

CONCUSSION ASSESSMENT RELIABILITY

by

STEVEN PHILIP BROGLIO

(Under the direction of Michael S. Ferrara)

ABSTRACT

The neurocognitive assessment has been regarded as the gold standard for concussion assessment. With the recent advances in technology this assessment has become computerized, and several programs now available specifically for sport concussion assessment. While these programs are based on the traditional pencil and paper assessments, the psychometric properties have not been established. More specifically, the reliability of the computer programs using clinically relevant assessment intervals has not been performed. In addition, recent evidence suggests that test performance during multiple administrations may be influenced by test taker effort. Therefore, the purpose of this project was to evaluate the test-retest reliability of three commercially available computer-based concussion assessment programs while simultaneously controlling for participant effort. One-hundred and eighteen (N=118) healthy, college aged students were recruited for this study. Each participant completed the Headminder CRI, the Concussion Sentinel, and the ImPACT concussion assessment tests at three time points: baseline, day 45, and day 50. Green's Memory and Concentration Test for effort was also administered on each day. The data were reviewed and cleaned of invalid baseline tests or those with a poor understanding of the test administration. Seventy-three (n=73) participants were included for data analysis. Intraclass correlation coefficients (ICC) were calculated for each output and each subtest score. Repeated measures analyses of variance was used to evaluate for changes in effort across administration days. The ICC test-retest reliability results were lower than previously

reported in the literature. All measures of effort were deemed high on all days of testing with significant increases on delayed recall ($F_{1.81,130.54} = 6.464, p=.003$), consistency ($F_{2,144} = 5.800, p = .004$), and free recall ($F_{1.655, 119.191} = 15.935, p < .000$) variables. Results from this study indicate the test-retest reliabilities of three commercially available computer-based concussion assessment programs are not as high as previously reported. Differences in our results and those previously reported are not likely attributed to effort by the participants. The differences may be accredited to differing test-retest time intervals or the inability of the programs to consistently measure neurocognitive functioning.

INDEX WORDS: concussion, test-retest reliability, intraclass correlation coefficient, standard error of measurement

CONCUSSION ASSESSMENT RELIABILITY

by

STEVEN PHILIP BROGLIO

B.A., The University of North Carolina at Chapel Hill, 2000

M.S., University of Pittsburgh, 2002

A dissertation to the Graduate Faculty of the University of Georgia in Partial Fulfillment of the
Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GA

2006

©2006

Steven Philip Broglia

All Right Reserved

CONCUSSION ASSESSMENT RELIABILITY

by

STEVEN PHILIP BROGLIO

Approved

Major Professor: Michael S. Ferrara

Committee: Ted Baumgartner
Ronald Elliott
Stephen N. Macciocchi
Stephen F. Olejnik

Electronic Version Approved:
Mauren Grasso
Dean of the Graduate School
The University of Georgia
May, 2006

DEDICATION

Jane

ACKNOWLEDGMENTS

First and foremost I need to thank Jane Elizabeth Broglio for her support and love. Not only during my time as a student, but as a friend, partner, spouse. You took a blind leap of faith when you moved Georgia and sacrificed more than anyone ever should.

Mike Ferrara, thank you for taking me in when no one else would. You have provided me with opportunities to grow and develop as a researcher, teacher, and a individual. Thank you for your patience.

My committee members, Dr's Baumgartner, Macciocchi, Elliott, and Olejnik, for their support and confidence in me throughout the process.

Thank you to the Louise E. Kindig research foundation and the University of Georgia Graduate School Doctoral Dissertation Completion Award for their financial support of this project.

TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	v
CHAPTER	
1. INTRODUCTION	
Background.....	1
Specific Aims and Null Hypotheses.....	5
Limitations and Delimitations.....	6
2. A REVIEW OF LITERATURE	
The Mechanics of Concussion.....	8
Measuring Concussion.....	20
Concussion Physiology: The Neurometabolic Cascade.....	25
Concussion Assessment.....	28
Neuropsychological Testing.....	39
Imaging Techniques for Concussion.....	57
Concussion Grading Scales.....	57
Second Impact Syndrome.....	58
3. METHODS	
Study 1: Concussion assessment reliability with maximal effort.....	59
Testing Sessions.....	60
Study 2: Expected change of computer-based concussion assessments and subtest reliability	62
Testing Sessions.....	63
Statistical Analysis.....	64
Pilot Testing.....	65

4. CONCUSSION ASSESSMENT RELIABILITY WITH MAXIMAL EFFORT	
Abstract.....	70
Introduction.....	72
Methods.....	74
Results.....	77
Discussion.....	79
Conclusion.....	83
Tables.....	84
References.....	88
5. ARTICLE 2: EXPECTED CHANGE OF COMPUTER-BASED CONCUSSION ASSESSMENTS AND SUBTEST RELIABILITY	
Abstract.....	92
Introduction.....	94
Methods.....	96
Results.....	98
Discussion.....	99
Conclusion.....	103
Tables.....	104
References.....	116
6. SUMMARY.....	119
APPENDICES.....	121
FIGURE.....	124
REFERENCES.....	125

CHAPTER 1

INTRODUCTION

Background

Cerebral concussion is the most common head injury sustained by athletes during both games and practices (45). In 2001, the Concussion in Sport Group defined cerebral concussion as “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” (3). While the long term effects of concussion vary greatly from person to person depending largely on injury severity, those sustaining a single injury are likely to have a temporary decrease in information processing skills (38). While any athlete is at risk for this injury, much attention has been placed on American football athletes.

Nearly 300,000 sports-related head and brain injuries occur each year in all sports in the United States (17). High school and middle school American football squads account for 1.5 million total players with nearly 250,000 concussive injuries reported in high school football alone (116). At the collegiate level, approximately 75,000 athletes participate in American football annually. A recent investigation of cerebral concussion the incidence rates of high school and collegiate American football found a combined injury rate of .70 per 1000 athlete exposures in the sport. Most of the injuries (59%) occurred during games due to an increased intensity of play. High school American football players appear to have the highest risk of injury with 5.6 percent of the athletes sustaining a concussion during the competitive season. Only 4.4 percent of Division I American football athletes sustained a concussion during the

season (45). An increase in skill level at the collegiate level may explain the lower incidence rate among these athletes. Once an athlete sustains a concussion, a reluctance to inform the sports medicine care giver may exist for fear of removal from play and losing playing time. These athletes may also be unaware of the signs and symptoms of concussion (22).

The athlete's inability to recognize cerebral concussion is likely a reflection of overall lack of knowledge concerning the injury. Despite a considerable increase in research addressing sport-related concussion over the previous decade, the injury continues to be perhaps the most complicated and poorly understood by sports medicine personnel. Currently, more than 14 concussion grading scales are available to the sports medicine clinicians(19). While two of these scales (Cantu and Colorado grading scales) are the most commonly utilized (28) for assessment, most of them are based on empirical evidence rather than objective data. In fact, several widely utilized concussion assessment scales use loss of consciousness (LOC) as an indicator of severity. Despite the heavy reliance on these scales, recent evidence has shown LOC does not need to be present for an athlete to sustain a concussion (64;71).

In addition to the LOC misnomer, cerebral concussion often results in a widely varying array of clinical signs and symptoms. This may result from the complex structure of the brain, which lends itself to be sensitive to direction, location, or force of impact. As a result, to evaluate varying aspects of brain function, an omnifarious battery of clinical tests are often employed in the assessment protocol. The summary statement from the Second International Conference on Concussion in Sport suggests employing an assessment of concussion related symptoms, postural control, and neuropsychological function (72).

A neuropsychological assessment following a concussion is considered the gold standard of concussion assessment, providing significant information on brain function injury (38). As such, clinicians often implement tests to evaluate distinct areas of cerebral functioning. Experts in the field of sport concussion have suggested that a cognitive evaluation should evaluate the areas of information processing, planning, memory, and switching mental set (3). The typical cognitive assessment battery consists of several pencil and paper tests to address this recommendation. These tests are often administered before a competitive season, as a baseline evaluation, and then re-administered serially following injury. When the post-concussion scores return to pre-injury levels, the athlete is thought to have recovered from the injury.

The administration of pencil and paper based tests can be extremely time consuming for the clinician. A complete battery of tests may take several hours to administer, making it impractical for a single clinician to obtain baseline scores from a large sports team. As a result, sports medicine clinicians have implemented a brief test battery taking approximately 45 minutes to complete (43;44;100). In either scenario, each test must be administered to the individual athlete one at a time. This battery can still consume a large portion of time, with perhaps several days or weeks of testing in the pre-season to obtain baseline scores on all athletes. In addition to the time commitment required for baseline testing, the pencil and paper tests were not designed for concussion assessment, nor for serial administration following injury as is commonly done in the clinical setting (38).

Recent advances in computer technology have allowed for concussion assessment to utilize computer-based formats. The use of computer-based assessments offers many advantages over the pencil and paper format, but their clinical reliability is unproven. Previous reliability

studies have not implemented time intervals commonly used in a sports medicine setting (18;26) and the reliability results of computer-based testing are mixed. Collie et al. reports the intra-class correlation for the speed of psychomotor, decision making, working memory, and learning variables in the CogSport (Concussion Sentinel) program ranged from .69 to .82. These data were based on a sample of volunteers whom they tested serially with seven days separating testing sessions (18). Erlanger et al reported the two week test-retest reliability of the Headminder CRI in college aged or adult athletes to be .90 for processing speed index, .73 for simple reaction time, and .72 for complex reaction time (26). The test-retest reliabilities reported in these studies are acceptable; however, the test intervals simply do not apply to the baseline/follow-up model used in athletic settings where the follow-up time from baseline may be 45 days or longer.

Some computer based concussion assessment programs do appear sensitive to fluctuations in a limited number of cognitive areas following injury following concussion (18;27;63). At this time however, it remains unknown if the programs will generate false positive results following a non-concussive injury. Daily fluctuation in cognitive performance may influence test performance as reflected by changes in test scores without the influence of cerebral injury. Fluctuations may result from the stresses of daily life or motivation to perform at the peak of one's ability during serial test administrations.

The serial testing model employed with concussion evaluation may also influence neuropsychological scores. In the majority of concussion assessment models, the cognitive assessment battery is administered multiple times before the scores return to baseline values. Three to five test administrations are often required before an athlete returns to a baseline level of functioning (44). The repetitive and mundane nature of serial testing may result in the athlete

putting forth less effort with each additional administration resulting in a performance decrement (38). Presently, no research has evaluated the effort exerted by participants when completing a computer-based concussion assessment program.

With the information that is currently available, the test administrator must assume the test taker is putting forth his best effort on both the baseline administration and any follow-up tests. Effort on the baseline evaluation is crucial when considering clinicians regard this measurement as ‘normal’ following injury. If an athlete performs lower than capable on the baseline evaluation then it becomes impossible to make an accurate comparison from the follow-up evaluations. In a worst case scenario, an athlete’s suppressed scores from injury will appear better than his baseline evaluation. This may result in an early return to play and increase susceptibility to another concussion, or second impact syndrome {560}. Conversely, should an athlete perform his best on the baseline evaluation, but sub-par on a follow-up evaluation the only consequence would be a delayed return to play. While a delayed return to play would only increase recovery time following injury, the athlete may be fully capable of safely participating. As such, it behooves the clinician to evaluate the athlete’s effort on the baseline and follow-up tests.

Specific Aims and Null Hypotheses

Specific Aim 1: To establish the test-retest reliability of the output scores generated by the Headminder CRI, ImPACT, and Concussion Sentinel computer-based concussion assessment programs using clinically relevant test administration times.

Null Hypothesis 1: Intraclass correlation coefficients calculated for the Headminder CRI, ImPACT, and Concussion Sentinel test output scores from baseline, day 45, and day 50 administrations, in normal healthy participants, will be large enough for clinical interpretation ($R=0.70 - .80$) or greater.

Specific Aim 2: To establish the test-retest reliability of the subtests used to generate output scores by the Headminder CRI, ImPACT, and Concussion Sentinel computer-based concussion assessment programs using clinically relevant test administration times.

Null Hypothesis 2: Intraclass correlation coefficients calculated for the subtests used to generate Headminder CRI, ImPACT, and Concussion Sentinel test output scores from baseline, day 45, and day 50 administrations, in normal healthy participants, will be large enough for clinical interpretation ($R=0.70 - .80$) or greater.

Specific Aim 3: To demonstrate the effect of effort on multiple administrations of the Headminder CRI, ImPACT, and Concussion Sentinel computer tests as indicated by Green's Word Memory Test.

Null Hypothesis 3a: Effort will show no change across administrations of the computer-based concussion assessment tests.

Null Hypothesis 3b: Effort will not correlate with indices of the computer-based concussion assessment tests.

Limitations and Delimitations

Limitations:

1) The ImPACT, Concussion Sentinel, and Headminder CRI measure the cognitive function of the participant.

- 2) Green's Memory and Concentration Test effectively measures participant effort.
- 3) Time of day of testing will not be controlled for
- 4) Exercise prior to testing will not be controlled for
- 5) Consumption of food and beverages before the assessments will not be controlled for

Delimitations:

- 1) All participants were drawn from the student body at the University of Georgia.
- 2) Only participants between the ages of 18 and 30 will be included in this study.
- 3) Each participant will have a minimum of a high school education.

CHAPTER 2

A REVIEW OF LITERATURE

The Mechanics of Concussion

Animal studies provide the basis for the majority of current knowledge surrounding the biomechanics of cerebral concussion. A large body of research from the mid 1960's to the late 1970's evaluated outcomes following experimentally induced head trauma in animals (77;85-88;93;97). Since then however, no studies investigating the biomechanics of cerebral concussion in animals are not available. Investigations that experimentally induced cerebral concussion in human subjects do not exist. An investigation of this nature would be prove damaging to the subject's well-being and highly unethical.

Applying the findings of animal studies investigating cerebral concussion to humans is difficult. As stated previously, researchers conducted several studies involving experimentally induced concussion between 1960 and 1977. During this time the understanding of cerebral concussion was limited. Medical personnel defined a concussion as a transient loss of neural function accompanied by a loss of consciousness (109). Cantu has since reported 90% of sport related concussions do not result in loss of consciousness (14). More recent investigations support this finding by showing a loss of consciousness is not related to cognitive outcome following a blow to the head (91). As such, a summary statement from the first International Conference on Concussion did not include loss of consciousness as a criterion for cerebral concussion (3). Injuries that involve a loss of consciousness are ones that specifically affect the

brainstem (73). This suggests the injury may affect that varying aspects of the brain, independent of the brainstem.

Differing properties between human and animal brains also makes the correlation of animal studies to humans difficult. In a review of the mechanical properties of nervous system tissues, Ommaya reports that the human brain is slightly denser than water (91). Animal brains are more dense and therefore less likely to deform under a load, reducing its susceptibility to injury (91). Under this premise, a direct correlation of the forces applied to the head and brain in animals cannot be made to human subjects. The human brain is also much larger than an animal brain, even when put in relation with body size. This makes the human brain more susceptible to injury (91). Despite these differences, researchers have obtained valuable information on the effect of concussion on the human brain from animal studies.

The varying nature of brain injuries has led us to believe two types of brain injury are common to sports: focal and diffuse axonal injuries. A focal injury is the result of damage to a specific localized area of the brain (31). These injuries typically result from a direct impact of the cerebral tissue to the inner surface of the cranium (29). A diffuse axonal injury is the result of a shearing and stretching of the neurovascular tissues within the brain that have global implications on brain function. Brain tissue appears to be especially susceptible to this type of injury in areas of the brain where tissue density changes (95).

Focal injuries typically result from a coup or contrecoup motion of the brain within the cranium. This motion occurs when the head moves either linearly or rotationally when it collides with another object. The impact may result from sudden contact with another athlete, equipment such as a goal post, the ground, or simply the physical restraint of the neck anatomy.

In any of these situations the result is a rapid acceleration followed by a rapid deceleration of the head. In a linear impact the head will move along the sagittal plane in an anterior/posterior motion. In the rotational impact the head moves in the transverse plane, about the neck along the vertical axis. Focal injuries result in either scenario when the brain contacts the inner cranium in a coup and/or contrecoup injury.

The running back traveling down field at 8.5m/s illustrates the coup mechanism of brain injury. A head-on/linear outside force (a linebacker) suddenly stops the athlete when initial contact is made to the head. The cranium of the running back can go from full speed to zero in less than 200 milliseconds (32). Following Newton's first law of motion, the brain will continue to travel forward within the cranium until an outside force has acted upon it. This outside force will come from the brain stem, meninges, and cerebral spinal fluid that surrounds the brain within the cranium. The brain stem provides physical resistance to brain motion and the cerebral spinal fluid acts to slow brain motion, increasing the time of force application. When this is not enough to counteract the brain momentum, the frontal lobe collides with the interior frontal bone, resulting in a focal injury. Injury to the brain on the same side as the impact is a coup injury (39). If the frontal lobe collides with the inner cranium and rebounds into the contralateral cranium, a contrecoup injury may result. In the linear impact model, the frontal lobe collides with the frontal bone, resulting in a coup injury, and then rebounds into the occipital bone, thus injuring the occipital lobe in a contrecoup injury (39).

Impacts to the lateral aspects of the cranium resulting in rotation of the head may also cause coup/contrecoup injuries (104). In a classic study, the direct observation of monkey brains during impact indicated the mechanisms for coup and contrecoup injuries from a rotational

impact are similar. An antero-lateral blow to the head may cause a rotation that can directly injure the ipsilateral antero-lateral cortex (coup injury) and/or contralateral posterior-lateral cortex. A transient increase in strain is also placed on the superficial blood vessels of the cortex and presumably the associated axons (104). Injuries to axons, a diffuse axonal injury, are more common in athletics than coup/contrecoup focal injuries (92).

When the brain undergoes a rotational acceleration within the cranium, stress is placed on the brainstem and the higher tissues. According to Ommaya's theory of centripetal concussion "the damaging strains induced by inertial loading would decrease in magnitude from the surface to the center of . . . the brain mass" (95). This stress can be in either the form of a stretching tension generated by a linear impact or torque generated by a rotational impact, or a combination of the two. If the forces are extreme enough, an axonal depolarization or damage to the neural tracts from shearing may result (34). Brainstem fibers appear to have an increased susceptibility to rotational loads due to the linear alignment of the fibers (2). Fiber alignment also results in increased tension of the brainstem with cervical flexion and a relaxation with extension (94). Manifestation of concussion following injury to the fibers depends on the specific structures involved, while the threshold for concussion corresponds to the injury severity.

The Gadd Severity Index (SI) and the Head Injury Criterion (HIC) equations are commonly used to estimate the threshold for concussion in humans. These formulas take both the magnitude and duration of impact into account when quantifying the impact(21). The intent is to discern between injurious impacts and those a human brain can tolerate (16).

The Society of Automotive Engineers developed the SI to quantify head injuries that result from automobile accidents(30). More recently, the National Operating Committee for the

Safety of Athletic Equipment (NOCSAE) adopted the SI to determine protective headgear's ability to reduce impact forces (21). Researchers and manufacturers assume that by decreasing impact forces the forces transferred to the brain as decrease. Under a standardized testing environment, the NOCSAE guideline for protective headgear in athletic competition is 1200 for football helmets. Forces applied to helmets producing a peak SI greater than this amount are deemed unsafe for use (89). The SI equation is presented below:

$$SI = \int_0^T A^{2.5} dt$$

Gadd Severity Index

The variables in the SI equation presented above are: T = pulse duration (seconds), A = acceleration in g's, and t = time interval (seconds). The final score calculated by the SI only takes the peak acceleration into account (82).

The development of the HIC is considered more advanced by taking both the acceleration and deceleration of the head into account when determining the likelihood of head injury.

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_0^T a(t) dt \right]^{5/2} \right\}_{\max}$$

Head Injury Criterion Equation

In the HIC formula, t_2 and t_1 represent the end and start times of the impact (duration of impact in seconds). Average acceleration is $a(t)$ over the given interval. The proposed threshold for concussion based upon the HIC formula is 1000 (82). Not taking brain mass or direction of impact into account within the formula limits the HIC equation (2).

Using one or both of these equations, helmet manufactures and others interested in head injury (eg. automobile safety engineers) may be able to predict head injury in individuals based on a few variables. The equations presented above provide an estimate of the forces and duration of impact necessary to cause concussion. Research has shown the fundamental makeup of these equations to be correct, but they are only estimates for head injury (62) and their one-dimensional assessment of the injury has limited them. Some have proposed more complex equations that consider brain mass and direction of impact using a multi-dimensional approach (62).

Ommaya takes both head rotation and brain mass into account in his 2002 biomechanical review of head injury. In this paper he suggests an angular acceleration or deceleration of 4500 radians/second² is required to induce a shear injury in the adult brain. In this model he implemented a 1400 gram brain, the average mass of an adult human brain (96). By decreasing the mass to 800 grams, as with a child's brain, then the required rotational acceleration increases to approximately 5500 radians/second².

The rotational aspect of cerebral concussion is significant when considering recent evidence suggests that blows to the temporal region of the head may be more common than linear impacts to the front or rear of the head. A review of game footage of Australian rules football athletes receiving concussive blows to the lateral aspect of the head show the athlete is often unaware of the impending impact (76). A relative example would be the American football tight-end going across the middle for a pass. The athlete may be focused on receiving a pass from the quarterback and not the defensive player. In this instance the athlete is unaware of the impending impact and does not brace himself for the blow resulting in a lateral blow and a

rotation of the head about the neck. Conversely, when an impact comes from the front, such as heading a soccer ball, the athlete is more likely to see the forthcoming impact and tense the neck musculature. When the athlete tightens the neck muscles, the head and torso become rigid and act as one unit, increasing the functional mass of the head and lessening the chance for injury. Coaches regularly instruct soccer athletes to move the head and body toward the ball at impact (54) to generate a greater functional mass that will counteract the momentum of the ball.

The collision of an object with the head can be described using the principle of conservation of momentum and effective mass. When two athletes collide with the point of contact on the head, a transfer of momentum will occur. The following equation explains this concept: $v_1 m_1 + v_2 (m_2 + m_3) = m_1 v_3 + m_2 v_4 + m_3 v_5$ + momentum lost from energy transfer. The left side of the equation represents pre-collision conditions, while the right side represents the post-collision conditions. The variables $v_1 m_1$ represent the velocity and effective striking mass of the athlete doing the hitting. While $v_2 (m_2 + m_3)$ represents the velocity of the athlete being hit (v_2) and the effective striking mass of the body (m_2) and the head (m_3).

Following impact, the velocity of athlete one (v_1) will decrease as momentum transfers to athlete two. The transferred momentum will be split between the head and body of athlete two. If athlete two is unable to contract his neck musculature the effective mass decreases from $m_2 + m_3$ (mass of the body and head) to just m_3 . Following impact (v_5) will increase to maintain a balanced equation.

The law of conservation of momentum, as described above, applies only to rigid objects. The body however, is not a rigid object, but a series of linked, rigid objects. Therefore, the effective mass of the athletes must be considered. Effective mass is dependent on the force

being applied during impact, the time of force application, and the speed at which the collision occurs ($m_{\text{effective}} = \sum(F_i \Delta t)/v_i$). The effect of increasing the effective striking mass will consequently influence the kinematics involved.

