomech.* 2014;30(6):707-712.

215. Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for walking: Age-related changes. In: Anne-Marie F, Normand T, eds. *Advances in Psychology.* Vol Volume 114: North-Holland; 1996:235-256.