RELIABILITY OF THE SENSORY ORGANIZATION TEST OVER CLINICAL ADMINISTRATION TIME INTERVALS OF CONCUSSION ASSESSMENT

by

HYUNG ROCK LEE

(Under the Direction of Michael S. Ferrara)

ABSTRACT

Evaluating postural stability using instrumented posturography is recommended as one of the integral assessments in the concussion test battery. Traditionally, linear mathematical measures have been used for assessing postural stability, but measures that can detect the underlying nonlinear control of balance (e.g., multiscale entropy [MSE]) may be more valid. However, practice effects may affect intra- and inter-day reliability. Therefore, the purposes of this study were to: a) evaluate the test-retest reliability of the NeuroCom Sensory Organization Test (SOT), using the SOT software's 'equilibrium scores' and the complexity index (C_I) of laboratory-generated MSE values; and b) assess the interday reliability of practice effects at clinically-relevant time intervals. Healthy, college-age subjects (N=92) were randomly divided into two testing-order groups: block and random. At all test sessions, the block group performed the three trials of each of the six sensory conditions in the same order, from least to most sensory challenging; the random group performed the conditions in a random order. All subjects performed the SOT three times on day 1 (20-minute break), and one time on days 45 and 50. C_I was computed for each trial by integrating the MSE-scale values (N=2000, m=2, scales=2 to 20). Mixed-measures ANOVA and intraclass correlation coefficients were calculated (SPSS and R software). Major findings include a range of reliability from fair-to-good to excellent for C_{I}s as well as ESs in the anterior-posterior direction for 10 out of 12 SOT conditions, and fair-to-good reliability for C_{I}s in the medial-lateral direction. The results provided evidence of the clinically acceptable reliability of the SOT using C_{I} scores for AP and ML directions, especially for the AP direction for which the highest reliability was reported. Practice effects were exhibited between the first and second test, as increased SOT scores for composite and visual equilibrium scores were displayed at the second test. However, no differences in the SOT scores were found between test-order groups. The findings support that clinicians should administer at least one preliminary SOT to obtain the best baseline score for concussion assessment, thereby eliminating potential practice effects that would affect balance scores obtained from multiple administrations of the SOT.

INDEX WORDS: Sport-related concussion, Intraclass correlation coefficient, Postural stability, Non-linear dynamics.

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DEDICATION

To my lovely wife, Dr. Jaeyun Sung Ph.D:

For your love and support, from which I learned so much.

To my lovely family, Yang Soo Lee, Ki Sook Kim, and Hyung Chul Lee:

For all of your support and gift of education

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TABLE OF CONTENTS

Page

CHAPTER

1 INTRODUCTION

2 A REVIEW OF LITERATURE

3 METHODS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Background

Approximately 300,000 contact sport athletes sustain concussions in a single year in the U.S. [1]. However, this only accounts for Sport-Related Concussions (SRCs) that are accompanied by a loss of consciousness. In fact, SRCs with loss of consciousness make up fewer than 10% of the total brain injuries in the sports setting [2]. A recent epidemiology study in the U.S. has found that between 1.6 million and 3.8 million SRCs occur each year [3]. Although the estimated number of concussions includes people who do not seek medical care, the estimation still may not account for all of the SRCs because many athletes do not recognize the signs and symptoms of SRC, nor do they consider these injuries significant [4]. According to the previous research, the highest rates of SRC occur in football, but this sport also has the largest number of participants. Approximately 1,500,000 high school and 75,000 college athletes were estimated to have participated in football in the United States during the 2009 - 2010 football season [5]. Over the 2005 - 2006 seasons in the high school setting, 201 concussions were reported. The SRC rates were 0.21 per 1000 Athlete Exposure (A-E) in practice and 1.55 per 1000 A-E in competition. In college football, 246 SRCs were also reported. The SRC rates were 0.39 per 1000 A-E in practice and 3.02 SRCs per 1000 A-E in competition. Overall, both high school and college athletes were exposed to a higher risk of SRC during competition [6].

Over the last two decades, SRC has gained considerable attention from the media as well as the medical and scientific community. SRCs are still one of the most mystifying neurological dysfunctions and one of the least understood mechanisms of injuries facing the sport medicine clinicians. Many physical activities, especially contact sports, are associated with a high risk of SRC caused by direct and/or indirect contact to the head, neck, face, or other parts of the body, which transmits an impulsive force to the head [7]. SRC is understood as the result of the mechanical forces acting on the concussed brain, which is related to subsequent dysfunction due to the bimolecular and physiological changes in the concussed brain [8].

Accurately defining concussion plays an essential role in identifying the initial and continuous management of SRC while health care providers attempt to diagnose and assess the injury. The majority of SRCs are classified as mild traumatic brain injuries (mTBI) because they are at the less severe end of the brain injury range [9]. However, the Concussion In Sport Group (CISG) has suggested that the terminology for both concussion and mild traumatic brain injury should not be used interchangeably because they describe different injury constructs [10]. In addition, several organizations suggest a treatment protocol based on their definition of mild traumatic brain injury and/or concussion [7, 11, 12]. Recently, the CISG revised their definition of concussion as follows: "…a concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical force" [13]. With the increased attention on SRC, more concussion research has been conducted, resulting in the development of newer SRC management protocols [14].

The concussion studies include concern for the areas of long-term consequences of multiple concussions as well as mild cognitive impairment, increased self-reported symptoms, and postural instability following SRC [15-19]. While the majority of concussions are mild, SRC may result in long-term medical consequences with repeated head impact [20-22], and repeated concussions occurring over an extended period can result in cumulative cognitive deficits [23, 24]. Second Impact Syndrome can also occur as the result of repeated concussions over a short period of time and can be related to catastrophic fatal injuries due to an increase in intracranial vasodilatation and pressure [25].

Studies supporting that contact sports have a high incidence of concussion are well published [26-29] and various instruments for assessing SRC have been established [30-32]. Baseline testing is an essential part of concussion management and is ideally measured at the beginning of the appropriate sport season prior to contact drills. Serving as an individual's pre-injury performance score, baseline testing is critical in identifying and managing an SRC once injury has occurred. The recommended baseline testing consists of the neurocognitive test, the balance test, and the signs-and-symptoms test [12, 33].

A neuropsychological evaluation is commonly considered the cornerstone of concussion management, and is performed to assess the cognitive domain of neurologic function [13]. The relationship between neuropsychological performance and concussion has been explored in the literature [30, 34, 35] and has been found to be sensitive to subtle cognitive declines with SRCs [16, 31, 36]. A postural stability assessment has also been used to evaluate concussed athletes by measuring coordination of motor and sensory functions, and it is one of the objective domains of post-injury evaluation. Balance deficits may be associated with a declined ability to integrate the visual, vestibular, and somatosensory systems for maintaining the body in an upright position. Many researchers have investigated computerized dynamic posturography and clinical balance assessment in the SRC management protocol [37, 38]; both postural stability tests have been validated to detect subtle declines in balance performance [39, 40]. Currently, SRC management protocols have utilized both computerized balance systems and clinical balance tests to recognize declines in postural stability of post-concussive athletes 3-5 days following a concussion [37, 38, 40].

Self-reported concussion-related signs and symptoms are the most common tool for post-concussion evaluation and a major method for monitoring recovery [41, 42]. However, unlike neuropsychological and postural stability tests, self-reported symptoms are very subjective and based on the athletes' awareness, honesty, and willingness to present accurate information [43-45]. Since healthcare providers have faced difficulty with concussion assessments, it is recommended that clinicians rely on objective data and a multifaceted approach of concussion management [30, 46]. All of this attention, along with the research, is leading to a change in concussion guidelines, new position statements, and/or new recommendations for SRC management [13, 47].

Rationale of the Study

Healthcare providers utilize standardized concussion management tools to diagnose SRCs accurately and to obtain more objective evaluation data from the neuropsychological, postural stability, and self-reported symptoms tests [13, 47]. The purpose of each individual SRC management battery is to provide objective information to the sports medicine clinician for accurate evaluation and diagnosis of SRC and for making safe return-to-play decisions.

The use of the postural stability test for the management of SRC is gradually becoming more common among sport medicine clinicians, and clinical and laboratory postural stability evaluation has been adapted for the sports medicine setting. The Sensory Organization Test (SOT) has been developed based on existing theories of posturography in order to identify balance impairment related to the abnormal coordination between the sensory and motor functions of the central nervous system [37]. For an advanced understanding of concussion in sport, sophisticated concussion evaluation tools have also been applied in the management of SRC. The SOT on the SMART Balance Master® is designed to measure upright balance function under a variety of tasks. While equipment for computerized balance testing, such as the SOT on the SMART Balance Master®, is associated with high cost and time requirements, such sophisticated equipment provides more sensitive and objective information during concussion evaluation and recovery.

Generally, center of pressure (COP) data from the SMART Balance Master® are often used to evaluate human postural stability in concussion assessment [40]. However, since the human body is a complex system, analysis of the complex data is usually limited to linear consideration. For example, equilibrium scores (ES) on the SMART Balance Master® have three limitations. First, each healthy individual may vary in the limits of stability based on age and height. However, since the ES calculation is used for the overall magnitude of the limits of stability in degrees, 12.5^0 (8^0 for anterior sway and 4.5^0 for posterior sway), this estimation may introduce errors into the ES calculation for each individual [48]. Second, the ES for a given trial uses only the two extreme angular values, that are not behaviorally related to one another, to calculates an angular sway ‘displacement’, while discarding all of the richness of the rest of the sway angle data. Moreover, by using only two sway angles to estimate sway motion, one or both of the sway angles may skew the ES. Also, many combinations of the anterior and posterior sway angles can produce the same ES. For example, if the combination of the overall anterior and posterior sway angles is 6^0, the anterior sway could be 6^0 and posterior sway could be 0^0, or the angles could be 4^0 of anterior sway and 2^0 of posterior sway. However, a subject with 6^0 of anterior sway has a higher risk of falling because the subject is close to the limit of stability (8^0). Third, major biomechanical information, such as body mass and height, and ankle torque, is not included in the ES calculations [49-51], although these factors affect the limits of how far a person can sway and be stable. Therefore, the validity of the sway angle estimate is unclear.

Recently, a family of entropy measures has been applied to assess and understand postural control during physical activity, as well as other movement tasks [52, 53, 55, 56], because the ability to discern levels of complexity within biological data sets has become increasingly important. Approximate entropy (ApEn) and sample entropy (SampEn) are two similar entropy metrics of this family. Both are measures of randomness versus regularity of a phenomenological, time-series signal [54]. Thus, the family of entropy measures provides researchers assessment of regularity to quantify levels of complexity within a time series. In addition, ApEn has been introduced as potentially useful for SRC assessment management [49, 52, 53]. Upon development of this ApEn algorithm, Pincus demonstrated that, compared to other non-linear algorithms, ApEn could differentiate between noisy and chaotic time series [54, 55]. However, the ApEn algorithm has not gone without scrutiny. ApEn inherently includes a bias towards regularity, as it will count a self-match of vectors. Also, ApEn lacks relative consistency; that is, as the input parameters are changed, the value of ApEn may “flip” [54, 55]. However, SampEn, which is a refinement of the ApEn, does not count a self-match, thus eliminating the bias towards regularity. In addition, it has been suggested that SampEn is independent of data length and demonstrates relative consistency [57].

Nevertheless, as ApEn and SampEn are calculated for only a single-time scale, the regularity (predictability) of the time series is only known for that time scale. Multiscale entropy (MSE), a method of measuring the complexity, was introduced as an improved computation for investigating the regularity of physical and physiological data sets [57], in that MSE takes into account meaningful measure of complexity with multiple time scales [57]. The postural stability can be measured by the displacement of center of pressure (COP), and the COP data analyzed by the multiscale entropy (MSE) is effectively better than that processed by the traditional methods such as ES, which is utilized in the sway angle estimated indirectly from the COP data.

Regardless of whether clinicians will use the ES provided by the SMART Balance Master® software and/or the MSE value as an improved measure to assess sports-related concussion, practice effects for ESs and test-retest reliability of MSE must be established first for both scores. First, only a limited number of corresponding studies for the ES have been conducted for practice effects with multiple administrations [58, 62], especially considering elimination of the practice effects for obtaining the most valid baseline measures. Second, at present, no study has been conducted for test-retest reliability over clinically relevant time intervals of concussion management using the MSE measure and equilibrium scores. If we can find better reliability methods among the two outcome metrics (ES or MSE), we may be able to adapt the methods within the concussion evaluation further because test-retest reliability of the assessment tools is important to the sports medicine clinician when making decisions for return-to-play following an SRC.

<u>Baseline Concussion Evaluation</u>

Concussion management protocols have two major concerns. One is measuring baseline tests, which are used to establish ‘normal’ functioning in a non-injured state. The accurate measurement of the baseline performance of each individual athlete is very important to allow for an accurate comparison of the baseline score to the post-injury test score during the post-concussion evaluation and recovery period to help determine a return-to-play decision. If there is an inaccurate baseline test, the athlete may return to play too soon after concussion, which may directly result in second impact syndrome or other adverse consequences. In general, a new or unusual testing environment may not obtain the athlete's true ability for postural stability or may result in an inaccurate baseline score due to the novel task associated with the SMART Balance Master® SOT. Previous SOT studies with repeated measures show the composite equilibrium score (ES) of the SOT on the SMART Balance Master® plateaus at the fourth testing session over the total of six sessions (five times over a two-week period, and one month later) [58], and other studies also presented that clinical balance tests have investigated test-retest reliability as well as practice effects of the tests [59, 60]. Based on their findings, the authors recommended that multiple baseline measures are desirable to estimate the true ability of postural stability and for the balance testing [58]. Overall, sports medicine clinicians should be concerned about obtaining the true individual baseline score. They should also consider reducing errors associated with baseline scores or practice effects, which are caused by the nature of the concussion evaluation paradigm, based on repeated test measures over a short period of time.

The SOT on the SMART Balance Master® is designed to evaluate athletes' upright postural stability within several different tasks. The SOT consists of six different sensory conditions, and each condition is composed of three trials. The first three SOT conditions test static postural stability, which is the ability to hold an upright position moving as little as possible. The last three conditions are designed to test dynamic postural stability, which is the ability to maintain equilibrium while moving through space. (Note. For the dynamic stability conditions of the SOT, the person isn't moving through space—the person is still expected to remain as stationary as possible, but the support surface and/or the surrounding walls of the test apparatus tilt.)

The SOT procedure is designed to be administered in a particular test order, a "block" of three trials for each of the six sensory input conditions. The sensory conditions are administered in an order that increase in difficulty. Therefore, for the block test-order group, the subject knows what the next testing condition will be, which might help the participant achieve a better score than a person in the random test-order group who cannot anticipate the next test condition. A previous study designed to examine the effects of repeating the test on ES measures using the usual block testing order demonstrated some practice effect [58, 62]. However, no study utilizing random testing order was conducted. Two different types of SOT testing orders, block and random, may explain what specific types of SOT conditions reduce or inflate the practice effect.

Post-Injury Concussion Evaluation

The post-concussion evaluation interval, determined from unpublished University of Georgia data, is the estimated time between baseline testing and the first concussion assessment of collegiate athletes-baseline, 45 days, and 50 days after baseline. This investigation seeks to investigate the effect of the SOT on the SMART Balance Master® testing order. The second concern of a concussion assessment of athletes focuses on the post-injury evaluation. Previous studies have found that injured athletes demonstrate significantly declined postural control on the SOT [38] and the SOT has provided an accurate measure of the balance disturbance caused by the concussion [40, 61]. The test-retest reliability of SOT studies previously conducted used different populations, including the healthy young population [58, 62, 63], and only the composite equilibrium scores were used to measure the test-retest reliability of the SOT [58]. However, there have been no test-retest reliability studies using a clinically relevant time interval for concussion management.

This test-retest study is the most closely related to the above different types of testing conditions. The SOT with different types of testing conditions, block and random, along with the different measurement methods, ES and MSE, may be correlated and affect each other’s reliability scores. In order to accurately measure baseline norms, reduce test-retest practice effect, and increase test-retest reliability, all of the above considerations need to be reviewed throughout our research to correctly diagnose concussions and make for a safe return-to-play.

Purpose of the Study

The purpose of this study was two-fold. The first purpose of this study was to determine whether repeated SOTs performed on the SMART Balance Master® with two different testing-order groups (block and random) show different amounts of practice effects, that is improvement of balance scores with repeated performance.

The second purpose of this study was to identify test-retest reliability of the SOT using two different postural stability measures (ES and MSE) and the two different test orders for tests administered at time intervals that are the same as those used in pre- and post-concussion assessment (baseline, day 45, and day 50).

Specific Aims and Hypotheses

Topic 1: Practice Effects in Clinical Concussion Assessment: Serial Administration of the Sensory Organization Test (SOT) in Healthy Young Adults.

***Specific Aim 1*:** To determine whether block and random testing orders result in practice effects of the composite equilibrium score (ES) generated by the SMART Balance Master® using 5 consecutive administrations of the sensory organization test (SOT).

Hypothesis 1: Neither block nor random testing order in repetitive administrations of the SOT will produce practice effects of the composite ES throughout sessions 1 through 5.

Specific Aim 2: To determine whether block and random testing orders result in practice effects of the sub-composite equilibrium scores, including somatosensory (SOM), visual (VIS), vestibular (VEST), and preference (PREF), generated by the SMART Balance Master® using 5 consecutive administrations of the sensory organization test (SOT).

Hypothesis 2: Neither block nor random testing order in repetitive administrations of the SOT will produce practice effects of the sub-composite ESs (SOM, VIS, VEST, and PREF) throughout sessions 1 through 5.

Specific Aim 3: To determine whether differences exist between block and random testing-order groups for sessions 1-5 of the SMART Balance Master® SOT using the composite equilibrium (ES), somatosensory (SOM), visual (VIS), vestibular (VEST), and preference (PREF) scores.

Hypothesis 3: No group differences exist between block and random testing-order groups for sessions 1-5 of the SMART Balance Master® SOT using the composite equilibrium (ES), somatosensory (SOM), visual (VIS), vestibular (VEST), and preference (PREF) scores.

Topic 2: Test-retest reliability of the sensory organization test (SOT): multiscale entropy (MSE) values and equilibrium scores in healthy young adults.

Specific Aim 1: To establish the test-retest reliability of the MSE complexity index (C_I) for the block and random groups generated by the SMART Balance Master® SOT using the clinical administration intervals of concussion management.

Hypothesis 1.1: Intraclass correlation coefficients (ICC) calculated based on the C_I of MSE (AP) for the block and random groups between baseline and day 45 in healthy young adults will demonstrate excellent reliability.

Hypothesis 1.2: Intraclass correlation coefficients (ICC) calculated based on the C_I of MSE (ML) for the block and random groups between baseline and day 45 in healthy young adults will demonstrate excellent reliability.

Hypothesis 1.3: Intraclass correlation coefficients (ICC) calculated based on the C_I of MSE (AP) for the block and random groups between day 45 and day 50 in healthy young adults will demonstrate excellent reliability.

Hypothesis 1.4: Intraclass correlation coefficients (ICC) calculated based on the C_I of MSE (ML) for the block and random groups between day 45 and day 50 in healthy young adults will demonstrate excellent reliability.

Hypothesis 1.5: Intraclass correlation coefficients (ICC) calculated based on the ESs for the block and random groups between baseline and day 45 in healthy young adults will demonstrate excellent reliability.

Hypothesis 1.6: Intraclass correlation coefficients (ICC) calculated based on the ESs for the block and random groups between day 45 and day 50 in healthy young adults will demonstrate excellent reliability.

<u>Specific Aim 2:</u> To determine the effects of block and random testing orders on baseline, day 45, and day 50 of the SMART Balance Master® SOT using multiscale entropy (MSE) complexity index (C_I).

Hypothesis 2.1: Block and random testing-order groups will demonstrate no group differences on baseline, day 45, and day 50 of the SOT using the C_I of MSE (AP).

Hypothesis 2.2: Block and random testing-order groups will demonstrate no group differences on baseline, day 45, and day 50 of the SOT using the C_I of MSE (ML).

Hypothesis 2.3: Block and random testing-order groups will demonstrate no group differences on baseline, day 45, and day 50 of the SOT using the ESs.

Limitations and Delimitations

Limitations:

1. Time of day of testing was not controlled for.
2. Sleep and fatigue, prior to testing, was not controlled for.
3. Consumption of food and beverages before the test was not controlled for.
4. Exercise, including intensity or frequency, prior to testing was not controlled for.

Delimitations:

1. All subjects were drawn from undergraduate and graduate student population at the University of Georgia, Athens, GA campus.
2. All participants were healthy young adults, between ages of 18 and 38 yr.
3. All participants had self-report for no present injuries and/or pathologies related to balance.
4. All participants refrained from alcohol or drug use 24 hours prior to testing.

CHAPTER 2

A REVIEW OF LITERATURE

Epidemiology of Sports-Related Concussion

A comprehensive review of the literature indicates the recent increased attention to Sport-Related Concussion (SRC), as the number of SRCs with contact and non-contact sports has increased over the past decade [64, 65]. Approximately 300,000 SRCs are reported annually in the U.S. [28]. However, many SRCs have not been reported because athletes often fail to report SRC signs and symptoms and/or they are not correctly identified as having SRC signs and symptoms [4]. Even though a considerable amount of literature has been published on the estimated number of mild traumatic brain injuries in elite and recreational athletes, the actual number of SRCs has recently been questioned as research has revealed that it is still uncertain [66]. One recent epidemiology study has estimated that a more realistic figure for SRCs occurring annually in the U.S. is between 1.6 million and 3.8 million [67].