If the athlete being hit can contract his neck and trunk musculature at the time of impact isometrically, he can increase his effective mass. If $m_{\text{effective}} = \sum(F_i \Delta t)/v_i = \sum(ma \Delta t)/v_i$, then contracting the neck and connecting it to the trunk, the mass and therefore effective mass increase. Conversely, the athlete doing the hitting can deliver a greater force of impact through a similar technique.

Thus, tightening the neck musculature and creating a single rigid unit of head and body will increase the effective mass (m_3) and decrease the resulting speed (v_3). Effective mass decreases and the resulting speed of the head increases when the athlete has not sufficiently contracted the neck muscles. Animal testing demonstrates this principle by showing an acceleration of 1230 gravitational units (g's) can induce concussion when the head is allowed to rotate freely. The researchers observed no concussion when the head secured by extraneous means in a fixed position and they administered an equivalent force (95). For reasons stated above, this threshold for concussion is much higher than the 200g threshold proposed for human concussion (75). However, the principle of effective mass remains sound. A prior investigation by Hollister demonstrated that tightening of the neck musculature produces similar results. In this study the researchers stretched the neck in cats to induced concussion. The application of an electrical stimulation of the neck musculature strong enough to prevent head motion prevented concussion (48). Bauer demonstrated a similar idea in soccer athletes when preparing to head a soccer ball. Through electromyography, Bauer found soccer athletes expecting a headball

activate the sternocleidomastoid muscle just prior to impact (5). This suggests an inherent attempt to prevent head motion and protect the brain from injury from the impacting soccer ball.

Similar to an inverted pendulum, blows to the head will result in angular motion of the head about the neck, generating a torque. The magnitude of torque equals the applied force times the length of the moment arm ($T = Fd$). At a given instant in time during an impact, the total force acts at the point of application, or the point of impact. The moment arm however, will vary according the direction of force application. A force applied from the anterior-posterior direction would have a moment arm equal to the distance from cervical vertebrae number one to the perpendicular intersection of the line of force application with the moment arm. The torque generated will result in a moment about the x-axis as seen in Figure 1. Force application such as this is most likely to result in an anterior or posterior coup-contrecoup injury. Forces applied from the lateral direction will result in a moment and rotation about the z-axis (Figure 1). Motion such as this would be the necessary mechanism for a rotational shear strain injury. Lastly, forces applied from the superior or inferior aspects of the head would result in a moment about the y-axis. Motion such as this would again result in coup-contrecoup injury, but to the lateral aspects of the brain.

The angular motion, and more specifically angular acceleration, of the head may be the most important variable in determining structural damage of the brain (95). Angular acceleration (α) is the sum of torques divided by inertia ($\sum T/I$). The previous discussion of torque suggests that by increasing either the force application magnitude or the moment arm, the torque will increase. This results in an increased angular acceleration. Conversely, if adding mass to the head increases inertia (eg. wearing a helmet), then angular acceleration decreases.

While the addition of helmets as protective equipment is universally accepted, consequences of their use do exist. Once the head is in motion, the neck musculature must generate more force and therefore torque to slow and stop this motion. Through the application of Finite Element models, Kleiven et al (55) provided indirect evidence to support the relationship between increasing head mass and increasing intracranial pressure following impact. While the authors were not able directly to assess clinical outcome following impact, intracranial pressure is reported to be related to the degree of structural damage to the brain (61).

A discussion of impacts incurred during collision sports must also include the impulse-momentum principle. In this situation, consider an athlete who is wearing a helmet taking a direct blow to the head. Total Impulse (I) is calculated as the $\sum [\text{Force } (F_i) \times \text{change in time } (t_i)]$. Impulse is calculated from the first to the last interval of time and permits an explanation of the effect the helmet padding has on force transfer.

$$\begin{aligned}
 \text{If } I &= Ft & \#1 \\
 &= m(a)t \\
 &= m[(v_2 - v_1)/t]t \\
 &= m[v_2 - v_1] & \#2 \\
 &= m[d/t_2 - d/t_1] & \#3
 \end{aligned}$$

The derivation of the impulse formula (formula #3) shows that once an impact occurs, the padding within the helmet will compress, slowing the rate of force application when compared to a force directly applied to the head. Increased time of force application will increase athlete safety. Bishop et al provided evidence to support the idea of increased force application time with additional padding in football helmets. Eighty-one suspension style and padded football helmets were fitted over a headform with a triaxial accelerometer mounted internally. The researchers then dropped each helmet from a 1.5 meter height onto an anvil. The authors

reported that padded helmets reduced peak acceleration and increased time of force application when compared to suspension style helmets(9). Ultimately the padding decreases the force transferred through the helmet to the head. In addition to the force reduction, football helmet padding also increases the surface area of force application. This decreases the pressure applied to the head during impact. Pressure is equal to the force divided by the surface area ($P=F/A$), showing that a decrease in pressure will result in a lower force transfer to any given point on the head.

Manufacturers initially designed American football helmets to reduce the risk of skull to skull contact that resulted in fracture. The current trend in helmet design is to reduce cerebral concussions by reducing head acceleration from impact. A recent change to American football helmet design is an increase in padding around the temporal region on the head (106). The thickened padding in this area protects the athlete from blows to the area most likely to result in concussion (75). In addition, the helmet's outer surface is slick, designed to make the colliding helmets to slide off each other. This results in a glancing blow to the person being struck, a lower degree of force transfer, and ultimately a lower resultant velocity of the head. While the recent changes to helmet design appear to decrease the risk of cerebral concussion, no current research has directly measured the head acceleration from impact directly resulting in cerebral concussion. Without these data, the direct ability of the modern helmet to decrease impacts remains unknown.

Any impact to the head will result in a transfer of force to the brain tissue at an unknown rate (83). If the transferred force exceeds the tissue threshold for injury, the resulting damage varies according to the magnitude the threshold is crossed. Conversely, forces applied to the

brain that are below this threshold will not result in injury. Like all tissues in the body, the material properties of brain tissue contain both an elastic and plastic region to force application(24). Applying a load to a tissue causes the tissue to bend or stretch in compliance with the load. Up to a certain degree of loading the tissue will return to its beginning shape as it remains within the elastic region. As the loading continues to increase however, the tissue properties will cross into the plastic region and the tissue will no longer return to its beginning form. Forces applied to tissue that exceed the range of the plastic region would result in failure (tearing) of the brain tissue. The various layers of the brain of differing densities and mechanical properties make it impossible to establish a single stress-strain curve that addresses the entire brain. The areas where two tissues of differing densities meet may be the most susceptible to injury (94).

The mechanics of concussion is complicated and what has been presented here is a limited explanation. Variation in the size of the athletes, equipment worn, direction of impact, readiness for impact, anatomical and other variables will all influence the clinical outcome of the injury. Early research used animal models to explain human outcomes following injury but in recent years the mechanics have become clearer. Various physics properties help explain focal diffuse axonal injuries and have been used to generate various severity scores and proposed thresholds to the injury. As research technology improves, these values will become more refined and the ability to protect athletes against concussion will become better.

Measuring Concussion

Motion Analysis

Current attempts to record the acceleration of the head that results in cerebral concussion are limited to video analysis. In a retrospective analysis, McIntosh and colleagues evaluated 97 concussive episodes during Australian rules football matches. The researchers evaluated both professional and university level matches. A video tape of each impact allowed the researchers to apply two-dimensional analysis to estimate head kinematics at impact(76). They made no mention if any of the players were wearing helmets at the time of injury. However, regulations do not require helmets during game play and if given the option athletes usually choose not to wear protective headgear(101). The researchers estimated that concussion occurred when the impact force generated 50-60 joules, the equivalent to 200g's. The authors estimated the error of their system to be 10% and suggested a three-dimensional analysis may have been more accurate(76).

Most recently, Pellman et al(99)published the first in a series of reports evaluating concussive impacts recorded on video from National Football League games. The data were collected between 1996 and 2001, with 182 cases captured on video. Of these cases, the authors evaluated 23 impacts through laboratory reconstruction. To reconstruct each injury, Hybrid III dummies fitted with football helmets and each impact simulated the same velocity, direction, and head kinematics as recorded on game footage. Each dummy was equipped with several translational and rotational accelerometers that measured kinematic variables at impact. Error was reported to be less than 15% of the peak values. Pellman and colleagues concluded that a high degree of velocity change was necessary to induce concussion. The authors also suggested

altering helmet design to account for impacts delivered to the side of the head and face mask. In the reconstructed impacts, concussion appeared related to translational acceleration when an athlete was struck on the facemask or side of the helmet by another player or object. Similar blows to the head have also been reported as a factor for concussion in rugby athletes(76). Head acceleration of the concussed football athletes averaged $9.3 \pm 1.9 \text{ m/s}$ and $98 \pm 28 \text{ g's}$, with an impact duration of 15ms. The gravitational units are far lower than the 200g threshold previously reported to result in concussion for rugby athletes (76).

Helmet Accelerometers

A study of American high school football used a more direct measure of head acceleration. Researchers mounted a single triaxial accelerometer within the padding of the helmet of an offensive and defensive football lineman. They connected the accelerometer to a portable data recorder housed within the shoulder pads of the two football players. They recorded data over a season of games when the impact exceeded the preset 10g's recording threshold. Although a defensive lineman has the second highest risk of concussion(22), neither athlete sustained a concussion during the season. Mean peak acceleration from 158 impacts were reported at $29.2 \pm 1.1 \text{ g's}$. This value is far below the estimated acceleration of 200g's required to cause cerebral concussion. The authors of this article stated that the brain tolerance for concussion from head acceleration remains unknown(84).

An investigation of prior literature revealed one research group has recorded cerebral concussion during an American football game. Using a single subject design, Reid et al (105) mounted a triaxial accelerometer to the shell of the football helmet. In addition, the investigators mounted several EEG leads directly to the scalp of the athlete which monitored brain activity

and confirmed the presence of cerebral concussion. A telemetry system affixed to the posterior shoulder pads of the athlete transmitted data recorded by these instruments to the press box. During the 1970 playing season the athlete competed in 418 plays that produced 169 measurable impacts to the head. Accelerations of these impact ranged from 40-230g's with the blows coming from both the left and right sides. One recorded impact ensued in a cerebral concussion. The impact to the player's head resulted an acceleration of 188g's and 310miliseconds long. This value appears to be consistent with the proposed threshold of concussion in the human brain as previously suggested (76). However, the acceleration recorded by the triaxial accelerometer attached to the helmet does not provide a clear look at the acceleration of the head. The acceleration of the head was, most likely, lower than that of the helmet. The section on "Mouthgaurd Accelerometers" better explains this rational. As such, the combination of peak acceleration and duration of the acceleration may provide a better estimate of cerebral concussion prediction (105). Ommaya confirmed this theory by demonstrating that as the duration of impact decreased, the higher the head acceleration must be to induce cerebral concussion in Rhesus monkeys (91).

Mouthgaurd Accelerometers

The Naunheim group conducted a follow-up study, aiming to measure head acceleration from impact more directly. The authors compared acceleration of the head as measured by both an accelerometer mounted within the American football helmet padding and an accelerometer mounted to a plastic mouthpiece (intraoral) attached to the maxillary teeth. A soccer ball kicked from 30 yards with a mean speed of 39.3 mph served as the standardized impacting force. Three volunteers headed an unspecified number of soccer balls while wearing and not wearing the

helmet. In the helmeted condition, mean peak acceleration reported by the helmet accelerometer was 49.3 g's. This value was consistent with a previous study evaluating soccer heading while wearing an American football helmet with the ball traveling at a similar speed(84). The intraoral acceleration readings were reported at 7.7g's, nearly 6.5 times less than that of the helmet (59). The difference between the two measures is likely a result of the helmet functioning as a cushion. As intended, the padding of the helmet absorbs some impacting force lessening its ability to accelerate the head. Heading the soccer ball without the helmet revealed an increase in intraoral acceleration to 19.2 g's (59). Without the helmet present to reduce the force of impact from the soccer ball, this increase is expected.

Affixing an accelerometer to the mouthpiece covering the maxillary teeth gives the instrument a direct connection to the cranium. Exact measurement of cranial motion is then possible. Inferring that head acceleration recorded from helmet accelerometers are uncertain because of the helmet's ability to absorb the outside force of impact. The difference in measures recorded by the intraoral and helmet accelerometers represent the shock absorption the helmet insulation is providing for the head. Even while wearing a helmet however, the forces acting on the head can still be great enough to cause a concussion. As such, using an intraoral accelerometer attached to the maxillary teeth provides a measure of only head acceleration irrespective of the helmet.

Citing the limitation of only recording linear changes in motion, Naunheim et al (82) conducted a follow-up study that evaluated linear and angular head accelerations during soccer heading. The authors expanded on their original methodology of the intraoral accelerometer by adding three triaxial accelerometers around the head. The addition of these accelerometers

allowed for the calculation of rotational accelerations. Four subjects wore a headgear affixed with the three triaxial accelerometers in addition to a mouthpiece with the intraoral accelerometer. Each subject then headed three balls projected at nine and 12 m/s from a distance of 6m. Data collection from the 18-channels of input data allowed for the calculation of both linear and angular accelerations of the head along and about three axes of rotation. The formulas used by Naunheim et al to calculate angular accelerations were previously developed and validated by Padgaonkar (98). The three head mounted accelerometers measured the linear and angular acceleration of the head's center of mass during soccer heading. Linear accelerations were reported to range between 15-20g, with angular accelerations ranging from 1000-2000 radians/sec. The authors reported the intraoral accelerometer to provide only a rough estimate of the peak acceleration of the head. The location of this accelerometer, anterior and inferior to the center of mass of the head, lead to a 15% lower acceleration value.

Measuring concussion impact forces will ultimately result in the establishment of injury threshold in the human brain. Early assessments of concussive impacts began by inserting accelerometers into American football helmets. Although this technique is fraught with methodological flaws, it provided the foundation for future research. The addition of multiple accelerometers allowed for measurement of head motion in three dimensions and the application of an accelerometer to a mouthguard permitted head measurement in sports not requiring a helmet. The greatest advances have been with the reconstruction of concussive injuries from competition video footage. A post-injury analysis of the impact has allowed researchers to begin to identify the threshold for concussion in the human model. The improved understanding of the injury may ultimately result in a potential injury prevention mechanism.

Concussion Physiology: The Neurometabolic Cascade

The neurometabolic cascade that follows concussion is complex. Although researchers have studied this chain of events extensively in animal models, a short fall of basic science research as it directly pertains to humans exists. A 2001 review by Giza and Hovda provides an excellent overview of both basic science research and clinical literature (34).

In most instances, sports-related concussion is generally thought to not permanently impair or damage the axons of the brain. The number of axons permanently damaged following cerebral concussion are reported to be too few and disbursed widely enough throughout the brain to explain clinical signs and symptoms following injury. The ionic and metabolic changes that take place may better explain clinical outcome following injury (31). In instances where structural changes to the brain take place, imaging techniques such as magnetic resonance imaging or computed tomography may assist in evaluating the injury. These instances are rare in athletics and most imaging techniques often prove ineffective (52).

Following a low-grade concussive blow those axons within the brain affected by the injury begin depolarizing at an uncontrolled rate. This occurs as potassium (K^+) channels located along the axon are mechanically stretched open and K^+ ions flow into the extracellular space (114). As K^+ flow into the extracellular space and the surrounding support cells are unable to take up the excess, an additional release of several amino acids and other proteins cause further depolarization of non-traumatized neurons (53). The efflux of K^+ stimulates the release of transmitters that allow a calcium (Ca^{2+}) influx to the axons. Large amounts of K^+ released into the extracellular space heighten this process. The outcome of this non-discriminate

depolarization of cells is a huge amount of K^+ within the extracellular space and Ca^{2+} within the intracellular space.

In an effort to restore the normal balance of ions within the tissue, the sodium-potassium (Na^+-K^+) ion pump located within the axon membranes increase their rate of transport. Unlike other ion pumps in the body, the Na^+-K^+ pump requires energy, adenosine triphosphate (ATP), to function. Under normal, non-injured, circumstances the glycolytic process produces ATP and supplying the brain tissues (12). Lactate is a byproduct of this process, but is typically shuttled into the oxidative metabolism to supply more energy (12). In the injured state, the Na^+-K^+ pump works at a greater rate than usual and thus requires more energy/ATP. Meyer supported this idea by finding the metabolic need for oxygen within the brain increases following injury(77).

Only a small amount of ATP is available within the cells to allow the Na^+-K^+ pump to continue functioning. This results in increased reliance on glycolysis for energy production(120) and increased lactate production as a byproduct (77). Following cerebral injury however, mitochondrial function becomes impaired and the oxidative metabolism cannot use much of the excess lactate. Although it is not entirely clear, Ca^{2+} that accumulates within the cell may pool within the mitochondria and thus suppress their ability to perform oxidative metabolism (120). The levels of magnesium within the neural cells are also reduced following injury. The loss of this ion negatively impacts both the glycolytic and oxidative metabolism and therefore ATP production(119).

The result of the complex neurometabolic cascade following cerebral concussion is twofold. First, a greater dependence on the glycolytic process for energy production results.

Secondly, as the levels of lactate in the surrounding cells increase the risk of secondary injury to neural cells exists (34).

Increases in the glycolytic process occur with a simultaneous increase in cerebral blood flow. Increased blood flow allows for the delivery of glucose to the cells for ATP production. In the scenario of cerebral concussion however, suppressed cerebral blood flow occurs (122), further disrupting the energy supply and demand balance.

In animal models the period of hyperglycolysis appears to end by twenty-four hours post injury (121), although cerebral glucose metabolism remains suppressed for up to four weeks in humans (8). Giza (34) speculates that during this time of suppressed glucose metabolism the brain may be at a greater susceptibility to second injury. A second impact during this time would likely further the reliance on the glycolytic process for energy production within the cerebral tissue.

Following a concussive injury voltage gated channels in the cerebral neurons are physically opened resulting in an uncontrolled movement of ions in and out of the cells. The shift in ions is followed by an increased demand for energy as the ion pumps begin to correct the imbalance. The increased energy demand however, cannot be immediately met as cerebral blood flow is decreased, thus limiting glucose delivery to the cells. Until normal blood flow and the ion imbalance can be corrected the injured neurons do not function properly. Abnormal neuron function may manifest itself clinically in a variety of ways, such as concussion related symptoms, decreased postural control, or decreased neurocognitive functioning. On the clinical side, the injured athlete may return to normal in three to five days following impact. Biochemically however, this recovery may take upwards of ten to 14 days.

Concussion Assessment

Assessing, diagnosing and deciding return to play for the injured athlete can be a daunting task for sports medicine personnel. Each injury is unique to the athlete and no two athletes will respond to an injury in an identical pattern. Assessing a concussion typically occurs with a battery of tests that may or may not include self-reported symptoms, postural control assessment, and a neurocognitive evaluation (41). In addition, a clinician may also use various imaging techniques to evaluate the injury. Clinicians employ a broad spectrum of tests because of a poor understanding of both the cause and outcome for cerebral injury. Recent investigations into the recovery of sports-related concussion however, have established recovery trends based on a battery of tests administered to the injured athlete (28;60).

Symptomatology

The number one evaluation tool used to assess concussion by professional (13 of 18), high school (91 of 109) and clinical athletic trainers (57 of 80) is a symptom checklist (28). Ferrara reported that athletic trainers based in the collegiate setting may also use the symptom checklist (94 of 131), but this evaluation tool was second to the clinical evaluation. This study was based on a sample of 339 returned surveys of athletic trainers who attended a minicourse on concussion assessment during the National Athletic Trainers' Association Annual Meeting and Clinical Symposium. Despite the heavy use of self-report symptomology in the assessment of concussion, Lezak (60) reports of their inherent weaknesses.

Use of self-report symptomology for the assessment of concussion began in 1983 when Barth preseason baseline tested 2350 collegiate football athletes. The researchers tracked these athletes over a four-year period, during which 195 injured subjects were followed up on days

one, five, and ten post injury. A comparison was made of these athletes to both healthy college students and other athletes who had sustained mild orthopaedic injuries. Analysis of the symptoms reported by all three groups showed the concussed athletes to have a significantly higher number of symptoms up to ten days following the injury(4).

Macciocchi et al reported similar results (65)in a study of 2300 athletes from ten Division IA football programs. Each athlete was baseline tested on a battery of neuropsychological tests and self-reported symptomology. The investigators matched each injured subject by gender, age, and education to forty-eight controls. Twenty-four hours and five days post-injury, the football athletes reported significantly higher levels of headache, memory problems, and dizziness. In contrast to the Barth study (4), no difference existed between groups by day 10. Athletes have reported headache as the number one symptom experienced by those who have sustained a concussion (45) and in baseline measures of symptomology (102). Although the findings between the Barth and Macciocchi studies (4;65) vary only slightly, one reason may be that each project employed a differing list of concussion related symptoms.

The Post-Concussion Symptom Checklist was introduced in 1998 and suggested as a standardized assessment tool for the evaluation of concussion related symptoms following injury (63). This checklist included sixteen items similar to those employed by Barth (4) and the National Football League and National Hockey League have adopted it as part of their standardized concussion assessment battery. Although this assessment form is referred to as a checklist, it asks not for the presence or absence of a given symptom, but the severity based on a seven-point Likert scale. Maroon (67)later suggested categorizing each of these symptoms into three specific groupings: 1) somatic symptoms such as headache, dizziness, or nausea; 2)

neuropsychiatric symptoms such as anxiety, depression, or irritability; and 3) cognitive symptoms such as attention, memory, or processing speed deficits.

Using the three categories suggested by Maroon (67), Piland et al (102) evaluated the sixteen item scale using confirmatory factor analysis. The authors evaluated 279 college athletes with the Head Injury Scale during the preseason. This scale included symptoms considered classically related to concussion. An evaluation of the data showed the variables vomiting, sadness, nervousness, sleeping more than usual, sensitivity to light and noise, difficulty remembering, and feeling numbness or tingling did not fit the three category model previously suggested. As such, the researchers removed each of these variables from the scale for a nearly perfect fit to the three category model (NNFI = 0.993, CFI = 0.995). In the second part to the study, the authors compared the new nine-item scale to the sixteen-item scale on seventeen concussed athletes compared to sixteen controls. Each subject was administered both symptom scales on days 1, 2, 3, and 10 following injury. ANOVA results showed significant differences between the groups on both the nine and sixteen item scales on days one and two following injury. The authors concluded that they had provided evidence for both factorial and construct validity to the new nine-item scale when used on college athletes. In addition, removing the seven items from the sixteen-item scale and increasing the fit of the three category model, reduces the chance of gaining a false positive.

Physiology of Postural Stability

Postural stability is the ability to maintain a center of gravity (COG) within the individual's limits of stability (LOS). To maintain postural stability, an individual performs minute muscle contractions at the ankle and hip to keep themselves within their individual limits

of stability. Limits of stability can be thought of as an imaginary cone surrounding an individual. The narrow end of the cone is at the feet and broadens as it rises. If a person were to lean in any direction, they would employ one or more of the above strategies to keep themselves within the confines of the cone and not fall. If the person goes beyond the edge of the cone, they will need to employ a stepping strategy to avoid falling (40).

The ankle strategy is the most commonly employed method to maintain balance. Small contractions of the gastrocnemius and soleus complex are paired against the contractions of the tibialis anterior, with the ankle acting as the pivot point allowing for anterior and posterior sway (49). This method is used almost exclusively to keep the body within the limits of stability during static balance. In scenarios when motion about the ankle is unable to maintain postural control, the hip strategy is employed. The musculature that allows for hip flexion or extension contract, offering gross movement about the hip joint to control extreme postural sway while contractions at the ankle joint take place simultaneously (107).

The ability to contract the appropriate muscles when using the three strategies listed above is a combination of three forms of afferent signals received by the brain from the body. The first sensory signal, somatosensory, is the ability of the body to "feel" the location of the body and its extremities in relation to the surface on which it is standing. The visual sense is collected through the eyes and uses fixed objects as a reference to help maintain postural stability. The third sensory faculty is the vestibular mechanism in the ear. This mechanism functions to supply information on the body's "gravitational, linear, and angular accelerations of the head in relation to inertial space" (40). Since this mechanism does not provide reference of the body to external objects, it plays only a small role in maintaining postural stability (40).

The afferent somatosensory pathway plays the most vital role in maintaining an individual's postural control. Under normal conditions afferent signals from the receptors about the feet and ankle will provide the CNS with the information necessary to maintain postural equilibrium. The visual system will also provide information to the CNS, by focusing the eyes on a non-moving point on the horizon. If inappropriate information is being supplied to both the somatosensory (moving or compliant support surface) and visual (moving visual field) systems, the vestibular system will resolve the conflict between the two to maintain the body within the limits of stability(23;80;81).

Somatosensory Physiology

Somatosensation is the process by which the balance centers of the brain integrate peripheral information sent by nerve endings that provide information based on nociception (pain), thermoreception (heat), mechanoreception (mechanical deformation of tissue), electromagnetic receptors (vision), and chemoreceptors (chemical changes). Mechanoreceptors play an important roll in maintaining balance and are responsible for transforming mechanical stimuli into an electrical (nerve) impulse that can be integrated as afferent information. Several varieties of mechanoreceptors are present in the body to interpret a variety of mechanical stimuli that an individual may incur.

Nerve endings in the skin consist of the free nerve endings, Merkel's discs, Ruffini's endings, Meissner's corpuscles, hair end-organs, and Pacinian corpuscles (68). The Ruffini endings and Pacinian corpuscles may also be found within a joint articulation. These nerve endings may be quick or slow adapting. The quick adapting (QA) nerve fiber will quickly raise its resting membrane potential once it is stimulated, requiring a stronger stimulus to continue

producing nerve impulses. A slow adapting (SA) nerve fiber will not raise the resting membrane potential. Thus, a stronger stimulus is not immediately needed to create a nerve impulse.

Free Nerve Ending: SA fiber that is sensitive to touch and pressure

Merkel's Disc: SA fiber sensitive to light touch

Ruffini's Endings: SA fiber that responds to the stretch and distortion of the skin

Meissner's Corpuscles: QA fiber that is sensitive to light touch, movement and vibration

Hair End-Organs: QA fiber that is found only in the hair follicle. They are sensitive to motion of the hair strand

Pacinian Corpuscles: QA fiber that responds to direct pressure such as pulsing or vibration

Golgi Tendon Organ: SA structure that provides afferent information on tension when a muscle contracts or is placed on a stretch

Muscle Spindle: The muscle spindle (MS) is a modified muscle fiber consisting of three to ten intrafusal muscle fibers that are connected to an extrafusal skeletal muscle fiber. The MS is aligned in parallel with the muscle fiber making it sensitive to changes in length and rate and degree of change of the muscle tissue (117). Of the intrafusal muscle fibers, there can be a mix of three different varieties: nuclear chain fibers, nuclear static bag fibers, and nuclear dynamic bag fibers. The dynamic bag fibers are sensitive to rate of muscle length change, while the static bag fibers are sensitive to muscle length (107). Both the chain and bag fibers are innervated by Group Ia (primary afferent) fibers, but Group II (secondary afferent) innervate only the chain fiber fibers (46).

The central region of the MS contains no contractile components and is thus uninnervated. Efferent innervation of the MS occurs only on the periphery of the fiber by gamma (γ)-motorneurons (58) where contractile elements are present. Static γ -motorneurons

innervate the static bag and nuclear chain endings and the dynamic γ -motorneurons innervate the dynamic bag endings. When the contractile elements of the MS are activated, the afferent information concerning the length and rate of length change of the muscle is combined with information from the other receptors (Ruffini, Meissner, etc.) to form a final impulse. Labeled the “final common input,” this impulse is a combination of all peripheral afferent information that will be processed and regulated by the MS before sending a final signal to the alpha-motor neuron to make adjustments in length and tension of the muscle (58). In this model, the muscle spindle has the most influence over joint and limb position sense, and thus somatosensory input used during balance control.

Vestibular Physiology

The vestibular apparatus is made up of two chambers referred to as the utricle and saccule and three semicircular canals. Within the utricle and saccule are chambers of sensation called the maculae. The maculae is covered by thousands of hair follicles that synapse with the vestibular nerve and are sensitive to gravitational forces when standing (utricle) or lying (saccule) (46). The semicircular canals are labeled anterior, posterior and horizontal and arranged perpendicular to each other. Each duct is connected to the ampullae and is filled with a fluid called endolymph. When motion of the head occurs the endolymph remains stationary while the semicircular canal moves within the head. The fluid moves into the ampullae and stimulates the hair follicles that transmit the information to the balance centers of the brain via the vestibular nerve (68).

Visual Physiology

The role of vision in the process of maintaining balance is to provide orientation and relationship information about the head in reference to the environment. The perception of motion interpreted by the eyes may be from either motion of the individual or motion of the environment. If either is in motion, the eyes will focus on a stationary point to provide reference to a fixed object (11). In the event that the object being focused on is also in motion, and no other fixed point for the individual to concentrate on is available, the sway of the individual will vary with the sway of the moving reference point(79). Although this instance does not often occur in real world situations, it can easily be replicated in the laboratory with a visual conflict dome or sway reference device.

Although vision plays an important role in maintaining static posture, balance can be maintained in its absence. In the event the eyes are closed, terminating the afferent signal to the balance centers of the brain are stopped, the individual will show a slight increase in postural sway if both the somatosensory and vestibular systems are healthy. If either of these systems has been compromised, then postural sway will greatly increase without visual input(40).

The design of the postural control system in the human body is such that if the vestibular system is not functioning properly (i.e. damaged), then the other two systems will be able to maintain the body within the limits of stability under normal circumstances. Depending on the degree of damage to the vestibular system, deficits to this pathway may not become apparent until the other two pathways are unable to provide appropriate information to the CNS and the body must rely upon the vestibular system for balance control.

On a physiological level, postural stability is maintained through a continuous afferent and efferent loop. The three components of balance, somatosensory, vestibular and visual, combine to provide information about body stability to the balance centers (cerebellum and brain stem). This information is then processed and an efferent signal is sent to the proper musculature needed to maintain the COS within the LOS. This process is classically viewed as a feedback mechanism, whereby the brain provides only reactive, efferent signals to the afferent input it receives(113). Discussion of this process, however, has been in reference to the proprioceptive capacities at a joint. Logic would maintain that the same process would occur at the hip, knee, and ankle joints in order for an individual to maintain static balance. A more contemporary view of this process, however, is seen to be both a feedback and feed-forward mechanism.

In the feed-forward mechanism, the balance centers are aware of the position of the body in relation to the environment and of the individual segments in relation to each other. With this information, preprogrammed responses (efferent impulses) are sent to the proper balance musculature as a result of learning what should be done to maintain balance during a certain condition (113). The feed-forward mechanism of balance seems to be a more likely scenario due to the latency that exists in neural pathways. If the balance process were to function as a feedback procedure, a large delay would occur from the time the stimuli was induced, the afferent signal was transmitted and interpreted, and an efferent impulse was finally sent and the appropriate muscles reacted accordingly. In the feed-forward model, afferent and efferent signals are continually being sent to maintain postural equilibrium.

Studies on Postural Stability

At the time of concussion, the injury to the brain may cause one or more of the three afferent signals to be disrupted. As a result, balance becomes compromised and the patient experiences an equilibrium imbalance, or dizziness. Using a force plate such as the NeuroCom Smart Balance Master, the clinician can manipulate the conditions to remove or “confuse” different portions of the balance mechanism. Guskiewicz et al (43) found that a composite of visual, somatosensory, and vestibular scores were significantly different by day when comparing the eleven Division I athletes to eleven control subjects. Individual analysis of the various parts of the balance mechanism also showed a significant difference in the visual mechanism following concussion. A difference in the vestibular ratio was also reported, but deemed non-significant. They saw no difference in the somatosensory scores (43).

Using a similar design study, but with less sophisticated equipment, Guskiewicz (42) completed an earlier study using ten subjects previously tested for postural stability in the preseason. These subjects later sustained a mild head injury and were matched against ten control subjects. Employing the Chatter Balance System with three surface conditions (firm, foam, and dynamic platforms), and three eye conditions (open, closed, and visual-conflict dome), Guskiewicz found significant deficits in the concussed athletes for the three days following injury when compared to the control subjects. He also noted that those subjects, whom they screened in the preseason, had significantly worse scores on Day 1 following injury. Suggesting that individuals who have sustained a mild head injury may have difficulty incorporating sensory information in the acute stages of the injury. Those subjects sustaining a mild head injury,

however, did show significant improvement from Day 1 to Day 3 following the injury, while controls showed no change.

The recommendation to use different surface and visual conditions as Guskiewicz (42) employed, was suggested by Shumway-Cook(110). The authors suggest that three mechanisms help maintain postural stability, as previously described. Afferent data sent to the CNS through the somatosensory, visual and vestibular pathways are incorporated and returned on efferent pathways to skeletal muscle to maintain the subject's balance. Shumway-Cook developed a protocol to allow a clinician to assess the "influence of sensory interaction on postural stability" during static balance. Six conditions were employed: 1) normal vision and surface, 2) blindfolded and a normal surface, 3) conflict dome and a normal surface, 4) normal vision on a foam pad, 5) blindfolded on a foam pad, and 6) conflict dome on a foam pad. The examiner tests each condition for 30 seconds while the subject maintained their balance with their hands at their side for the duration of the trial. The authors reported that most healthy adults and children maintained their balance for all conditions, but anterior-posterior sway increased on conditions five and six. These conditions emphasize the vestibular input, while deficits seen in conditions three through six may suggest an interaction problem.

Ingersoll and Armstrong (50) used a force platform to test the effects of postural stability of 48 volunteers using the Romberg protocol. They divided the subjects for this test into four equal groups: those never sustaining a concussion, those sustaining a concussion without a loss of consciousness (LOC), those sustaining a concussion with a LOC less than six hours, and those with a concussion and a LOC greater than six hours. Subjects performed the Romberg test three times with the feet together and hands at the side under six different conditions. The conditions

were the same as those suggested by Shumway-Cook (110). The data analysis concluded that the greatest amount of postural sway occurred in those subjects that had received a concussion and were unconscious for greater than six hours. The amount of postural sway between concussion groups did not differ significantly, but it was greater than the non-concussion group (50).

In recent years concussion assessment in athletics has turned to the baseline-follow-up model. This model calls for the baseline assessment of athletes during the off-season and then follow-up assessments post-injury. While the days of assessment following injury have varied from study to study, many have implemented self-reported symptoms and postural control as part of the evaluation. A long list of symptoms related to concussion has typically been performed, although not all of these symptoms may be related to the injury. Additionally, the postural control assessment has only recently gained notoriety as a valid and reliable tool for concussion assessment. Regardless, the use of both techniques, in addition to a neuropsychological assessment, is strongly recommended for the clinician. The vast array of signs and symptoms that may result following concussion calls for a battery of tests to be administered. Each test evaluate a differing area of cerebral functioning which may or may not have been injured from the concussive impact.

Neuropsychological Testing

Neuropsychological testing is considered the gold standard of concussion assessment. A cognitive assessment can provide significant information to the sports medicine clinician following injury (38). A consensus statement from the First International Symposium on Concussion in Sport agreed that a cognitive evaluation should include an assessment of the

domains of information processing, planning, memory, and switching mental set (3). While a veritable myriad of cognitive tests are available, those most commonly used for concussion assessment are reviewed here. Caution is warranted in using neuropsychological tests for the assessment of concussion. Results from these tests may prove misleading as Grindel (38) states “neuropsychological testing itself has yet to be validated in the evaluation of concussion.”

Pencil and Paper Neuropsychological Tests

Trail Making Test Part B (Reitan Neuropsychological Laboratory, Tucson AZ): The subject has as much time as necessary to complete a “connect the dots” puzzle. The sequence of the “dots” alternate between numbers and letters. Beginning with 1, the pattern goes A, 2, B, 3 . . . , until the subject reaches number 13. Time is taken to the nearest tenth of a second and recorded as a score. If the subject connects the dots in a non-sequential order or misses a dot, an additional second is added to the score as a penalty. Before the test is given, the subject prepares on a practice test to ensure that they understand the instructions. The Trail Making Test Part B measures the subjects “orientation, concentration, visuospatial capacity, and problem-solving abilities” through a ‘connect the dots’ puzzle (90).

Controlled Oral Word Association Test (COWAT) (Multilingual Aphasia Examination):

In this test the examiner gives the patient sixty seconds per trial to generate as many words beginning with a given letter, C, F, or L. Words that are proper nouns, numbers, and are derivations of words already used are not counted. The final score is the sum of the three trials. The COWAT is “designed to evaluate the subject’s ability to make verbal associations to specific letters” and “detect changes in word association fluency” by having them list as many words as possible in 60 seconds that begin with the designated letter (112).

Stroop Color Word Test Page 3 (Stoelting Co., Wood Dale, IL): The test consists of 100 words separated into five columns of 20. The words RED, BLUE or GREEN are printed in a color not correlated with the word. The examiner asks that the subject identify as many ink colors, ignoring the word written out. Scoring is based on the number correct answers in 45 seconds the Stroop Color Word Test Page 3 is designed to assess the cognitive flexibility and attention span of the subject by examining their ability to separate word and color naming stimuli (43).

Hopkins Verbal Learning Test (The Johns Hopkins University, Baltimore, MD): In the recall portion of the test the examiner reads a list of twelve words to the subject. After the tester has read the list twice, the subject repeats as many words as he can remember in no particular order. The same list is read again before the subject repeats the list for the second time. The third trial follows the same process by reading the list again and having the subject repeat as many words as possible. After the third trial the discrimination portion of the test begins with the examiner reading a list of twenty-four words consisting of the twelve original and an additional twelve words. As each word is read, the administrator asks the subject if it was part of the original list or if it is a new word. Scoring is based on the total number of words repeated in the recall portion added to the number of original words identified, minus any incorrectly identified words. The Hopkins Verbal Learning Test is designed to “test the subject’s verbal memory” by recall of a list of twelve words (43).

Symbol Digit Modalities Test (Western Psychological Service, Los Angeles, CA): In this ninety-second test the subject fills in as many numbers as possible that corresponds to a given symbol according to a key provided at the top of the page. Scoring is based on the number of

correct answers minus the number of incorrect answers. Subjects are given a ten symbol trial to familiarize themselves with the test before beginning the test. The Symbol Digit Modalities Test utilizes visual tracking and incidental learning by having the subject write a number correlating with a symbol on the page.

Digit Span Test Forward and Backward (Psychological Corporation, San Antonio, TX):

In the Forward portion of the test, the patient is read a list of numbers and asked to repeat them in the same order. The sequences are presented in six pairs ranging from three to eight digits in length. The test is scored by the number of correct sequences recalled. For the Backwards portion, a sequence of numbers is read aloud and the subject is asked to repeat them in the reverse order. A total of six sequences are read, with digits spanning from two to seven.

Scoring is based on the number of proper recalls (90). The Digit Span Test assesses the subject's "concentration and immediate memory recall" by repeating a list of numbers forward and backward (43).

Neuropsychological Studies of Concussed Athletes

Use of neuropsychological testing is widespread for concussion assessment. Sports medicine personnel have used varying combinations of the tests listed above to evaluate the varying domains of cognitive functioning. Barth et al (4) used the Trail Making Test parts A and B, and the Symbol Digit Test to evaluate the cognitive function of 182 American football players who had sustained a reported total of 192 concussions. The authors administered these tests in the preseason to get a baseline value and then compared the scores to post-injury results. When compared to the 107 control subjects, the concussed group showed statistically significant impairment on the Symbol Digit Test. The Trail Making Test, both parts A and B, did not show

significant differences between groups. Injury to differing parts of the brain may explain the non-significant findings on the Trail Making tests. These cerebral areas may remain unaffected, while the injury may have directly affected the areas that affect performance on the Symbol Digit test.

The Trail Making Test was again used to assess neuropsychological deficits following cerebral concussion in 183 NCAA Division one American football players. Each of the concussed athlete and the controls matched for sex, age and education were evaluated prior to the season, within 24 hours post-injury, and at days five and ten. The authors found a significant difference between baseline tests and post-injury tests administered 24 hours after the injury. In this instance the results of the Trail Making Test, both parts A and B, were significantly slower than control subjects (65). The decreased performance by the concussed group indicated a mild impairment in cognitive functioning.

The Symbol Digit Modalities Test has shown consistency across groups when implemented to evaluate a rugby league football team. The researchers evaluated each of the 54 members of the team twice in the preseason and then again if they displayed any of the signs and symptoms of a concussion. The total number of players that received a concussion during the season was ten, with an average age of 22.1 years. The researchers matched the ten concussed players to a control group of ten subjects. Each control subject was evaluated following the same protocol as the rugby players. The concussed athletes provided fewer correct answers in the same time frame, indicating cognitive impairment from the injury (47).

Using data obtained from 53 subjects that had received concussions, Leininger et al (57) performed a neuropsychological assessment using the WAIS-R Vocabulary, WAIS-R Digit Span

Backward, Category, Trail Making Test Part B, Auditory Verbal Learning, Complex Figure Copy and Memory Trials, Controlled Oral Word Association (COWAT), and the Paced Auditory Serial Addition Task - Revised (PASAT-R) tests. Thirty-one of these subjects received a concussion strong enough to render them unconscious, while the other displayed other signs and symptoms of a concussion. These include, but were not limited to, dizziness, confusion, and amnesia. Of those patients rendered unconscious, they must not have been unconscious for more than twenty minutes for inclusion in the study. The results of the neuropsychological testing showed the concussion subjects performing significantly worse on the Category, PASAT-R, Auditory Verbal Learning, Complex Figure Copy and Memory Trials when compared to a control group of twenty-three subjects. The significance of the Complex Figure Copy and Memory Trials was lost after a Bonferroni correction.

In a well controlled study of sport-related concussion, 11 injured subjects were paired with 11 control subjects based on age, height, weight, and gender. The investigators used the Stroop, Trail Making, Digit Span, and the Hopkins Verbal Learning cognitive tests as a tool to assess the concussed athletes and control subjects. Subject evaluation took place on days 1, 3, 5, and 10. No significant difference was seen between groups or days during the entire 10-day testing period. The researchers paired this test battery with a balance assessment which did show significant findings. These findings contraindicated previous research on cognitive impairment following sport related cerebral concussion. The authors suggested that these cognitive tests may not be sensitive enough to show deficits in cognitive function following injury.

To evaluate the effects of repeated exposure to head trauma, Tysvaer (118) evaluated former soccer players with a battery of neuropsychological tests. The players had ended their

careers an average of 14 years earlier after playing an average of 359 games. The thirty-seven former players, none of whom reportedly abused alcohol, were self-selected into a “header” and “non-header” group. Each athlete completed the Trail Making Test A and B, Halstead-Wepman-Reitan Aphasia Screening Test, Motor Tests, Tests for Hemisphere Dominance, Tests for Sensory-Perceptual functions, and the Benton Visual Retention Test Part C. Data analysis showed 30 of the 37 former players (81%) showed some level of neuropsychological impairment. Where as a control group of twenty subjects only found eight (40%) to have some level of neuropsychological impairment. The authors also state that “header” group showed a higher degree (20%) of neuropsychological impairment than the “non-header” group (8%). This finding, however, was not significant. The findings of this study are referenced often, but they are also criticized. Tsyvaer recruited older athletes who played in an era when soccer balls were made of leather. When playing in the rain or on a wet field, the balls would absorb water, resulting in an increased impact force when heading. Modern era balls are made from a synthetic, waterproof materials. Thus the force of impact may not be as great as in previous years.

Matser et al (69) conducted a similar study, this time using 53 active Dutch professional soccer players paired with 27 male control subjects. In this study the male control subjects were all members of elite swimming and track teams. The researchers again divided the current soccer players into a “header” and “non-header” group, but by position. The authors categorized midfielders and goalies as “non-header,” while forwards and defensive players were deemed “headers.” The tests utilized for this analysis were: Raven Progressive Matrices Test, Wisconsin Card Sorting Task, Paced Auditory Serial Addition Task, Digit Symbol Test, Trail Making A

and B, Stroop Test, Bourdon-Wiersma Test, subtests of the Wechler Memory Scale, Complex Figure Test, 15-Word Learning Test, Benton's Facial Recognition Task, Figure Detection Test, Verbal Fluency Test, and the Puncture Test. Data analysis showed significant cognitive impairment in the players when compared to the control group. The soccer players displayed deficits in verbal and visual memory, planning, and visuoperceptual processing tasks. The significance between the two groups remained even after correcting for confounding variables.

A follow-up study on the effects of repeated blows to the head, Matser et al (70) evaluated amateur soccer players. Thirty-three amateur players who played for an average of 17 years were matched with 27 control subjects of swimmers and runners. The authors performed a series of neuropsychological tests that included: Raven Progressive Matrices Test, Wisconsin Card Sorting Task, Paced Auditory Serial Addition Task, Digit symbol Test, Trail Making A and B, Stroop Test, Bourdon-Wiersma Test, Wechler Memory Scale, Complex Figure Test, 15-Word Learning Test, Benton's Facial Recognition Task, Figure Detection Test, Verbal Fluency Test, and the Puncture Test. Results of the study showed planning and memory impairments in the amateur players. Impairments in memory for the soccer players included 27% of the subjects and 7% of the control group. While 39% of the amateur players showed moderate to severe impairments on the planning tests compared to 13% of the controls. These scores remained significant after correcting for variables. Soccer players also showed deficits in the Complex Figure Test, Digit Span, Logical Memory, Visual Reproduction, Associate Learning and sections of the Wechler Memory Scale. These deficits remained after the authors made corrections for non-soccer related concussions, alcohol intake, education level, and number of general anaesthesias.

Both studies presented by Matser and his colleagues have come under a high level of criticism for the range of alcohol consumption (0-99 drinks/month) reported by the athletes. This aspect of subject demographics may have caused the significantly lower performance by the soccer group that was unrelated to soccer heading. Alcohol consumption to this degree is well known to decrease cognitive functioning and may have confounded test results.