SRCs occur much more frequently in competition rather than during practice in high schools and colleges [6, 27], and more commonly in certain sports such as football, wrestling, girls' and boys' soccer, and girls' basketball [6]. In all sports, college athletes, most likely those in contact sports, have a higher rate of SRCs than high school athletes [6]. During the years 2004-2009, the incidence rate during a game based on 1,000 exposures was reported as 3.1 for football, 2.6 for men's lacrosse, 2.4 for men's ice hockey, 2.2 for women's ice hockey, 1.2 for field hockey, and 0.6 for men's basketball. An exposure was defined as 1 athlete participating in

1 practice or game (athlete-exposure, A-E), and injury rates were expressed as the number of injuries per 1000 A-Es [68].

Terminology of Sport-Related Concussion

In large part, Sport-Related Concussions (SRCs), which are on the less-severe end of the brain injury spectrum, refer to the subcategory of Mild Traumatic Brain Injury (mTBI) [9]. However, concussion, a term used interchangeably with mTBI, has been broadly used among the general public, and its definition remains ambiguous. This interchangeable terminology has made defining concussion difficult, and it has caused misunderstanding or confusion in the evaluation of concussion. Recently, the international conference on Concussion In Sport Group (CISG) [13, 69, 70] suggested that the term concussion should be separated from the term mild traumatic brain injury (mTBI), and the terms should not be used interchangeably.

Definition of Sport-Related Concussion

The definition of SRC should be simple, clear, and understandable for everyone, including athletes, coaches, and parents. However, defining and classifying SRC is difficult because concussion evaluations are represented with heterogeneous outcomes: diverse patterns of neurocognitive, sensorimotor, and self-reported signs and symptoms [71]. Although the definition of SRC remains vague, it is recommended that health care providers understand typical SRC definitions for clinical SRC management. First, the most widely mentioned definition of SRC was proposed by the Committee on Head Injury Nomenclature of the Congress of Neurological Surgeons in 1966 [11]. Concussion was defined as “a clinical syndrome characterized by immediate and transient impairment of neural functions, such as alternation of consciousness, disturbance of vision, equilibrium, etc. due to mechanical forces” [11]. However, this definition may not specify loss of consciousness and has shown limitation in explaining overall concussion [72]. In 1997, the American Orthopedic Society for Sports Medicine (AOSSM) Concussion Workshop Group [73] defined concussion as "any alteration in cerebral function caused by a direct or indirect (rotation) force transmitted to the head resulting in one or more of the following acute signs or symptoms: a brief loss of consciousness (LOC), light-headedness, vertigo, cognitive and memory dysfunction etc." Since the AOSSM definition includes a wide range of concussion signs and symptoms, the lack of a universal agreement on the definition of concussion has made it difficult to reach a consensus on concussion management. Recently, the International Conference on Concussion in Sport Group (CISG) has provided the following consensus statement for the definition of concussion management [13, 14, 69, 70]:

> Concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces. Several common features that incorporate clinical, pathologic, and biomechanical injury constructs that may be utilized in defining the nature of a concussive head injury include the following:
>
> 1. Concussion may be caused either by a direct blow to the head, face, neck or a blow elsewhere on the body with an "impulsive" force transmitted to the head.
> 2. Concussion typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously.
> 3. Concussion may result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury.
> 4. Concussion results in a graded set of clinical syndromes that may or may not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically

follows a sequential course. In a small percentage of cases, however, post-concussive symptoms may be prolonged.

5. No abnormality on standard structural neuroimaging studies is seen in concussion [13].

Classification of Concussion

Although there is a large volume of published studies describing the role of Sport-Related Concussion (SRC) grading systems, these grading systems currently exist with no consensus. The reason is that these grading-systems presume that loss of consciousness (LOC) is related to more severe SRC. However, more recently, the literature has emerged that offers the contradictory finding that LOC does not correlate with severity of SRC [19, 74]. For a systematic evaluation for SRC, although these grading systems are not validated and do not represent a view of all sports medicine clinicians, health care providers in the sport medicine setting have become familiar with their grading scheme. More than 16 different concussion-grading systems have been published [75-79]. Among these, the three concussion-grading systems below are the most widely used in sports medicine [80]. In particular, the Colorado grading system (28%) and Cantu grading system (19.3%) are the most commonly used in the athletic setting by Certified Athletic Trainers (ATC) [81]. These three grading scales are addressed in detail below.

American Academy of Neurology grading system for SRC [79]

Grade 1: No loss of consciousness
Transient confusion
Concussion symptoms or mental status abnormalities resolve in less than 15 min

Grade 2: No loss of consciousness
Transient confusion
Concussion symptoms or mental status abnormalities last more than 15 min.

Grade 3: Any loss of consciousness (either brief or prolonged)

Cantu grading system for SRC [75, 82].

Grade 1: No loss of consciousness
Post-traumatic amnesia is less than 30 min
Grade 2: Loss of consciousness is less than 5 min
Post-traumatic amnesia is greater than 30 min and less than 24 h
Grade 3: Loss of consciousness is greater than 5 min
Post-traumatic amnesia is greater than 24 h

Colorado grading system for SRC [83].

Grading 1: No loss of consciousness
Confusion without amnesia
Grading 2: No loss of consciousness
Confusion with amnesia
Grading 3: Loss of consciousness

However, it is important to remember that a recent study by the international conference on Concussion In Sport Group (CISG) reports that SRC grading systems should not be used to dictate concussion management [13, 69, 70], and no grading scale for SRC is universally accepted in the sport medicine field. SRC management should be used to treat concussed athletes with an individual approach, based on when the symptoms stop advancing and a complete return to a neurological and postural stability baseline is reached.

Biomechanics of Sport-Related Concussion

The past decade has seen the rapid development of the biomechanical aspect of the research, which has improved our understanding of SRC. The studies report major brain dysfunction with shearing force as a principal cause of injury [84], investigated as the stretching or tearing of axons through neuroimaging techniques, such as the MRI or CT scan [85]. SRC typically results from either a direct or indirect impact to the head [86]. First, SRC occurs with direct impact related to head-to-head contact, head-to-ground contact, and contact of head to other objects such as equipment (e.g. goal post) or an opponent's body part. The common mechanism in SRC is the coup and contrecoup injuries [85]. The slapping effect of the skull causes coup injury, and the brain tissue is damaged directly below the site of impact. A contrecoup injury is usually related to translational linear acceleration injuries, which cause the brain to bounce against and strike the rough bony protrusions on the opposite side of the skull. Second, SRC also results from an indirect impact, which can transmit forceful energy to the applied brain to cause concussion when the upper body is stopped or accelerated rapidly [86].

Currently, linear and rotational force are recognized as the two major mechanisms of brain injury [86]. Linear force usually produces intracranial damage to deformation of the skull and focal brain injuries [86]. A large and growing body of literature has investigated angular acceleration and rotational force, related to diffusing axonal brain injuries and leading to more serious concussive injuries [86, 87]. In most cases, SRC occurs from rapid acceleration-deceleration motion resulting from sustaining a combined linear and rotational force.

For measurement of direct head impacts, peak g's are used for measured acceleration. Like other measurements of head impact, the Gadd injury Severity Index (GSI) and the Head Injury Criterion (HIC) score are calculated by using peak g's and duration of impact by using the standard formulae. These equations are used to estimate the threshold for brain injury. A recent study by Naunheim et al. suggests threshold values as follows: "A GSI score of 1,500, a HIC score of 1,000, or a peak acceleration of 200g is considered the threshold value for a single impact to be likely to cause a significant brain injury" [88].

Numerous studies have attempted to establish the biomechanics of SRC with video analysis, crush dummy reconstruction, and live instrumentation of human sport participants, which provide us with real impact data for a minimal threshold of linear and/or rotational force to the head [87, 89-92]. A series of professional football concussion studies have published reconstruction of severity and specific direction of head impact with a crush dummy, which is reproduced based on the analysis of NFL game video [87, 89]. The authors report that the primary cause of concussion is translational head acceleration forces from a helmet's impact to the facemask at an oblique to lateral angle [87, 89]. The peak head acceleration in SRC is 98g (±28), and the peak linear acceleration in non-injured players is 60g (±24) [87]. However, a serious National Football League (NFL) study of concussions had the limitation of having an indirect measure for specific head impact. Another limitation in the reconstruction technique is making errors during the determination of the relative impact velocity of a helmet colliding with another object [91]. The previous study reported the velocity can be represented as much as 11% from the actual velocity [91].

Naunheim et al. measured the peak acceleration (peak g's) with a padding-embedded triaxial accelerometer, a triaxial accelerometer, Techmark IS100 (Lansing, Michigan), during high school football, ice hockey, and soccer games [88, 91]. The average acceleration was 29.2g (±1.0) for football and 35.0g (±1.7) for ice hockey. Peak acceleration in the head measures 54.7±4.1 for soccer heading, and no concussions were reported in this study. As a new technique for head impact measurement, Duma et al. conducted research using the Head Impact Telemetry (HIT) System (Simbex, Lebanon, New Hampshire), which is a wireless device that provides real-time data from an impact receiver in the inside of the helmet to the laptop computer located on the sideline [90]. The average peak acceleration was 32g (±64g) for the 3311 impacts that did not report an SRC [90]. Another study using the HIT system reported that an average impact acceleration was 20.9 g (±18.7g) with no concussion [92]. This is considerably lower than the average for non-injured players of 60g (±24) previously reported by Pullman and colleagues

[87]. However, Naunheim et al. reported the average peak acceleration for high school football was 29.2g (±1.0), which is very similar to Duma's reporting of 32g (±64g). Despite their differences, these current studies should be considered with the following two major differences: NFL studies analyze only severe open-field impacts in NFL games [87, 89], but high school and college football studies analyze all head impacts occurring during the game and/or practice without concussion. The peak acceleration with SRC was 98g (±28g) in the Pullman study [87] and 94g (±28g) in the Viano study [93]. Three peak linear head accelerations with SRC were also reported by Brolinson – 55.7g, 136.7g, and 117.6g [92].

The Molecular Pathophysiology of Concussive Brain Injury

Sport-related concussion has been defined primarily as a "complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" [70]. During the last two decades, much more information has become available for SRC assessment including neurological, neuropsychological, and neurophysiological studies. However, unfortunately, a pathophysiological understanding of SRC is still lacking, and no objective measurement methods of neurophysiological change following an SRC exist in order to determine the severity of the injury. Now, most of the studies on the neurometabolic cascade of SRC are limited in their application to concussion management, as these studies are based on the animal model. However, this animal model research has suggested a general understanding of the pathophysiological cascade following SRCs [8].

After an impulsive force to the brain or after a mechanical head trauma, these mechanical forces initiate a complex cascade of neurochemical and neurometabolic events. These events begin an abrupt change in the neurotransmitter and ion shifting cycle. An imbalance of sodium and potassium between intra- and extracellular space is related to releasing more excitatory neurotransmitters and accelerating efflux of potassium. Cell membranes increase their energy requirement (Glycolysis) for activating sodium-potassium pumps to restore homeostasis. As a by-product of energy, lactate is accumulated in the cell. This elevates the lactate level inducing acidosis, which in turn damages the membrane. It continues to change the blood brain barrier permeability and cerebral edema. Because of calcium influx, the mitochondria, which usually produce Adenosine Triphosphate (ATP), lead to the malfunction and impairment of oxidative metabolism. This kind of tremendous metabolic stress can damage the neural tissue. In addition, this injury-induced increase in glucose metabolism has been associated with lower cerebral blood flow. These imbalances between glycolysis and cerebral blood flow can result in remarkable neural cell damage. The metabolic cascade of concussion leading to this dysfunction is multidimensional, resulting initially in an acute stage of hyperglycolysis. This is followed by a more chronic period that has been termed “spreading depression” [8]. Based on animal research, researchers have documented the fact that an energy crisis exists after head trauma or injury. However, the critical questions for sport medicine clinicians are whether this energy crisis of SRC can be applied in our clinical evaluation and how long the crisis lasts. Although applying the findings of experimental studies using animals, which have a much shorter life span, to humans is tricky, we are able to understand the basic physiological and physiochemical change after concussion. For example, a glucose metabolism crisis resolves within seven to ten days for rats. In general, when comparing head injury-induced physiological and physiochemical change in animals to what is seen clinically, the time course of events appears to be longer for human athletes because the time frame or life span of rats is much shorter than that of humans. In addition, clinicians should use the time frame of the neurometabolic cascade of concussion for the reference material. The location of injury, the type of injury, and the severity of injury also affect the duration of this injury.

Sport-Related Concussion Management

SRC management and/or assessment including return-to-play decisions remain one of the most challenging responsibilities of health care providers. During the 1980s, researchers developed the Sport as a Laboratory Assessment Model (SLAM) and suggested standardized concussion management guidelines with the potential for collecting objective data. Finally, SLAM helped health care providers to make safe return-to-play decisions following SRCs [15]. Baseline assessment is a vital part of concussion management, and is ideally evaluated at the beginning of the specific sport season prior to when practice starts. Baseline testing is often composed of a self-reported symptoms checklist, a computerized neuropsychological test, and a postural stability test. These components can give an accurately established assessment of the individual player's normal performance of cognitive, postural stability, and pre-existing symptoms [94]. An athlete who takes baseline tests prior to the beginning of the season will have the same components of concussion assessment again when the athlete has a SRC. This baseline evaluation is important to accurately measure changing clinical signs and symptoms in a deteriorating situation. The differences between the pre- and post-injury test scores will help health care providers in making the return-to-play decision. Recently, the CDC has made a couple of important points concerning baseline testing: first, only a trained health care provider should administer baseline testing, and, second, only a health care provider trained in concussion management should interpret the results of a baseline test [28].

On-field and Sideline Concussion Management

The main purpose of an on-field evaluation for an unconscious concussed athlete is to confirm whether or not the athlete has a life-threatening head and neck injury. The on-field Sport-Related Concussion (SRC) management should include an assessment of airway, breathing, and circulation (ABCs), followed by the assessments for the cervical spine fracture, spinal cord injury, and/or cranium associated injury. If an athlete is suspected to have a closed head injury, the concussed athlete may exhibit delayed verbal responses, be confused, and/or be emotionally unstable etc. A Glasgow Coma Scale may be applied to assess the level of consciousness. The main purpose of this assessment tool is to measure objectively and quantify the level of consciousness of a concussed athlete.

With sideline evaluation of SRCs, the suspected concussed athlete has to stop participating in the sport or play, and a physical exam should be performed by a licensed health care provider, who has specialized training in the management of SRCs [14]. General medical history and neurologic screening, such as the cranial nerve test, should be included in the physical exam. Several different tools for the standardized SRC evaluation on the sideline are well published: the cognitive test, balance test, and self-reported symptom checklist [14]. First, the Standardized Assessment of Concussion (SAC) is developed to establish a systematical assessment immediately following the SRC [95]. Since SRCs are often associated with mild cognitive deficit, the SAC includes measuring orientation, immediate memory, concentration, and delayed recall. It simply provides the presence and severity of neurocognitive impairment associated with SRCs [96]. Results of a previous study indicated that a decline of 1 point on the SAC classified injured and non-injured athletes with a level of 94 % sensitivity and 76% specificity [97]. Other research also found that the SAC assessed that cognitive function significantly declined in orientation, concentration, and memory immediately at post-injury with a level of 95% sensitivity and 76% specificity. Based on the literature review, the SAC appears to be a valid instrument for detecting the immediate effects of SRCs. However, since McCrea et al. found some practice effect with multiple administrations of the SAC, clinicians should consider using alternate forms of the test within a short period of time before making a return-to-play decision [96].

The 2nd International Symposium on Concussion In Sport (CIS) led to the development of a new Sport Concussion Assessment Tool (SCAT) for athletes. The SCAT combines existing assessment tools for self-concussion evaluation and physician's assessments of SRCs, and is designed for concussed youth hockey players aged 9-17 years. The SCAT provides a sideline assessment tool that evaluates SRC via a self-reported symptoms checklist and assessment of attention, memory, and concentration [70]. The 3rd International Conference on CIS in 2008 produced the Sport Concussion Assessment Tool 2 (SCAT 2) [13] for standardized assessment of SRCs by trained health care providers. SCAT 2 is designed for concussed athletes aged 10 years and older, and is the first sideline assessment tool for combining multi-facet SRC management; SCAT 2 includes the self-reported symptoms checklist, SAC score (cognition, delayed recall, coordination etc.), Glasgow Coma Scale, and modified Balance Error Scoring System (M-BESS). SCAT 2 has been recommended and widely accepted as a standardized method of evaluating concussed athletes on the sideline.

Since athletes with SRC experience a decline in not only neuropsychological functions but also motor control functions, the balance test is one of the major indicators of deterioration of motor functions with SRC. Various clinical postural stability tests are used in the sports medicine setting to assess diverse aspects of motor functions. Since one of the most common clinical assessments of balance, Romberg’s test, does not detect SRC, one of the most widely used measures is the Balance Error Scoring System (BESS), which is developed to objectively measure postural stability in athletes following SRC. The BESS includes three different stands (double, single, and tandem) and two different surfaces (firm and foam). A modified BESS (M-BESS) utilizes the three different stands on a firm surface only. Athletes are requested to assume the required stance by placing their hands on the iliac crests and the twenty-second testing begins upon eye closure. The athlete’s performance is scored by the accumulation of error points (one error point for each error). According to the previous studies, the BESS seems to be a reliable method of assessing postural stability for concussed athletes. Previous studies indicated that test-retest reliability was good for the BESS with the non-concussed population [37]. However, McCrea et al. conducted a meta-analysis study, which reported that the sensitivity and reliability of the M-BESS needed further research for detecting balance deficits in concussed athletes assessed on the sidelines [98]. Since concussion evaluation is a repeated measure in nature, sports medicine clinicians should also consider the practice effect with clinical administration. Results of previous studies indicated that there were no practice effects with multiple administrations of the BESS [99, 100], but other studies reported practice effects with multiple administrations of the BESS [37]. More research to refine the BESS for use on the sidelines is warranted.

In March 2013, SCAT 2 was replaced by SCAT 3, which was issued after the 4th International Conference on CIS in 2012. SCAT 3 is designed for concussed athletes aged 13 years and older, and the new version, child SCAT 3, was issued for children aged 5 to 12 years [14]. Although the SCAT series of SRC management has been recommended and widely accepted as a standardized method of assessing concussed athletes on the sidelines, a number of concerns have been expressed about the scoring and design. Also, since few sensitivity and specificity studies have been conducted with concussed athletes, further research is required to examine the reliability of both SCAT 2 and 3 [98].

Off-Field Concussion Management

Sport-Related Concussion (SRC) is characterized by the rapid onset of neuropsychological impairment, declining postural stability, and increased concussion-related signs and symptoms. It is recommended that SRCs should be evaluated in a timely manner and with a systematic approach of management consisting of a multi-faceted assessment that includes computerized neuropsychological assessment, computerized postural stability test, and concussion-related signs and symptoms test [101].

Neuropsychological Assessment of Sport-Related Concussion

A group of experts at the most recent International Conference on Concussion In Sport (CIS) [10] agreed that the neuropsychological (NP) test is one of the "cornerstones" of SRC management in determining when it is safe for an athlete to return-to-play after a concussion [69]. For high-risk sports such as football, hockey, lacrosse, soccer, and basketball, regardless of the athlete's age, the formal baseline NP test is recommended. Baseline testing provides a "pre-injury" and/or normal level of neurocognitive function, and a post-injury neuropsychological test is common at the professional and college level. Now, it is increasingly used at the high school level as well [12].

Over the past decade, NP assessment has moved away from the traditional paper-pencil based NP test to the computerized neurocognitive assessment tools. Paper-pencil based NP tests are administrated individually by licensed clinical neuropsychologists, and these NP tests assess various domains of cognitive functions, specifically identified as memory, concentration and attention, orientation, processing speed, reaction time and impulse control [17, 95, 102, 103]. The common names of paper-pencil NP tests and their respective domains of cognitive function are listed in Table 1 [10].

Table 1. Common Neuropsychological Tests used in SRC Management [10]

Neuropsychological Test	Domain of cognitive function
Wechsler Letter-Number sequencing Test	Verbal working memory
Wechsler Digit Span Test: (Digits forward and digits backward test)	Attention, concentration
Controlled Oral Word Association Test	Verbal fluency
Stroop Color Word Test	Attention, information processing speed
Hoskins Verbal Learning Test	Verbal learning, immediate and delayed memory
Train Making Test: Part A and B	Visual scanning, attention, information processing speed, psychomotor speed
Symbol Digit Modalities Test	Psychomotor speed, attention, concentration

In the 1980s, Barth and colleagues conducted the first large-scale study on NP assessment of concussed athletes. They developed the foundation for current concussion management practice [104] with a paper-pencil based NP test, which generally evaluated the global domains of cognitive functions for the concussed athletes. This global approach of the neurocognitive test was the strength of the paper-pencil based test. However, one weakness of the paper-pencil based test was that it was neither practical nor economical for a large number of athletes within a short period of time [105].