Computerized Neuropsychological Testing

The initial intent of computerized neuropsychological testing was to aid in the diagnosis of those suffering from neurological and psychiatric illnesses (18). The recent proliferation of computers into the everyday life has resulted in these tests to be used for concussion assessment. Three tests have found their way to the forefront of sport related concussion assessment: ImPACT (www.impacttest.com), Concussion Resolution Index (CRI) (www.headminder.com), and Cogsport (www.cogsport.com). The use of computerized testing in the assessment of cerebral concussion has both benefits and limitations over the traditional pencil and paper tests.

The advantages of a computer based testing program include: more precise measurement of reaction times, decreased practice effects, time for administration, and ease of administration. Reaction times recorded on a computer can be measured to the thousandth of a second. Hand measurements of reaction time by stopwatch are much less accurate (hundredth of a second) and are subject to variability of the tester's own reaction time. The time recorded will be influenced by the time it takes for the test administrator to recognize the test has completed and stopped the timing clock.

Computer based testing also offers the advantage of allowing for a nearly infinite number of alternate forms. A variety of forms may help decrease practice effects often seen with the

serial administration of neuropsychological tests. Many pencil and paper tests now used for concussion assessment were designed for a single administration, not serially as they have been implemented (18). Following a sport related concussion, pencil and paper tests have been administered three or four times within the first seven days following recovery (41-44). Thus, practice effects reduce the ability to make inferences about the recovery of an athlete following injury.

Finally, the time of administration and ease of administration for computer based tests offers a distinct advantage over the pencil and paper tests. Many high-risk athletes now undergo a baseline test to establish 'normal' functioning in a non-injured, baseline state. If an athlete subsequently becomes injured, clinicians may elect to test him serially to determine when he returns to a base rate of functioning. The process of baseline testing high-risk athletes can be time consuming. A complete neuropsychological evaluation of an athlete may take up to four hours, although modified batteries of tests typically take 45 minutes. In addition, the clinician must administer each test on a one on one basis with the athlete. Time to complete a computer based test can be 20 to 30 minutes and the number of athletes simultaneously tested is limited only by the number of computers available. The concurrent testing of athletes is particularly important during the preseason when whole teams will require as part of their pre-season physical exam.

The use of computer-based assessments offers many advantages over the pencil and paper format, but their clinical reliability is unproven. Previous reliability studies have not implemented time intervals commonly used in a sports medicine setting (18;27). In the sports medicine setting, a traditional evaluation involves comparing preseason baseline values to results

from post-concussion serial testing. The follow-up time from baseline to concussion is often 45 days or more. Once the athlete has sustained a concussive injury, serial neuropsychological evaluations are commonly administered prior to the athlete returning to baseline levels.

Previous reports on computer-based testing reliability are mixed. Collie et al reports the intra-class correlation for the speed of psychomotor, decision making, working memory, and learning variables in the CogSport (Concussion Sentinel) program to range from .69 to .90. These data were based on a sample of volunteers whom they tested serially with twenty-four hours separating testing sessions (18). Erlanger et al reported the two week test-retest reliability of the Headminder CRI in college aged or adult athletes to be .90 for processing speed index, .73 for simple reaction time, and .72 for complex reaction time (27). The test-retest reliabilities reported in these studies are acceptable, but the test intervals simply do not apply to the baseline/follow-up model used in athletic settings.

In an evaluation of the test-retest reliability of the ImPACT test, Iverson et al evaluated 49 high school and collegiate athletes on three separate occasions (51). A baseline administration was given, followed by a follow-up assessment 14 days later, and a third administration given 4.5 days following the second test. The authors evaluated test-retest reliability using a Pearson's correlation coefficient between individual time points. Correlations ranged from .54-.76 for the reaction time, processing speed, and memory portions of the test from Time One to Time Two. From Time Two to Time Three the correlations ranged from .48-.86 and from Time One to Time Three the correlations ranged from .40-.80. While some of these correlations seem acceptable, both the time frame of test administration and reported measures should be considered. The authors reported on reaction time, processing speed, and

memory. The ImPACT test however, reports scores for visual and verbal memory, visual motor speed, reaction time, and impulse control. The authors provided no explanation as to which measures were used to calculate which correlation coefficients.

In addition, while the Pearson correlation coefficient is an acceptable measure of test-retest reliability with only two test administrations, the authors failed to provide a single intraclass correlation coefficient for all three time points. These data would prove most useful to clinicians who are likely to administer a concussion assessment at least three separate time intervals: baseline, immediately post-concussion, and when the patient no longer has symptoms.

Computer Based Neuropsychological Tests

Four neuropsychological tests using computer programs are currently available to clinicians. The components of three of these tests are described below.

Headminder Concussion Resolution Index (CRI): The CRI implements six tests to produce five index scores that indicate processing speed, simple reaction time, complex reaction time, and simple and complex reaction time errors. Each test is listed and described below as written in the CRI users manual (25).

Reaction Time: The participant is instructed to press the spacebar whenever they see a white circle appear on the computer screen.

Cued Reaction Time: The participant is instructed to press the spacebar whenever they see a white circle following a black square appear on the computer screen.

Visual Recognition 1: A series of pictures are presented to the participant. He is asked to press the spacebar whenever a picture is repeated.

Visual Recognition 2: Following a delay, the participant is presented with a series of pictures. He is asked to press the spacebar if any picture has been duplicated from the Visual Recognition 1 test.

Animal Decoding: Nine animals are presented with a corresponding number from one to nine. A row of the same animals is presented and the participant is asked to fill in the corresponding number to each animal.

Symbol Scanning: Two shapes are presented on the left hand side of the screen and a row of eight shapes are presented on the right. The participant is asked to press one if only one of the shapes is included in the eight. The participant is asked to press two if both shapes appear in the series of eight.

The Headminder CRI has been shown to be specific to sport related concussion. Following the baseline evaluation of 834 collegiate and high school athletes, 26 sustained a sport related concussion. CRI evaluation was completed in one or two day intervals following the injury and continued until the symptoms resolved. The authors reported the CRI to accurately identify 23 of the 26 (88%) athletes as concussed (27). While the CRI did not correctly identify all 26 athletes as concussed, it should be noted that a neuropsychological assessment test is only one part of the concussion assessment battery. Additional tests, such as postural control or symptomology, would have likely led to an appropriate assessment.

ImPACT: ImPACT uses six modules to produce five index scores that indicate verbal memory, visual memory, processing speed, reaction time, and impulse control. Each of the modules are described below as presented in the ImPACT users manual (1).

Module 1 (Word Discrimination): Twelve words separated by 750 milliseconds are presented to the participant two times. The participant is then asked to pick the 12 original words from a series of 24 words. A delayed recall of these words are presented to the participant at the end of the session.

Module 2 (Design Memory): Twelve designs separated by 750 milliseconds are presented to the participant two times. The participant is then asked to pick the 12 original designs from a series of 24 designs. A delayed recall of these designs are presented to the participant at the end of the session.

Module 3 (X's and O's): The participant is presented with a random display of X's and O's on the screen. Three letters are highlighted for 1.5 seconds for him/her to remember. A distraction task measuring reaction time when either a red circle or blue box appears is then given. The X's and O's then reappear on the screen and the participant is asked to identify the previously highlighted letters.

Module 4 (Symbol Matching): The participant is presented with a row of nine symbols and associated number from one to nine. A single symbol is then presented at the bottom of the screen and the participant is asked to depress the corresponding number as quickly as possible.

Module 5 (Color Match): The participant is presented the words 'RED,' 'BLUE,' or 'GREEN' written in red, blue, or green letters. When the word and the word color are identical the participant is instructed to press the mouse key as quickly as possible.

Module 6 (Three Letters): The participant is presented with 25 numbers from one to twenty-five in a five by five grid. He/she is asked to count down as quickly as possible by clicking on the corresponding number. He/she is then presented with three random letters to

later recall. The grid countdown re-administered. The participant then has to recall the three letters.

ImPACT has been shown to be specific to concussion in 72 concussed high school athletes and compared them to 66 athletes with no previous history of concussion. Each athlete (control and injured) were evaluated in the pre-season using the ImPACT computer-based test. Following concussion, each athlete was evaluated within 72 hours of injury. ImPACT test results were able to correctly identify 85% of the athletes as concussed following injury (108). Similar to the CRI test, the Impact is designed to be used as one of a battery of tests for concussion assessment. While the test was able to correctly identify a majority of concussed athletes, the remaining 15% would likely have been correctly evaluated using postural control and/or symptomology.

Concussion Sentinel: The Concussion Sentinel implements a series of seven tests to develop five scores of cognitive function: reaction time, decision making, matching, attention, and working memory. The five scores are derived from seven tasks that include between 15 and 40 trials that evaluate reaction time and response accuracy. In addition, responses that unusually rapid (<100ms) or unusually slow (>3500ms) are recorded as errors (111).

Internationally the Concussion Sentinel is marketed as CogSport. The two computer programs are identical in testing methodology and vary only in data reporting (personal communication). The CogSport test has been shown to be specific to concussion. The researchers performed baseline evaluations on 240 Australian rules football athletes. Each evaluation included an assessment using the CogSport test as well as the Digit Symbol Substitution Test and the Trail Making Test-Part B. Players were tracked throughout the

competitive season where six concussions were diagnosed by physicians. Each athlete was re-administered the same tests as the baseline evaluation. Following concussion the Digit Symbol Substitution Test and the Trail Making Test-Part B showed no decline when compared to baseline performance. The simple reaction time component of the CogSport test however, showed significantly impaired performance in all the athletes tested (66). The correct assessment of all athletes shows the specificity of the CogSport test, but a large sample size would be warranted in a follow-up study.

Effort Assessment of Neuropsychological Testing

Serial administration of neuropsychological tests following concussion has brought forward the notion that an injured athlete may not put forth the highest level of effort during testing (38). Repeated administrations of the same test battery may result in general boredom or a lackadaisical attitude by the athlete. The result may be fluctuating neuropsychological scores across days of testing. While none of the computer-based or pencil and paper tests have a means to assess effort, other measurement tools are available.

Green and Astner first developed the oral word memory test (WMT) to evaluate effort during neuropsychological testing(37). Since then, the delivery platform has changed from oral delivery of the words to a computer based model. According to the operators manual, the computer based WMT has been validated in eleven separate studies with 50 comparison groups, accounting for 2800 individual cases(36). Gervais reported in 904 subjects making injury disability claims that neuropsychological test scores were significantly lower in those who failed to pass the WMT(33). Most recently, the Memory and Concentration Test (MACT), a shorter and more concise version of the WMT, has been developed to assess effort.

The MACT is a verbal memory test that evaluates effort through a series of tests including immediate recognition (IR), delayed recognition (DR), response consistency, paired associates, and free recall. To administer the test, the participant sits in front of a computer monitor and reads 20 words presented as pairs. Following two cycles of word presentation, the participant then picks the original 20 words when mixed with 20 new words to calculate an IR score. The program provides auditory and visual responses with each correct and incorrect answer. Following a ten minutes delay, the DR score is calculated when the participant selects the original words mixed with a new set of 20 additional words. A consistency score is calculated by tallying the same correct answers on the IR and DR portions of the MACT. The paired associates portion requires the test administrator to present the participant the first word of the pair and ask for the associated word. Finally, the test taker is asked to provide as many word pairs as possible from memory in the free recall portion.

The MACT is an equivalent test to the WMT, with greater specificity because of the easier word pairs (115). In unpublished data, Gervais evaluated 127 subjects who were selected for showing high effort on the WMT. One-hundred and nine of these subjects were evaluated on the oral MACT and compared to the computer based WMT and 18 participants were administered the computer MACT and compared to the oral WMT. Participants showed similarly high performance on the MACT compared to equivalent components of the WMT (35). Additionally, correlation of the IR and DR scores generated by the MACT and WMT a high level of agreement. Green reports the DR correlation to be $r=0.792$ and the IR correlation to be $r=0.700$ (35). These values would suggest the MACT provides a similar evaluation of effort as the WMT.

Several samples have been evaluated to establish passing and failing guidelines on the MACT. In a sample of 47 adults who passed the WMT, they were administered the MACT and scored 98% and 97% on the MACT IR and DR respectfully. A separate sample of 55 adults who failed the WMT also completed the MACT. These individuals scored an 86% and 83% on the MACT IR and DR respectfully(33). From this analysis the developers defined good effort as scoring greater than 85% on the IR, DR, and consistency portions of the evaluation. The effort is thought to be poor when one of the three test scores falls below 85%. The cutoff passing score of 85% represents a two standard deviation deficit from normal adults putting forth good effort on the MACT (35).

Neuropsychological testing is widely considered the gold standard for concussion assessment. Prior to the advent and proliferation of personal computers, a battery of pencil and paper tests were administered to assess an injury. For reasons discussed in detail above, this technique was laden with problems such as time constraints, practice effects from lack of multiple equivalent forms, and measurement error. Computer based formats offer a solution to each of these issues, but as with any new tool the validity and reliability must be established before the appropriate clinical decisions can be made. Several studies have shown the computer based tests to be sensitive to concussion, and a few have shown reliability. These studies however, have failed to utilize a test-retest interval that is useful for the clinician. Interpretation of multiple follow-up tests on a concussed athlete can be difficult. For one reason or another the athlete may not put forth maximum effort on either the pre-season baseline evaluation or on the follow-up tests. Currently, effort is not evaluated on any of the computer-based tests, although it has been suggested that error scores may provide an indication of effort.

Imaging Techniques for Concussion

A physician may order magnetic resonance imaging or computed tomography to detect cerebral injuries that occur during athletics. Their use however, is limited as sports-related concussions often do not produce structural lesions detectable through these techniques (52). Sports-related cerebral concussion injuries often result in only a transient ion flux and changes in glucose metabolism as described above. Detecting changes in glucose metabolism within specific brain regions affected by concussion may be accomplished with positron emission tomography. Brain injuries that result in visible structural injuries are more common in high speeds accidents that exceed 50km/h, such as automobile accidents. Most athletic events occur at much slower speeds (<10m/s) (76). In the absence of useful data from imaging techniques, athletic trainers and physicians must decide, largely through a subjective evaluation consisting of the components mentioned above, the presence and severity of concussion in the injured athlete.

Concussion Grading Scales

To the sports medicine clinician, the area of cerebral concussion is perplexing. There currently exists no consensus on symptoms, grading scales, or the proper treatment for the injury. Collins reports fourteen peer-reviewed concussion grading scales are available for the assessment of concussion (19). Among these, two grading scales, the Colorado (28%) and the Cantu (19.3%), were shown to be the most widely used among athletic trainers at all levels (28). These two scales are discussed in detail below. This study also reported that nearly twenty percent of athletic trainers use no grading scale at all when assessing a concussion (28).

Colorado Medical Society Grading System for Concussion (1991) (20)

Grade 1: No loss of consciousness, confusion, no amnesia

Grade 2: No loss of consciousness, confusion, amnesia

Grade 3: loss of consciousness

Cantu Grading System for Concussion (1986) (13)

- Grade 1: No loss of consciousness, post-traumatic amnesia less than 30 minutes
- Grade 2: Loss of consciousness less than 5 minutes or post-traumatic amnesia of 30 minutes to 24 hours
- Grade 3: Loss of consciousness greater than 5 minutes or post-traumatic amnesia greater than 24 hours.

Cantu later revised his concussion grading scale (15). This scale, unlike the original scale published in 1986, was based on evidence he collected the ten years prior. The 1986 scale was simply based on his personal observations as a neurologist.

Evidence-Based Cantu Grading System for Concussion (2001) (15)

- Grade 1: No loss of consciousness, post-traumatic amnesia, or post concussive signs and symptoms lasting less than 30 minutes
- Grade 2: Loss of consciousness of less than 1 minute, post-traumatic amnesia or post concussive signs and symptoms lasting more than 30 minutes, but less than 24 hours
- Grade 3: Loss of consciousness of more than 1 minute, post-traumatic amnesia more than 24 hours, or postconcussive signs and symptoms lasting longer than 7 days

Second Impact Syndrome

Returning an athlete to play prior to the resolution of a concussion may place the athlete at risk for second impact syndrome (SIS) (78). SIS results from the malfunctioning of the autoregulation of the cerebrovascular system. The outcome for SIS is poor with the mortality rate approaching 100% (74). A recent review of seventeen published cases, where SIS was suspected as the cause of death, the author suggested this condition may be a misnomer. Instead, McCrory suggests that diffuse cerebral swelling may be a more accurate term (74). In this instance a concussed athlete is injured a second time, before recovery from the first injury. Swelling from the two injuries may be compounded leading to death of the athlete.

CHAPTER 3

METHODS

Study 1: Concussion assessment reliability with maximal effort

The purpose of this study is to evaluate the reliability of three computer-based concussion assessment programs: ImPACT, Headminder Concussion Resolution Index (CRI), and the Concussion Sentinel. In addition, participant effort will be measured during each session using Green's Memory and Concentration Test (MACT).

Participants: A total of one hundred eighteen (N=118) students were recruited from the University of Georgia student body. Sample size was estimated based on guidelines provided by Baumgartner and Chung for the estimation of sample size for reliability studies using a one-way analysis of variance estimation of the intraclass correlation coefficient(6). Students were recruited from classes held within the Department of Kinesiology on the University of Georgia campus.

Participants were excluded from the study if they meet any of the following conditions: English was not a first language, the participant sustained an orthopedic injury requiring surgery, a physician has diagnosed the participant with a learning disability or attention deficit disorder, and any student was receiving treatment for a diagnosed concussive injury at the start of the study .

Testing Sessions

Session 1: Upon arriving at the testing facility, each participant was described the testing protocol in detail. The investigator provided the opportunity for any questions concerning the test protocol. Each participant read and signed a University of Georgia Institutional Review Board informed consent form (Appendix I). The participant completed a brief demographics comprised of questions such as age, height, weight, and previous number of diagnosed concussions (Appendix II).

The testing protocol consisted of three computer-based concussion assessment programs and a computer-based measure of effort. The concussion assessment programs include: ImPACT Concussion Management Software (ImPACT Applications, Pittsburgh, PA), Headminder Concussion Resolution Index (Headminder Inc, New York, NY), and Concussion Sentinel (CogState LTD, Victoria, Australia). The effort test is Green's Word Memory and Concentration Test (Edmonton, Canada).

The three concussion assessment programs are designed to evaluate neuropsychological functioning following a concussive injury. The CRI implements six tests to produce five index scores that indicate processing speed, simple reaction time, complex reaction time, and simple and complex reaction time errors. ImPACT implements six modules to produce five index scores that indicate verbal memory, visual memory, processing speed, reaction time, and impulse control. The Concussion Sentinel implements a series of tests to develop five scores of cognitive function. Green's MACT is a computer based test that presents the participant with a series of word pairs. The participant is asked to recall the word pairs immediately and following a ten minute delay. Effort is based on scores of immediate recall, delayed recall, consistency of

responses, paired associates, and free recall of the word pairs. Green's MACT takes approximately five minutes to complete and is designed to evaluate the effort put forth by the participant.

Each program requires a desktop or laptop computer and an external mouse for proper administration. Total test time for the ImPACT and the CRI is approximately 20 minutes each. The Concussion Sentinel takes approximately ten minutes to complete. The immediate recognition portion and a delayed recognition portion of Green's MACT are designed to be administered ten minutes apart. The immediate recognition portion of the MACT was administered prior to the Concussion Sentinel and the delayed recognition portion administered following the Concussion Sentinel. The Sentinel test provides the appropriate time interval between the immediate and delayed recall portions of the MACT. Each participant was instructed to work at his/her own pace with each test administered directly following the other. Total testing time for one session took 60 to 70 minutes.

Testing Environment: Each test session took place in Room 110 (St Mary's Athletic Training Research and Education Laboratory) of the Ramsey Center. Each participant sat comfortably in front of a computer and worked at his own pace. Each program is self-explanatory and did not require direct interaction with the investigator during administration. However, the investigator was available (in the adjacent room) to answer any questions the participants had during the testing sessions. The investigator did not actively participate in the administration of the computer-based tests and did not actively monitor the participant during testing.

Sessions 2 and 3: Following a baseline evaluation, each participant was re-tested on each of the programs 45 days following the first test administration. A 45 day interval represents the estimated time between baseline testing and the first concussion assessment in collegiate athletes (unpublished University of Georgia Athletic Association data). A final assessment on the same program was administered five days later, day 50. A five day follow-up represents the mean time interval concussed athletes are given a follow-up assessment following their initial concussion evaluation. Testing on day 45 and day 50 followed the same procedure as described in Session 1, test administration was counter balanced.

Study 2: Expected change of computer-based concussion assessments and subtest reliability

The purpose of this study was to evaluate the reliability of subtests used to generate the output scores of three computer-based concussion assessment programs: ImPACT, CRI, and the Concussion Sentinel. In addition, participant effort was measured during each session.

Participants: Data from the same 118 used in the previous study were used to evaluate subtest scores in this study. All students were recruited from the University of Georgia student body, but primarily from classes held within the Department of Kinesiology on the University of Georgia campus. Sample size was estimated based on guidelines provided by Baumgartner and Chung for the estimation of sample size for reliability studies using a one-way analysis of variance estimation of the intraclass correlation coefficient(6).

Participants were excluded from the study if they meet any of the following conditions: English was not a first language, a physician has diagnosed the participant with a learning disability or attention deficit disorder, and any student received treatment for a diagnosed concussive injury at the start of the study.

Testing Sessions

Session 1: All testing took place in Room 110 of the Ramsey Center as described above. The study design and testing protocol was described to each participant and an opportunity was provided for him to ask any questions. Each participant read and signed a University of Georgia Institutional Review Board informed consent form (Appendix I). A brief questionnaire addressing demographics such as age, height, weight, and previous number of diagnosed concussions was also administered (Appendix II).

The testing protocol was identical to that of Study 1 and consisted of three computer-based concussion assessment programs and a computer-based measure of effort. The concussion assessment programs included: ImPACT, CRI, and Concussion Sentinel. The effort test was Green's MACT. Each program requires a desktop or laptop computer and an external mouse for proper administration. Total test time for the ImPACT and the CRI is approximately 20 minutes each. The Concussion Sentinel takes approximately ten minutes to complete. The immediate recognition portion and a delayed recognition portion of Green's MACT are designed to be administered ten minutes apart. The two portions of the MACT were always administered immediately prior to and following the Sentinel because of the required ten minute delay between sections. The Sentinel provides the appropriate time interval. Each participant was instructed to work at his own pace with each test administered directly following the other. Total testing time for one session took 60 to 70 minutes.

Sessions 2 and 3: Following the initial evaluation, each participant was re-tested on each of the programs 45 days following the first test administration. A final testing session took place

at day 50, five days following the second administration. Test administration was a counter balanced design.

Statistical Analysis:

Specific Aim 1: Intraclass correlation coefficient (ICC) were calculated for each output score for each computer test for all subjects. Two ICC calculations were made: from baseline to Day 45 and Day 45 to Day 50. No ICC encompassing all three data points was calculated because of the difference in time between data collection points. A low intraclass correlation coefficients would indicate test results are not stable across days in normal healthy subjects.

Specific Aim 2: ICCs were calculated for each subtest score used to generate the output scores for each computer test for all subjects. Two ICC calculations were made for each subtest: from baseline to Day 45 and Day 45 to Day 50. No ICC encompassing all three data points were calculated because of the difference in time between data collection points.

Specific Aim 3a: Multiple repeated measure analysis of variance were used to evaluate differences in MACT effort test scores between days. When significance was indicated, paired contrasts were performed for post-hoc analysis.

Specific Aim 3b: Pearson's r correlation coefficients between each effort variable and each computer-based test output score and subtest were calculated for each assessment point.

Finally, the standard error of measurement (SEM) was calculated for each score generated by the computer-based tests. The SEM is a measure of response stability that estimates the standard error in multiple assessments. The SEM is calculated by $s_p \sqrt{1 - r_{xx}}$, whereby s_p is equal to the pooled standard deviation of the two test scores and r_{xx} is equal to the reliability coefficient of the test scores. The interpretation of the SEM calculation can be made

in reference to the normal curve. One SEM will encompass 68% of true scores. Two and three SEMs encompass 95 and 99% of true scores respectfully (103).

An intraclass correlation coefficient was implemented to evaluate the test-retest reliability of the computer based tests. The ICC is a one-way analysis of variance model with a single measure as a participant's score. The coefficient (R) is equal to $[MS_A - MS_W] / [MS_A + MS_W]$. Whereby, MS_A is equal to the mean squares among participants and MS_W is equal to the within participant mean squares(7). Since the primary purpose of this calculation is to evaluate the stability of the computer tests between test administrations, Pearson's correlation coefficients will not be calculated. Pearson's r is not sensitive to systematic changes in test administration, such as learning effects or practice effects. In addition the use of a Pearson's r statistic measures the strength of the relationship between variable and not the level of agreement between them (10). All data analyses were conducted using SPSS version 13.0 (SPSS, Chicago, IL) and statistical significance was set at $\alpha < 0.05$.

Pilot Testing:

The proposed study protocol was evaluated on twelve (N=12, 9 females) college aged participants during the Spring 2005 semester. At the time of participation, each student had been admitted to the Athletic Training Education Program at the University of Georgia. At the time of data collection, each participant was enrolled in EXRS 3110 and was a student of the investigator. After hearing a description of the study, each participant read and signed an IRB approved informed consent. All participants met the inclusion criteria and none were being treated for any orthopaedic injury prior to beginning or during participation in the study. Participant demographics are available in Table 3.1.

Each participant completed each of the three computer-based concussion assessment programs and the computer-based effort test on three separate occasions: baseline, day 45, and day 50. Test-retest reliability coefficients were calculated as described above and a repeated measures analysis of variance evaluated differences in effort across the three testing sessions. Mauchly's test of sphericity was utilized for each assessment and a Greenhouse-Geisser adjustment was implemented as indicated. Significance was set at $\alpha < 0.05$.

The first follow-up test of the subjects occurred 43.50 (± 3.26) days after the baseline administration of tests. The second follow-up test occurred 4.50 (± 1.26) days later. Reliability coefficients for each sub-tests of the three computer based concussion assessment programs are presented in Table 3.2. The test-retest reliability coefficients calculated from the pilot data indicated a substantial or almost perfect correlation on four of the five measures calculated by the Headminder CRI. Only one measure on the ImPACT showed to be substantial. No data are available from the Concussion Sentinel program due to administrator error.

Mean values for each measure generated by Green's MACT during each testing session are presented in Table 3. Of the five measures produced by Green's MACT, only consistency was indicated as varying significantly across days ($F_{1.353, 14.885} = 5.037, p = 0.032$). All other measures were not deemed statistically significant. An evaluation of the daily mean scores indicated an improvement in the consistency measure across the three testing sessions. Mean scores improved from 96.667 on the baseline test to 99.583 on both days 45 and 50.

Results from the pilot data suggest a more extensive evaluation of test-retest reliability should be conducted. While our pilot data appear to agree with the previously reported test-retest reliability of the Headminder CRI from Erlanger et al (27), other results appear to conflict

with previously reported results. Correlation coefficients reported for the ImPACT test (51) were calculated using Pearson correlation coefficients for two of the three test administrations. Our results indicate a much lower trend in test-retest reliability than previously reported. Differences in the estimation techniques and data collection methods may account for some discrepancies. Collie et al. report the intra-class correlation for the speed of psychomotor, decision making, working memory, and learning variables in the CogSport (Concussion Sentinel) program ranges from .69 to .90 (18). These data were based on a sample of volunteers whom they tested serially with twenty-four hours separating testing sessions. The interval between test sessions varies from our methodology and warrants further investigation.

Scores in all areas of Green's MACT indicate the participants provided good effort on the test (Table 3.3). While a significant difference did exist between days for the consistency measure, these values are all above the recommended pass rate of 85 (35). The high scores seen on Green's MACT were expected as the subject pool consisted of highly motivated athletic training students.

	Age	Height (in)	Weight (lbs)	SAT total
Mean	21.667	66.000	150.250	1178.182
Std. Deviation	2.270	3.275	23.270	106.284

Table 3.1: Pilot testing subject demographics

ImPACT Measures	<i>Verbal Memory</i>	<i>Visual Memory</i>	<i>Visual Motor Speed</i>	<i>Reaction Time</i>	<i>Impulse Control</i>
	0.533	0.38	0.68*	0.566	0.124
CRI Measures	<i>Simple Reaction Time</i>	<i>Simple Reaction Time Errors</i>	<i>Complex Reaction Time</i>	<i>Complex Reaction Time Errors</i>	<i>Processing Speed Index</i>
	0.773*	0.036	0.757*	0.835**	0.803*
Concussion Sentinel Measures	<i>Reaction Time</i>	<i>Decision Making</i>	<i>Matching</i>	<i>Attention</i>	<i>Working Memory</i>

Table 3.2: Reliability coefficients for the three computer based concussion assessment program measures. * indicates a substantial correlation coefficient and ** indicates an almost perfect correlation coefficient.

Baseline	Immediate Recall	Delayed Recall	Consistency	Pair Associates	Free Recall
Mean	98.750	97.917	96.667	99.167	85.833
Std. Deviation	2.261	3.965	4.438	2.887	15.201
Day 45					
Mean	99.583	99.167	99.583	100.000	83.333
Std. Deviation	1.443	1.946	1.443	0.000	15.126
Day 50					
Mean	100.000	100	99.583	100.000	90.000
Std. Deviation	0.000	0	1.443	0.000	11.282

Table 3.3: Means and Standard Deviations for Green's Memory and Concentration Test from three test sessions. Eighty-five (85) or higher on the immediate recall, delayed recall, and consistency scores is consistent with good effort. A score of less than 85 on either the immediate recall, delayed recall, or consistency portions indicates poor effort.

CHAPTER 4

CONCUSSION ASSESSMENT RELIABILITY WITH MAXIMAL EFFORT¹

¹ Broglio SP, Ferrara MS, Macchiocchi SN. To be submitted to the *Journal of the American Medical Association*.

Abstract

Context Computer-based neurocognitive assessment programs are commonly used under the baseline-follow-up model for concussion assessment. These tests have been readily adopted without a thorough evaluation of reliability or the effect effort may have on test performance.

Objective The purpose of this study was to estimate the test-retest reliability of three commercially available computer-based neurocognitive assessments using clinically relevant times and to evaluate effort across multiple days of testing.

Design, Setting, and Participants One-hundred and eighteen (N=118) healthy participants were enrolled. Each participant completed the ImPACT, Concussion Sentinel, and the Headminder Concussion Resolution Index on three days of testing: baseline, day 45 and day 50. In addition, each participant completed Green's Memory and Concentration Test to evaluate effort. We included data from 73 participants in the statistical analysis.

Main Outcome Measure Intraclass correlation coefficients (ICC) were calculated for each output score generated by each computer program. Repeated measures analyses of variance (ANOVA) evaluated change in effort across days of testing.

Results Interpretation of ICCs indicated most output scores fell below the acceptable level necessary to make reliable clinical interpretations. An evaluation of individual scores found all participants demonstrated high effort on all days of testing. ANOVA results indicated an improvement in effort on the delayed recall ($F_{1.81,130.54} = 6.464, p=.003$) and consistency ($F_{2,144} = 5.800, p = .004$) over baseline.

Conclusion Our results suggest that the three computer-based concussion assessments used in this study were unable to produce reliable results when administered under clinically applicable

intervals. Our participants exhibited high effort on all days of testing and showed improved effort with multiple test administrations. This data suggests that multiple administrations may not affect effort and motivation to perform well on the tests.

Key Words intraclass correlation coefficient, effort, ImPACT, Concussion Resolution Index, Concussion Sentinel

Introduction

A lack of readily available diagnostic tools makes sport-related concussion a difficult injury to assess. A neurocognitive assessment has been suggested to be a cornerstone of the evaluation process and is commonly used to provide an index of cognitive functioning following concussive injury. A number of research studies have demonstrated decreases in cognitive function following concussion, with a gradual recover to pre-injury baseline assessment.

Over the past 15 years, a number of neurocognitive tests have been used in sports concussion studies. Commonly utilized pencil and paper tests have assessed attention, information processing speed, learning and memory (2;23). The majority of pencil and paper tests have undergone thorough psychometric evaluation on the reliability, validity and test stability. Recently, similar psychometric instruments have been developed that are administered through computer programs. The advantages of the computer assessment are believed to include ease of administration, rapid scoring, and increased reliability secondary to standardized administration and scoring, and improved reliability (10). While computer-based assessments potentially offer advantages over traditional testing methods, several psychometric issues must be addressed to assess their clinical utility.

First and foremost, neurocognitive tests used in post concussive clinical decision making must be reliable and sensitive to the effects of concussive injuries. Before an examination of sensitivity can occur, each instrument's reliability must be established. Thus far, only a limited number of reliability studies have focused on currently available computer-based sport concussion programs, other than those provided by test developers. In addition, existing reliability studies have not utilized test-retest time intervals typically observed when managing

actual return to play following concussion. For instance, Collie et al. report the intraclass correlation coefficient (ICC) for response speed, decision making, working memory, and learning variables in the CogSport program to range from .69 to .82. These ICCs were based on a sample of volunteers who were tested twice over a one week period (9). Another investigation examined test-retest reliability of the Headminder Concussion Resolution Index (CRI) over a two week period in college aged students and adult athletes. The CRI was found to have reliabilities of .90 for the processing speed index, .73 for simple reaction time, and .72 for complex reaction time(13). An evaluation of the ImPACT reliability used 49 high school and collegiate athletes on three separate occasions. A baseline administration was given followed by a day 14 follow-up assessment. Test-retest reliabilities from baseline to day 14 were reported as Pearson's correlation coefficients ranging from .54 on memory to .76 on processing speed (17).

These test-retest reliabilities fall within an acceptable range, but the interval between assessments is shorter than the typical test-retest interval seen in concussion management and return to play. In the first year of implementing a standardized concussion assessment protocol, our data suggests the mean duration from baseline to initial evaluation was 45 days and approximately five days longer before the athlete begins a return to play protocol (unpublished data). Our time from baseline to initial follow-up was similar to baseline-follow-up interval reported by Lovell et al. in high school athletes (20) . Further, the use of the Pearson's correlation coefficient may not be appropriate in estimating test-retest reliability (4).

Current computer-based neurocognitive test scores may be affected by factors other than neurocognitive change. The proceedings of the 2nd International Symposium on Concussion in Sport recommended athletes be administered an effort test in conjunction with baseline

neurocognitive assessments (21). Effort tests are not sensitive to brain dysfunction, but do provide an index of performance motivation and may identify athletes who do not exert maximum effort at baseline testing. Less than maximum effort at baseline would not only affect test-retest reliability, but also seriously hamper return to play decision making based on neurocognitive test performance. While assessing effort seems clinically prudent, we were unable to find any studies that examined effort in conjunction with test-retest reliability of computer based concussion assessments

Our investigation was designed to examine the test-retest reliability of three commercially available computer-based concussion assessment programs using clinically relevant time intervals while controlling for effort. Based on existing research, we hypothesized that all three computer based assessment applications would yield acceptable test-retest reliability using pragmatic test-retest intervals. We also hypothesized that impaired effort at any point in time would reduce reliability.

Methods

Students volunteers (N=118) were recruited from the general university population. Sample size was estimated based on guidelines provided by Baumgartner and Chung (3) for reliability studies using a one-way analysis of variance model to estimate the ICC for a single score. Participants were excluded from the study if English was not their primary language, if there was a prior history of learning disability/attention deficit disorder, and/or participants had a history of a concussive injury within six months prior to or during the study.

Testing Sessions

Baseline: Upon arriving at the testing facility, all participants read and signed an institutional review board approved informed consent. Each participant then completed a brief questionnaire concerning age, height, weight, previous number of diagnosed concussions, and the exclusion criteria. Participants then completed three commercial computer-based concussion assessment programs and a computer-based measure of effort. The concussion assessment programs included the ImPACT Concussion Management Software version 4.5.729 (ImPACT Applications, Pittsburgh, PA), the Headminder Concussion Resolution Index (CRI) (Headminder Inc., New York, NY), and the Concussion Sentinel version 3.0 (CogState LTD., Victoria, Australia). The effort test administered was Green's Word Memory and Concentration Test for Windows (MACT) (Edmonton, Canada)

The CRI uses six tests to produce five index scores, including processing speed, simple reaction time, complex reaction time, and simple and complex reaction time errors. ImPACT utilizes six modules to produce five index scores including verbal memory, visual memory, visual motor speed, reaction time, and impulse control. The Concussion Sentinel consists of seven tests to develop five output scores including reaction time, decision making, matching, attention, and working memory. The MACT is a computer-based effort assessment that presents the participant with a series of word pairs. Following two presentations of the word pairs, the participant is asked to recall the words immediately and again following a ten minute delay. In the paired associates portion, which follows the delayed recall, the participant is given the first word of the pair and asked to provide the second. Finally, in the free recall section the participant is asked to provide as many word pairs as possible without prompting. Scores for

immediate recall, delayed recall, and consistency of responses are used to establish the level of effort put forth by the participant. Actual testing time for Green's MACT is approximately five minutes. Total time to complete neurocognitive and effort testing for each participant was approximately 60 minutes.

Days 45 and 50: Following the baseline evaluation, each participant was re-tested on each program approximately 45 days following the first test administration (mean 45.08 ± 1.56 days). The final assessment was administered approximately five days later, (mean 5.56 ± 0.90 days). Testing on day 45 and day 50 followed the same procedure as described above, although test administration order was counter balanced and randomly assigned. All tests were administered according to the manufactures recommendations in a quiet laboratory setting.

Statistical procedures: We calculated an ICC to estimate the test-retest reliability of each computer-based test output variable between the baseline and day 45 assessments and the day 45 and day 50 assessments (24). This model ICC uses a one-way analysis of variance (ANOVA), whereby coefficient R is equal to $[MS_A - MS_W] / [MS_A + MS_W]$. The MS_A term is equal to the mean squares among participants and MS_W is equal to the mean squares within participants (24). The ICC produces a value between zero and one and is interpreted in a similar manner as a correlation coefficient. Anastasi (1) recommends the ICC be no lower than .60 when making clinical interpretations. Portney and Watkins (24) suggest that ICCs greater than .75 represent good reliability and those less than .75 to be poor to moderate reliability. Randolph (25) however, states the ICC must be greater than .90 to establish acceptable validity.

Level of effort was determined using the MACT test manufacture's guidelines (14) and a repeated measures ANOVA evaluated differences in effort measures across days of testing. A

Greenhouse-Geisser correction was implemented when sphericity violations occurred. A Bonferroni adjustment was made for multiple pairwise comparisons used during post-hoc analysis. Pearson product correlations were calculated between the MACT effort measures and all scores for each of the computer programs. All data analyses were conducted using SPSS version 13.0 (SPSS, Chicago, IL) and statistical significance was set at $\alpha < 0.05$.

Results

Data from 73 of the original 118 participants were included in all analyses. Five participants dropped out of the study following the baseline assessment. Data were excluded from analysis for 40 participants [Concussion Sentinel (n=6), CRI (n=5), ImPACT (n=29)] based on automated invalidation features (Sentinel and CRI) or guidelines for questionable validity recommended by the manufacturer (ImPACT) (19). If a participant's baseline evaluation was identified as invalid or of questionable validity on a single computer-based test, then all of their data were removed from further analyses. These data were removed to provide optimal conditions for the ICC calculations.

The self-reported demographics of the 73 participants were as follows: age 21.39 (± 2.78) years, height 170.95 (± 9.00) cm, weight 69.09 (± 15.07) kg, and total self-report Scholastic Aptitude Test score of 1168.17 (± 99.76) (verbal and math). Twelve participants (16.4%) reported having a history of diagnosed concussion ranging from one to five injuries. No participants reported sustaining a concussion during the testing process or six months prior to participation.

The mean scores and standard deviations for each output variable listed by computer program are presented in Table 4.1. Performance on each of the computer output scores by this

cohort appears to be slightly higher than previous reports (12;16) and may be attributed to greater cognitive capacity as represented by a higher Scholastic Aptitude Test total score than the current national average (6). The calculated ICC values for each output score on the three computer-concussion tests from baseline to day 45 and day 45 to day 50 are presented in Table 4.2. Amongst the programs evaluated here, the Concussion Sentinel and CRI have similar test-retest reliabilities from baseline to the day 45 evaluation, while the Concussion Sentinel seems to have the highest reliabilities for the day 45 to day 50 evaluations.

Based on the guidelines for the interpretation of an ICC described previously, the reliability of all variables would fall below the acceptable level for a good ICC. Overall, the ICC values were higher between the day 45 to day 50 evaluations than the baseline to day 45 evaluations. The reliability of all ImPACT scores improved between days 45 and 50, as did many output scores on the Concussion Sentinel and the CRI. The reliability of all output scores continued to fall below the acceptable level.

Each computer program was designed to interpret changes in the current score from the baseline assessment. Automated features within each program indicate a significant change from baseline on each follow-up evaluation (Days 45 and 50). No participant sustained a concussion during the study, making any significant change a false positive for cognitive impairment. The number of false positives for each output variable are presented in Table 4.3. A false positive was defined as indicating a normal, healthy participant as impaired when he/she was not. Based on the significant change indications by each computer-based concussion assessment program, the percentage of participants with one or more false positive on any variable on the day 45 assessment was: ImPACT - 38.4% (n=28), Concussion Sentinel - 21.9% (n=16), CRI - 19.2%

(n=14). On day 50, the percentage of participants with false positive reports on one or more variable was: ImPACT - 34.2% (n=25), Concussion Sentinel - 32.9% (n=24), CRI - 23.3% (n=17).

Mean scores and standard deviations for the MACT effort test are presented in Table 4.4. Violations to sphericity were noted on the delayed recall ($W_2 = .897$, $p = .021$) and free recall ($W_2 = .792$, $p < .000$). Following a Greenhouse-Geisser correction for these violations, the repeated measures ANOVA results revealed a significant difference across days for the delayed recall ($F_{1.81, 130.54} = 6.464$, $p = .003$), consistency ($F_{2, 144} = 5.800$, $p = .004$), and free recall ($F_{1.655, 119.191} = 15.935$, $p < .001$) variables of the MACT. Post-hoc analyses indicated days 45 and 50 were significantly greater than baseline for the delayed recall ($p < 0.05$). Days 45 and 50 were significantly greater than baseline for consistency ($p < 0.05$) and day 45 free recall was significantly less than baseline ($p < 0.05$). Scores on the immediate recall, delayed recall, and consistency variables for each day of testing were greater than 85%, indicating the cohort put forth good effort on all three days of testing (14). A review of individual subject data revealed no instances of poor effort on any day of testing.

Discussion

Our study focused on evaluating the test-retest reliability of the Concussion Sentinel, the ImPACT, and the Headminder CRI concussion assessment programs in an ecologically relevant manner, while simultaneously controlling for sub-optimal effort. Our data contrasts with reliability coefficients reported by test developers on all three computer based instruments. ICCs from baseline to day 45 were variable, but generally, disappointing. ImPACT ICCs varied across index scores ranging from .139 to .388. Sentinel ICCs varied from .236 to .642 depending

on the output score. The CRI ICCs varied from .153 to .645. All of these ICCs were lower than currently reported in the literature. As shown in Table 4.2, when calculated over a five day period most ICCs increased, but did not approach levels reported in the literature or those necessary for making clinical decisions.

Differences in our ICC scores relative to previous reports may be related to the testing interval or the statistical method. This reliability study implemented clinically relevant intervals between assessments. Our times approximated testing intervals seen in a clinical setting, while previous evaluations of test-retest reliability have used follow-up intervals of one (9) or two weeks (13). The time from baseline to the first follow-up of approximately 6.5 weeks used in our study is similar to that reported by Lovell (20) in a clinical evaluation model, but is shorter than some reports. Bleiberg (5), followed up on 68 concussed military cadets 161.7 days following a baseline evaluation and Pellman (22) noted the time to follow-up from the initial baseline evaluation was 531 days in professional football athletes. Before a definitive conclusion can be drawn on the reliability of computer-based concussion assessment programs, more research is needed using a variety of follow-up assessment intervals and differing population samples .

In addition, the previous use of the Pearson's correlation coefficient may not be statistic to evaluate test-retest reliability. A Pearson's r statistic measures the strength of the relationship between variables and not the level of agreement between them. Also, Pearson's r is not sensitive to systematic changes in test administration (learning or practice effects) and the correlation coefficient is known to overestimate the correlation when using small sample sizes (4;8).

ICCs on some indexes met or exceeded 0.60, the minimum acceptable level for reliabilities used in clinical interpretations (1). At the first follow-up assessment on the Concussion Sentinel, these were the Reaction Time and Working Memory indexes. At the same time point, the CRI Simple Reaction Time and the Processing Speed Index met the minimum level. A greater number of indexes exceed the lowest acceptable level on the final assessment. These included the Visual Motor Speed index on the ImPACT, the Decision Making, Matching, and Working Memory indexes on the Sentinel, and the Complex Reaction Time on the CRI. Regardless, we feel an acceptable reliability correlation coefficient should range from 0.70 to 0.80, slightly lower than suggested by Randolph (25).

Poor test-retest reliability makes clinical interpretation of output scores complex and potentially invalid. Our data would suggest that large fluctuations in test performance may be related to test characteristics rather than cognitive impairment resulting from cerebral insult. Neurocognitive testing is suggested to provide the greatest amount of information in the concussion assessment (15), but the clinician should be selective when interpreting scores from the post-concussion assessment. To improve test-retest stability one author has suggested performing two baseline evaluations to reduce practice effects and using only the second for comparison following concussive injury (8). Multiple test administrations may reduce large changes in test performance (5), making for a clearer interpretation of post-concussion assessment scores. The trade-off becomes an increased test administration time.

The MACT was implemented to screen for individuals putting forth less than optimal effort. Our findings suggest that our participants put forth good effort on each day of testing. As recommended in the user's manual (14), good effort was defined as scoring greater than 85% on

the immediate recall, delayed recall, and consistency portions of the MACT test. Scores of less than 85% and a significant decline from baseline to Day 45 were noted in the free recall category. No cutoff value for interpreting the free recall score was provided, but our results were higher than those reported by Green in a normal healthy population (14). As such, variation in test performance resulting in overall low ICC values are likely not the result of poor effort.