During the late 1990s, researchers developed multiple computerized NP test batteries for the management of SRC [106]. The most common available programs include Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), Cog-Sport (recently renamed

CogState), Concussion Sentinel, and Headminder-Concussion Resolution Index. Computerized NP assessment tools have been self-administrated without the assistance of trained and/or supervised health care providers. There are several major advantages. First, the computerized NP test is efficient and has an economical advantage for SRC management, especially baseline testing, in that large numbers of athletes can be tested within a short period of time. Other advantages of computerized NP tests are that the practice effects can be reduced by using randomization of multiple versions of the test, accuracy for reaction time measure is increased within 0.001 second, a standardized test battery is available, centralized data storage can be maintained [12, 107, 108], and the inter-rater reliability issue or error is reduced. Since the main purpose of NP testing is to evaluate for possible change in cognitive function between baseline and post-concussion evaluations, the critical considerations of the concussion assessment are sufficient reliability [101], validity [109], sensitivity [31], and specificity [110] of the test. Several previous studies have demonstrated test-retest reliability of computerized NP tests. Broglio et al. investigated the reliability of three different computerized NP testing platforms with clinical administration time intervals: baseline, day 45, and day 50. The reliability of the three different platforms ranged from 0.15 to 0.39 for the ImPACT, from 0.23 to 0.65 for the Concussion Sentinel, and from 0.15 to 0.66 for the Concussion Resolution Index between baseline and day 45 [101]. Schatz et al. reported the sensitivity and specificity of the ImPACT as 81.9% and 89.4%, respectively. Other recent studies have reported the sensitivity of two other different computerized NP tests (HeadMinder Concussion Resolution Index, 78.6 %; and Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), 79.2%) [31]. However, although computerized NP testing has been become the standard in SRC assessment in the sport medicine setting, Randolph et al. suggested that more research is needed on the validity, reliability, and sensitivity of computerized NP testing to provide valid clinical SRC management [107]. Overall, several studies have demonstrated that concussed athletes significantly decline in their cognitive level when compared with baseline testing. The results indicate that concussed athletes return to normal within 10 days after injury [21, 111]. In large part, high school and college athletes usually recover relatively quickly from concussion, with NP test returning to baseline within 3 to 5 days of initial injury [21]. However, previous research has suggested that high school athletes take longer to reach baseline, with average recovery times of 10 to 14 days [111].

Currently, computerized NP testing is widely accepted in a variety of athletic settings, such as those at the professional, college, and high school levels, and plays a major role in the evaluation and management of SRC. Several sports-related concussion statements recommend a multifaceted approach for SRC management, including NP testing, a postural stability test, and a self-reported symptoms checklist [10, 12], which increases sensitivity and specificity of SRC evaluation up to 90% [31].

Posturography Assessment of Sport-Related Concussion

Concussed athletes experience a decline not only in neuropsychological function but also motor control function. The postural stability test is one of the major indicators of deterioration of motor function following SRC. The most common postural stability test in the clinical setting is Romberg’s test, but it is not sufficiently sensitive to detect SRC. The Balance Error Scoring System (BESS) and the modified BESS (M-BESS) were developed to objectively measure postural stability in athletes, and they are utilized in clinical evaluation such as a sideline test following SRC. Although dynamic as a posturography testing system, the SOT on the SMART Balance Master® (Natus Medical Incorporate, Clackamas, Oregon USA) has a limitation for a clinical evaluation due to the expensive cost of the NeuroCom. However, the SOT is the gold standard in postural stability testing.

Commonly, postural stability is defined as the ability to control the center of gravity (COG) maintained within the body's base of support, and a base of support (BOS) is defined as the area contained within the perimeter of contact between the surface and the 2 feet. The postural stability system in humans has a complex network of neural connections related by central and peripheral nerve feedback mechanisms, which are divided into 2 major parts to maintain balance: "sensory organization" and "muscle coordination" [40, 112]. Sensory organization is comprised of somatosensory (SOM), visual (VIS), and vestibular (VEST) sensory feedback mechanism [113], and it can determine a human's timing, direction, and amplitude of postural corrective actions to maintain balance based on the information from these three different inputs, SOM, VIS, VEST system. The SOT on the SMART Balance Master® was developed on the feedback mechanism, especially sensory organization [40]. The cerebellum is also a vital structure for controlling balance, and the afferent signals from three different inputs are integrated in the pre-motor and supplementary motor cortex in the cerebellum. The muscle coordination describes controlling muscles' contractile activity and/or temporal sequencing of the muscles for movement and balance. The efferent pathways are alpha motor neurons, which innervate the skeletal muscles allowing for regulation of balance [114].

Many researchers, therapists, and health care providers use the equilibrium score (ES) on the SMART Balance Master®, which measures the coordination of the visual, vestibular, and proprioceptive inputs of the balance system while maintaining upright posture. Composite ES indicates the overall level of individual postural stability performance, and it is the major test outcome of the SOT on the SMART Balance Master®. The SOT on the SMART Balance

Master® is designed to systematically disrupt the coordination of the 3 sensory inputs, such as the visual, vestibular and proprioceptive, while at the same time measuring the subjects' ability to maintain a motionless stance. The SOT on the SMART Balance Master® is composed of 3 different visual conditions (eyes open, eyes closed and sway-referenced visual surround) and crossed with 2 different surface conditions (fixed and sway referenced). During the experiment, athletes are asked to stand as motionless as possible. The SOT has a total of 6 conditions with 3 separate trials for each condition; the test contains 18 trials total [18]. This is the most reliable and sensitive balance-testing instrument currently used in the sports medicine and clinic setting. Thus, this instrument clinically provides more objective data that can help with return-to-play decisions more precisely.

The concussed brain after SRC deteriorates in coordinating the function of 3 different sensory systems—the visual, vestibular, and somatosensory systems. This results in increased postural instability with anterior-posterior direction, medial-lateral direction, or both. These deficits are most likely temporary dysfunction, but sometimes, permanent postural instability is reported after several concussions [18, 115]. Previous studies investigating concussed athletes using SOT on the SMART Balance Master® detected a subtle change in sensory interaction causing a balance deficit. Results of these studies indicated that the postural stability of concussed athletes declined with increasing task demands during the SOT on the SMART Balance Master® [37, 40, 115]. The declined SOT score identified a disruption of sensory integration lasting for an average of 3 - 5 days post-injury. This result is similar to that of the clinical balance test, BESS, following SRC [18, 37].

Recently, a new paradigm for concussion management, dual-tasking methodology, has been introduced in the sport medicine setting [114]. Compared with single-task conditions, in the dual-tasking paradigm, which is natural in the athletic environment, subjects face both physical and mental demands so that they must perform two different tasks, cognitive and motor tasks, simultaneously. However, as further research is needed, application of dual-tasking methodology is not currently advocated for SRC management [114].

Multiscale Entropy (MSE)

Healthy humans (i.e., those with a healthy physiological system) maintain balance in daily life by constantly monitoring the complex intrinsic sensory input that is sensitive to changes in the body's kinematics and the extrinsic forces and environmental factors (e.g., unstable surface) that threatens loss of balance and then making appropriate postural responses. Humans learn how to anticipate and adapt their postural responses to a myriad of threats to postural stability. Therefore, because of experience and the complexity of the postural control system, a human is able produce optimal postural responses as needed using anticipatory postural control, feedback mechanisms, reflexes and appropriate muscle responses (e.g., postural muscle synergies) [116, 119, 120].

A hallmark of a healthy physiological system is its " extraordinary complexity" of movement of patterns associated with system stability [117]. The healthy postural control system demonstrates highly complex, and often irregular, dynamics that arise from the integration of complex networks of the motor and sensory control systems with many degrees of freedom [121,122]. This complexity, signifying the presence of chaotic temporal variations in the steady state output of a healthy system, represents the underlying physiologic capability to make flexible adaptations to everyday stresses placed on the human body [117], in that healthy systems are adaptable and flexible in an unpredictable and dynamic environment.

In general, there are two general postural control models upon which interpretations for measures of postural control are based: (A) the linear-dynamical model [58] and (B) the non-linear dynamic model [54]. The linear-dynamical model of postural control is based on a stimulus-response paradigm within a sensory-motor feedback loop: the sensorimotor system encompasses all of the sensory, motor, and central integration and processing components involved in maintaining postural stability. Greater sway is believed to be associated with control deficiencies of individual postural control system components. Thus, investigators who use these linear models of postural control to investigate or assess balance generally assume that the variability of the center of gravity movement is related to postural control deficits. These linear dynamics models also assume that the magnitude of variability of the balance measure represents the severity of disruptions in the sensory-motor feedback loop in the individual system. For example, from center of pressure (COP) data obtained during an SOT using the SMART Balance Master®, SOT equilibrium scores (ESs) are generated using the maximum COP displacements of each sensory condition. Higher displacements translate into higher sway and a lower than typical SOT equilibrium composite score. The lower ES score would be interpreted as a sign of poor balance and deficient postural control. However, as this postural stability measurement does not consider the human complexity and regularity of temporal and spatial components, the linear model is limited in explaining this analysis of interactions among underlying postural control systems [112, 123].

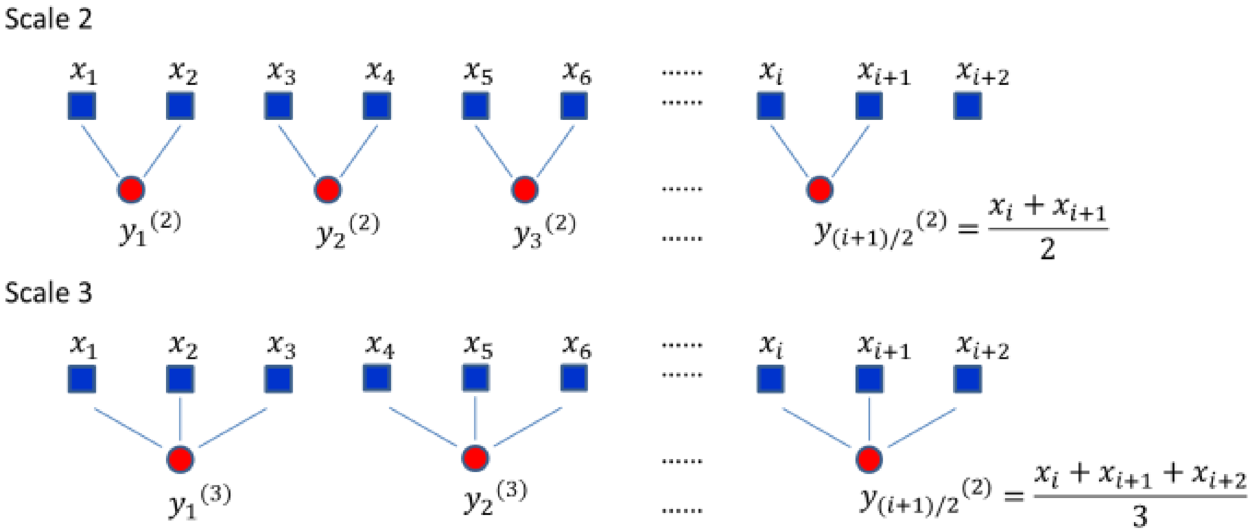
Scholars have long been interested in analyzing biological signals in terms of their complexity and nonlinear behavior [54, 55]. For the nonlinear, dynamical systems approach to understanding or assessing postural control, the irregular dynamics of physiological outputs (e.g., COP-time patterns) are considered "complex," containing "meaningful structural richness" and "hidden information" [117, 124], which include COP signals with the highest information content over multiple temporal / spatial scales. However, there is no agreement on the definition of 'complexity' and, consequently, no single measure of complexity. Entropy of the physiological system, as measured using statistical mechanics, is thought (although not proven) to be related to the complexity of the system. Roughly speaking, the level of entropy displayed during standing posture actually is more of a measure of the regularity or predictability of COP data [125]. Underlying the conceptual framework of the non-linear model are the notions that: 1) a healthy physiological system with intact regulatory mechanisms, which have the highest capacity to adapt to a dynamic environment, generates the richest outputs, and 2) intervention that enhances postural balance control also enhances dynamic complexity.

Approximate Entropy (ApEn) and Sample Entropy (SampEn), which are two similar entropy metrics, can quantify the degree of regularity of COP data for a single trial of a balance task [55, 127]. When determining the 'repeatability' or regularity of the data, the data are divided into windows of a set length of time, and then the windows are compared to one another to see how many match within a given tolerance level. The probabilities of the number of matches of similar windows and the number of those window matches that also display similarity when the next corresponding data sample is added to each window are then used in Shannon's information entropy equation. Information entropy represents the probability of improvement in predictability of the data when more information is added (in this case, when another data point is added to each window and the windows still match). Therefore, if the time series data are perfectly repetitive, the value of ApEn or SampEn is zero. With increasing irregularity or randomness (unpredictability) of the data, correspondingly, the entropy value increases.

Entropy-based algorithms, such as ApEn or SampEn, are only associated with regularity (predictability) of time-series data on a single time scale. What this means is that typically, entropy is calculated using windows of data of a set length of time, that is, a single-time scale. For example, Cavanaugh et al. conducted a post-concussion balance test with ApEn techniques using the SOT data. Results of this study supported that concussed athletes had postural stability deficits persisting 3 to 4 days after SRC [53, 56]. However, a single-time scale may not capture the structural characteristics of an output signal known to be complex at a variety of time scales, and thus these single scale entropies may fail to detect physiological complexity.

To overcome this issue, multiscale entropy (MSE) has been proposed as an improved computational process for investigating physical and physiological phenomena [57] including postural data [56]. There are two main computational differences between MSE and single-scale entropy measures: a) the data to be analyzed are converted into multiple-time scale data for a range of scales thought to be behaviorally meaningful; and b) a sample entropy value is calculated for the data of each time-scale, thereby generating multiple entropy values. Therefore, to carry out the MSE procedure, first, multiple data sets ($y^{(\tau)}$), each representing a different time scale (τ), are generated as shown in Figure 1. Using the original time-series data for each time scale of interest, each new time-scale set of data $y^{(\tau)}$ is constructed by “coarse-graining” the data. The original data (x_i where i = data sample number; i = 1 to N, the total number of data samples) are divided into non-overlapping windows, whose lengths are the current time-scale length (τ). Then, for each data window, the data contained in the data window are averaged. Therefore, the average of each window becomes an element of the new data series, $y_j^{(\tau)}$, where *j* represents a given data window of the current time -scale, τ. This process is akin to down sampling and, simultaneously, smoothing the data at a cutoff frequency related to the current time -scale.

SampEn entropy is then calculated at that time scale, and the process is repeated for each of the remaining time scales [57, 130].



$$y_j^{(\tau)} = \frac{1}{\tau} \sum_{i=(j-1)\tau+1}^{j\tau} x_i \qquad 1 \leq j \leq \frac{N}{\tau}$$

Figure 1. Schematic Illustration of the Coarse-Grained Procedures and the Averaging Equation used to generate the new data (*y*) from the original data (*x*) for the scale factor (τ). N/τ represents the length of each coarse-grained time series (Adapted from Shuen-De et al., 2013) [131]. The coarse-grained procedure is shown for two time scales, “Scale 2” and “Scale 3”. Scale one is not shown, as it represents the original time series data).

As the output of MSE is SampEn values of every time scale from the lowest to the highest chosen by the researcher, MSE is a more sensitive measure of physiologic variability. Therefore, when assessing the balance of a performer with a diseased or injured system, if the medical condition causes the postural control system to produce more ‘regular’ behavior, the single-scale, traditional entropy value may show reduced entropy (or no changes to entropy) compared with the dynamics of people with healthy postural control systems. However, this interpretation may be erroneous. Certain pathologies, such as cardiac arrhythmia, are associated with highly erratic outputs with statistical properties resembling uncorrelated, random noise. In these situations, the single traditional entropy value may yield an increase in entropy compared to a healthy system. Therefore, increased entropy could be misinterpreted as high physiological complexity similar to that of a healthy cardiac system. Hence, MSE can represent more accurately the complex temporal fluctuations inherent in healthy physiologic control systems [57].

Costa, Goldberger, and Peng [57, 130, 135] proposed that MSE was more appropriate than single-time series entropy measures based on three basic premises:

1. The complexity of a biological system reflects its ability to adapt and function in an ever-changing environment.
2. Biological systems need to operate across multiple spatial and temporal scales, and hence their complexity is also multiscale
3. A wide class of disease states, as well as aging, reduces the adaptive capacity of the individual. In turn, these compromised states appear to degrade the information carried by output variables. Thus, loss of complexity may be a generic feature of pathologic dynamics [57].

Self-Reported Signs and Symptoms of Sport-Related Concussion

The self-reported signs and symptoms checklist (SRSC) is a major part of SRC management, and many different SRSCs exist for SRC management. Unlike the NP and postural stability tests, the SRSCs have been developed based on the clinicians' empirical knowledge about SRC management. The 6 major signs and symptoms checklists for concussion management frequently used in the sports medicine setting are shown in Table 2 below [45] . Most of these major SRSCs use a 7-point Likert scale to measure severity and duration of SRC

[45], and only a few previous studies have provided scientific support for developing their psychometric properties of the SRSC: the Post Concussion Scale (PCS), the Immediate Post-Concussion Assessment and Cognitive Testing Post Concussion Symptom Scale (ImPACT-PCSS), and the Head Injury Scale (HIS), all of which reported their test-retest reliability [132]. Some other studies have also reported validity and sensitivity for the ImPACT-PCSS, the Sport Concussion Assessment Tool (SCAT), the Graded Symptom Checklist (GSC), and the HIS [46].

Table 2. Summary of Concussion Signs and Symptoms Checklists [45]

Checklist/Scale	Date Published	Number of Items	Grading Scale
Six Core Scales			
Pittsburgh Steelers Post Concussion Scale	1980s	17	7-Point Likert Scale
Post Concussion Symptom Assessment Questionnaire (PCSQ)	1999	10	Yes/No with 10 cm VAS
Concussion Resolution Index	2001	15	4-Point Likert Scale
Sign and Symptoms Checklist (SSC)	2004	34	Yes/No
Sport Concussion Assessment Tool (SCAT)	2004	25	7-Point Likert Scale
Concussion Symptom Inventory (CSI)	2009	12	7-Point Likert Scale

VAS = Visual Analog Scale

Since previous studies have mostly emphasized discriminating between concussed athletes and non-concussed athletes and have focused on a certain population, such as adolescent and young adult, further research is recommended. Especially, more research is needed on test-retest reliability, validity, and sensitivity, and studies on more diverse age groups are required.

Signs and symptoms on the acute SRSC are often obvious or straightforward, but many on other SRSCs are subtle or difficult to discern. Headache and dizziness are the most common signs and symptoms of SRCs, and loss of consciousness (LOC) is the second most common. [133]. However, the relationships among common signs and symptoms of SRCs were not identified. For example, several studies reported no correlation between LOC and a decline in neurocognitive function during the post-concussion assessment [74, 134] and between LOC and duration of concussion symptoms [42, 115]. Unlike the correlation between LOC and neurocognitive tests, some previous studies have reported a statistically significant correlation between amnesia and neurocognitive tests [21, 135].

Structural Imaging Technique

Mild, moderate, and severe types of concussion are commonly seen in sport-related activity. Magnetic resonance imaging (MRI) offers a noninvasive means of assessing the degree of damage to musculoskeletal structures or the human brain. MRI utilizes magnetic fields, radio waves, to produce detailed pictures of organs, different types of tissue, and bone. MRIs are depicted via protons, which are the most abundant in water content between various body tissues. Due to different proton densities and relaxation time, the brain and other tissue types are well delineated with many MR pulse sequences.

Functional Imaging Technique

Functional magnetic resonance imaging (fMRI) provides a non-invasive approach to evaluating the function and physiology of the brain. Since most SRCs result in mainly functional disturbances rather than structural damage, SRC research with fMRI can provide additional insights into pathophysiological and functional sequelae of brain injury and help in demonstrating functional brain abnormality after injury [136]. Also, fMRI allows the clinicians the ability to examine physiological brain activity during cognitive processes allowing for a greater understanding of the sport-related concussion. During the fMRI examination, the patient performs different tasks, such as finger tapping, rubbing a block of sandpaper, or answering simple questions. These tasks cause an increase in metabolic activity in the area of the brain responsible for the task. These metabolic changes are partly due to the expansion of blood vessels to facilitate the delivery of extra oxygen. fMRI detects level of oxygen in the blood, point by point, throughout the brain [137].

Because of limitations of traditional brain-scanning techniques, such as MRI and CT, fMRI is more helpful in viewing subtle change to the brain functions. fMRI may also demonstrate that the functioning of the network of the brain region is related to both the severity of concussion symptoms and time to recover. Chen et al. found some difference in behavioral performance between the experimental and control groups. Working memory activated the primary left and right dorsolateral prefrontal cortex (DLPC), dorsal anterior cingulated cortex, left premotor cortex, and left and right rostral insula. The authors’ major finding was that symptomatic concussed athletes showed an abnormal brain activation pattern in the DLPC [138]. Generally speaking, the authors believed that the fMRI outcome was correlated with postconcussive symptoms (PCS) and a reduction of brain activation mainly in the left DLPC. However, these findings could not be generalized in performance differences on the working memory task because both groups performed similarly. Limitations of this research included the lack of a large population and the lack of female concussed athletes due to sample limitation and bias. Jantzen et al. also established that concussed subjects showed an increase in Blood-Oxygen-Level Dependent (BOLD) activity during sequencing tasks. Patients with moderate to severe brain injury had increased functional activity in the brain. These increased brain functions reflected the recruitment of additional resources in response to moderate processing loads [139]. fMRI provided valuable functional information on the brain after SRC and was considered a good research tool for the assessment of concussion injuries of athletes. However, more research is required to investigate using fMRI with concussed athletes and other patients with health disparities.

The Special Issues with Sport-Related Concussion

Gender Difference

Recently, several studies have reported potential gender differences in performance on the NP test and in severity of self-reported symptoms during recovery from SRC [140-142]. Females tend to have more symptoms and declined neurocognitive performance when compared with male athletes [140, 141]. However, although new evidence of gender differences supports the findings of previous studies, there has been limited research on comparing gender differences using computerized neuropsychological performance measures and severity of self-reported symptoms. Further research should be conducted to clarify gender differences in such areas as brain physiology and neck strength.

Age-Related Issue

Several previous studies have demonstrated differences on the NP test among children, adolescents, and adult athletes. Most concussion statements have focused on the adult concussion management [10, 12] although in 2013 the Concussion in Sport Group (CISG) added a statement related to SRC assessment for children [33]. Generally, high school and college athletes usually recover relatively quickly from concussion according to NP test results, returning to baseline within 3 to 5 days of initial injury [21]. However, McClincy et al. and Field et al. compared NP test evaluations for high school and college athletes following SRC and found that high school athletes take longer to reach baseline level, with average recovery times of 10 to 14 days [111, 143]. McCory et al. investigated baseline evaluation based on age groups and reported that, based on the CogSport results, 9- to 18-year-olds significantly improved their cognitive function for the baseline test, with the most improvement of cognitive function occurring from the ages 9 to 15 [144].

CHAPTER 3

METHODS

Subjects

A total of 125 students (N=125) were recruited from classes within the Department of Kinesiology as well as other departments at the University of Georgia, but 33 were removed from the study due to not completing SOT sessions, not meeting the inclusion criteria, or being determined as outliers (Figure 2). The final sample consisted of 92 healthy young male and female students, aged 18-38 years old. The means and standard deviations of demographics are presented in Table 3. Participants were divided into two groups: block group and random group (Figure 2).

Table 3. Means (Standard Deviations) of Demographics

Group	Gender	Age	Height	Weight	College (yr)
Block	M (N=17)	23.8 (±5.4)	177.0(±7.4)	76.5(±11.5)	3.8 (±1.2)
	F (N=33)	21.2 (±2.9)	164.2(±5.1)	58.2(±6.0)	3.4 (±1.1)
Random	M (N=17)	22.3(±5.0)	178.7(±5.9)	78.0(±9.6)	3.7 (±1.3)
	F (N=25)	20.8 (±2.7)	163.1(±6.8)	57.0(±5.8)	3.0 (±1.3)
Total	N=92	22.0 (±4.0)	169.3(±9.3)	65.7(±12.6)	3.4 (±1.2)

M: Male, F: Female

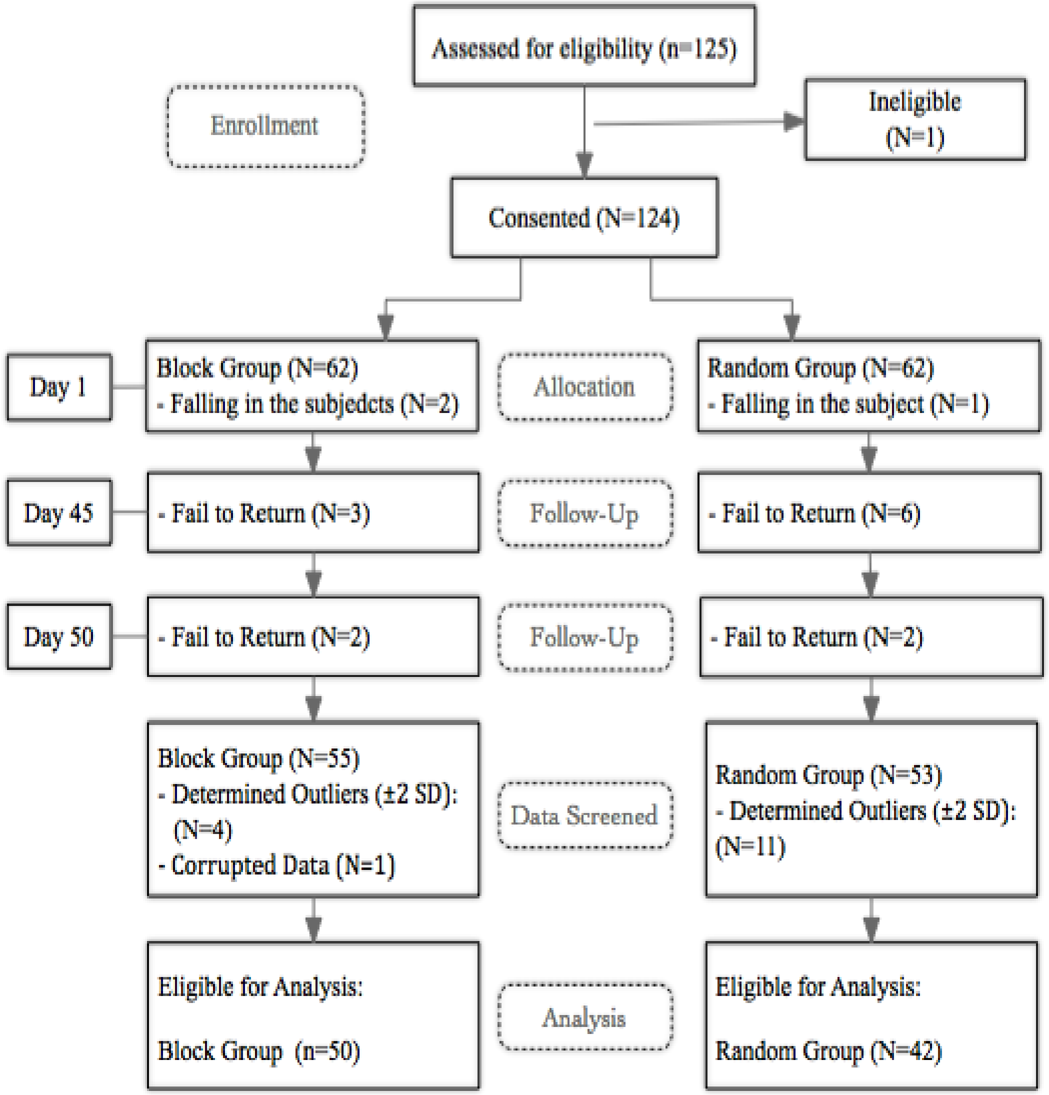


Figure 2. Flow-Chart of Study Participants

Inclusion Criteria

All of the 92 subjects met the inclusion criteria: (1) no history of concussion within the previous six months, (2) no musculoskeletal injuries in the lower extremities and/or torso that might affect postural steadiness prior to or during the testing period, (3) no neurological, visual, and/or vestibular pathology, and (4) no consumption of alcohol or use of any drugs 24 hours prior to testing. Subjects were required to avoid any vigorous physical activity within 3 hours prior to testing.

Instrumentation

Balance Assessment

The Sensory Organization Test (SOT) on the Balance Master$^{®}$ (Natus Medical Incorporated, Clackamas, Oregon USA) utilizes a dynamic force plate and a 3-sided wall, the “surround” that surrounds the front and sides of the performer and tilts about the same medial-lateral axis as the force platforms. The SOT on SMART Balance Master$^{®}$ is designed to systematically disrupt the sensory systems (somatosensory, vision, and vestibular), which is commonly referred to as “sway-referencing,” while the subjects attempt to maintain equilibrium (Table 4 & Figure 3). The SOT of the SMART Balance Master$^{®}$ balance assessment system can provide 3 visual sensory conditions (eyes open, eyes closed, and sway of the visual surround) and 2 surface-sway conditions (fixed, i.e., no sway; and sway). The test conditions consisted of 6 combinations of the various sensory conditions (Table 4 & Figure 3). For the most difficult condition (#6), the surround and the force platforms swayed synchronously. During each balance trial, signals representing the vertical forces applied to the four corners of the force platform system were collected at a sampling frequency of 100 Hz.

Table 4. Conditions of Sensory Organization Test (SOT) on the SMART Balance Master® (*Balance Manager Systems: Clinical Interpretation Guide, Natus Medical Incorporated)*

	Environment		***Expected Sensory System Response***	
Condition	***Vision***	***Surface***	***Disadvantaged***	***Using***
Condition 1	Eyes Open	Fixed		Somatosensory
Condition 2	Eyes Closed	Fixed	Vision	Somatosensory
Condition 3	Sway Referenced Visual surround	Fixed	Vision	Somatosensory
Condition 4	Eyes Open	Sway Referenced Surface	Somatosensory	Vision
Condition 5	Eyes Closed	Sway Referenced Surface	Somatosensory & Vision	Vestibular
Condition 6	Sway Referenced Visual surround	Sway Referenced Surface	Somatosensory & Vision	Vestibular

Fixed = Stable or Accurate; Sway Referenced = Unstable or Inaccurate

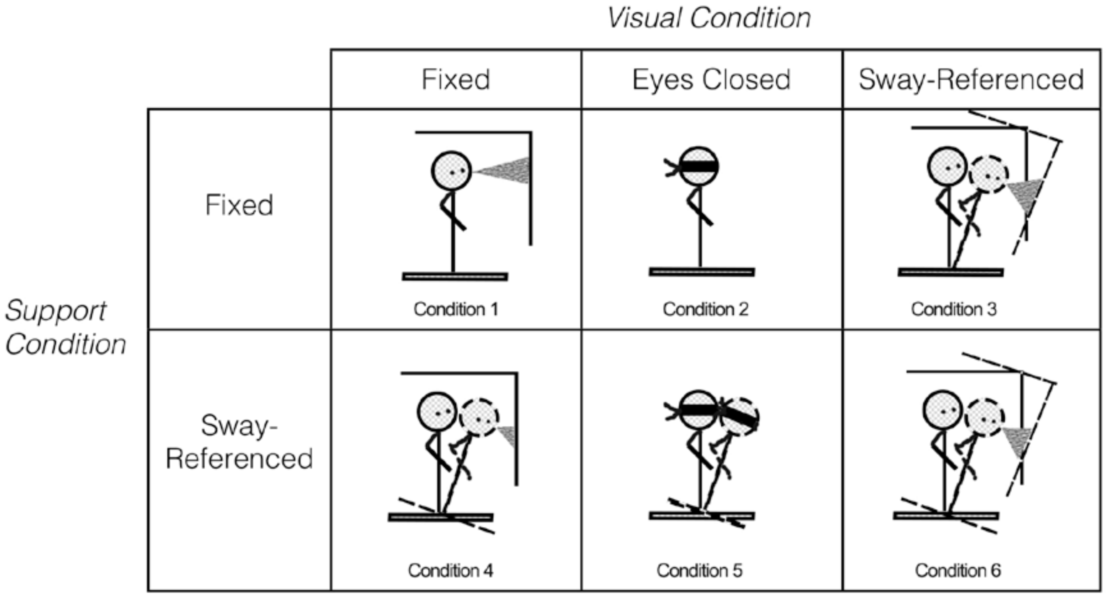


Figure 3. Sensory Organization Test (SOT) six conditions. In the test conditions indicating sway referenced input, either the support surface, the visual surround, or both will move in response to the subject's measured sway. This is not a perturbation or a random movement. The movement follows the patient's sway, providing inaccurate sensory feedback information to the patient.

STUDY ONE: Practice Effects in Clinical Concussion Assessment: Serial Administration of the Sensory Organization Test (SOT) in Healthy Young Adults

Data Collection Procedures

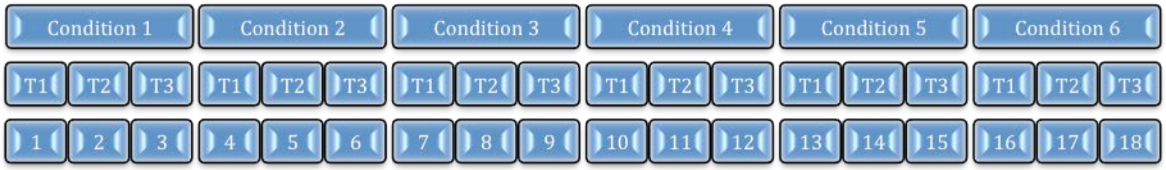
All data collection was conducted during the fall semester (September –December) of 2011. All investigators had training for administration of the test instrument, SOT, on the SMART Balance Master®. This study used a total of five SOT sessions: three repetitions of the SOT in one day with 20-minute breaks between each SOT (the first day of the SOT), and another SOT for day 45, followed by another SOT for day 50.

Preparation procedures on day 1:

Upon arriving at the testing facility, subjects were notified of the testing procedures and signed an Institutional Review Board approved informed consent form (Appendix A). Subjects were informed that participation in the study was voluntary and they had the right to withdraw from the study at any time. The participants completed a questionnaire including brief demographics, previous concussion history (number of concussions), and balance-related pathological questions (Appendix B). If a subject did not meet the inclusion criteria, he/she was excluded from the study. If all the inclusion criteria were met, then the subjects were randomly assigned to one of two groups: block and random. Subjects in the block group completed the SOT with conditions presented in the order suggested in the manufacturer’s instructions and with increased difficulty from condition 1 through condition 6. Subjects in the random group completed the SOT with conditions presented in random order (Figures 4 and 5). The random order of conditions for each trial was generated by Microsoft Excel® software using the “rand” function. All of the subjects watched the standardized introduction video for the SOT, which included test instruction and demonstration of subject position and specific SOT conditions.

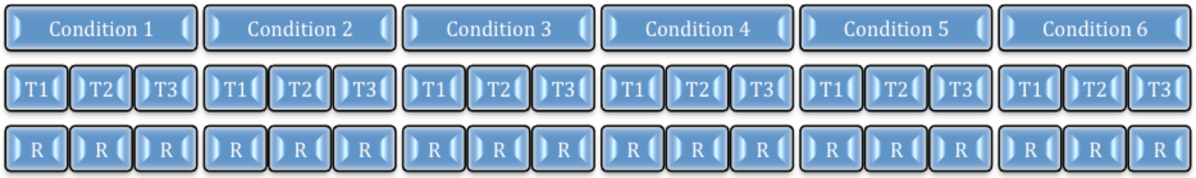
Participants remained in the same assigned group throughout all testing sessions (sessions 1 through 5). Randomized group allocation is illustrated in Figure 6.

Sensory Organization Test Testing-order Groups:



Condition 1			Condition 2			Condition 3			Condition 4			Condition 5			Condition 6		
T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Figure 4. Block testing order: the SOT started with condition1 in trial 1 and continued through condition 6 in trial 3. This followed the manufacturer's suggested methods



Condition 1			Condition 2			Condition 3			Condition 4			Condition 5			Condition 6		
T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R

Figure 5. Random testing order: Performance of the SOT followed a completely random order of conditions for the 18 trials. (R = Random order test)

Sensory Organization Test on the SMART Balance Master®: Day 1 assessment (Sessions 1, 2, and 3)

Based on the NeuroCom guideline, subjects were positioned with a standardized foot placement relative to their height: the medial maleolis of the ankle is centered directly over a marking stripe that laterally transects the two faceplates. During each trial, the subject was instructed to ignore any surface or visual surround motion and remain upright and as steady as possible. For each of the six sensory conditions, the participant completed 3 trials, with each trial lasting for 20 s. The subjects performed the SOT three times on day 1 with 20-minute breaks between each test. If the subjects moved a foot or if anything else changed the normal testing position, that particular trial was stopped and discarded, and that trial was restarted after the subjects were reminded of the testing procedures.

Sensory Organization Test on the SMART Balance Master®: Day 45 assessment (Session 4)

Subjects in the experimental groups returned to the Athletic Training Laboratory 45 days following the baseline testing (day 1). Prior to balance testing, subjects were required to answer the modified health questionnaire to confirm that they still met all inclusion criteria. Any participants not meeting such criteria were excluded from our study. The subjects in both groups (block and random) performed the SOT (see Figures 4 and 5) and were then scheduled to return for day 50 testing.

Sensory Organization Test on the SMART Balance Master®: Day 50 assessment (Session 5)

Subjects in the experimental groups returned to the Athletic Training Laboratory 5 days after day 45 assessment (50 days after the baseline testing). Again, the modified health questionnaire was administered to all subjects to confirm their eligibility to continue participating in this study. The subjects in both groups (block and random) performed the SOT as the final test (see Figure 6).

Data Generation and Reduction

For each balance trial, the manufacturer's software (Version 8.5 NeuroCom, A Division of Natus, Clackamas, Oregon USA) was used to generate several quantities. First, the anterior-posterior (AP) center of pressure (COP) data was derived from the vertical force platform data. Next, based on the relationships between the movement of the COP and COM, and the movement of the COM and body sway, the manufacturer's algorithm [48], the body's AP sway angle was calculated using the COP data. Assuming that a person sways in the sagittal plane as a rigid mass about the ankles' flexion-extension axis, the AP COG sway angle is the angle between a line extending vertically from the center of foot support and a line extending from the center of foot support through the COG [48]. Second, the manufacturer's software determined the maximum sway angle (θ max ant) in the anterior direction and the maximum angle in the posterior direction (θ max post) to then calculate an angular displacement (θ max(ant) - θ max(post)). According to the equation below [48], individual equilibrium scores (ESs) were calculated by subtracting the angular displacement from 12.5°, the theoretical maximum angular displacement possible at the limits of stability); and then converting this difference into a percentage of the maximum angular displacement possible. Therefore, if a person does not sway at all, the ES would be a value of 100 indicating perfect stability. However, scores approaching 0 indicate sway amplitudes approaching the limits of stability (12.5°). A score of 0 indicates that the patient "fell" on that trial condition;

- $ES = \{12.5 - [\theta \max(ant) – \theta \max(post)]\}/12.5 * 100$ where

θ max(ant) is the maximum anterior sway angle in degrees during a trial;

θ max(post) is the maximum posterior sway angle in degrees during the same trial; and

12.5 is the limit of sway displacement (in degrees) in the sagittal plane during normal quiet stance.

The equilibrium scores for composite and sub-composite scores were generated by the manufacturer's algorithm, developed by NeruoCom (Natus Medical Incorporated, Clackamas, Oregon USA), and then the equilibrium scores were extracted from the SMART Balance Master® and the data were entered into Excel® software (Microsoft Inc). The grand mean of each condition's equilibrium score for each of the 18 trials was calculated. Then, I considered any of the 18 SOT trials to be an outlier if its ES value was greater than 2 SD of the grand mean calculated for each of the 18 trials. Subjects who failed to complete all 5 SOT sessions were considered missing values and were eliminated from the data analysis.

<u>Composite Equilibrium Score</u>

The composite equilibrium score (composite ES) is best described as a subject's overall level of performance on the SOT [48]. The composite ES is calculated as the average of the following 14 equilibrium scores: condition 1 average score, condition 2 average score, and the three trial scores from each of conditions 3 through 6 [48].

$$Composite(ES) = \frac{ES\ (1)\ +\ ES\ (2)\ +\ 3\,[ES\ (3)\ +\ ES\ (4)\ +\ ES\ (5)\ +\ ES\ (6)]}{14}$$

The greater weighting of conditions 3 through 6 in the composite equilibrium equation is used because sensory balance deficits are more pronounced during testing under the more difficult sensory conditions.

<u>Sub-Composite Equilibrium Scores</u>

The SOT of the SMART Balance Master® calculates the individual sensory system scores (sub-composite equilibrium scores): Somatosensory (SOM) score, Visual (VIS) score, Vestibular (VEST) score, and Vision Preference (PREF) score (Table 5). These scores represent the subject's ability to use the sensory system cues effectively for postural control, and the individual's functional abnormality based on the specific pathologies or sport-related concussion [48].

Table 5. Sensory Analysis Ratios.

Sensory Analysis		
Ratio Name	Ratio Pair	Significance
SOM Somatosensory;	Condition 2 /Condition 1	Patient's ability to use input from the somatosensory system to maintain balance
VIS Vision	Condition 4 /Condition 1	Patient's ability to use input from the visual system to maintain balance
VEST Vestibular	Condition5 /Condition1	Patient's ability to use input from the vestibular system to maintain balance
PREF Vision Preference	Condition 3+6 /Condition 2+5	Degree to which patient relies on visual information to maintain balance, even when the information is incorrect

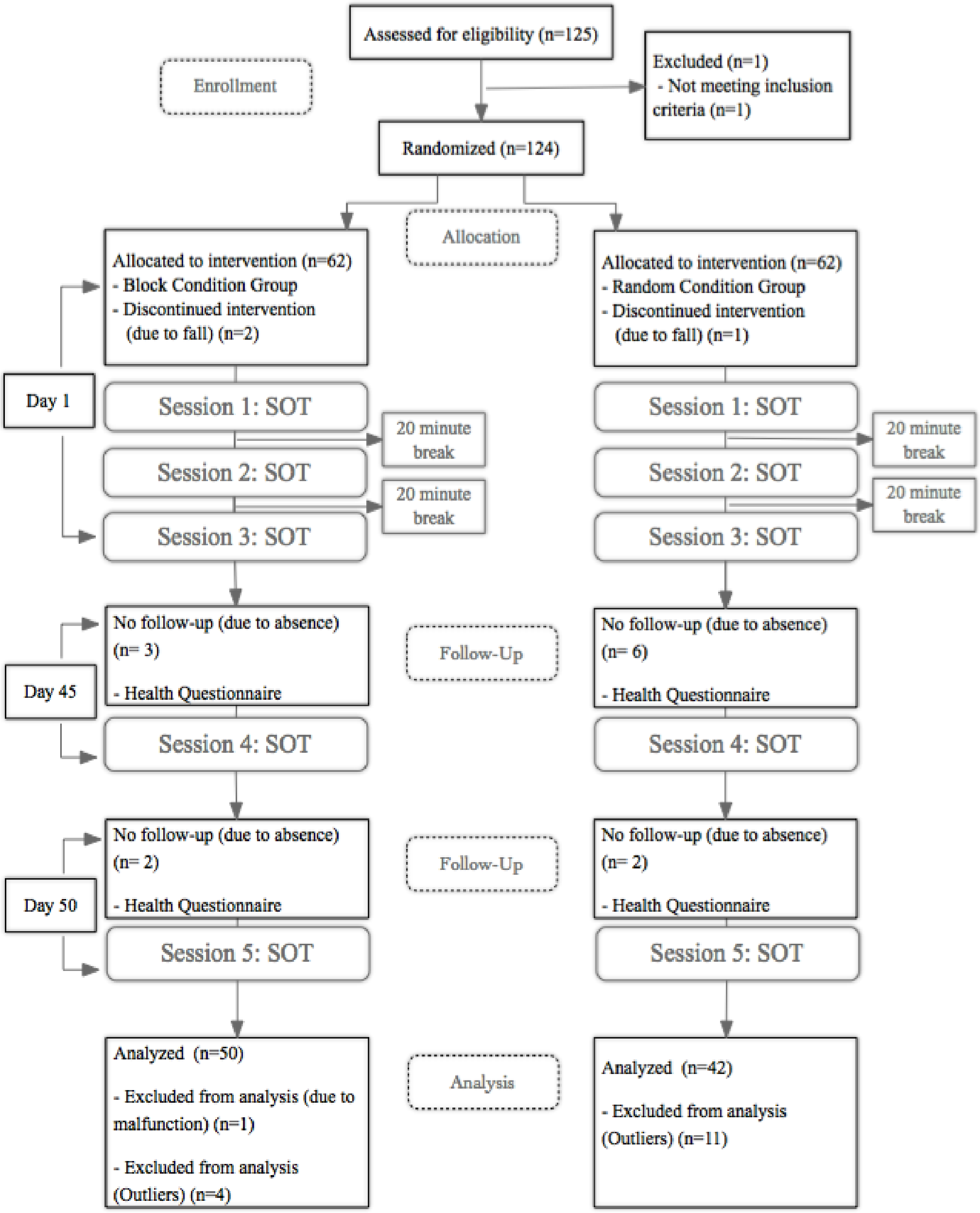


Figure 6. Schematic Illustration of the Research Procedures

STUDY TWO: Test-Retest Reliability of the Sensory Organization Test using Multiscale Entropy Values and Equilibrium Scores in Healthy Young Adults

The second study was conducted to determine test-retest reliability of the SOT using multiscale entropy (MSE) and equilibrium scores (ES). Repeated balance tests using the center of pressure (COP) have not been previously conducted with these two different measures for the purpose of clinical administration of the SOT at time points when recovery from concussion is typically assessed (baseline, day 45, and day 50).