Variable test performance resulted in the computer tests' automated features identifying several participants as showing a decline in performance at Day 45 and Day 50. Clinically, these declines may be interpreted as cognitive impairment and delay a return to participation. In our study, no participant reported sustaining a concussion during the testing period. Yet, 20% to 40% of the cohort was identified as impaired on at least one variable on any one of the computer-based assessment during the follow-up evaluations (Table 4.3). The percentage of participants showing decline in one or more areas on the ImPACT test was only slightly higher than previously reported (16).

To our knowledge, this was the first study evaluating test-retest reliability of computer-based concussion assessment programs using clinically relevant assessment points while simultaneously controlling for effort. As such, these results should be interpreted cautiously. We are continuing to investigate this issue using a variety of test intervals and different populations. More specifically, the reliability of these tests in youths and those with differing academic backgrounds should be addressed. The rapidly developing adolescent brain may influence reliability statistics (11) making it unknown if these individuals should receive a new baseline assessment annually.

Conclusion

This study evaluated the test-retest reliability of three commercially available computer-based concussion assessment programs. When controlling for sub-optimal effort and implementing clinically relevant times between the baseline evaluation and the two follow-up sessions, our findings indicate the reliabilities were lower than previously reported by the manufacturers. Reliabilities on some output scores fell within an acceptable range necessary for clinical interpretations, but no one test had all indexes that were acceptable. We speculate that longer test-retest intervals would only serve to decrease the reliability as previous reports have found higher reliabilities using shorter test administrations intervals (7;13). The exact interval between baseline and post-injury follow-up where reliability falls below the acceptable level is unknown at this time.

Despite the finding that our ICCs are lower than previously reported, clinicians should continue to use neurocognitive testing within their concussion assessment protocol. A cognitive evaluation is regarded as providing the greatest assessment of functioning following sport related concussion (15), although other evaluative techniques should also be included when making a return to play decision (15). While a baseline assessment prior to the competitive season would be ideal for every athlete, at a minimum those engaged in high-risk sports should be evaluated. Following injury, self-reported symptoms related to concussion should be monitored closely and neurocognitive testing should only be performed once the individual no longer reports symptoms (21). Regardless of the findings from the neurocognitive evaluation, no athlete should be returned to play unless he is asymptomatic at rest and 24 hours following exertion (18).

	<i>ImPACT</i>					<i>Concussion Sentinel</i>					<i>Concussion Resolution Index</i>				
	Memory Composite - Verbal	Memory Composite - Visual	Visual Motor Speed	Composite Reaction Time	Impulse Control	Reaction Time	Decision Making	Matching	Attention	Working Memory	Simple Reaction Time	Simple Reaction Time Errors	Complex Reaction Time	Complex Reaction Time Errors	Processing Speed Index
Baseline	.912 (.078)	.854 (.0736)	40.769 (5.592)	.543 (.064)	5.616 (3.992)	103.548 (7.922)	101.178 (8.407)	100.411 (17.973)	101.890 (8.468)	97.247 (8.775)	.342 (.042)	.630 (.905)	.641 (.076)	3.110 (5.117)	2.509 (.344)
Day 45	.913 (.062)	.823 (.097)	42.195 (7.119)	.530 (.050)	8.206 (15.512)	104.671 (9.167)	103.178 (7.113)	100.767 (7.3627)	104.986 (8.292)	99.986 (8.329)	.346 (.046)	.685 (.984)	.659 (.098)	3.808 (4.551)	2.325 (.309)
Day 50	.907 (.076)	.821 (.114)	43.323 (7.035)	.525 (.075)	12.384 (24.370)	105.151 (7.982)	103.438 (7.439)	102.041 (8.538)	104.534 (8.721)	101.904 (8.243)	.354 (.059)	.744 (.955)	.638 (.084)	2.973 (3.628)	2.216 (.391)

Table 4.1: Means (standard deviations) of each output score listed by computer test for the baseline evaluation and days 45 and 50 follow-up assessments.

	<i>ImPACT</i>					<i>Concussion Sentinel</i>					<i>Concussion Resolution Index</i>				
	Memory Composite - Verbal	Memory Composite - Visual	Visual Motor Speed	Composite Reaction Time	Impulse Control	Reaction Time	Decision Making	Matching	Attention	Working Memory	Simple Reaction Time	Simple Reaction Time Errors	Complex Reaction Time	Complex Reaction Time Errors	Processing Speed Index
Baseline to Day 45	.236	.303	.378	.388	.139	.602	.553	.236	.408	.642	.645	.153	.421	.255	.633
Day 45 to Day 50	.402	.391	.611	.512	.534	.553	.620	.656	.392	.639	.356	.022	.657	.460	.567

Table 4.2: Intraclass Correlation Coefficients for each output between Baseline and Day 45 and Day 45 and Day 50.

	<i>ImPACT</i>						<i>Concussion Sentinel</i>						<i>Concussion Resolution Index</i>			
	Memory Composite - Verbal	Memory Composite - Visual	Visual Motor Speed	Composite Reaction Time	Impulse Control	Impaired on Any Variable	Reaction Time	Decision Making	Matching	Attention	Working Memory	Impaired on Any Variable	Simple Reaction Time	Complex Reaction Time	Processing Speed Index	Impaired on Any Variable
Day 45	n = 9 12.3%	n = 9 12.3%	n = 11 15.1%	n = 4 5.5%	n = 0 0.0%	n = 28 38.4%	n = 7 9.6%	n = 1 1.4%	n = 3 4.1%	n = 7 9.6%	n = 5 6.8%	n = 16 21.9%	n = 2 2.7%	n = 9 12.3%	n = 5 6.8%	n = 14 19.2%
Day 50	n = 11 15.1%	n = 12 16.4%	n = 9 12.3%	n = 3 4.1%	n = 4 5.5%	n = 25 34.2%	n = 10 13.7%	n = 4 5.5%	n = 4 5.5%	n = 10 13.7%	n = 4 5.5%	n = 24 32.9%	n = 7 9.6%	n = 9 12.3%	n = 6 8.2%	n = 17 23.3%

Table 4.3: Number of participants, and percentage of total, labeled as impaired by each computer program's automated feature for indicating statistical change from baseline.

	Immediate Recall	Delayed Recall	Consistency	Paired Associates	Free Recall
Baseline	99.658 (1.272)	97.603 (3.345)	97.260 (3.540)	100.000 (0.000)	82.671 (10.772)
Day 45	99.726 (1.458)	99.178 † (2.207)	98.904 † (2.534)	100.000 (0.000)	75.548 † (10.755)
Day 50	99.658 (1.520)	98.767 † (2.469)	98.493 † (2.968)	100.000 (0.000)	84.795 (11.500)

Table 4.4: Means (standard deviation) for Green's MACT.

† indicates a significant difference from the baseline evaluation.

References

- (1) Anastasi A. Psychological testing. 6 ed. New York, NY.: McMillian, 1998.
- (2) Aubry M, Cantu R, Dvorak J, Graf-Baumann T, Johnston K, Kelly J et al. Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. Br J Sports Med 2002; 36(1):6-7.
- (3) Baumgartner TA, Chung H. Confidence limits for intraclass reliability coefficients. Measurement in Physical Education and Exercise Science 2001; 5(3):179-188.
- (4) Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1(8476):307-310.
- (5) Bleiberg J, Cernich AN, Cameron K, Sun W, Peck K, Ecklund J et al. Duration of cognitive impairment after sports concussion. Neurosurgery 2004; 54(5):1073-1080.
- (6) College Board. Average SAT Scores of Entering College Classes, 1967-2001. The College Board . 2005.
- (7) Collie A, Darby D, Maruff P. Computerized cognitive assessment of athletes with sports related head injury. Br J Sports Med 2001; 35(5):297-302.
- (8) Collie A, Maruff P, Darby D, McStephen M. The effects of practice on the cognitive test performance of neurologically normal individuals assessed at brief test-retest intervals. J Int Neuropsychol Soc 2003; 9:419-428.
- (9) Collie A, Maruff P, Makdissi M, McCrory P, McStephen M, Darby D. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. Clin J Sport Med 2003; 13(1):28-32.

(10) Collie A, Maruff P, McStephen M, Darby DG. Psychometric issues associated with computerized neuropsychological assessment of concussed athletes. *Br J Sports Med* 2003; 37(6):556-559.

(11) Daniel JC, Olesniewicz MH, Reeves D, Tam D, Bleiberg J, Thatcher R et al. Repeated measures of cognitive processing efficiency in adolescent athletes: Implications for monitoring recovery from concussion. *Neuropsychiatry, Neuropsychology and Behavioral Neurology* 1999; 12(3):167-169.

(12) Erlanger D. HeadMinder Concussion Resolution Index (CRI) - Professional Manual. 1 ed. 2002.

(13) Erlanger DM, Saliba E, Barth JT, Almquist J, Webright W, Freeman J. Monitoring resolution of postconcussion symptoms in athletes: Preliminary results of a web-based neuropsychological test protocol. *J Athl Train* 2001; 36 (3):280-287.

(14) Green P. Green's Memory and Concentration Test (MACT) for Microsoft Windows User's Manual. Edmonton, Canada: Green's Publishing Inc., 2004.

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

(16) Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol* 2003; 17(4):460-470.

(17) Reliability and validity of ImPACT. Annual Conference of the International Neuropsychological Society; Honolulu HI: International Neuropsychological Society, 2003.

- (18) Kissick J, Johnston KM. Return to play after concussion: Principles and practice. Clin J Sport Med 2005; 15(6):426-431.
- (19) Lovell MR. ImPACT 2005 (4.0) Clinical Interpretation Manual. <http://www.impacttest.com/tf.htm> . 2005. Accessed 11-18-2005.
- (20) Lovell MR, Collins MW, Iverson GL, Field M, Maroon JC, Cantu RC et al. Recovery from mild concussion in high school athletes . J Neurosurg 2003; 98(2):296-301.
- (21) McCrory P, Johnston K, Meeuwisse W, Aubry M, Cantu R, Dvorak J et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. Br J Sports Med 2005; 39(4):196-204.
- (22) Pellman EJ, Lovell MR, Viano DC, Casson IR, Tucker AM. Concussion in professional football: Neuropsychological testing - Part 6. Neurosurgery 2004; 55(6):1290-1305.
- (23) Peterson CL, Ferrara MS, Mrazik M, Piland SG, Elliot R. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. Clinical Journal of Sport Medicine 2003; 13(4):230-237.
- (24) Portney LG, Watkins MP. Foundations of Clinical Research: Applications to Practice. 1 ed. Norwalk CT: Appleton & Lange, 1993.
- (25) Randolph C, McCrea M, Barr WB. Is neuropsychological testing useful in the management of sport-related concussion? J Athl Train 2005; 40(3):139-154.

CHAPTER 5

EXPECTED CHANGE OF COMPUTER-BASED CONCUSSION ASSESSMENTS AND SUBTEST RELIABILITY²

²Broglia SP, Ferrara MS, Macciocchi SN. To be submitted to the *British Journal of Sports Medicine*.

Abstract

Concussion evaluation commonly employs a computerized neurocognitive assessment to measure changes in cognitive performance following the injury. Sports medicine personnel often compare post-injury scores to preseason baseline assessments collected as normal data on an individual athlete. Previous investigations have evaluated the reliability of the output scores using various test-retest intervals. To date, no study has reported the test-retest reliability of the subtests used in deriving output scores. Further, fluctuations in test scores commonly seen with multiple test administrations may lead to an incorrect concussion evaluation. The purpose of this project was to evaluate the test-retest reliability of subtests used to calculate output scores on three commercially available computerized neurocognitive assessment programs. In addition, we sought to identify those showing exceptional improvement between test days. One-hundred and eighteen (N=118) uninjured participants completed three commercially available computer-based concussion assessment programs. A baseline, Day 45 and Day 50 assessment on the ImPACT, Concussion Sentinel, and Headminder Concussion Resolution Index (CRI) was completed. Automated features within each program indicated invalid baseline assessments on some participants, leaving 73 included in the statistical analysis. Intraclass correlation coefficients (ICC) were calculated for each subtest used in the calculation of an output score. The standard error of measure (SEM) was also calculated for each computer output score. ICCs calculations suggested no subtest score was reliable enough for clinical use. An evaluation of Day 45 SEM scores indicated 9.59% of CRI, 26.03% of ImPACT, and 39.73% of Concussion Sentinel test takers exceeded the two SEM range. On Day 50, 15.07% of CRI, 26.03% of ImPACT, and 32.88% of Concussion Sentinel test takers exceeded the two SEM range. These

results suggest that low ICCs previously reported are not attributable to any individual subtest.

An evaluation of change in output scores shows 10 to 40% of the sample had a large improvement from baseline to Day 45, and 15 to 33% had large improvements over baseline at Day 50. Changes such as these may mask neurocognitive deficits resulting from concussion. As such, clinicians should not rely solely on a single assessment tool, but rather implement a battery of tests.

Key Words: concussion assessment, test specificity, ImPACT, Concussion Resolution Index, Concussion Sentinel

Introduction

International meetings addressing sport related concussion have led to an updated injury definition reflecting recent research findings (1) and new guidelines for injury assessment (21). The current concussion assessment recommendation includes the administration of a baseline battery of tests containing evaluations of self-reported concussion related symptoms, a postural control, and neurocognitive functioning. Following a suspected concussive episode, the battery is re-administered and results are compared to the pre-season evaluation. Our laboratory performs baseline assessments on our high risk university athletes and those with a history of concussion. In the first year of implementing this model, we found the average time from baseline to initial follow-up to be approximately 45 days. This interval is consistent with other reports (18).

The neurocognitive assessment has been described as the gold-standard of concussion assessment, providing the most significant information related to post-concussion impairments (1). Traditionally, a neurocognitive evaluation is completed using pencil and paper assessments. Recent improvements in computer technology have increased the presence of computer-based concussion assessments in the clinical practice. Sports medicine personnel have used computer tests in a variety of settings including high school, collegiate, and professional athletics and the tests appear sensitive to neurocognitive changes following concussion (7;17;19).

Test-retest variance, a consequence of normal fluctuations in neurocognitive performance, is expected with multiple neurocognitive assessment administrations. External factors such as lack of sleep, poor motivation, or daily stressors may influence test performance and may be reflected in the output scores interpreted by the clinician. Assessments that are not

influenced by external factors only measure neurocognitive functioning. These tests generate consistent output scores in healthy individuals, allowing the clinician to recognize subtle declines in cognitive performance resulting from impaired ability rather than external circumstances. Using the SEM score, the clinician can interpret scores that above or below the SEM range as changes in neurocognitive functioning and not measurement variance.

The test-retest reliability, or intraclass correlation coefficient (ICC), also gives the clinician a guide on the ability of a program to provide consistent results across multiple days of testing. Previous studies have reported the reliability of some commonly used computer-based assessments (9;11) using brief test-retest intervals. Our laboratory recently investigated the test-retest reliability of output scores in three computer-based concussion assessment programs (5). By implementing a baseline, day 45, day 50 test-retest model described above, the findings suggest an inability of the programs to produce stable results in healthy, non-concussed participants. Reliability of the output scores generated by the programs was lowest between the baseline to day 45 assessment. Output score reliability did improve during the five day follow-up between the second and third test administration. Every intraclass correlation coefficient (ICC) however, remained below the level necessary to produce good decisions regarding changes in cognitive status following concussion (22).

Computer-based concussion assessment programs use several subtests to evaluate neurocognitive functioning. The ImPACT and Concussion Resolution Index (CRI) use six subtests each and the Concussion Sentinel uses seven. During testing, various aspects of the subtests (e.g. number correct responses, reaction time, or consistency) are recorded and combined mathematically to generate output scores for assessment or return to play decision

making. An evaluation of the subtest score reliability has yet to be reported and may indicate which subtests are most reliable. This information may aid in improving the overall reliability of the computer-based neurocognitive assessments.

In this project we sought to provide SEM scores during follow-up administrations based on normal fluctuations in test taking. We also evaluated the reliability of computer-based neuropsychological assessment subtest scores to identify which components of the output scores are the most reliable.

Methods

Data for this study are part of a larger project. We have reported the methodology for data collection in detail previously (5), but it will be reviewed briefly. One-hundred and eighteen (N=118) college volunteers were recruited from the general student body to participate in this study. All participants read and signed an Institutional Review Board informed consent prior to beginning the study. Participants completed a self-report demographics questionnaire and was excluded from the study if they meet any of the following conditions: English was not a first language, a physician had previously diagnosed the volunteer with a learning disability or attention deficit disorder.

Each participant completed three days of testing that required the completion of three commercially available computer-based concussion assessment programs during each session: ImPACT Concussion Management Software version 4.5.729 (ImPACT Applications, Pittsburgh, PA), Headminder Concussion Resolution Index (CRI) (Headminder Inc., New York, NY), and Concussion Sentinel version 3.0 (CogState LTD., Victoria, Australia). We also administered an effort assessment as part of a larger study. Those data are presented elsewhere (5).

All testing was conducted in a controlled laboratory environment free from diversions. All tests were administered according to the manufactures' recommendations. Following the baseline assessment, the participant completed follow-up evaluations approximately 45 and 50 days following baseline. Test administration orders were counterbalanced and then randomly assigned to the participants. Each session lasted approximately one hour.

Statistical Analysis: One and two SEMs were calculated for each output score. The SEM was calculated using the equation: $s_p \sqrt{1 - r_{xx}}$. Whereby, s_p is equal to the standard deviation calculation using the pooled variance between the scores for two test administrations (baseline and day 45 or days 45 and 50) and r_{xx} is equal to the reliability coefficient between the test administrations. The interpretation of the SEM calculation can be made relative to the normal distribution curve. One SEM encompasses 68% of measurement error, while two and three SEMs encompass 95 and 99% of measurement error respectfully (22). In general, the smaller the SEM, the less error there is associated with the assessment.

Each computer program uses a different statistical technique to establish clinically meaningful changes in the output scores. Changes in ImPACT and CRI scores are deemed significant using the reliable change index (10;14). Concussion Sentinel uses within-subject standard deviation (2).

One-way analysis of variance intraclass correlation coefficients were calculated for each subtest score used in calculating an output score (10;16). Two ICC calculations were made for each subtest: from baseline to day 45 and day 45 to day 50. No ICC encompassing all three data points was calculated because of differing lengths of time between data collection points. Sample size was estimated based on guidelines provided by Baumgartner and Chung (3) for

reliability studies using a one-way analysis of variance model to estimate the ICC for a single score. Data analyses were conducted using SPSS version 13.0 (SPSS, Chicago, IL).

Results

A total of seventy-three participants (n=24 male) were included for data analysis. Forty-five participants were removed or dropped out of the study. Forty participants' complete data were removed from analysis if the computer program (Concussion Sentinel or Headminder CRI) invalidated their baseline evaluation on a single test or showed questionable validity based on guidelines recommended by the manufacturer (ImPACT) (16). Another five participants failed to finish the study after completing the baseline assessment. Self-reported demographics of the participants are presented in Table 5.1. Twelve participants reported previously diagnosed concussions with occurrence ranging from one to five [one (n=6), two (n=4), three (n=1), five (n=1)]. No participants reported sustaining a diagnosed concussion during the study. The mean time to follow-up from baseline was 45.08 (\pm 1.56) days and another 5.56 (\pm 0.09) days to the final assessment.

As reported previously, the means and standard deviations for each of the output scores on each assessment day are presented in Table 5.2 (5). Tables 5.3, 5.4, and 5.5 present the means and standard deviations for each subtest score for each assessment day. Only subtest scores used to calculate output variables are presented and grouped according to the output score based on descriptions in the users' manuals (10;16). While the computer programs recorded other variables, we did not include them in this analysis.

Test-retest reliability for subtest scores from each computer-based concussion assessment are presented as ICCs in Tables 5.6, 5.7, and 5.8. Overall, the ICC's improve from day 45 to day

50 when compared to the baseline to day 45 evaluation. ICC values typically increase from the first test interval to the second. A few subtest ICCs met the 0.75 level suggested for making clinical interpretations (22).

One and two SEM scores are presented in Tables 5.9, 5.10, and 5.11. Scores were calculated for each output score for the baseline to day 45 and day 45 to day 50 test administrations. Both the Total Correct hidden and visible are included in Table 5.11 because of ambiguity in calculating the ImPACT Verbal Memory Composite score. The hidden and visible Average Correct Reaction Time values are also presented for the Reaction Time Composite Score because of similar circumstances (16). Table 5.12 shows the number and percentage of participants that exceeded the two SEM values for each output score on the two follow-up days of testing. On day 45, the CRI had the lowest number of participants exceeding the two SEM level on one or more output scores (n=7, 9.59%). The ImPACT had 19 participants (26.03%) and the Sentinel had 29 participants (39.73%) exceed this SEM level. The CRI again had the lowest number of participants exceeding the two SEM level on one or more output scores on day 50 (n=11, 15.07%). The ImPACT again had 19 participants (26.03%) and the Sentinel had 24 (32.88%) exceed the SEM level on one or more tests.

Discussion

On the day 45 evaluation, over a quarter of the test takers on the ImPACT, and two-thirds on the Concussion Sentinel, improved over their previous assessment and exceeded the two SEM range. Those participants performing exceptionally better on the follow-up assessment have the potential of being labeled as false negative if concussed. A false negative finding is one in which the test taker is concussed, but the computer test is unable to detect neurocognitive deficits

resulting from injury. Large improvements from baseline seen in the follow-up tests result from measurement error and may mask any cognitive decrement resulting from the cerebral concussion. If this were to occur, the clinician may conclude the athlete is not impaired and return him to play with the potential for a more significant injury (6). Concussed participants were not included in the study, making the direct evaluation of false negative findings impossible. Future research should closely examine the false-negative phenomenon by evaluating concussed athletes' responses on computer-based concussion assessment programs and comparing them to baseline evaluations.

Because of the potential for false negative findings when using computer-based assessments, clinicians are implored to continue using a battery of tests that evaluate multiple aspects of cerebral functioning. The concussion assessment battery is far more likely to assess cerebral concussion accurately than any single test. McCrea et al (20) found the Standardized Assessment of Concussion neurocognitive evaluation to be sensitive to concussion, identifying 80% of concussed athletes in their study. The self-reported symptom inventory however, was the most sensitive and correctly identify 90% of concussed athletes. The Balance Error Scoring System postural control assessment identified 34% of injured athletes as concussed. Combining the three assessment techniques, the test battery accurately identified 94% of the athletes as concussed. The additional assessments clearly reduce the risk of returning an athlete to play while still concussed.

Test administrators should expect some fluctuation in test scores with multiple administrations, and the SEM scores presented in this paper may help the clinician identify an expected range. Large changes in test scores without concussion may represent a poor

understanding of test instructions, poor effort by the test taker, test learning effects, or external factors associated with daily living. Guidelines to identify a lack of test understanding have been proposed (16) and were used to eliminate participants from evaluation in this study. Automated test features on the CRI and Concussion Sentinel indicating poor performance during baseline were also used to eliminate participant data. Using these evaluative measures, we feel those participants who did not understand the test administration processes were removed prior to data analysis.

Score changes from those remaining in the data set may have resulted from other factors such as effort, learning effects, or other factors such as daily stressors. One paper has attempted to evaluate effort during serial testing. Using university students as participants, the brief assessment did not identify a single instance of poor effort. The researchers stated the participants may have all been performing at maximal effort or the assessment may not have been sensitive to differences in effort (5). Longer and more comprehensive effort assessments are available and should be considered in future studies (3;4).