Data Collection Procedures

Data collection procedures for study 2 were the same as those described above for study 1.

Data Generation and Reduction

For each trial, center of pressure (COP) data were calculated using the SMART Balance Master® software as described earlier and exported for further analysis. Upon visual inspection of the data, high-frequency instrumentation noise was suspected. Thus, a frequency content analysis was performed to determine an appropriate cutoff frequency (PSI Plot Software: Version 9.5., Poly Software International, New York). A Butterworth 2nd-order low-pass filter with a 5 Hz cut-off frequency was used to filter the COP data (Butterworth filter routine, Matlab, Version 8.1.0., The Mathworks, Natick, MA) [145, 146].

To measure the regularity of the COP-time patterns, MSE values were then generated for the anterior-posterior (AP) and medial-lateral (ML) directions separately. Costa's MSE algorithm was used to calculate MSE using his C language source code [130] from PhysioNet (http://www.physionet.org), sponsored by the National Institutes of Health (NIH).

The MSE calculation consisted of generating sample entropy values at every ‘scale’ from a scale of 2 to 20. For each scale, two steps were performed (Figures 1 and 7)[131]: (1) conversion of original COP data into ‘coarse-grained’ data; and (2) calculating SampEn. For the first step, the COP-time series data were divided into non-overlapping windows of the scale length, τ, (i.e., the number of data points in each window = τ). The data points inside each window were averaged to produce ‘coarse’ grained data (y^{τ}) as shown in the equation below. For each window, element (*j*) of the new coarse-grained data time series, $y_j^{(\tau)}$, was calculated according to the following equation:

$$y_j^{(\tau)} = \frac{1}{\tau} \sum_{i=(j-1)\tau+1}^{j\tau} x_i$$

For step 2, SampEn was calculated. SampEn is a mathematical algorithm created to measure the repeatability of predictabilty within a time series. Sample entropy (SampEn) was calculated from the coarse-grained data [130] with m=2 and r=.15. The input parameters are (a) m, the length of data that will be compared; (b) r, the similarity criterion; and (c) N, the length of the data. Typically, for clinical data, m is to be set at 2, r to be set between 0.1 and 0.25 times the standard deviation of the data, and N as 1000 [130]. SampEn was utilized for MSE calculation instead of Approximate Entropy (ApEn) because SampEn does not count self-matches of windows, thus eliminating the bias towards regularity, and data length does not have as great of an impact on the calcluation of SampEn unlike ApEn.

Last, a complexity index (C_I) that represents an overall measure of entropy that incorporates the SampEn at all scales, was computed as the integral of the SampEn values over the range of scales from 2 to 20 using the numerical method: ($C_I = \sum_{i=1}^{Scale} SampEn(i)$) where i = scale and Scale is the highest time scale used; *i* = the change in scale which equals 1 in this study

[147]. Thus a high C_I indicates high irregularity (potentially representing high complexity) of the COP-time data. As the COP-time series is a global measure reflecting the postural system making adjustments to the body's posture, high and low C_I would suggest high and low complexity of the postural control system.

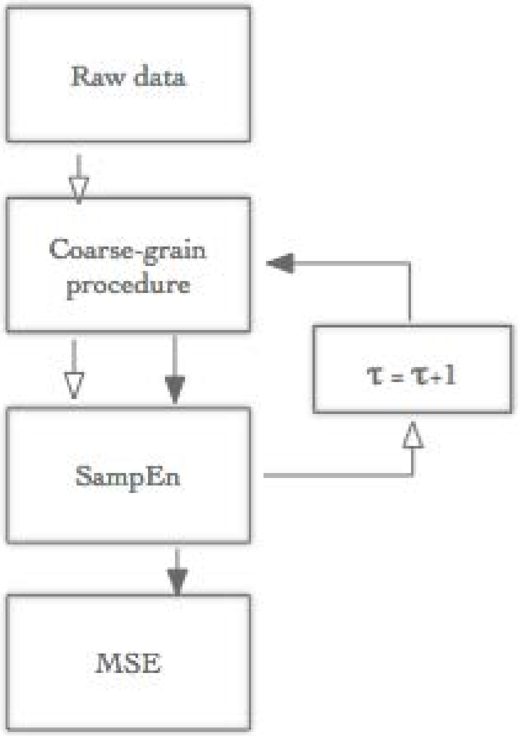


Figure 7. Flow-Chart of MSE Procedure

Statistical Analysis

All data analyses were conducted using IBM SPSS 22.0 (IBM Corporation, Somers, NY) and using R software (Core Team, 2013). The significant levels were set *a priori* at $p \leq 0.05$.

Statistical analysis 1: Repeated ANOVA for practice effect of SOT

Repeated measure analysis of variance was conducted for the composite equilibrium score and each subtest scores (somatosensory, visual, vestibular, and visual conflict) of the SMART Balance Master® test for all subjects under the assigned SOT conditions (block and random), and according to the clinical administration times of concussion management (baseline, day 45, and day 50).

Statistical analysis 2: Independent sample t-test for group differences (block and random) of SOT

Independent sample t-test was used to evaluate equilibrium score (ES) differences in the two SOT conditions: block and random and at each session (sessions 1, 2, 3 on day 1, session 4 on day 45, and session 5 on day 50).

Statistical analyses 3 and 4: ICC for reliability of anterior-posterior MSE (AP) and medial-lateral MSE (ML)

Intraclass correlation coefficients (ICC) for both AP and ML were calculated for each SOT condition (conditions 1 – 6) for the Sensory Organization Test (SOT) on the SMART Balance Master® test for all subjects under the assigned SOT conditions (block and random) and according to the clinical administration times of concussion management (baseline, day 45, and day 50).

Power Analysis

A-priori power analysis using the G*power Version 3.1.7 [148] indicated that a total sample of 90 people would be needed to detect small effects size (d=.3) (under guidelines from Cohen, 1988) with 95% power (1- β) using repeated measure ANOVA with a correlation of .5 between and within sessions. Sample size was also considered based on guidelines provided by Baumgartner and Chung [149] for test-retest reliability studies using a one-way ANOVA model to estimated the ICC for a single scores.

Pilot Testing

Postural control is a complex feedback process utilizing multiple sensory-motor systems, gathering input from the visual, vestibular and somatosensory receptors. The sensory organization test (SOT) assesses these sensory-motor systems and is utilized in concussion management. However, limited research on the SOT has been conducted to evaluate the practice effect. The pilot study objective was to evaluate the practice effects of four administrations of the SOT within one day compared to one test on four consecutive days. Results from this pilot study were used to establish methods for Study 1 and Study 2.

Twenty-eight healthy college students participated in this study. All subjects were divided into two groups; Group A (10 males, 7 females, age 22.82 ± 5.1 years) and Group B (7 males, 4 females, age 20.27 ± 1.1). Subjects in Group A performed the SOT once a day over four consecutive days. Subjects in Group B performed the SOT four times in one day with 20-minute breaks between each SOT. Repeated measures ANOVA was used with statistical significance set at $p < .05$.

The SOT composite equilibrium score provided an overall determination of balance performance for each subject. Sub-composite scores were also calculated for somatosensory

(SOM), visual (VIS), vestibular (VEST), and preference (PREF). These scores were analyzed to determine practice effects.

We found statistically significant increases in the composite equilibrium scores between sessions 1 and 2 and between sessions 2 and 3. There were also statistically significant increases in the visual (VIS) scores and in vestibular (VEST) scores between sessions 1 and 2. We also found no statistically significant group differences for composite equilibrium scores and for each of the sub-composite scores. This pilot study demonstrated that elimination of practice effects requires three tests; all three assessments can be performed in one day.

CHAPTER 4

PRACTICE EFFECTS IN CLINICAL CONCUSSION ASSESSMENT: SERIAL ADMINISTRATION OF THE SENSORY ORGANIZATION TEST (SOT) IN HEALTHY YOUNG ADULTS[1]

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[1] Lee HR, Ferrara MS, Brown CN, Simpson KJ. To be submitted to the Archives of Physical Medicine and Rehabilitation.

Abstract

Purpose: To determine if performance scores of the Sensory Organization Test (SOT) on the SMART Balance Master® improve over repetitive administrations of concussion assessment using two different testing-order groups.

Design: Repeated measure design.

Setting: Athletic Training Laboratory.

Participants: Ninety-two healthy college-aged subjects (34 males, 58 females; 21.8 ± 4.0 years).

Intervention: All subjects were randomly divided into block and random test-order groups. Subjects in the block testing-order group completed 3 trials for each of the 6 sensory conditions in the testing order suggested by the manufacturer (order of increasing difficulty) and Subjects in the random testing-order group completed the SOT in random order. All subjects performed the SOT three times (sessions 1-3) in one day with a 20-minute break between each SOT and then all participants completed the SOT once approximately 45 (session 4) days and 50 days later (session 5).

Main Outcome Measures: SOT composite and sub-composite equilibrium scores.

Results: Repeated-measure ANOVA (2 test-order groups over 5 sessions) revealed a statistically significant ($p<0.05$) increase in the composite equilibrium score between sessions 1 and 2 ($p = 0.001$), 3 and 4 ($p = 0.006$), and 4 and 5 ($p = 0.001$). A statistically significant increase in the vestibular ($p = 0.001$) score was found between sessions 1 and 2. A significant testing-order group difference in the visual score was found for session 1 ($p = 0.01$).

Conclusions: As the most significant increase in the composite and vestibular equilibrium scores occurred between sessions 1 and 2, the second administration of the SOT is recommended to develop a valid baseline in concussion assessment to control for practice effect.

Key Words: Postural stability; Sensory integration; Sensory motor performance; and Baseline assessment

Introduction

Over the last two decades, sport-related concussion (SRC)–also referred to in the literature and by clinicians as mild traumatic brain injury (mTBI)–has received considerably more attention by the media and scientific community. SRC ranks as one of the common injuries among high school and college athletes [6, 28, 150], and it is considered as an important public health concern because of the large number of athletes sustaining head injuries [59]. SRC has been defined by the Concussion in Sport Group as “a complex pathophysiological process affecting the brain, induced by biomechanical forces” [33]. Due to this complexity, the exact pathomechanics, cellular changes and the viability of recovery are yet to be understood by sports medicine professionals.

SRC management typically includes an SRC battery of tests composed of self-reported symptoms, neurocognitive testing, and postural stability testing [18, 151]. Regarding postural stability, concussed athletes have demonstrated balance deficits up to 10 days post-concussion and, more specifically, have reported impairment in the visual and vestibular systems following concussion [61]. The decline of both sensory systems was directly related to the overall inability to maintain optimal balance.

Postural control is defined as a complex network of neural connections with a feedback mechanism utilizing multiple sensory-motor systems, coordinating input from the visual, vestibular, and somatosensory receptors [152]. Based on this coordination, appropriate body responses for maintaining stability are generated [153]. However, the impaired ability to coordinate multiple sensory-motor systems appropriately may be related to SRC.

Although a variety of assessment techniques for postural stability are available in the clinical and laboratory setting [9], computerized dynamic posturography has become an important tool for SRC evaluation to assess objective measures of postural stability in concussion assessment [40, 154, 155]. The Sensory Organization Test (SOT) using the Smart Balance Master® (Natus Medical Incorporated, Clackamas, Oregon USA), one of the dynamic postural stability assessments, was implemented in the SRC battery to identify the relative contributions of the 3 main sensory systems involved in postural control (vision, vestibular, and somatosensory).

In clinical practice, serial assessment is recommended in the SRC evaluation process [33]. Comparing an athlete's baseline postural stability performance to the post-injury tests provides the best way to establish a balance deficit following concussion and to make decisions regarding when an athlete can safely return to play. However, previous studies with neurocognitive assessment and measures of postural stability (SOT) have demonstrated practice effects in which athletes' test scores improve due to repeated exposure to the same test [99, 105, 156], allowing them to develop more efficient postural strategies to reduce energy expenditure and to learn the safe position of balance both within a session and over time [157-159].

It is unclear whether practice effects exist with repeated administration of the SOT using the two different testing conditions: block condition (subjects complete 3 trials for each of the 6 sensory conditions in order) and random condition (subjects complete the trials and conditions of the SOT in random order) on day 1 and over the clinical administration time points (day 45 and day 50). Therefore, the purpose of this study was three-fold: 1) to identify the practice effects of repeated administrations of the SOT on the same day (day 1) to establish a framework for obtaining an optimal baseline score; 2) to identify the magnitude of practice effects with repeated administrations of the SOT over clinical administration time points (day 45 and day 50); and 3) to compare outcomes on two different groups (block and random) on day 1 and over the clinical administration time points (day 45 and day 50). We hypothesized that we would find practice effects with repeated administrations of the SOT on day 1, but we did not expect to find practice effects with clinical administration of the SOT on subsequent days (day 45 and day 50).

Methods

Participants

The sample consisted of 92 healthy young adults (34 males, 58 females; mean age, 21.8 ± 4.0 year) enrolled in a state university. The sample size of 92 subjects provided a power of .99 for detecting a large effect size (F= .90) using repeated measure analysis of variance (ANOVA) with correlation of .5 between sessions. Participants were randomly divided into two testing-order groups (Figure 6): block group (17 males–mean age, 23.8 ± 5.4 years; and 33 females–mean age, 21.2 ± 2.9 years) and random group (17 males–mean age, 22.3 ± 5.0 years; and 25 females–mean age, 20.8 ± 2.7 years). All subjects met the following inclusion criteria for this study: (1) no self-reported history of concussion or no recent concussion within the past 6 months; (2) no current musculoskeletal injuries in the lower extremities and/or other body parts that might affect postural stability; (3) no physical sickness including visual and vestibular pathologies; (4) no ingesting of any substance such as pharmacological or recreational drugs; and (5) no severe tiredness or fatigue. Each subject was asked to refrain from alcohol consumption for 24 hours prior to any testing session and alcohol consumption was monitored through a self-reported health questionnaire before each session of the test.

Pilot Testing

We conducted a pilot test for repeated administration of the SOT using varying time intervals for two groups: group A with four SOTs on the same day and group B with one SOT on each of four consecutive days study. No statistical difference was found in performance between groups. Based on the pilot study findings, our study utilized the three-repeated evaluation of the SOT with 20-minute breaks between each SOT evaluation on day 1.

Instrumentation

The SOT from NeuroCom (Natus Medical Incorporated, Clackamas, Oregon USA) utilizes 3 visual conditions (eyes open, eyes closed, and sway referenced) and 2 surface conditions (fixed and sway referenced) to present 6 different test conditions (see Table 4). These different conditions of the SOT are designed to systematically disrupt the sensory input processes while the subject maintains balance. The specific conditions of the SOT are described in Figure 3. The SOT utilizes a moveable platform and visual surround that rotates in the anterior-posterior (AP) plane. Based on NeuroCom guidelines, subjects were positioned with a standardized foot placement relative to their height, their arms relaxed at their side, looking forward, and standing as still as possible. As participants performed the SOT, the test administrator remained in closed proximity in order to protect them from injury if they lost balance as no harness was applied. Each subject completed 3 trials, each of which consisted of 6 different conditions, with each trial lasting for 20 seconds.

Testing Procedure

All subjects reported to the university’s Athletic Training Research Laboratory for five test sessions, and were randomly assigned to either the block or random testing-order groups. Figure 6 illustrates sample selection and research procedure. Subjects in the block group completed the SOT with conditions presented in the order suggested in the manufacturer’s instructions and with increased difficulty from condition 1 through condition 6. Since the subjects might expect the next condition or trial, the testing score might allow for improvement during the SOT. Subjects in the random group completed the SOT with conditions presented in random order. Therefore, the subjects were unaware of the next testing condition.

The computer-generated composite equilibrium score, which is based on the formula developed by NeuroCom [160], provides a way of understanding the subject's level of postural stability compared to age-based normative data. Sub-composite scores, which include the somatosensory (SOM), visual (VIS), vestibular (VEST), and preference (PREF) scores, were calculated using the formula provided by NeuroCom Inc [160]. The SOM, VIS, and VEST scores provide each subject's ability to use input from each sensory system (somatosensory, visual, and vestibular) to maintain postural stability [160]. The PREF score explains the degree to which the subject relies on visual information to maintain postural stability, even when the information is incorrect [160]. The results of composite equilibrium score and sub-composite scores range from 0 to 100. Scores approaching 100 indicate perfect stability and scores closer to 0 represent instability, with a score of 0 indicating that the subject fell during the test.

Day 1 assessment (sessions 1, 2, and 3)

In session 1, participants read and signed an informed consent form and completed a health questionnaire, which included a concussion symptoms checklist. The health questionnaire also consisted of demographic information, concussion history, and current health status. Subjects who did not meet the inclusion criteria were excluded from our study. All of the subjects watched the standardized introduction video for the SOT, which included test instructions and demonstration of subject position and specific SOT conditions. No additional information was provided during the SOT administration. Each participant completed 3 sessions on day 1. Each subject had a 20-minute break between each SOT administration (Figure 6).

Day 45 (session 4) and day 50 (session 5) assessment

Subjects were asked to return to the Athletic Training Laboratory 45 days and 50 days after day 1 testing. A modified health questionnaire was administered to screen for any health problems; subjects who did not meet the inclusion criteria were excluded. Participants performed the SOT on day 45 and again on day 50 (Figure 6).

Data Analysis

A repeated-measure ANOVA was used to analyze composite equilibrium score and sub-composite scores (SOM, VIS, VEST and PREF) to determine whether practice effects existed for the three SOT administrations on day 1 and for repeated SOT administration on day 45 and day 50. The repeated measure ANOVA utilized 1 between factor (between-group difference) and 1 within factor (difference across time points; day 1, day 45, and day 50). The level of significance was set at $\alpha < .05$. In order to compare group differences at each time point (each session), an independent sample t-test was performed at each session ($\alpha < .05$). Data analyses were conducted using IBM SPSS Statistics for windows (Version 22.0. Armonk, NY: IBM Corp).

Results

A total of 125 subjects volunteered to participate in our study. One subject was excluded due to sustaining SRCs within 6 months prior to the study. Thirty-two subjects were removed from the study because of incomplete SOT sessions or a fall during the SOT (Figure 2). Therefore, a total 92 subjects were included for final data analysis. The flow diagram of the sample selection and research procedures is displayed in Figure 6. The mean time period between day 1 and day 45 was 47.3 (± 3.9) days and between day 45 and day 50 was 5.3(± 2.2) days.

Practice effects on day 1

We assessed for practice effects across baseline testing sessions 1 through 3. Mauchly’s test indicated that the assumption of sphericity had been violated, $\chi^2(9) = 72.23$, $p < 0.05$; therefore, the degrees of freedom was corrected using Greenhouse-Geisser for estimating sphericity ($\varepsilon = 0.70$). A significant main effect was revealed for the composite equilibrium score between sessions 1 and 2 ($F_{(1,90)}$=103.10, $p = 0.001$, η_p^2= 0.53) (Figure 8). No statistically significant differences were found for the composite equilibrium score between sessions 2 and 3. Also, no group effects for the composite equilibrium score were reported across the three sessions on day 1(Figure 8).

Significant main effects were found for the sub-composite scores: These results revealed a statistically significant increase for the VEST score between sessions 1 and 2 ($F_{(1,90)}$=62.81, p = 0.001, η_p^2= 0.41), while a statistically significant decrease was found for the VEST score between sessions 2 and 3 ($F_{(1,90)}$=4.85, $p = 0.030$, η_p^2= 0.05) (Figure 9). The results for the VIS score revealed a significant interaction between groups across sessions 1 and 2 ($F_{(1,90)}$=9.37, p = 0.003, η_p^2= 0.94) (Figure 10).

An independent sample t-test was conducted to compare group differences for each SOT session. Significant differences were also found between the block and random groups in the VIS score for sessions 1 (block group [M=89.33, SD=7.59] and random group [M=94.31, SD=3.82], t(90)= -3.86, p = 0.01) (Figure 10). The SOM score indicated no practice effect across the 5 sessions. However, a significant group difference was found for session 3: the SOM score for the block group (M=97.98, SD=1.44) and the random group (M=96.67, SD=1.87), t(90)= 3.76, p = 0.01 (Figure 11).

Practice effects on day 45 (session 4) and day 50 (session 5)

The composite equilibrium scores in sessions 4 and 5 were significantly higher than those in session 1. The mean composite equilibrium scores and the 95% confidence intervals (CI) for the 5 sessions are illustrated in Figure 8. A significant practice effect for the composite equilibrium score was found between sessions 3 and 4 ($F_{(1,90)}$=7.97, p = 0.006, η_p^2= 0.81), and between sessions 4 and 5 ($F_{(1,90)}$=17.25, p = 0.001, η_p^2= 0.161). The result also showed that a practice effect was found for the VEST score between sessions 4 and 5 ($F_{(1,90)}$=5.95, p = 0.013, η_p^2= 0.017) (Figure 9). However, no significant practice effects for the VIS, the SOM, and the PREF scores were reported across sessions (Figures 10, 11, and 12).

An independent sample t-test was conducted to compare group differences of the SOM for sessions 4 and 5. A significant group difference was found for session 4 (block group [M=97.82, SD=1.52] and random group [M=96.23, SD=2.15], t(90)= 4.14, p=0.01) and for session 5 (block group [M=97.98, SD=1.44] and random group [M=96.68, SD=1.87], t(90)=3.76, p=0.01) (Figure 11).

Discussion

Practice effects on the composite equilibrium scores

The primary findings with repeated administrations of the SOT showed that composite equilibrium scores were significantly higher in session 2 than in session 1, and also significantly higher in sessions 3 through 5 than in session 1. Therefore, these findings do not support hypothesis 1. The most significant practice effect for the composite equilibrium score was found between sessions 1 and 2 (Figure 8). These findings are similar to those of the previous SOT study, which was designed for 5 test sessions over a 2-week period with follow-up test 1 month later and which reported a significant practice effect for the composite equilibrium score between sessions 1 and 2 [161]. Another postural stability study showed that even one simple quiet standing with eyes closed resulted in progressively reducing the posture sway, due to spending less energy and learning the safe position of balance [162]. These practice effects have also been shown in more complex postural stability tasks such as those using the anterior-posterior moveable platform with normal or short length of the surfaces or vibratory perturbations [157, 163, 164]. These findings strongly support that at least 1 practice session of the SOT should be given when establishing a valid baseline as part of the SRC evaluation.

Practice effects on sub-composite scores

This study was unique in that it examined practice effects for sub-composite scores of the SOT. The current findings only partially support hypothesis 2 in that although we reported a significant practice effect for composite equilibrium scores, sub-composite scores did not demonstrate the same effect with repeated administration of the SOT. A major finding of our study was that there was a statistically significant increase in the VEST score between sessions 1 and 2, indicating practice effects. Interestingly, a statistically significant decrease in the VEST score was found between sessions 2 and 3 (Figure 9). This may be related to the loss of the subjects' concentration during the 3rd SOT because of the repetitive administrations of the SOT within a short period of time. However, no practice effects were found for the SOM and PREF scores across all 5 sessions (Figures 11 &12). Although the PREF scores have been used in concussion assessment in clinical settings to monitor recovery response, surprisingly most PREF scores exceeded the maximum scores (ceiling effects) across all 5 sessions. Ceiling effects can be caused by a variety of factors, but these could threaten the validity of the test scores that demonstrate almost no variation at the upper end of their potential range (100%). Therefore, the sub-composite score for PREF might be limited in application for clinical interpretation in concussion assessment. More research is recommended to identify how each individual sensory system contributes to maintaining postural stability following sport-related concussion.

Block and random testing-order groups of the SOT

Several studies have been conducted based on the manufacturer's recommended testing order (increased difficulty from condition 1 through condition 6) of the SOT [161, 165], but no study has been conducted with randomized testing orders of the SOT, possibly resulting in different levels of practice effects. The current study demonstrated no group differences for the composite equilibrium score and the VEST score. The group differences for PREF were not considered meaningful because of ceiling effects. A group difference was revealed for the VIS score at baseline, with a statistically significant lower score reported for the block group. Conversely, a group difference was demonstrated for the SOM score at sessions 3, 4, and 5, with a statistically significant higher score reported for the block group. These findings provided partial support for hypothesis 3. These inconsistencies may limit the generalizability of our results on the effectiveness of the two different group methods. Therefore, of more importance to sports medicine clinicians are the results clearly indicating that practice effects can be eliminated by administering a preliminary SOT to familiarize the subjects with the sensory organization environment and then re-testing to obtain baseline scores.

Retained equilibrium scores

Postural control adaptations during repeated balance testing is common in the human biological system; it is observed in the motor control [166] and in the central nerve systems [167]. The postural adaptation process can be seen in the progressive reduction of body sway in response to stimuli, and in the change of posture or body learning over time [168]. In the 2 major processes, short-term (i.e., day) and long-term (i.e., months), adaptation occurs with controlling balance [157, 169]. The short-term adaptation reduces postural sway either by modifying the postural strategies or through changing the weighting of sensory information [158]. Previous studies where participants repeated the balance test over varying administration intervals reported the most significant practice effect with the short-term interval (1-2 days) for static and dynamic postural stability [99, 170], and our study also showed practice effects with the short-term adaptation for the composite equilibrium scores of the repeated SOT. Long-term adaptation indicates that experience with the postural task increases ability of postural control over time [157, 169], and our study also demonstrated long-term adaptation of the SOT. The majority of subjects either retained or improved their composite equilibrium scores on day 45 (session 4) and day 50 (session 5) (see Figure 8). Therefore, hypothesis 1 was not supported.

Clinical application of the repeated SOT

Obtaining a valid baseline test is paramount in concussion assessment. Acquiring a "true" baseline score requires elimination of practice effects for repeated administration of the SOT; at least one pre-session of the SOT is strongly recommended to establish the plateau of performance based on our results. Utilizing this information will assist sport medicine clinicians in obtaining the best baseline scores to be used in making return-to play decisions following sport-related concussions. However, the reality is that the concussion assessment battery may not support these multiple administered baseline sessions in that they are not cost-effective. Therefore, our study attempted to establish the amount of improvement in scores throughout all sessions that could be attributed to practice effects. Our study showed the most significant improvement (around 3.2-points) in composite equilibrium scores between sessions 1 and 2 as well as a 5.0-point improvement across the 5 sessions. This investigation supports the findings of a previous study, which also reported significant improvement (approximately 6 points) in composite equilibrium scores over multiple sessions [161]. These findings may provide clinicians with practical guidelines for interpreting SOT results with recognition of potential practice effects in post-concussion evaluation due to long-term adaptation. The seriousness of concussion assessment and its potential consequences warrants further study.

Study Limitations

This study is not without limitations. Generalizability of the findings of this study is limited in that it was conducted with only healthy college-aged adults. Therefore, other samples, such as older adults, adolescents, and/or individuals who have a degenerative disease affecting balance, may show different practice effects. Future research on the sensitivity and specificity of concussion management as well as the investigation of other factors can contribute to developing more effective concussion assessment. Furthermore, future studies should examine performance improvements with repeated testing after SRC.

Conclusion

The SOT on the Smart Balance Master® was performed by healthy young adults five times (5 sessions). The most significant practice effects were found between sessions 1 and 2 for the composite and sub-composite scores, except the SOM, VIS, and PREF scores. Based on the findings of this study and to obtain the best baseline score for concussion assessment, it is recommended one practice test be administered and the second test can be used for the baseline examination. In addition, practice effects were also found between sessions 3 and 4, and sessions 4 and 5, indicated by a statistically significant increase in the composite equilibrium scores. Clinicians should be aware that these practice effects might exist following the baseline SOT with about a 2-point improvement, especially in post-concussion evaluation.

There was no difference in performance based on the testing-order application, indicating that either the block or random testing order could be used as part of the concussion assessment battery. Furthermore, this study can raise awareness of potential practice effects during multiple administrations of the SOT, thereby contributing to developing a reliable criterion that can be used by clinicians in concussion assessment.

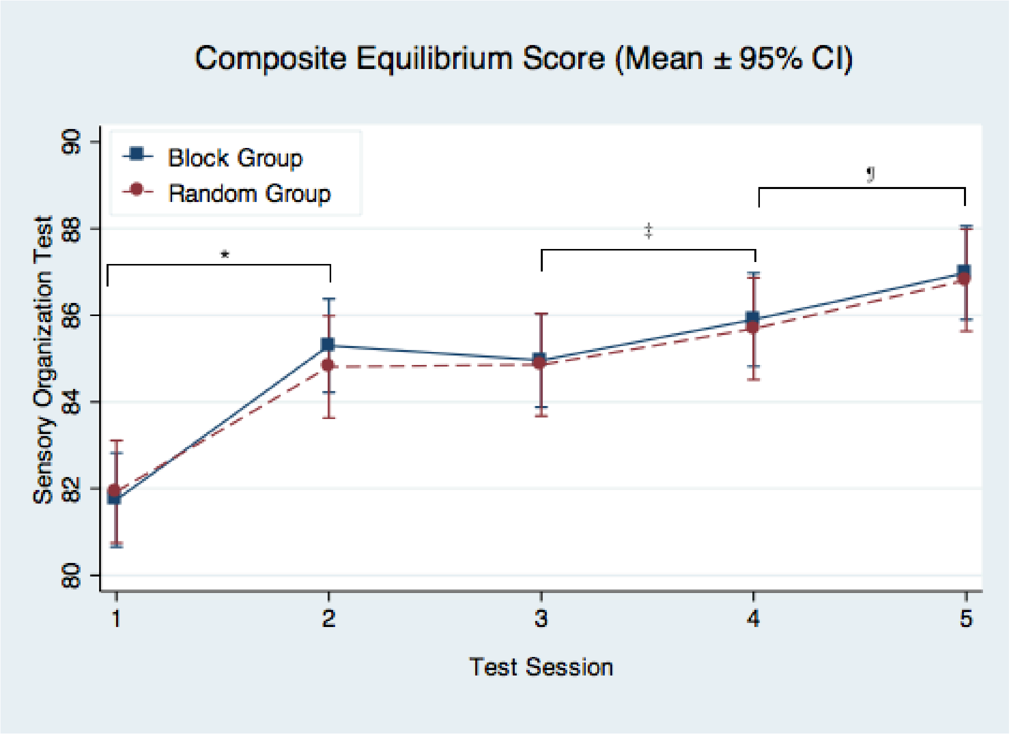

Figure 8. Composite Equilibrium Scores between Groups across 5 Sessions
[*]Statistically significant mean differences between sessions 1 and 2
[‡]Statistically significant mean differences between sessions 3 and 4
[¶]Statistically significant mean differences between sessions 4 and 5

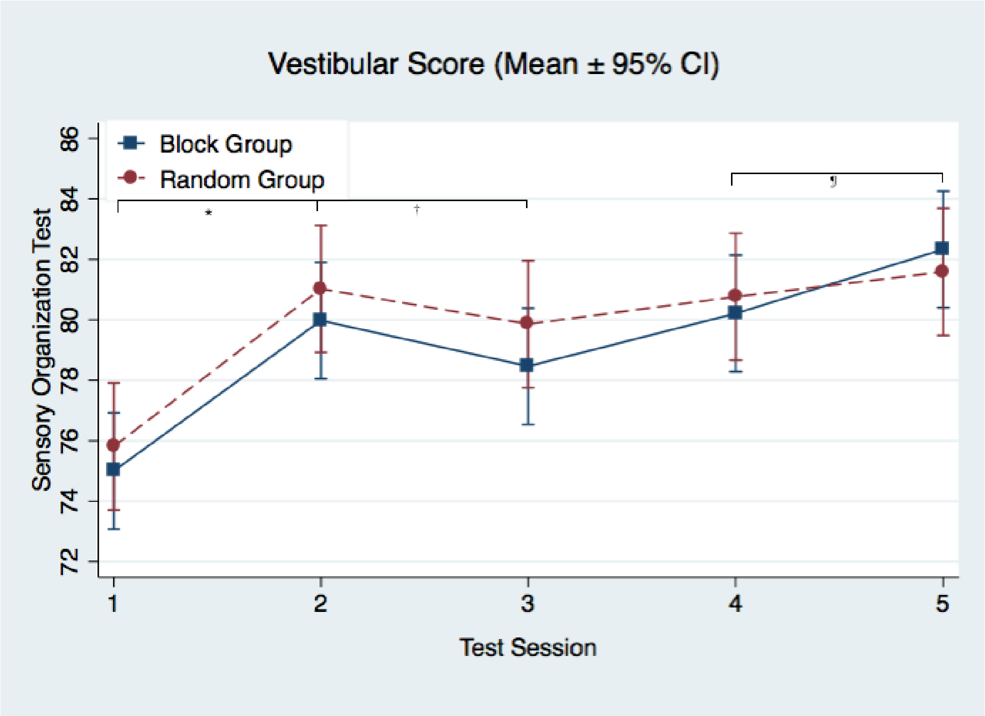

Figure 9. Vestibular (VEST) Scores between Groups across 5 Sessions
*Statistically significant mean differences between sessions 1 and 2
†Statistically significant mean differences between sessions 2 and 3
¶Statistically significant mean differences between sessions 4 and 5

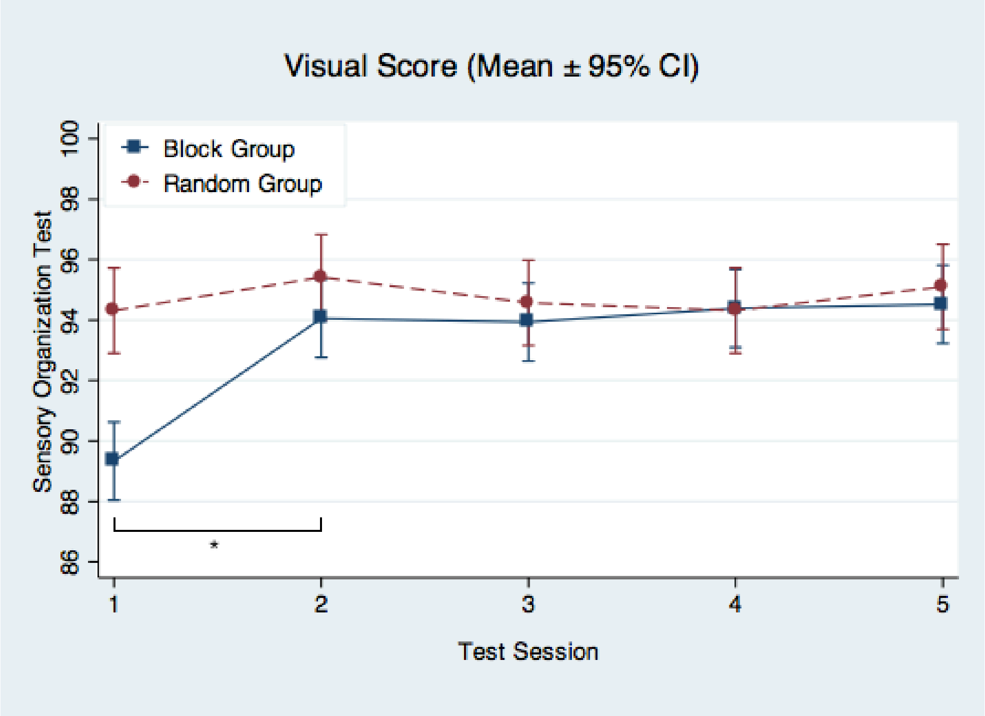

Figure 10. Visual (VIS) Scores between Groups across 5 Sessions
*Statistically significant interaction between block and random testing-order group

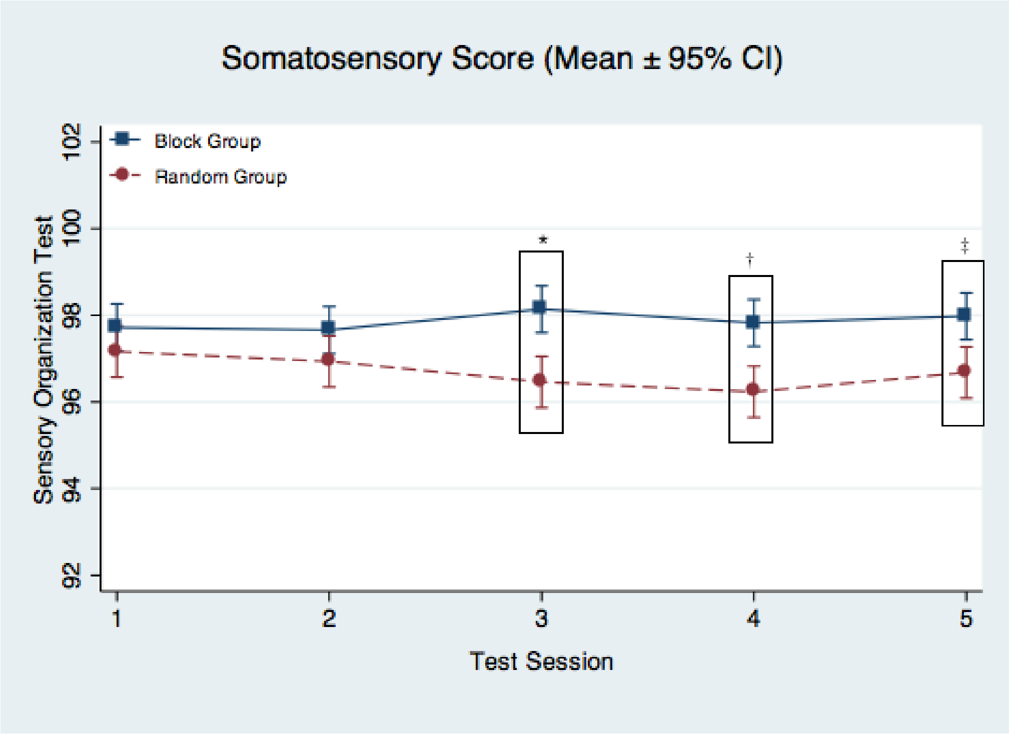

Figure 11. Somatosensory (SOM) Scores between Groups across 5 Sessions
[*]Statistically significant group differences at sessions 3
[†]Statistically significant group differences at sessions 4
[‡]Statistically significant group differences at sessions 5

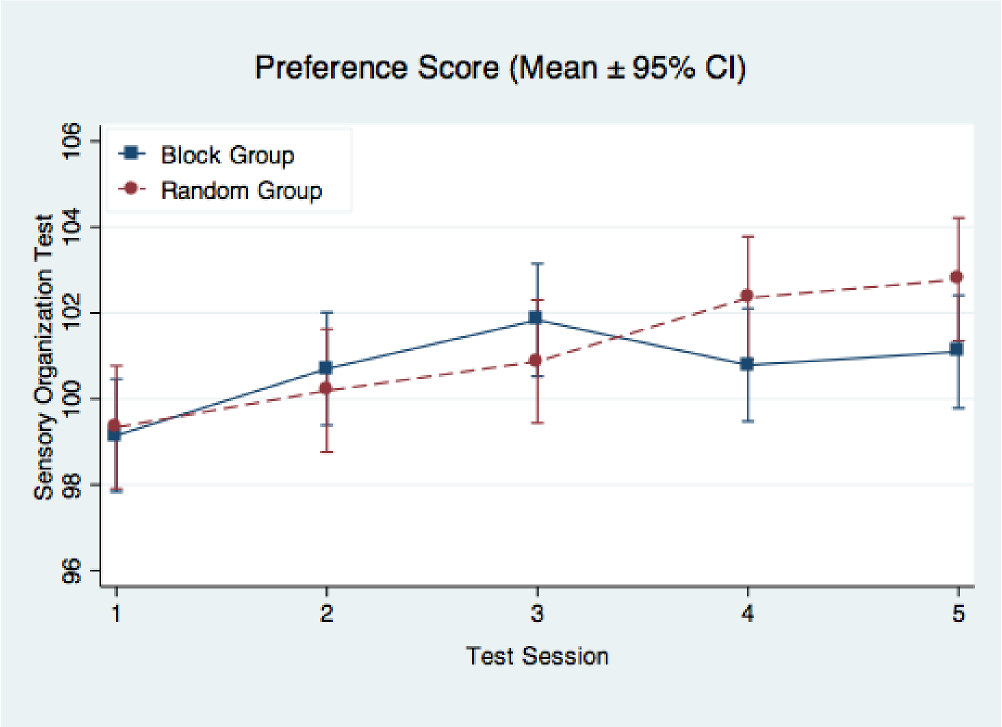

Figure 12. Preference (PREF) Scores between Groups across 5 Sessions

Table 6. Increase in composite and sub-composite scores between session 1 and subsequent sessions.

SOT	Session			
	2	3	4	5
Composite score	3.22 (2.31 to 4.13)[*]	3.07 (1.95 to 4.20)[*]	3.96 (2.76 to 5.17)[*, †]	5.06 (3.75 to 6.37)[*, †, ‡, ¶]
Somatosensory (SOM)	- .14 (-1.03 to .74)	- .14 (-.92 to .64)	- .41 (-1.16 to .33)	- .11 (-.87 to .64)
Visual (VIS)	2.91 (1.21 to 4.61)[*]	2.43 (.80 to 4.07)[*]	2.53 (.67 to 4.39)[*]	2.99 (1.13 to 4.84)[*]
Vestibular (VEST)	5.009 (3.24 to 6.94)[*]	3.76 (1.46 to 6.05)[*]	5.08 (2.70 to 7.46)[*]	6.55 (4.31 to 8.79)[*, ‡]
Preference (PREF)	1.20 (-.57 to 2.97)	2.11 (.23 to 3.99)[*]	2.33 (.49 to 4.16)[*]	2.70 (.54 to 4.85)[*, †]

NOTE. Values are mean difference (95% confidential interval).

Based on the marginal means. Adjustment for multiple comparisons: Bonferroni.

[*] Statistically significant mean differences between session 1 and subsequent sessions.

[†] Statistically significant mean differences between session 2 and subsequent sessions.