Test results may have also been influenced by learning effects. Some evidence exists suggesting that improved performance on neurocognitive testing related to practice or learning effects can be controlled for. Computer-based tests use multiple forms to decrease the likelihood of practice effects, but Collie et al. (8) found improvements on the CogSport test with repeat administration. Significant improvements were not seen with additional test administrations. The researchers proposed administering two assessments prior to the competitive season and using the second assessment as the baseline score if a concussion occurs. The dual baseline technique will likely decrease test learning effects on all computer-based concussion

assessments, but will increase the total test administration time. We did not administer two baseline assessments in this study, making the possibility of learning effects feasible. Clinicians should consider using a dual baseline, but must consider the choice between the improving baseline accuracy and the additional time necessary to administer a second test.

Factors of daily life may have also influenced data outcomes. Some factors can be controlled for, such as administration time in relation to exercise (13). Clinicians can control for such things by conducting baseline assessments before exercise. This should mimic the conditions on the day following injury when the initial post-concussion assessment is performed. Other factors such as stress from course work or relationships are more difficult to control. Test administrators should try to optimize the testing environment by eliminating distractions and allowing the athlete to concentrate on test taking.

The test-retest reliability of computer-based concussion evaluations should also be considered when evaluating athletes. Previous investigations of three commercially available computer assessments reported that ICCs of output score on no single test were strong enough to make useful inferences concerning change in neurocognitive performance (5;23). As such, we felt it important to evaluate the subtest score ICCs to identify components of the output scores providing the highest test-retest reliability. Our results presented in Tables 5.6, 5.7, and 5.8 indicate the reliability of most subtests fall at or below the minimum acceptable level of 0.75 (22).

Our initial intent was to identify the specific output score components with the highest test-retest reliability to improve the overall reliability of the output scores. From these data however, most measures used in generating output scores are not consistent with multiple

administrations. Increasing the weight of the subtests with the highest reliabilities may prove fruitful in improving the overall output score ICC, but may decrease the sensitivity to concussion. Until additional investigations are conducted, the use of computer-based concussion assessments should continue. Continued research of these assessment techniques will only lead to the development of better products as new versions and tests are made available.

Conclusion

Our research shows several participants improved between their baseline and day 45 assessment. These improvements makes for the possibility of a false negative concussion finding when using these assessment programs. Although our findings only suggest this possibility and additional research on the direct assessment of the false negative incidence with concussed athletes should be performed. In the interim, clinicians are encouraged to continue using a test battery for concussion assessment. To establish post-injury decrements accurately, concussion evaluation models should establish a baseline level of functioning on all tests before the competitive season. Following any suspected concussive incident, the test battery may be re-administered daily until the athlete's decrements return to baseline levels (12) or once symptom resolution has occurred (21). Waiting for symptom resolution to occur may reduce practice effects reported with test serial administration. Despite the clinical protocol adopted, an athlete should never be returned to play while still symptomatic at rest and within 24 hours of exertion (15). The exertion protocol should be progressive and occur over several days with careful monitoring of a return of concussion related symptoms.

	Age (years)	Height (cm)	Weight (kg)	SAT Total
<i>Male</i>	22.88 (3.89)	180.02 (5.77)	81.68 (13.94)	1139.57 (108.86)
<i>Female</i>	20.67 (1.65)	166.50 (6.64)	62.92 (11.38)	1181.88 (93.19)
<i>Overall</i>	21.39 (2.78)	170.95 (9.00)	69.09 (15.07)	1168.17 (99.76)

Table 5.1: Means (standard deviations) of self-reported participant demographics

	ImPACT					Concussion Sentinel					Concussion Resolution Index				
	Memory Composite - Verbal	Memory Composite - Visual	Visual Motor Speed	Composite Reaction Time	Impulse Control	Reaction Time	Decision Making	Matching	Attention	Working Memory	Simple Reaction Time	Simple Reaction Time Errors	Complex Reaction Time	Complex Reaction Time Errors	Processing Speed Index
Baseline	.912 (.078)	.854 (.0736)	40.769 (5.592)	.543 (.064)	5.616 (3.992)	103.548 (7.922)	101.178 (8.407)	100.411 (17.973)	101.890 (8.468)	97.247 (8.775)	.342 (.0423)	.630 (.905)	.641 (.076)	3.110 (5.117)	2.509 (.344)
Day 45	.913 (.062)	.823 (.097)	42.195 (7.119)	.530 (.050)	8.206 (15.512)	104.671 (9.167)	103.178 (7.113)	100.767 (7.3627)	104.986 (8.292)	99.986 (8.329)	.346 (.046)	.685 (.984)	.659 (.098)	3.808 (4.551)	2.325 (.309)
Day 50	.907 (.076)	.821 (.114)	43.323 (7.035)	.525 (.075)	12.384 (24.370)	105.151 (7.982)	103.438 (7.439)	102.041 (8.538)	104.534 (8.721)	101.904 (8.243)	.354 (.059)	.744 (.955)	.638 (.084)	2.973 (3.628)	2.216 (.391)

Table 5.2: Means (standard deviations) of each output score listed by computer test for the baseline evaluation and days 45 and 50 follow-up assessments.

		Baseline	Day 45	Day 50
Verbal Memory Composite	Word Memory (Module 1) - Total Percent Correct	0.961 (0.040)	0.964 (0.044)	0.934 (0.081)
	Symbol Match (Module 4) - Total Correct (visible)	26.849 (0.397)	26.658 (0.768)	26.726 (0.559)
	Symbol Match (Module 4) - Total Correct (hidden)	7.370 (1.671)	7.151 (1.497)	7.260 (1.564)
	Three Letters (Module 6) - Total Percent Correct	0.957 (0.071)	0.981 (0.042)	0.970 (0.061)
Visual Memory Composite	Design Memory (Module 2) - Total Percent Correct	0.871 (0.094)	0.852 (0.081)	0.875 (0.102)
	X's & O's (Module 3) - Total Correct (memory)	10.055 (1.212)	9.397 (2.053)	9.110 (2.112)
Visual Motor Speed Composite	X's & O's (Module 3) - Total Correct (interference)	130.699 (6.150)	128.849 (15.097)	126.233 (24.605)
	Three Letters (Module 6) - Average Counted Correctly	16.430 (3.605)	17.438 (4.441)	18.334 (3.784)
Reaction Time Composite Score	X's & O's (Module 3) - Average Correct Reaction Time (interference)	0.391 (0.043)	0.385 (0.039)	0.374 (0.051)
	Symbol Match (Module 4) - Average Correct Reaction Time (visible)	1.423 (0.236)	1.397 (0.239)	1.432 (0.252)
	Symbol Match (Module 4) - Average Correct Reaction Time (hidden)	1.498 (0.394)	1.428 (0.332)	1.452 (0.372)
	Color Match (Module 5) - Average Correct Reaction Time	0.761 (0.139)	0.739 (0.086)	0.725 (0.162)
Impulse Control Composite	X's & O's (Module 3) - Total Incorrect (interference)	5.192 (3.883)	7.959 (15.517)	12.014 (24.350)
	Color Match (Module 5) - Total Commissions	0.425 (1.026)	0.247 (0.434)	0.205 (0.440)

Table 5.3: Means (standard deviations) of subtest scores for the ImPACT test grouped by output score.

		Baseline	Day 45	Day 50
Simple Reaction Time and Errors	Reaction Time: Latency	0.349 (0.047)	0.351 (0.057)	0.360 (0.090)
	Reaction Time: Omissions	0.000 (0.000)	0.000 (0.000)	0.028 (0.165)
	Reaction Time: Commissions	0.123 (0.371)	0.123 (0.439)	0.056 (0.231)
	Cued Reaction Time: Latency	0.334 (0.048)	0.336 (0.047)	0.350 (0.052)
	Cued Reaction Time: Omissions	0.068 (0.254)	0.082 (0.323)	0.056 (0.285)
	Cued Reaction Time: Commissions	0.452 (0.688)	0.466 (0.709)	0.639 (0.877)
Complex Reaction Time and Errors	Visual Recognition 1: Latency	0.620 (0.078)	0.643 (0.115)	0.636 (0.097)
	Visual Recognition 1: Correct	59.397 (0.829)	59.194 (1.318)	59.110 (1.429)
	Visual Recognition 1: Omissions	0.356 (0.770)	0.493 (0.974)	0.444 (1.086)
	Visual Recognition 1: Commissions	0.247 (0.465)	0.397 (0.829)	0.361 (0.718)
	Visual Recognition 2: Latency	0.661 (0.095)	0.670 (0.096)	0.641 (0.078)
	Visual Recognition 2: Correct	57.301 (5.054)	57.137 (3.318)	57.472 (3.390)
	Visual Recognition 2: Omissions	2.178 (5.067)	2.014 (2.855)	1.847 (2.657)
	Visual Recognition 2: Commissions	0.521 (0.747)	0.849 (1.569)	0.681 (2.200)
Processing Speed Index	Animal Decoding: Correct	47.288 (9.426)	49.836 (9.396)	50.042 (10.992)
	Symbol Scanning: Number Correct	27.959 (1.611)	27.863 (2.502)	28.431 (1.362)
	Symbol Scanning: Response Time	3.030 (0.449)	2.771 (0.410)	2.651 (0.389)

Table 5.4: Means (standard deviations) of subtest scores for the Concussion Resolution Index test grouped by output score.

	Baseline	Day 45	Day 50
Simple Reaction Time 1 *	2.42 (0.060)	2.402 (0.066)	2.39 (0.056)
Choice Reaction Time Task *	2.629 (0.065)	2.613 (0.054)	2.611 (0.057)
One-back Task *	94.424 (6.658)	94.852 (3.973)	95.381 (3.917)
One-back task: Percent Correct	2.802 (0.089)	2.766 (0.090)	2.742 (0.088)
Congruent Choice Reaction task*	2.777 (0.064)	2.760 (0.059)	2.750 (0.067)
Dynamic Monitoring Task*	2.491 (0.078)	2.452 (0.074)	2.451 (0.082)
Simple Reaction Time 2 *	2.407 (0.054)	2.405 (0.064)	2.404 (0.056)

Table 5.5: Means (standard deviations) of subtest scores for the Concussion Sentinel test grouped by output score.

* Values are presented as Log10 transformation of the mean

		Baseline to Day 45	Day 45 to Day 50
Simple Reaction Time and Errors	Reaction Time: Latency	0.558	0.206
	Reaction Time: Omissions	n/a	-0.007
	Reaction Time: Commissions	-0.002	-0.059
	Cued Reaction Time: Latency	0.648	0.399
	Cued Reaction Time: Omissions	0.103	0.105
	Cued Reaction Time: Commissions	0.138	0.024
Complex Reaction Time and Errors	Visual Recognition 1: Latency	0.299	0.573
	Visual Recognition 1: Correct	0.090	0.343
	Visual Recognition 1: Omissions	0.058	0.282
	Visual Recognition 1: Commissions	0.172	0.343
	Visual Recognition 2: Latency	0.521	0.626
	Visual Recognition 2: Correct	0.235	0.433
	Visual Recognition 2: Omissions	0.258	0.643
	Visual Recognition 2: Commissions	0.113	0.057
Processing Speed Index	Animal Decoding: Correct	0.662	0.753
	Symbol Scanning: Number Correct	0.296	0.355
	Symbol Scanning: Response Time	0.590	0.763

Table 5.6: Intraclass Correlation Coefficients of subtest scores for the Concussion Resolution Index test grouped by output score. n/a - no analysis was possible because there was no variance on this variable

		Baseline to Day 45	Day 45 to Day 50
Verbal Memory Composite	Word Memory (Module 1) - Total Percent Correct	0.253	0.309
	Symbol Match (Module 4) - Total Correct (visible)	0.064	0.070
	Symbol Match (Module 4) - Total Correct (hidden)	0.172	0.337
	Three Letters (Module 6) - Total Percent Correct	-0.078	0.928
Visual Memory Composite	Design Memory (Module 2) - Total Percent Correct	0.517	0.514
	X's & O's (Module 3) - Total Correct (memory)	0.061	0.161
Visual Motor Speed Composite	X's & O's (Module 3) - Total Correct (interference)	0.296	0.515
	Three Letters (Module 6) - Average Counted Correctly	0.341	0.521
Reaction Time Composite Score	X's & O's (Module 3) - Average Correct Reaction Time (interference)	0.530	0.468
	Symbol Match (Module 4) - Average Correct Reaction Time (visible)	0.533	0.677
	Symbol Match (Module 4) - Average Correct Reaction Time (hidden)	0.390	0.296
	Color Match (Module 5) - Average Correct Reaction Time	0.139	0.297
Impulse Control Composite	X's & O's (Module 3) - Total Incorrect (interference)	0.102	0.538
	Color Match (Module 5) - Total Commissions	-0.042	-0.119

Table 5.7: Intraclass Correlation Coefficients of subtest scores for the ImPACT test grouped by output score.

	Baseline to Day 45	Day 45 to Day 50
Simple Reaction Time 1	0.656	0.452
Choice Reaction Time Task	0.553	0.625
One-back Task	0.264	0.316
One-back task: Percent Correct	0.646	0.658
Congruent Choice Reaction Task	0.520	0.639
Dynamic Monitoring Task	0.435	0.396
Simple Reaction Time 2	0.418	0.572

Table 5.8: Intraclass Correlation Coefficients of subtest scores for the Concussion Sentinel test

	One SEM		Two SEM	
	Baseline to Day 45	Day 45 to Day 50	Baseline to Day 45	Day 45 to Day 50
<i>Simple Reaction Time</i>	0.026	0.042	0.052	0.084
<i>Simple Reaction Time Errors</i>	0.873	0.983	1.746	1.967
<i>Complex Reaction Time</i>	0.065	0.051	0.131	0.103
<i>Complex Reaction Time Errors</i>	4.174	2.962	8.348	5.924
<i>Processing Speed Index</i>	0.158	0.218	0.317	0.436

Table 5.9: One and two Standard Error of Measure values for the Headminder CRI

	One SEM		Two SEM	
	Baseline to Day 45	Day 45 to Day 50	Baseline to Day 45	Day 45 to Day 50
<i>Reaction Time</i>	5.336	5.740	10.672	11.480
<i>Decision Making</i>	5.034	4.504	10.069	9.008
<i>Matching</i>	11.258	4.580	22.517	9.159
<i>Attention</i>	6.210	6.657	12.419	13.314
<i>Working Memory</i>	4.832	4.853	9.664	9.706

Table 5.10: One and two Standard Error of Measure values for the Concussion Sentinel

	One SEM		Two SEM	
	Baseline to Day 45	Day 45 to Day 50	Baseline to Day 45	Day 45 to Day 50
<i>Verbal Memory Composite</i>	6.166	5.330	12.332	10.660
<i>Visual Memory Composite</i>	6.913	8.251	13.826	16.501
<i>Visual Motor Speed Composite</i>	4.963	4.386	9.926	8.772
<i>Reaction Time Composite</i>	0.044	0.043	0.088	0.085
<i>Impulse Control</i>	9.442	12.887	18.884	25.773

Table 5.11: One and two Standard Error of Measure values for the ImPACT

	ImPACT					Concussion Sentinel					CRI		
	Memory Composite - Verbal	Memory Composite - Visual	Visual Motor Speed	Composite Reaction Time	Impulse Control	Reaction Time	Decision Making	Matching	Attention	Working Memory	Simple Reaction Time	Complex Reaction Time	Processing Speed Index
Day 45	n = 9 (12.3%)	n = 2 (2.7%)	n = 5 (6.8%)	n = 6 (8.2%)	n = 1 (1.4%)	n = 6 (8.2%)	n = 9 (12.3%)	n = 0 (0.0%)	n = 10 (13.7%)	n = 11 (15.1%)	n = 5 (6.8%)	n = 2 (2.7%)	n = 0 (0.0%)
Day 50	n = 6 (8.2%)	n = 4 (5.5%)	n = 5 (6.8%)	n = 3 (4.1%)	n = 2 (2.7%)	n = 8 (11.0%)	n = 3 (4.1%)	n = 5 (6.8%)	n = 6 (8.2%)	n = 8 (11.0%)	n = 2 (2.7%)	n = 9 (12.3%)	n = 0 (0.0%)

Table 5.12: Number of participants (percentage of total) exceeding two SEM on output scores for each computer program on the Day 45 and Day 50 assessment.

References

- (1) Aubry M, Cantu R, Dvorak J, Graf-Baumann T, Johnston K, Kelly J et al. Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. Br J Sports Med 2002; 36(1):6-7.
- (2) Bland JM, Altman DG. Statistical notes: measurement error. Br Med J 1996; 313:744.
- (3) Boone KB, Lu P, Back C, King C, Lee A, Phipott L et al. Sensitivity and specificity of the Rey Dot Counting Test in patients with suspect effort and various clinical samples. Arch Clin Neuropsychol 2002; 17(7):625-642.
- (4) Boone KB, Salazar X, Lu P, Warner-Chacon K, Razani J. The Rey 15-Item Recognition Trial: A Technique to Enhance Sensitivity of the Rey 15-Item Memorization Test. J Clin Exp Neuropsychol 2002; 24(5):561-573.
- (5) Broglio SP. Concussion assessment program reliability. University of Georgia, 2006.
- (6) Cantu RC. Second impact syndrome: a risk in any contact sport. Phys Sportsmed 1995; 23:27-34.
- (7) Collie A, Darby D, Maruff P. Computerised cognitive assessment of athletes with sports related head injury. Br J Sports Med 2001; 35(5):297-302.
- (8) Collie A, Maruff P, Darby D, McStephen M. The effects of practice on the cognitive test performance of neurologically normal individuals assessed at brief test-retest intervals. J Int Neuropsychol Soc 2003; 9:419-428.

(9) Collie A, Maruff P, Makdissi M, McCrory P, McStephen M, Darby D. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations . Clin J Sport Med 2003; 13(1):28-32.

(10) Erlanger D. HeadMinder Concussion Resolution Index (CRI) - Professional Manual. 1 ed. 2002.

(11) Development and validation of a web-based protocol for management of sports-related concussion.: 2000.

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

(13) Hillman CH, Snook EM, Jerome GJ. Acute cardiovascular exercise and executive control function. Int J Psychophysiol 2006; 48(3):307-314.

(14) Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. Clin Neuropsychol 2003; 17(4):460-470.

(15) Kissick J, Johnston KM. Return to play after concussion: Principles and practice. Clin J Sport Med 2005; 15(6):426-431.

(16) Lovell MR. ImPACT 2005 (4.0) Clinical Interpretation Manual.
<http://www.impacttest.com/tf.htm> . 2005. 11-18-2005.

Ref Type: Electronic Citation

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

- (18) Lovell MR, Collins MW, Iverson GL, Field M, Maroon JC, Cantu RC et al.
Recovery from mild concussion in high school athletes . J Neurosurg 2003; 98_(2):296-301.
- (19) Makdissi M, Collie A, Maruff P, Darby DG, Bush A, McCrory P et al.
Computerised cognitive assessment of concussed Australian Rules footballers. Br J Sports Med 2001; 35(5):354-360.
- (20) McCrea M, Barr WB, Guskiewicz KM, Randolph C, Marshall SW, Cantu R et al.
Standard regression-based methods for measuring recovery after sport-related concussion. J Int Neuropsychol Soc 2005; 11:58-69.
- (21) McCrory P, Johnston K, Meeuwisse W, Aubry M, Cantu R, Dvorak J et al.
Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. Br J Sports Med 2005; 39(4):196-204.
- (22) Portney LG, Watkins MP. Foundations of Clinical Research: Applications to Practice. 1 ed. Norwalk CT: Appleton & Lange, 1993.
- (23) Randolph C, McCrea M, Barr WB. Is neuropsychological testing useful in the management of sport-related concussion? J Athl Train 2005; 40(3):139-154.

CHAPTER 6

SUMMARY

This dissertation evaluated the test-retest reliability of three commercially available computer-based concussion assessment programs. The Headminder Concussion Resolution Index (CRI), the Concussion Sentinel, and the ImPACT tests were evaluated using clinically relevant assessment intervals. While administering these tests we simultaneously controlled for effort using Green's Memory and Concentration Test. A limited number of investigations by the product manufacturers have evaluated test-retest reliability, but have used short follow-up assessment times that do not apply to the clinical model. We are unaware of any investigations that have evaluated effort with the use of computer-based concussion assessment programs.

We evaluated each of our participants on three days (baseline, day 45 and day 50). Each participant completed the CRI, the ImPACT, and the Concussion Sentinel on each assessment day. Our data analysis indicates the test-retest reliability of the three computer-based concussion assessment programs are weak. Effort testing results suggest that all of our participants put forth good effort. We feel that factors other than poor effort, such as the inability of the tests to evaluate neurocognitive functioning consistently, may have contributed to low scores.

These results are particularly troubling for the sports medicine clinician. The neurocognitive assessment is typically considered the gold standard in concussion evaluation by providing the best indication of cognitive functioning change following concussion. Our evidence indicates these programs are unable accurately assess cognitive functioning in a healthy

population. This would suggesting that the ability to accurately measure cognitive change in an injured population may not be possible.

Clinicians should be cautious when using neurocognitive assessments in making a concussion assessment and return to play decisions. These outcomes highlights the importance of a concussion assessment battery. Previous suggestions for a battery include the use of self-report concussion related symptoms and a postural control assessment in addition to the neurocognitive evaluation. Regardless of the tests included in the evaluation battery, no athlete should be returned to practice or competition while still exhibiting concussion related symptoms.

Appendix 1

CONSENT FORM

I agree to take part in a study titled “**Reliability and specificity of computer based concussion assessment protocols**” which is being conducted by Mr. Steven P. Broglio and Dr. Mike Ferrara from the Department of Kinesiology at the University of Georgia (706-542-3273). I understand that this participation is entirely voluntary; I can withdraw from this study at any time without penalty and have the results of the participation returned to me, removed from the research records or destroyed.

The following points have been explained to me:

The research is being conducted to determine the reliability and specificity of computer based concussion assessment programs.

The research will use three computer based concussion assessment programs and a computer based word memory test. The test battery will be conducted three times: baseline, 45 days following my initial visit, and then five days following my second visit. If I was referred from the University of Georgia Health Center because I have sustained a non-surgical orthopedic injury prior to my enrollment in the study, my testing schedule will begin the day following my injury, 5 days later and a final visit 45 days later.

The procedures are as follows: On my scheduled test days, I will report to the Sports Medicine Laboratory within the Department of Exercise Science on the University of Georgia campus (room 110 Ramsey Center). Each day I will complete three computer based concussion assessment tests and computer based word memory test. The computer based tests are all designed to evaluate neuropsychological function and will last approximately 10-20 minutes each, for a total of 1 hour of testing per session.

The computer based neuropsychological testing will include the ImPACT, Headminder, and Concussion Sentinel programs. Each program will take 10-20 minutes to complete and a rest period will be allotted between each computer test. Upon completion of the final computer test, I will be asked to complete Green’s Word Memory Test, a brief computer based assessment of how well I can remember a series of words.

As a participant, each computer test will ask me to remember and later recall a series of letters, words, and or shapes presented to me. I may also be asked to click on an object on the screen with the mouse as a measure of reaction time. In addition, I may be asked to recall a number associated with a shape or symbol. No physical exertion, outside of operating a computer, will be required of me to complete any of the tests.

The benefit that I may expect to receive from participating in this project is knowledge related to concussion assessment and neuropsychological function. Should I sustain a concussion during the course of this study my data may be used as a baseline value to aid in determining when I have recovered from my injury.

No risks, discomforts or stresses are expected as a result of the research

The results of this participation will be confidential and will not be released in any individually identifiable form unless otherwise required by law.

The investigators will answer any further questions about this research, now or during the course of the project and can be reached at 706-542-3273 or broglio@uga.edu.

I understand the study procedures described above. My questions have been answered to my satisfaction, and I agree to take part in this study. I have been given a copy of this form to keep.

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

<u>Steven P. Broglio</u>	_____	_____
Name of Researcher	Signature	Date
Telephone: <u>706-542-3273</u>	Email: <u>broglio@uga.edu</u>	
_____	_____	_____
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 Chairperson, Institutional Review Board, Human Subjects Office, University of Georgia, 606A Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu

Appendix 2: Participant Questionnaire

The reliability and specificity of computer-based concussion assessment programs

Participant Questionnaire

ID # _____

Age _____ Height _____ Weight _____ Sex: M / F

SAT scores: Verbal _____ Math _____

Is English your first language? Yes / No

Are you currently being treated for a lower extremity injury? Yes / No

If yes, does your injury require surgery? Yes / No

If yes, please describe _____

Have you every been diagnosed with a learning disability or attention deficit disorder? Yes / No

Are you currently being treated for a concussion? Yes / No

Have you every been diagnosed with a concussion Yes / No

If yes, how many times? _____

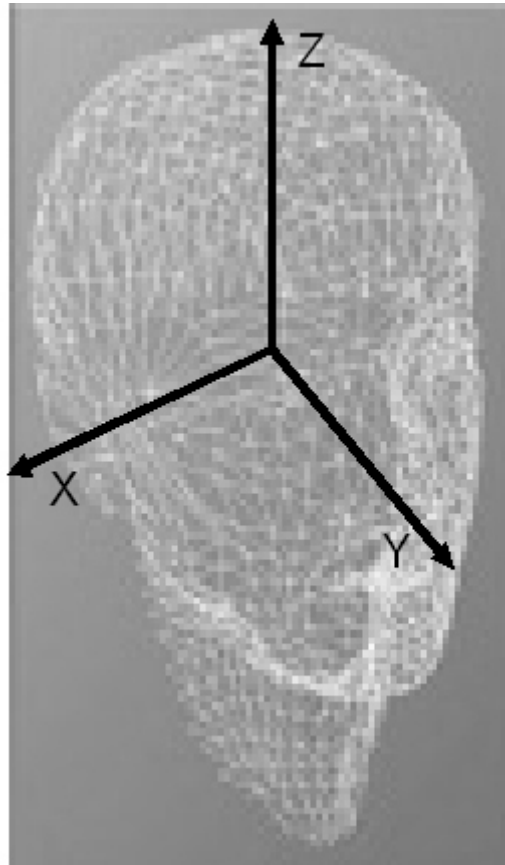


Figure 1: Right hand coordinate system for the head

REFERENCES

- (1) ImPACT 3.0 Software User's Manual. 2 ed. Pittsburgh PA: 2004.
- (2) Arbogast KB, Margulies SS. A fiber-reinforced composite model of the viscoelastic behavior of the brainstem in shear. *Journal of Biomechanics* 1999; 32(8):865-870.
- (3) Aubry M, Cantu R, Dvorak J, Graf-Baumann T, Johnston K, Kelly J et al. Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. *Br J Sports Med* 2002; 36(1):6-7.
- (4) Barth JT, Alves W, Ryan T. Mild head injury in sports: Neuropsychological sequella and recovery of function. In: Levin H, Eisenberg HA, Benton A, editors. *Mild Head Injury*. New York: Oxford University Press, 1989.
- (5) Bauer JA, Thomas TS, Cauraugh JH, Kaminski TW, Hass CJ. Impact forces and neck muscle activity in heading by collegiate female soccer players. *J Sports Sci* 2001; 19 (3):171-179.
- (6) Baumgartner TA, Chung H. Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science* 2001; 5(3):179-188.
- (7) Baumgartner TA, Jackson AS. *Measurement for Evaluation in Physical Education and Exercise Science*. 6 ed. Boston: WCB McGraw-Hill, 1999.
- (8) Bergsneider M, Hovda DA, Lee SM, Kelly DF, McArthur DL, Vespa PM et al. Dissociation of cerebral glucose metabolism and level of consciousness during the period of metabolic depression following human traumatic brain injury. *J Neurotrauma* 2000; 17 (5):389-401.

- (9) Bishop PJ, Norman RW, Kozey JW. An evaluation of football helmets under impact conditions. *Am J Sports Med* 1984; 12(3):233-236.
- (10) Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1(8476):307-310.
- (11) Brandt T. Vision and Posture. In: Bels W, Brandt J, editors. *Disorders of Posture and Gait*. New York: Elsevier Science, 1986: 157-175.
- (12) Brooks GA, Fahey TD, White TP, Baldwin KM. *Exercise Physiology*. 3 ed. Mountain View: Mayfield Publishing Co, 2000.
- (13) Cantu RC. Guidelines for return to contact sports after cerebral concussion. *Phys Sportsmed* 1986; 14 :75-83.
- (14) Cantu RC. Head injuries in sports. *Br J Sports Med* 1996; 30:289-296.
- (15) Cantu RC. Posttraumatic Retrograde and Anterograde Amnesia: Pathophysiology and Implications in Grading and Safe Return to Play. *J Athl Train* 2001; 36(3):244-248.
- (16) Caswell SV, Deivert RG. Lacrosse helmet designs and the effects of impact forces. *J Athl Train* 2002; 37 (2):164-171.
- (17) CDC. Sports-related recurrent brain injuries -- United States. *MMRW* 1997; 46 (10):224-227.
- (18) Collie A, Darby D, Maruff P. Computerised cognitive assessment of athletes with sports related head injury. *Br J Sports Med* 2001; 35(5):297-302.
- (19) Collins MW, Lovell MR, McKeag DB. Current issues in managing sports-related concussion . *JAMA* 1999; 282 (24):2283-2285.

- (20) Colorado Medical Society Sports Medicine Committee. Guidelines for the Management of Concussion in Sports. 1991. Denver. Colorado Medical Society.
- (21) Crisco JJ, Hendee SP, Greenwald RM. The influence of baseball modulus and mass on head and chest impacts: A theoretical study. *Med Sci Sports Exerc* 1997; 29 (1):26-36.
- (22) Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med* 2002; 12(6):331-338.
- (23) El Kashlan HK, Shepard NT, Asher AM, Smith-Wheelock M, Telian SA. Evaluation of clinical measures of equilibrium. *Laryngoscope* 1998; 108:311-319.
- (24) Enoka RM. *Neuromechanics of Human Movement*. 1 ed. Champaign: Human Kinetics, 2002.
- (25) Erlanger D. *HeadMinder Concussion Resolution Index (CRI) - Professional Manual*. 1 ed. 2002.
- (26) Development and validation of a web-based protocol for management of sports-related concussion.: 2000.
- (27) Erlanger DM, Saliba E, Barth JT, Almquist J, Webright W, Freeman J. Monitoring resolution of postconcussion symptoms in athletes: Preliminary results of a web-based neuropsychological test protocol. *J Athl Train* 2001; 36 (3):280-287.
- (28) Ferrara MS, McCrea M, Peterson CL, Guskiewicz KM. A survey of practice patterns in concussion assessment and management. *J Athl Train* 2001; 36(2):145-149.
- (29) Fu FH, Stone DA. *Sports Injuries: Mechanisms, Prevention, Treatment*. 2 ed. Philadelphia: Lippincott Williams, and Williams, 2001.
- (30) Use of weighted-impulse criterion for estimating injury hazard. New York: 1966.

- (31) Gennarelli TA. Mechanisms and pathophysiology of cerebral concussion. J Head Trauma Rehabil 1986; 1986 (1):2-23.
- (32) Gennarelli TA. Mechanisms of brain injury. J Emerg Med 1993; 11 (Suppl 1):5-11.
- (33) Gervais RO, Rohling ML, Green P, Ford W. A comparison of WMT, CARB, and TOMM failure rates in non-head injury disability claimants. Clin Neuropsychol 2004; 19:475-487.
- (34) Giza CC, Hovda DA. The Neurometabolic Cascade of Concussion. J Athl Train 2001; 36 (3):228-235.
- (35) Green P. Green's Memory and Concentration Test (MACT) for Microsoft Windows User's Manual. Edmonton, Canada: Green's Publishing Inc., 2004.
- (36) Green P. Green's Word Memory Test for Windows User's Manual. Edmonton, Canada: Green's Publishing Inc, 2005.
- (37) Green P, Astner K. Manual for the Oral Word Memory Test. Edmonton, Canada: Neurobehavioral Associates, 1995.
- (38) Grindel SH, Lovell MR, Collins MW. The assessment of sport-related concussion: The evidence behind neuropsychological testing and management . Clin J Sport Med 2001; 11 (3):134-143.
- (39) Gross LB. Boxing. In: Fu FH, Stone DA, editors. Sports Injuries: Mechanisms, prevention, treatment. Philadelphia: Lippincott Williams and Williams, 2001: 320-351.
- (40) Guskiewicz KM. Regaining balance and postural equilibrium. In: Prentice WE, editor. Rehabilitation Techniques in Sports Medicine. Boston: WCB McGraw-Hill , 1999: 107-133.
- (41) Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. Clin J Sport Med 2001; 11(3):182-189.

- (42) Guskiewicz KM, Perrin DH, Gansneder BM. Effects of mild head injury on postural stability in athletes. *J Athl Train* 1996; 31 (4):300-306.
- (43) Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc* 1997; 29(7 Suppl):S213-S221.
- (44) Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train* 2001; 36 (3):263-273.
- (45) Guskiewicz KM, Weaver NL, Padua DA, Garrett WE, Jr. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med* 2000; 28(5):643-650.
- (46) Guyton A, Hall J. *Textbook of Medical Physiology*. 10 ed. Philadelphia: WB Saunders, 2000.
- (47) Hinton-Bayre AD, Geffen G, McFarland K. Mild head injury and speed of information processing: A prospective study of professional rugby league players. *Clin Exp Neuropsych* 1997; 19(2):275-289.
- (48) Hollister NR, Jolley WP, Horne RG. Biophysics of concussion. WADC Technical Report 1958;58-193.
- (49) Horak FB. Clinical measurement of postural control in adults . *Phys Ther* 1987; 67 (12):1881-1885.
- (50) Ingersoll CD, Armstrong CW. The effects of closed-head injury on postural sway. *Med Sci Sports Exerc* 1992; 24(7):739-743.
- (51) Reliability and validity of ImpACT. Annual Conference of the International Neuropsychological Society; Honolulu HI: International Neuropsychological Society, 2003.

- (52) Johnston KM, McCrory PR, Mohtadi NG, Meeuwisse W. Evidence-Based review of sport-related concussion: clinical science . Clin J Sport Med 2001; 11 (3):150-159.
- (53) Katayama Y, Becker DP, Tamura T, Hovda DA. Massive increases in extracellular potassium and the indiscriminate release of glutamate following concussive brain injury. J Neurosurg 1990; 73 :889-900.
- (54) Kirkendall DT, Jordan SE, Garrett WE. Heading and head injuries in soccer. Sports Med 2001; 31 (5):369-386.
- (55) Kleiven S, von Holst H. Consequences of head size following trauma to the human head. Journal of Biomechanics 2002; 35(2):153-160.
- (56) Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977; 33:159-174.
- (57) Leininger BE, Gramling SE, Farrell AD, Kreutzer JS. Neuropsychological deficits in symptomatic minor head injury patients after concussion and mild concussion. J Neurol Neurosurg Psychiatry 1990; 53 (4):293-296.
- (58) Lephart SM, Fu FH. Proprioception and Neuromuscular Control in Joint Stability. 1 ed. Champaign: Human Kinetics, 2000.
- (59) Lewis LM, Naunheim R, Standeven J, Lauryssen C, Richter C, Jeffords B. Do Football Helmets Reduce Acceleration of Impact in Blunt Head Injuries? Acad Emerg Med 2001; 8(6):604-609.
- (60) Lezak MD. Neuropsychological assessment. 3 ed. New York: Oxford University Press, 1995.

- (61) Lissner HR, Lebow M, Evans FG. Experimental studies on the relation between acceleration and intracranial pressure changes in man. *Surgery, Gynecology, and Obstetrics* 1960; 111:329-338.
- (62) Lockett FJ. Biomechanics justification for empirical head tolerance criteria. *J Biomech* 1985; 18 (3):217-224.
- (63) Lovell MR, Collins MW. Neuropsychological assessment of the college football player. *J Head Trauma Rehabil* 1998; 13(2):9-26.
- (64) Lovell MR, Iverson GL, Collins MW, McKeag DB, Maroon JC. Does loss of consciousness predict neuropsychological decrements after concussion? *Clin J Sport Med* 1999; 9(4):193-198.
- (65) Macciocchi SN, Barth JT, Alves W, Rimel RW, Jane JA. Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurgery* 1996; 39(3):510-514.
- (66) Makdissi M, Collie A, Maruff P, Darby DG, Bush A, McCrory P et al. Computerised cognitive assessment of concussed Australian Rules footballers. *Br J Sports Med* 2001; 35(5):354-360.
- (67) Maroon JC, Lovell MR, Norwig J, Podell K, Powell JW, Hartl R. Cerebral concussion in athletes: Evaluation and neuropsychological testing. *Neurosurgery* 2000; 47(3):659-672.
- (68) Martini F. *Fundamentals of Anatomy and Physiology*. 4 ed. Prentice-Hall, 1998.
- (69) Matser EJT, Kessels AG, Jordan BD, Lezak MD, Troost J. Chronic traumatic brain injury in professional soccer players. *Neurology* 1998; 51 (3):791-796.

- (70) Matser EJT, Kessels AG, Lezak MD, Jordan BD, Troost J. Neuropsychological impairment in amateur soccer players. JAMA 1999; 282(10):971-973.
- (71) McCrea M, Kelly J, Randolph C, Cisler R, Berger L. Immediate neurocognitive effects of concussion. Neurosurgery 2002; 50(5):1032-1040.
- (72) McCrory P, Johnston K, Meeuwisse W, Aubry M, Cantu R, Dvorak J et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. Br J Sports Med 2005; 39(4):196-204.
- (73) McCrory P, Johnston KM, Mohtadi NG, Meeuwisse W. Evidence-based review of sport-related concussion: basic science. Clin J Sport Med 2001; 11 (3):160-165.
- (74) McCrory PR. Does second impact syndrome exist? Clin J Sport Med 2001; 11(3):144-149.
- (75) McIntosh AS, McCrory P. Impact energy attenuation performance of football headgear. Br J Sports Med 2000; 34(5):337-341.
- (76) McIntosh AS, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football . Med Sci Sports Exerc 2000; 32 (12):1980-1984.
- (77) Meyer JS, Kondo A, Nomura F, Sakamoto K, Teraura T. Cerebral hemodynamics and metabolism following experimental head injury. J Neurosurg 1970; 32 :304-319.
- (78) Mueller FO. Catastrophic Head Injuries in High School and Collegiate Sports. J Athl Train 2001; 36 (3):312-315.
- (79) Nashner LM, Berthoz A. Visual contribution to rapid motor responses during postural control. Brain Res 1978; 150:403-407.

- (80) Nashner LM, Black FO, Wall C. Adaptations to altered support and visual conditions during stance: patients with vestibular deficits. *J Neurosci* 1982; 2(5):536-544.
- (81) Nashner LM, Peters JF. Dynamic posturography in the diagnosis and management of dizziness and balance disorders . *Neurol Clin* 1990; 8(2):331-349.
- (82) Naunheim RS, Bayly PV, Standeven J, Neubauer JS, Lewis L, Genin GM. Linear and angular head accelerations during heading of a soccer ball. *Med Sci* 2003; 35 (8):1406-1412.
- (83) Naunheim RS, Ryden A, Standeven J, Genin G, Lewis L, Thompson P et al. Does Soccer Headgear Attenuate the Impact When Heading a Soccer Ball? *Acad Emerg Med* 2003; 10(1):85-90.
- (84) Naunheim RS, Standeven J, Richter C, Lewis LM. Comparison of impact data in hockey, football, and soccer. *J Trauma* 2000 May;48(5):938-41 2000; 48 (5):938-941.
- (85) Nilsson B, Nordstrom CH. Experimental head injury in the rat: Part 3: Cerebral blood flow and oxygen consumption after concussive impact acceleration. *J Neurosurg* 1977; 47 :262-273.
- (86) Nilsson B, Nordstrom CH. Rate of cerebral energy consumption in concussive head injury in the rat. *J Neurosurg* 1977; 47 :274-281.
- (87) Nilsson B, Ponten U. Experimental head injury in the rat: Part 2: Regional brain energy metabolism in concussive trauma. *J Neurosurg* 1977; 47 :252-261.
- (88) Nilsson B, Ponten U, Voigt G. Experimental head injury in rats: Part 1: Mechanics, pathophysiology, and morphology in an impact acceleration trauma model. *J Neurosurg* 1977; 47 :241-251.

- (89) NOCSAE. Standard performance specification for recertified football helmets. NOCSAE DOC (ND) 004-96m03. 2003. National Operating Committee on Standards for Athletic Equipment .
- (90) Oliaro SM, Guskiewicz KM, Prentice WE. Establishment of normative data on cognitive tests for comparison with athletes sustaining mild head injury. *Journal of Athletic Training* 1998; 33:36-40.
- (91) Ommaya AK. Mechanical Properties of tissues of the nervous systems. *J Biomech* 1968; 1 :127-138.
- (92) Ommaya AK. Head injury mechanisms and the concept of preventive management: a review and critical synthesis. *J Neurotrauma* 1995; 12(4):527-546.
- (93) Ommaya AK, Corrao P, Letcher FS. Head injury in the chimpanzee: Part 1: Biodynamics of traumatic unconsciousness. *J Neurosurg* 1973; 39 :152-166.
- (94) Ommaya AK, Faas F, Yarnell P. Whiplash injury and brain damage: An experimental study. *JAMA* 1968; 204 (4):75-79.
- (95) Ommaya AK, Gennarelli TA. Cerebral concussion and traumatic unconsciousness: Correlation of experimental and clinical observations on blunt head injuries. *Brain* 1974; 97 :633-654.
- (96) Ommaya AK, Goldsmith W, Thibault I. Biomechanics and neuropathology of adult and pediatric head injury. *British J of Neurosurg* 2002; 16 (3):220-242.
- (97) Ommaya AK, Rockoff SD, Baldwin M. Experimental concussion: A first report. *J Neurosurg* 1964; 21:249-265.

- (98) Padgaomkar AJ, King AI. Measurement of angular acceleration of a rigid body using linear accelerometers. *J Appl Mech* 1975; 42 :552-556.
- (99) Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: Reconstruction of game impacts and injuries. *Neurosurgery* 2003; 35(4):799-814.
- (100) Peterson CL, Ferrara MS, Mrazik M, Piland SG, Elliot R. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. *Clinical Journal of Sport Medicine* 2003; 13(4):230-237.
- (101) Pettersen JA. Does rugby headgear prevent concussion? Attitudes of Canadian players and coaches. *Br J Sports Med* 2002; 36(1):19-22.
- (102) Piland SG, Motl RW, Ferrara MS, Peterson CL. Evidence for the Factorial and Construct Validity of a Self-Report Concussion Symptoms Scale. *J Athl Train* 2003; 38(2):104-112.
- (103) Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 1 ed. Norwalk CT: Appleton & Lange, 1993.
- (104) Pundez RH, Shelden CH. The lucite calvarium - A method for direct observation of the brain. *J Neurosurg* 1946; 3 :487-505.
- (105) Reid SE, Tarkington JA, Epstein HM, O'Dea TJ. Brain tolerance to impact in football. *Surgery, Gynecology, and Obstetrics* 1971; 133 (6):929-936.
- (106) Riddell. Riddell. <http://www.riddell.com/>. Accessed 11-25-2003.
- (107) Riemann BL, Guskiewicz KM. Contribution of the peripheral somatosensory system to balance and postural equilibrium. In: Lephart SM, Fu FH, editors. *Proprioception and Neuromuscular Control in Joint Stability*. Champaign: Human Kinetics, 2000: 37-52.

- (108) Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol* 2005; in press.
- (109) Seward H, Orchard J, Hazard H, Collinson D. Football injuries in Australia at the elite level. *Medical Journal of Australia* 1993; 159(5):298-301.
- (110) Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction on balance. *Physical Therapy* 1986; 66(10):1548-1550.
- (111) Straume-Naesheim TM, Andersen TE, Bahr R. Reproducibility of computer based neuropsychological testing among Norwegian elite football players. *Br J Sports Med* 2005; 39(Suppl 1):i64-i69.
- (112) Summerall SW, Timmons PL, James AL, Ewing MJM, Oehlert ME. Expanded norms for the Controlled Oral Word Association Test. *J Clin Psychol* 1997; 53:517-521.
- (113) Swanik CB, Lephart SM, Giannantonio FG, Fu FH. Reestablishing proprioception and neuromuscular control in the ACL-injured athlete. *J of Sport Rehab* 1997; 6 :182-206.
- (114) Takahashi H, Manaka S, Sano K. Changes in extracellular potassium concentration in cortex and brain stem during the acute phase of experimental closed head injury. *J Neurosurg* 1981; 55 :708-717.
- (115) Tan JE, Slick DJ, Strauss E, Hultsch DF. How'd they do it? Malingering strategies on symptom validity tests. *Clin Neuropsychol* 2002; 16(4):495-505.
- (116) Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: Recent developments. *J Head Trauma Rehabil* 1998; 13(2):1-8.
- (117) Tortora G. *Principles of Human Anatomy*. 7 ed. New York: Harper Collins, 1995.

- (118) Tysvaer AT, Loochen EA. Soccer injuries to the brain. A neuropsychologic study of former soccer players. *Am J Sports Med* 1991; 19 (1):56-60.
- (119) Vink R, McIntosh TK. Pharmacological and physiological effects of magnesium on experimental traumatic brain injury. *Magnes Res* 1990; 3 :163-169.
- (120) Xiong Y, Peterson PL, Verweij BH, Vinas FC, Muizelaar JP, Lee CP. Mitochondrial dysfunction after experimental traumatic brain injury: Combined efficacy of SNX-111 and U-101033E. *J Neurotrauma* 1998; 15 (7):531-544.
- (121) Yoshino A, Hovda DA, Katayama Y, Becker DP. Dynamic changes in local cerebral glucose utilization following cerebral concussion in rats: Evidence of a hyper- and subsequent hypometabolic state. *Brain Res* 1991; 561 :106-119.
- (122) Yuan XQ, Prough DS, Smith TL, Dewitt, DS. The effects of traumatic brain injury on regional cerebral blood flow in rats. *J Neurotrauma* 1988; 5 (4):289-301.