[‡] Statistically significant mean differences between session 3 and subsequent sessions.

[¶] Statistically significant mean differences between session 4 and subsequent sessions.

Supplement 1. Mean (Standard Deviation) Composite Scores and Sub-Composite Scores

Comprehensive Report	Group	Baseline	Baseline	Baseline	Day 45	Day 50
		Session 1	Session 2	Session 3	Session 4	Session 5
Composite equilibrium scores	Block	81.74 (± 4.78)[*]	85.30 (± 3.14)[*]	84.96 (± 4.19)[‡]	85.90 (± 3.48)[‡¶]	86.98 (± 3.48)[¶]
	Random	81.93 (± 4.57)[*]	84.81 (± 3.81)[*]	84.86 (± 4.17)[‡]	85.69 (± 3.33)[‡¶]	86.81 (± 3.70)[¶]
Somatosensory (SOM) scores	Block	97.72 (± 2.18)	97.66 (± 1.74)	98.14 (± 1.64)	97.82 (± 1.52)	97.98 (± 1.44)
	Random	97.16 (± 2.35)	96.94 (± 2.66)	96.46 (± 1.84)	96.23 (± 2.15)	96.67 (± 1.87)
Visual (VIS) scores	Block	89.33 (± 7.59)[*]	94.05 (± 3.81)[*]	93.94 (± 4.75)	94.39 (± 3.64)	94.52 (± 3.93)
	Random	94.31 (± 3.82)[*]	95.42 (± 3.70)[*]	94.57 (± 4.53)	94.31 (± 4.84)	95.10 (± 4.34)
Vestibular (VEST) scores	Block	75.00 (± 7.66)[*]	79.98 (± 5.92)[*†]	78.46 (± 7.57)[†]	80.21 (± 6.46)[¶]	82.33 (± 5.40)[¶]
	Random	75.81 (± 9.17)[*]	81.02 (± 6.74)[*†]	79.86 (± 7.50)[†]	80.76 (± 6.50)[¶]	81.59 (± 6.02)[¶]
Preference (PREF)	Block	99.15 (± 6.02)	100.70 (± 4.15)	101.83 (± 3.93)	100.79 (± 4.20)	101.10 (± 4.19)
	Random	99.34 (± 5.88)	100.19 (± 5.06)	100.87 (± 4.83)	102.35 (± 4.39)	102.78 (± 4.32)

[*] Statistically significant mean differences between sessions 1 and 2.

[†] Statistically significant mean differences between sessions 2 and 3.

[‡] Statistically significant mean differences between sessions 3 and 4.

CHAPTER 5

TEST-RETEST RELIABILITY OF THE SENSORY ORGANIZATION TEST USING MULTISCALE ENTROPY VALUES AND EQUILIBRIUM SCORES IN HEALTHY YOUNG ADULTS[2]

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[2] Lee HR; Ferrara MS; Brown CN; Simpson, KJ. To be submitted to Journal of Rehabilitation Research & Development.

Abstract

The Sensory Organization Test (SOT) on the SMART Balance Master® is used in advanced clinical settings to measure postural stability in concussion assessment. Equilibrium scores (ESs) from the SOT provide information about the integration of the multiple sensory systems of balance using a linear measurement method. However, linear measures of a dynamical system may not fully describe the complexity of the human postural stability system. Complexity index (C_I) scores using multiscale entropy (MSE; non-linear model) may provide more sensitive options, but the test properties must be established prior to clinical use. The purpose of this study was to determine reliability of the SOT using C_I scores and ESs over clinically relevant administration time intervals of concussion assessment. Control subjects were divided into two groups (block and random) that underwent different testing order protocols. This study demonstrated fair-to-good/excellent reliability for C_Is as well as ESs in the anterior-posterior direction in 10 out of 12 conditions over clinically relevant time intervals. C_I scores for the medial-lateral direction also represented fair-to-good reliability. With careful consideration, C_I scores can serve as useful and reliable tools for measuring postural stability.

Key words: Nonlinear dynamics, Postural stability, Sensory motor performance, Sensory integration, and Sport-related concussion.

Introduction

Over the last decade, sport-related concussion (SRC) has been considered an important public health concern because of the large number of athletes sustaining head injuries with potential complications of returning to physical activity too early [33]. The growing literature reports that various tools for assessing SRC have been established [31]. Several sports medicine organizations have produced consensus statements [7, 12, 33] advocating using a battery of tests, typically including self-reported symptom checklists, neurocognitive testing, and postural stability testing [12, 33]. Regarding postural stability, several previous studies of college athletes have demonstrated a typical recovery pattern in which postural stability returned to baseline within approximately 3-5 days following SRC [18, 61, 171].

Balance consists of both postural steadiness and postural stability [51]. As Prieto et al. explained, “Postural steadiness is the characterization of postural sway during quiet standing” [172]. Postural stability alludes to dynamic posturography and/or dynamic balance, and it refers to the ability to maintain equilibrium by controlling the body’s center of mass through central and peripheral complex feedback mechanisms [40, 112]. These feedback mechanisms coordinate three different sensory inputs (somatosensory, visual, and vestibular) and send commands for the muscle contraction to maintain postural stability. The Sensory Organization Test (SOT) from NeuroCom (Natus Medical Incorporated, Clackamas, Oregon USA) attempts to isolate and clarify which sensory inputs are most involved with maintaining posture and how the interaction among these inputs affects postural control [113].

Currently, sports medicine clinicians and researchers use the SOT on the SMART Balance Master® to assess the postural stability of concussed athletes [173]. The SOT provides equilibrium scores (ESs), which are calculated by comparing the angular difference between subject displacement and theoretical center of pressure (COP) displacement. This formula is based on a linear model, which assumes that more stable subjects are able to stand with less postural sway and produce high ESs [56]. However, this assumption may be limited to explain the complexity of human postural stability [130]. Previous studies reported that the irregularity of the COP is location was not directly related to random error of postural stability [126], but is the results of interactions underlying the complex postural sensory organization system [56]. Thus the COP path irregularity reflects a higher level of complexity and control.

Healthy physiological systems have greater adaptability and functionality than unhealthy systems. Therefore, it has been assumed that disease, aging, and injury should degrade complexity [57]. Approximate Entropy (ApEn) is a measure that has been developed to assess postural control complexity under physiologic and pathologic conditions [174]. However, the ApEn algorithm has certain limitations that bias the values. Therefore, Costa el al. recently introduced a new method, Multiscale Entropy (MSE) analysis, for measuring the complexity of time series data of a finite length [175]. MSE, measuring system dynamics over multiple time scales, is a more sensitive measure of physiologic variability [57, 130]. The complexity of a healthy system yields an increase in the single scale entropy values, such as ApEn values. However, an unhealthy system (injured or pathologic) may also yield a similar increase in the single scale entropy values, as it is associated with highly erratic outputs with statistical properties resembling uncorrelated noise, which may erroneously be interpreted as representing the complexity of a healthy system. The major reason for this potential misinterpretation is that single scale entropy does not take into account the complex temporal fluctuations inherent in healthy physiologic control systems [147]. Therefore, MSE provides more reliable statistics and can be quite effectively used to quantify the complex trajectory of the COP data in a natural time series, which is an important consideration for concussed athletes [174, 176].

Like other physiological measurements, due to individual differences, the COP-time data obtained during balance testing have variability affecting the reliability and validity of postural control results. Therefore, the reliability of the COP with the MSE method should first be established before clinicians use it to monitor a patient's postural stability improvement over the course of a clinical intervention and/or to evaluate postural stability for concussion management. Several previous studies reported general test-retest reliability for the SOT score [161, 178, 179]. However, to date, limited studies have utilized COP time series data generated from the SOT on the SMART Balance Master® and no study has considered clinically relevant time intervals of SRC assessment. The clinical time intervals (baseline, day 45, and day 50) utilized in the current study were adopted from an unpublished study conducted by The University of Georgia Athletic Association (UGAA) [101]. The UGAA study estimated the mean time intervals between baseline testing and the first concussion assessment (day 45) and between initial concussion evaluation (day 45) and follow-up assessment (day 50) following the initial SRC evaluation.

The purpose of this study was to examine the test-retest reliability coefficients and standard error of measurement (SEM) for the complexity index (C_I) of MSE values and ESs using clinically relevant time intervals (baseline, day 45, and day 50). Another purpose of this study was to compare two different SOT test administration protocols to describe the group differences between block and random order testing protocols on the regularity of the COP time series. We hypothesized that (1) two different measurement models—linear (ESs) and non-linear (the C_I of MSE)—would yield excellent test-retest stability (>.75) using clinically relevant time intervals, and (2) the randomized test administration order of the SOT at any point would increase test-retest reliability, and (3) COP displacements would become more regular as sensory conditions became more difficult when sensory inputs were limited or withdrawn.

Methods

Subjects

A total of 92 college-aged students completed the SOT on the SMART Balance Master®. The demographic information is presented in Table 3. Sample size was determined based on the recommendation provided by Baumgartner and Chung [149] for test-retest reliability studies using a one-way ANOVA model to estimate the ICC for a single score. All of the subjects had to meet the inclusion criteria: (1) no self-reported history of concussion within the past 6 months; (2) no current musculoskeletal injuries in the lower extremities and/or other body parts that might affect postural stability; (3) no physical sickness including visual and vestibular pathologies; (4) no consumption of any pharmacological substances affecting balance, recreational drugs, or alcoholic beverages within 24 hours prior to the balance test; and (5) no severe tiredness or fatigue. All subjects signed the informed consent form that was approved by the University of Georgia's Institutional Review Board.

Instrumentation

The SMART Balance Master® (Version 8.5 NeuroCom, A Division of Natus, Clackamas, Oregon USA) was equipped with a dynamic platform and a moveable visual surround that rotates in the anterior and posterior (AP) plane. The SOT is computerized dynamic posturography, which tests balance function coordinated with somatosensory, visual, vestibular, and visual conflict. The SOT protocol consisted of 6 different sensory conditions, each of which is composed of 3 trials [48]. The specific conditions of the SOT on the SMART Balance Master® are described in Figure 3. The 6 different conditions of the SOT are designed to systematically alter the sensory input process while the subject keeps maintaining balance. Center-of-pressure (COP) time series were derived from the SMART Balance Master® force plate measurements at a sampling frequency of 100 Hz for 20 seconds for each trial [48].

Testing Procedure

Day 1 assessment (Sessions 1, 2, and 3): Upon arriving at the Athletic Training Laboratory, each subject signed an informed consent form (Appendix A) that was approved by the Institutional Review Board, and completed a general health questionnaire (Appendix B). Once the informed consent and health questionnaires were obtained, all subjects were randomly assigned to either the block or random group. Subjects in the block group completed the SOT with conditions presented in the order suggested in the manufacturer's guidelines (increased difficulty from condition 1 through condition 6). Subjects in the random group completed the SOT with conditions presented in a random order. The random testing order of conditions for each trial was generated by Microsoft Excel software using the "rand" function. For example, one participant in the random group may have had conditions 6-5-1-3-2-4 as the first trial, conditions 1-6-2-4-5-3 as the second trial, and conditions 3-4-1-6-2-5 as the third trial, whereas another participant may have been tested with a totally different set of conditions, randomly selected by administrators. All participants remained in the same assigned group throughout all testing sessions (sessions 1 through 5). In the day 1 assessment, each subject completed 3 sessions with 20-minute breaks within the same day. Sessions 1 and 2 were the practice sessions for SOT and session 3 was considered the baseline performance. Figure 6 illustrates the sample selection and research procedure.

Day 45(session 4) and day 50 (session 5) assessment: Following the day 1 evaluation, each subject returned to the Athletic Training Lab on day 45. Subjects completed a modified health questionnaire (Appendix C) to report any health problems; those who no longer met the inclusion criteria were excluded. Subjects then performed the SOT once in either the block or randomized order. On day 50, the subjects returned to the lab and the procedure described for day 45 was repeated (see Figure 6).

Data Reduction and Analysis

The ESs for each condition and trial were generated using the manufacturer's algorithm, developed by NeuroCom (Natus Medical Incorporated, Clackamas, Oregon USA) [48]. ESs are based on the assumption that normal individuals can exhibit anterior-posterior sway over the theoretical limit of stability, which is a total range of 12.5 degrees without losing balance [48].

Using Matlab software (Version 8.1, The Mathworks, Natick, MA), center of pressure (COP) data derived from the force plate on the SMART Balance Master® were filtered by a Butterworth low-pass filter with a cut-off frequency of 5 Hz [145, 146]. We defined outliers as values outside the internal mean ±2 SDs (Figure 2). The complexity of the COP time series was quantified in both anterior-posterior (AP) and medial-lateral (ML) directions using the MSE algorithm, which was introduced in the previous studies [57, 174]. MSE analysis was performed with MSE compiler, which is a computer program (or set of programs) from the PhysioNet, under the GNU General Public license (GPL) (Version 2, June 1991) [180]. This MSE analysis consisted of three steps. First, a coarse-graining procedure (see Figure 1) was used to derive the representations of a system's dynamics at different time scales (from scale 2 to scale 20 [$\tau=2$ to 20]). Second, the sample entropy (SampEn) algorithm was used to quantify the regularity of a coarse-grained time series at each time scale factor with $m=2$ and $r=0.15\sigma$ [181], where σ denotes the standard deviation (SD) of the original time series. Third, a complexity index (C_I) integrated all the SampEn values over the pre-defined range of scales (2 to 20). Scale 1 was excluded from the analysis, as it is the most affected by superimposed uncorrelated noise generated by recording devices [176, 182]. Briefly, MSE quantifies the degree of irregularity of a time series over multiple timescales. MSE demonstrates a higher degree of irregularity than a single time scale such as ApEn and SampEn [176]. The complexity degree of different combinations in each direction (AP and ML) is measured in terms of the complexity index (C_I), which is defined as the area under the MSE curve over all scales ($C_I = \sum_{i=1}^{Scale} SampEn(i)$), in which i=current scale, and *Scale* is the maximum of the scale factors, which is 20 in this study [183, 184]. Therefore, C_I provides us a single value index representing the degree of the regularity of the COP position at a range of time scales, thereby assessing the degree of the human body stability.

An intraclass correlation coefficient (ICC), as a single measure, informs the clinician about the degree of reliability of results across the clinical relevant time intervals of concussion assessment. Therefore, an intraclass correlation coefficient ($ICC_{1,3}$) estimates the test-retest reliability of the mean of each SOT condition between baseline and day 45 and between day 45 and day 50. The ICC produces a value between 0 and 1 and is interpreted in a manner similar to a correlation coefficient. According to the Fleiss criteria [185], ICC values are defined as poor reliability (less than 0.4), fair to good reliability (0.40 to 0.75), and excellent reliability (above 0.75). All data analyses were performed utilizing R software (R Core Team (2013) [186]. The level of significance was set at $p < .05$ [186].

Results

Of the total 125 subjects (N=125) participating in this study, data of 33 subjects were removed for subsequent analyses due to not completing SOT sessions, not meeting the inclusion criteria, or being determined as outliers ±2 standard deviations from the mean (Figure 2). The final analysis consisted of 92 subjects. Means and standard deviations for demographic information appear in Table 3. Thirteen subjects (14.1%) reported previous history of concussion as diagnosed by health care providers trained for sport-related concussion. Eleven of these subjects reported no more than 2 prior concussions, and only 2 participants reported a history of 3 or more concussions. No subjects were excluded from our study due to any kind of balance disorder and/or sport-related concussion. The mean time period to follow-up from the baseline was 47.3 (± 3.9) days and another 5.3 (± 2.2) days to the day 50 assessments.

The means and standard deviations for C_I values and ESs of individual SOT conditions are presented in Table 7. In general, the mean values for ESs and C_I values for AP reported for conditions 1 through 3 were higher than those values for conditions 4 through 6, but the standard deviations for conditions 1 through 3 were in the narrow range across the sessions.

The ICCs for the C_I values and ESs with individual SOT conditions from baseline to day 45 and from day 45 to day 50 are presented in Table 8. The highest ICCs for C_I (AP) (ranging from .62 to .87 for block group) were found between baseline and day 45. Overall, the ICC values for C_I (AP) demonstrated fair-to-good / excellent reliability across the time intervals and both groups (block and random). The ICCs for C_I (ML) reported fair-to-good reliability throughout baseline to day 50 (ranging from .40 to .77 for both groups) (Table 8). In addition, fair-to-good / excellent reliability for the ESs between baseline and day 45 was reported except for condition 1 (.29 in block group) and condition 2 (.22 in random group). Generally, the ICCs for the C_I (AP) and ESs reported for conditions 1 through 3 were lower than those for conditions 4 through 6 between baseline and day 45 (see Table 8). Our results demonstrated that as the level of task difficulty increased in conditions 4 through 6 (sway-referenced support), test-retest reliability also increased in both composite ESs and C_I values (AP).

Discussion

Our research focused on the test-retest reliability of the SOT on the SMART Balance Master® using the clinical relevant time intervals of concussion assessment. The major findings of our study demonstrated that (1) the C_I values for AP and ML, and ESs revealed fair-to-good and/or excellent test-retest reliability over clinically relevant time intervals of concussion assessment (baseline, day 45, and day 50) according to the criteria provided by Fleiss [185]; (2) ESs and C_I (AP) values for conditions 4 through 6 were higher than those for conditions 1 through 3; and (3) unlike the previous study, C_I (ML) values showed no difference between sway-reference conditions (3 through 6) and stable surface conditions (1 through 3) during the SOT. Our ICC estimates varied among the SOT conditions (conditions 1 through 6), measures of balance (linear and non-linear), and testing time points. Table 8 illustrates ICCs with different time points and conditions.

There are relatively few entropy measurements of postural stability with acceptable test-retest reliability [52, 188]. Our findings for the MSE stability measure (ranging from .50 to .87 in AP and ranging from .40 to .77 in ML) are similar to those of a previous ApEn study, which reported a range from 0.65 to 0.90 in AP and from 0.56 to 0.77 in ML over consecutive days of testing. However, the current study adopted clinically relevant time intervals for test-retest SOT (baseline, day 45, and day 50), which may demonstrate more clinically acceptable reliability [188]. The ICC findings for MSE AP partially support hypotheses 1.1 and 1.3. However, the ICC findings for MSE ML do not support hypotheses 1.2 and 1.4.

Traditionally, postural stability measures such as ESs have been used in analyzing the variability of the COP location for postural stability; healthier subjects are assumed to be able to stand with less postural sway [56]. The estimated ICCs for ESs in the current study resemble those found in previous studies, partially supporting hypotheses 1.5 and 1.6. Fair-to-good test-retest reliability was reported in one study of healthy adults with 1 to 3 days between tests [161], and in another study of older adults with a 1-week interval between tests (ranging from .26 to .64) [178]. In addition, Cavanaugh [56] claimed higher ICCs (ranging from .65 to .90) for ESs over consecutive days of testing than those reported in previous studies [161, 178]. Tsang et al. also reported excellent reliability of the individual SOT on NeuroCom with a 1-week interval between tests (ranging from .72 to .90) [179].

In this study, it was hypothesized that each condition of the SOT would achieve an ICC equal to or exceeding what is suggested for clinical interpretation. However, clinicians must be aware that clinical recommendations for ICC interpretation have been diverse. Portney and Watkins suggested that ICCs greater than .75 represent good reliability and those less than .75 denote poor-to-moderate reliability [189], while Anastasi and Urbina recommended that ICCs should meet or exceed .60, the minimum acceptable level for reliability used in clinical interpretations [190]. The ICCs for the SOT in the current study indicated that the measures closely met what is considered acceptable for clinical applications, except the ICCs for ES for condition 1 (the block group) and condition 2 (the random group) between baseline and day 45 (see Table 8). The ICCs for these two conditions (1 and 2) were determined to have poor test-retest reliability (see Table 9). Therefore, sports medicine clinicians have to be selective in choosing the SOT method (linear or non-linear model) that can provide the highest reliability for SOT assessment.

Overall, the findings of our investigation indicated both ESs and C_I values (AP) for sway-referenced surface conditions (4 through 6) of the SOT represented higher ICCs than those of stable surface conditions (1 through 3). A previous SOT study on ES agreed with our findings

[161]. In addition, consistent with the findings of Cavanaugh [188], the current MSE study demonstrated that COP for C_I (AP) became more regular with decreasing means of C_I values (AP) (Table 8). As previously indicated, the higher the C_I values, the greater the complexity; and the lower the C_I values, the less the complexity (more regularity). Cavanaugh stated that the increase in COP regularity during sway-referenced surface conditions might have been produced by the mechanical effect of standing on a moveable surface because the subjects needed a longer period of time to correct the COP position. However, the current study may not support Cavanaugh's findings [188] in that C_I values (ML) in this study did not appear different between sway-referenced surface conditions (3 through 6) and stable surface conditions (1 through 3). This result suggests that although mechanical restrictions need to be considered as an important factor in the SOT with sway-referenced surface conditions only in the AP direction, C_I values (ML) may include a higher degree of complexity of time series data compared with ApEn values . (e.g. Cavanaugh) [188]. Therefore, compared with ApEn, the current study supports that MSE can potentially detect more complexity of COP data and therefore serve as a better tool for post-concussion assessment.

Several factors may influence SOT scores. First, improved performance on the SOT with repeated tests may be influenced by practice effects. Previous studies suggested that since improved performance on the SOT related to practice effects can be controlled for [161, 191], multiple SOTs should be administered to establish the solid baseline testing and to update the baseline measure of postural stability periodically. A valid baseline can assist the clinician in making the return-to-play decision following SRC [161, 165]. Previous studies did not consider multiple baselines or feasible practice effects due to the increased total administration time and cost of the SOT. However, the current study was the first SOT study with multiple administrations of the baseline assessment for providing measurement stability by controlling for practice effect.

Second, for a clinician, it would be of great value to know which testing order protocol (block or random) would allow for the most accurate postural stability assessment when using the SOT on the SMART Balance Master®. In most SOT studies, the manufacturer's recommended testing order (increasing difficulty from condition 1 through condition 6) was chosen. An alternative available to the administrator is to randomize the testing conditions (random group protocol), which could result in a decrease in the likelihood of practice effects and/or show different levels of reliability on each condition. However, limited studies were conducted to investigate differences between block and random testing-order protocols [191]. The current findings suggest that measurement reliability of C_I (AP) is greatest when the SOT is performed according to the manufacturer's guidelines (block testing order), except for condition 1 between baseline and day 45. Thus, hypothesis 2.1 was partially supported. However, no group testing-order differences were found for the reliability of ESs and C_I (ML) scores, thus providing support for hypothesis 2.2. Based on the study results, sports medicine practitioners may select the block testing protocol using C_I (AP) for SOT administration in order to obtain highly reliable test scores, but further investigation is warranted.

Third, the time intervals among the sessions in previous studies of measurement stability were unrealistic in clinical application of concussion management [161, 178, 179]. However, the time intervals used in this current study, empirically determined in previous research, [101] demonstrated fair-to-good and/or excellent test-retest reliability. For the sports medicine clinician, test-retest time frames are an important consideration for the clinical interpretation following SRC because some athletes may have diagnosis of SRC from 1 month to a year after baseline testing.

Conclusion

The present study estimated the reliability of a large set of COP data using ESs and MSE measures among a population of healthy young college students. Postural stability tests (baseline, day 45, and day 50) yielded fair-to-good/excellent reliability of MSE (AP) and (ML), and of ES. The present study suggests that, for healthy young college students, ESs and MSE values can serve as worthy and reliable measurements for each of the six SOT conditions. More specifically, C_I scores for AP represented the most stable measurement over clinical relevant time intervals of SRC assessment, and C_I scores for ML demonstrated more sensitivity in detecting COP displacement than those of ApEn. This research can make a contribution to clinical assessment of sport-related concussion and subsequent decisions on return-to-play by providing evidence supporting that MSE is reliable and appears to overcome the limitations of ApEn. However, future studies are needed to test postural stability measurement using MSE with concussed athletes. For clinicians, the results indicate block testing provides the most accurate postural stability assessment when using the SOT with linear and non-linear models of calculation.

Table 7. Mean (S.D.) complexity index (C_I) values and Composite Equilibrium Score (ES) for conditions.

	Condition 1			Condition 2			Condition 3		
	MSE-AP	MSE-ML	SOT-EQ	MSE-AP	MSE-ML	SOT-EQ	MSE-AP	MSE-ML	SOT-EQ
BL	18.30(3.36)*	16.49(3.49)*	94.83(1.61)*	18.84(2.99)*	18.20(3.18)*	93.05(1.79)*	18.36(3.60)*	18.47(3.95)*	93.21(2.38)*
	19.00(3.41)$^+$	17.13(3.66)$^+$	94.78(1.12)$^+$	18.86(3.07)$^+$	17.42(3.62)$^+$	91.41(1.54)$^+$	18.19(3.33)$^+$	16.95(3.74)$^+$	92.56(1.59)$^+$
Day 45	18.10(3.13)*	18.40(4.16)*	95.45(1.17)*	18.57(3.29)*	19.51(4.13)*	93.37(1.68)*	18.55(3.50)*	19.26(3.33)*	93.37(2.03)*
	18.23(3.15)$^+$	18.02(3.65)$^+$	94.87(1.02)$^+$	18.69(3.47)$^+$	17.97(3.51)$^+$	91.29(2.01)$^+$	18.54(3.83)$^+$	17.39(3.53)$^+$	92.56(2.49)$^+$
Day 50	17.53(3.33)*	18.24(3.12)*	95.43(1.39)*	18.88(3.79)*	18.76(4.40)*	93.49(1.75)*	18.57(3.79)*	19.53(3.68)*	94.24(1.92)*
	18.54(4.23)$^+$	17.77(3.22)$^+$	95.22(1.18)$^+$	19.73(3.35)$^+$	17.19(2.83)$^+$	92.06(2.01)$^+$	20.08(4.32)$^+$	19.20(3.79)$^+$	93.62(1.93)$^+$

	Condition 4			Condition 5			Condition 6		
	MSE-AP	MSE-ML	SOT-EQ	MSE-AP	MSE-ML	SOT-EQ	MSE-AP	MSE-ML	SOT-EQ
BL	13.67(4.50)*	16.82(3.94)*	89.08(4.79)*	14.29(3.89)*	17.42(3.58)*	74.42(7.48)*	12.55(4.57)*	17.45(3.88)*	77.29(9.07)*
	13.81(4.17)$^+$	15.98(3.95)$^+$	89.63(4.47)$^+$	13.94(4.69)$^+$	17.10(3.58)$^+$	75.71(7.34)$^+$	11.46(3.95)$^+$	15.85(3.31)$^+$	75.97(9.74)$^+$
Day 45	14.72(4.62)*	17.11(3.41)*	90.09(3.73)*	15.00(4.28)*	17.81(3.58)*	76.55(6.10)*	12.23(4.47)*	17.82(4.28)*	77.85(8.23)*
	13.02(4.63)$^+$	16.91(3.78)$^+$	89.47(4.62)$^+$	15.39(4.18)$^+$	17.13(2.83)$^+$	76.62(6.26)$^+$	12.80(4.27)$^+$	16.85(3.18)$^+$	79.17(6.73)$^+$
Day 50	13.99(4.55)*	17.44(3.75)*	90.20(4.05)*	15.64(3.99)*	18.36(3.44)*	78.57(5.42)*	12.78(4.82)*	17.47(3.78)*	79.70(8.83)*
	13.85(4.87)$^+$	17.30(3.77)$^+$	90.55(4.08)$^+$	15.74(4.60)$^+$	17.25(3.53)$^+$	77.69(5.85)$^+$	13.39(5.13)$^+$	16.28(3.51)$^+$	80.81(9.04)$^+$

BL: Baseline, MSE: Multiscale entropy, SOT: Sensory Organization Test, EQ: Composite Equilibrium Score
Anterior-posterior direction (AP) and Medial-lateral direction (ML) / *Block protocol and $^+$Random protocol

Table 8. Between-sessions response stability (ICC) and precision estimates (SEM) for conditions.

	Condition 1			Condition 2			Condition 3		
ICC	C_I-AP	C_I-ML	SOT-ES	C_I-AP	C_I-ML	SOT-ES	C_I-AP	C_I-ML	SOT-ES
BL/D45	.62(2.30)*	.76(2.71)*	.29(0.98)*	.71(2.22)*	.57(2.59)*	.70(1.23)*	.62(2.51)*	.59(2.58)*	.61(1.56)*
	.72(2.32)$^+$	.76(2.59)$^+$	.66(0.76)$^+$	.61(2.31)$^+$	.71(2.53)$^+$	.22(1.26)$^+$	.50(2.89)$^+$	.66(2.78)$^+$	.44(1.57)$^+$
D45/D50	.63(2.56)*	.59(2.88)*	.62(1.01)*	.74(2.70)*	.75(3.38)*	.63(1.36)*	.84(2.53)*	.63(2.58)*	.72(1.44)*
	.78(2.92)$^+$	.44(2.73)$^+$	.57(0.87)$^+$	.62(2.70)$^+$	.73(2.51)$^+$	.50(1.59)$^+$	.72(3.23)$^+$	.54(2.90)$^+$	.58(1.75)$^+$

	Condition 4			Condition 5			Condition 6		
ICC	C_I-AP	C_I-ML	SOT-ES	C_I-AP	C_I-ML	SOT-ES	C_I-AP	C_I-ML	SOT-ES
BL/D45	.82(3.23)*	.62(2.60)*	.72(3.02)*	.87(2.84)*	.44(2.53)*	.65(4.81)*	.79(3.20)*	.68(2.89)*	.86(6.12)*
	.78(3.11)$^+$	.71(2.74)$^+$	.86(3.22)$^+$	.74(3.14)$^+$	.77(2.27)$^+$	.61(4.81)$^+$	.70(2.91)$^+$	.46(2.30)$^+$	.73(5.83)$^+$
D45/D50	.84(3.64)*	.72(2.84)*	.79(3.08)*	.86(3.28)*	.40(2.78)*	.67(4.56)*	.77(3.68)*	.63(3.19)*	.85(6.76)*
	.84(3.76)$^+$	.71(3.00)$^+$	.83(3.45)$^+$	.79(3.48)$^+$	.75(3.18)$^+$	.76(4.83)$^+$	.80(3.72)$^+$	.60(2.65)$^+$	.75(6.25)$^+$

Intraclass correlation coefficient (ICC) and Standard Error of Measure (SEM)

Anterior-posterior direction (AP), and Medial-lateral direction (ML) / *Block protocol, $^+$Random protocol

CHAPTER 6

SUMMARY

Sport-related concussion (SRC) should be evaluated in a timely manner with a multi-faceted assessment that incorporates multiple instruments for concussion management [30-32, 101]. Evaluating postural control is recommended as one of the integral assessments in the concussion battery of tests. The SOT on the SMART Balance Master® is typically considered the most advanced postural stability tool in SRC assessment and is designed to systematically disrupt the sensory input processes while the subject keeps maintaining balance [192]. In addition, in the forefront of proper SRC assessment is the implementation of baseline and post-injury tests [12, 33]. The accurate measurement of the baseline performance of individual athletes is very important to allow for an accurate comparison of the baseline score to the post-injury test score during the post-concussion evaluation and recovery period to help determine a return-to-play decision [12, 33]. Since obtaining a valid baseline and post-concussion test are paramount in the concussion management model, the sports medicine clinician should consider the reported practice effects and test-retest reliability of the SOT over clinical administration time intervals of SRC assessment.

In this dissertation, two studies were presented. The first study evaluated the practice effects of repetitive administrations of the SOT in healthy college-aged adults. Subjects were divided into two groups (block and random) that underwent different testing order protocols. The participants were tested at five times (3 sessions at baseline, 1 session at day 45, and 1 session at day 50). Statistically significant increases were found in the composite equilibrium and sub-composite (visual) scores between sessions 1 and 2. However, sub-composite scores (preference) may be limited in application for clinical interpretation in SRC management because of potential ceiling effects of that test. In addition, no differences were found between block and random groups, with the exception of the visual sub-composite score for session 1. Based on the results, sports medicine clinicians should use caution when performing repeated administrations of the SOT due to practice effects. More specifically, in multiple assessments, clinicians should have a valid baseline measure that takes into account possible practice effects. Thus, it is recommended that clinicians administer at least 1 preliminary practice session of the SOT and rely on the second SOT administration as a valid baseline of SRC assessment.

The second study evaluated the test-retest reliability of the SOT using MSE and SOT composite ESs at clinical relevant time intervals [174, 182]. The participants, divided into block and random groups, were tested at 3 sessions on day 1, 1 session on day 45, and 1 session on day 50. For this study, we utilized COP data from the SMART Balance Master® force plates and then generated a complexity index (C_I) score [176] to calculate intraclass correlation coefficients (ICCs) [149]. CI is defined as the area under the MSE curve over all scales (integrating MSE scales from 2 through 20); CI scores represent an index for assessing the degree of the human body stability [176]. The $ICC_{(1,3)}$ values for CI in the AP and ML direction reported fair-to-good / excellent reliability, while composite ESs fell below those considered clinically acceptable. Descriptively, the ICCs for composite ES and CI in the AP direction reported for conditions 4 through 6 were higher than those for conditions 1 through 3 between baseline and day 45. However, unlike the previous study, ICCs for CI in the ML direction showed no differences between sway-referenced surface conditions (3 through 6) and stable surface conditions (1 through 3). Overall, these results support that MSE can potentially detect more sensitive complexity of postural stability. Theoretically and practically, both models (nonlinear and linear dynamics) demonstrated unique and valuable insights for understanding the postural control system.

With careful consideration, CI scores in the AP and ML direction can serve as useful and reliable tools for measuring postural stability. However, sports medicine clinicians are advised to utilize a multi-faceted approach to increase accuracy of the concussion evaluation battery when managing sport-related concussion. Future research is needed to assess the sensitivity and specificity of CI scores between healthy and concussed subjects in the different age groups.

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APPENDIX A

Consent Form

I agree to participate in the research study entitled Test-Retest Reliability of the NeuroCom Sensory Organization Test conducted by Hyung Rock Lee (706-542-3273) and Dr. Michael Ferrara (706-542-4801) of the Department of Kinesiology at the University of Georgia. I understand that my participation is entirely voluntary. I can refuse to participate or withdraw my consent at any time without penalty or loss of benefits to which I am otherwise entitled and have the results of my participation, to the extent that they can be identified as mine, returned to me or removed from the research records and destroyed immediately post-withdrawal from this study. My decision to participate or not to participate will not affect my grades or class standing.

The following points have been explained to me:

The research is being conducted to study the test-retest reliability of the NeuroCom Smart Balance Master Sensory Organization Test (SOT) to compare three different testing methods. I will be randomly assigned to one of two different groups and testing will occur over 3 sessions in a period of about 8 weeks.

The procedures are as follows:

If I volunteer to take part in this study, I will be asked to attend three laboratory sessions over 8 weeks.

Session 1: This session will consist of three parts: 1) Completing a health questionnaire, UGA self-report symptom inventory, and measuring foot length, width and height; 2) Performing an orientation session on the Neurocom Sensory Organization Test for a baseline readings; and 3) Performing two test sessions of the Neurocom Sensory Organization Test. These tests will occur in the St. Mary's Athletic Training Laboratory (Room 110) and NeuroCom Lab. (Room 106F) in the Ramsey Center.

I will be asked to do the following things:

1) Answer the health questionnaire and UGA self-report inventory, which will take about 10 minutes. If I do not meet the inclusion criteria, I will be excluded from the study. If I meet the inclusion criteria, measurements for my foot will be gathered. I will be randomly assigned to one of the two groups (Block and Random condition) and perform the Sensory Organization Test. I will perform one orientation session to obtain baseline readings, then two test sessions; the first test session following a 20 minute break after the orientation (baseline) session, and the second test session following a 20 minute break after the first test session. Each Sensory Organization

Test will take 15-20 minutes. A Borg scale will be delivered to assess effort after each Sensory Organization Test. Total time for session 1 will be about 1.5 hours

Session 2: I will be asked to do the following things:

1) I will return to the Athletic Training Laboratory 45 days after session 1. A questionnaire concerning changes in my health status, injury, and any other illnesses will be filled out.
2) Perform the Sensory Organization Test, which will take about 15-20 minutes.
3) A Borg scale will be delivered to assess effort after Sensory Organization Test.

Session 3: I will be asked to do the following things:

1) I will return to the Athletic Training Laboratory 5 days from the completion of session 2. A questionnaire concerning changes in my health status, injury, and any other illnesses will be filled out.
2) Perform the Sensory Organization Test, which will take about 15-20 minute.
3) A Borg scale will be delivered to assess effort after Sensory Organization Test.

The benefit that I may expect from this research is to better understand my postural stability and contribute to the expanding body of knowledge regarding mild traumatic brain injury. Extra-credit will be offered for my participation in this study if my professor permits this option. Depending on the professor, extra credit for those not participating in this study may, or may not be available – this is to the discretion of the professor. At the conclusion of the study, I will receive information about my performance on the SOTs.

There is minimal risk from my participation in this project. The only potential injury that may occur would be from a fall during the balance testing. However, a trained spotter will be used to assist me in maintaining balance during the NeuroCom testing. In the event of injury resulting from participation in this project, immediate first aid will be provided. If additional care is needed, the researcher will arrange for my transportation to the UGA Health Center (if I am a fees-paid student) or a local hospital of my choice and I will be responsible for any expense that may be incurred. As a participant, I do not give up or waive any of my legal rights.

The results of this participation will be confidential. Any data used for research will not contain my personal information without my prior written consent, unless otherwise required by law.

The investigators will answer any further questions about the research, now and during the course of the project and can be reached at 706-542-4801 for Dr. Michael Ferrara and 706-542-3273 for Rock Lee.

I understand that by signing this form, I am agreeing to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

Michael S. Ferrara Telephone: 706-542-4801 E-mail: mferrara@uga.edu	Signature	Date
Name of Participant	Signature	Date

Please sign both copies, keep one and return one to the researcher.

Additional questions or problems regarding your rights as a research participant should be addressed to the Chairperson, Institutional Research Board, University of Georgia, 629 Boyd Graduate Studies Research Center, Athens, Georgia, 30602-7411 Telephone: (706) 542-3199: E-mail Address IRB@uga.edu

APPENDIX B

Health Questionnaire

Please answer the following questions as accurately and as thoroughly as you can.

NAME: Last:________________________Middle Initial:_____First:_________________

Circle your current year in school: 1 2 3 4 4+

What is your birth date? Month: ________________ Day: ________ Year:19__________

What is your current age? ____________ **Circle your sex:** Male Female

What is your RACE/ETHNICITY? (Check one)

☐ White (not of Hispanic origin)	☐ Asian or Pacific Islander
☐ Black (not of Hispanic origin)	☐ American Indian or Alaskan Native
☐ Hispanic	☐ Other

1. **How often do you participate in physical activity** (counting only for moderate intensity- i.e. cardio 30 minute a day, vigorous sporting activity for at least 20 min of participation, eight to 10 strength-training exercises with eight to 12 repetitions of each exercise, etc.)**?**
    - ☐ No physical activity
    - ☐ 1 - 2 times per week
    - ☐ 2 - 3 times per week
    - ☐ 3 - 5 times per week
    - ☐ 5 - 7 times per week

2. **Have you ever had a concussion** (Concussion is defined as a complex pathophysiological process affecting the brain induced by traumatic biomechanical forces)**? (CIRCLE ONE)** **YES** **NO**

3. **How many times have you had a concussion? (Skip if not applicable)**
   (CIRCLE ONE) 0 1 2 3 4 4+

4. **When was the year and month of your concussion(s)? (Skip if not applicable)**
   Please list your complete concussion history. Month/Year___________________________

5. **Have you ever had lower extremity surgery (ACL surgery etc)?**
   YES **NO**
   Please list your complete surgical history. Month/Year______________________________

6. **Are you physically sick (cold, flu, allergies) today? (CIRCLE ONE)**
   YES **NO**

7. **Are you currently receiving treatments for any type of injury?**
   (Example: ankle sprain, bruise, pulled muscle) (CIRCLE ONE)
   YES **NO**
   Please list of your treatment: ____

8. **Are you currently taking any medication?**
   YES **NO**
   Please List all: ____

9. **Do you have problems with inner ear pathologies?** (Such as vertigo, vestibular neuritis, middle ear infection, etc):
   YES **NO**

10. **Do you have problems with visual disturbances?** (Wearing new glasses, new contact lanes or double vision etc):
    YES **NO**
    Please describe your eye problem____

11. **Did you drink any alcohol beverages in the last 12 hours?**
    YES **NO**
    If you answer YES, Please answer the questions below:
    What type of alcohol beverage did you drink?______________________________________

About how much? ____

About what time? ____

- **Anthropometrics measurements**

Height: **Weight (optional):**

Hip Width	**Leg length R**	**Leg length L**	**Foot Width R**	**Foot Width L**	**Foot R**	**Foot L**	**Ankle R**	**Ankle L**

- ***The Borg Category Rating Scale for Effort***

Pre-test 1after SOT: ____

Pre-test 2 after SOT: ____

Baseline Test after SOT: ____

Day 45 after SOT: ____

Day 50 after SOT: ____

APPENDIX C

Modified Health Questionnaire

Day 45 Questionnaire

1. **Have you had a head injury since the baseline balance test?**

   YES **NO**

   Please list date and month of head injury___________________________________

2. **Do you have any lower extremity problems (Ankle sprain and/or ACL injury etc)?**

   YES **NO**

   Please list all: ______________________________________

3. **Are you physically sick (cold, flu, allergies) today? (CIRCLE ONE)**

   YES **NO**

4. **Are you currently receiving treatments for any type of injury?**

   (Example: Ankle sprain, Bruise, Pulled muscle) (CIRCLE ONE)

   YES **NO**

   Please list of your treatment: ____

5. **Are you currently taking any medication?**

   YES **NO**

   Please List all: ____

6. **Do you have problems with inner ear pathologies?** (Such as Vertigo, Vestibular neuritis, Middle ear infection, etc):

   YES **NO**

7. **Do you have problems with visual disturbances?** (Such as wearing new glasses or double vision etc):

YES **NO**

Please describe your eye problem____

8. **Did you drink any alcohol beverages in the last 12 hours?**

YES **NO**

If you answer YES, Please answer below questions:

What type of alcohol beverage did you drink? ______________________________

About how much? ____

About what time? ____

Day 50 Questionnaire

1. **Have you had a head injury since the baseline balance test?**

YES **NO**

Please list date and month of head injury____

2. **Do you have any lower extremity problems (Ankle sprain and/or ACL injury etc)?**

YES **NO**

Please list all: ____

3. **Are you physically sick (cold, flu, allergies) today? (CIRCLE ONE)**

YES **NO**

4. **Are you currently receiving treatments for any type of injury?**

(Example: Ankle sprain, Bruise, Pulled muscle) (CIRCLE ONE)

YES **NO**

Please list of your treatment: ____

5. **Are you currently taking any medication?**

YES **NO**

Please List all: ____

6. **Do you have problems with inner ear pathologies?** (Such as Vertigo, Vestibular neuritis, Middle ear infection, etc):

YES **NO**

7. **Do you have problems with visual disturbances?** (Such as wearing new glasses or double vision etc):

YES **NO**

Please describe your eye problem____

8. **Did you drink any alcohol beverages in the last 12 hours?**

YES **NO**

If you answer YES, Please answer below questions:
What type of alcohol beverage did you drink? ______________________________
About how much? ____
About what time? ____