FUNCTIONAL MOVEMENT ASSESSMENT AS A PREDICTOR OF HEAD IMPACT BIOMECHANICS

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ABSTRACT

Julia Margaret Ford: Movement Assessment as a Predictor of Head Impact Biomechanics
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This study sought to determine functional movement assessments' ability to predict head impact biomechanics in collegiate football players. Participants underwent preseason functional movement assessment screenings and wore instrumented helmets for the ensuing season. We hypothesized that players who perform poorly on Fusionetics and Landing Error Scoring System (LESS) would have greater linear and rotational acceleration and increased frequency of severe head impacts as compared to those who perform well on the movement assessments. We also hypothesized that players who sustained high impact frequencies throughout the season will demonstrate a decline in movement assessment performance, as measure by Fusionetics and LESS.

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LIST OF ABBREVIATIONS

CT	Computerized tomography
FMS	Functional Movement Screen
GFT	gForce Tracker
LESS	Landing Error Scoring System
MRI	Magnetic resonance imaging
NCAA	National Collegiate Athletic Association
NFL	National Football League
SEBT	Star Excursion Balance Test
SRS	Sideline Response System
TBI	Traumatic brain injury

CHAPTER 1

INTRODUCTION

An estimated 1.6 to 3.8 million traumatic brain injuries occur in sport and recreational activities annually. [1] Concussions are a subset of traumatic brain injuries that have been defined as a trauma-induced alteration in mental status. [2] Microstructural damage to the brain resulting from this injury present in physical, emotional, and cognitive symptoms. [3] A multifaceted approach is used to diagnose concussion due to the complexity of the injury. Several clinical tests have been established for diagnosis but none to determine who is at risk of sustaining the injury. Football contributes the highest concussion rates sustained in collision sports in the National Collegiate Athletics Association. [4, 5]

Head impacts likely increase injury risk in football. A growing body of literature has addressed a number of factors that may influence impact severity, including but not limited to event type, [4, 6, 7] collision anticipation, [8, 9] and play type. [10] Understanding the true nature of head impacts has been elusive to scientists. While previous studies suggest peak linear accelerations exceeding 70 to 75 g may be associated with greater concussion risk, [11] a definitive head injury threshold has yet to be identified. Of growing concern are the potential long-term neurological consequences of concussions and repetitive subinjurious head impacts. These concerns include chronic traumatic encephalopathy, mild cognitive impairment, and depression. [12-14] Given these long-term implications, studying head impacts using innovative head impact monitoring systems is an important tool in better understanding these phenomena.

Studies on short-term effects of concussion have focused almost entirely on the clinical manifestation including symptoms, balance, and neurocognition. [2, 15-18] Given the obvious link to the neuromuscular system, it is surprising that more attention has not been offered linking head impact biomechanics to functional movement patterns. Posture, voluntary movement and reaction to a changing environment are necessary in sport participation, and can be adversely affected following concussion. [19, 20] Concussion has been linked to musculoskeletal injury due to those impairments. [5, 19, 20] Concussed athletes are 2 times more likely to sustain a musculoskeletal injury post-concussion versus pre-concussion. [20] They are also more likely to sustain a musculoskeletal injury after returning to play as compared to their non-concussed counterparts.

Movement assessments are clinical tools to evaluate movement quality. [21] They are employed in many clinical settings to identify muscular imbalances, decreased flexibility and balance deficits associated with musculoskeletal injury risk. [21] Fusionetics is a movement assessment incorporating upper and lower extremity movement patterns to identify injury risk. [22] The Landing Error Scoring System is a dynamic movement assessment of jump landing biomechanics. [23] Poor performance and asymmetries on movement assessments put individuals at a greater risk of sustaining a musculoskeletal injury. [24-26]

Scientific inquiry has established an association between concussion history and increased musculoskeletal injury risk. Data support the notion that functional movement screening can identify patients at a higher musculoskeletal injury risk. Studying the association of functional movement and head impact biomechanics is a feasible and necessary progression in this body of science. Therefore, the overall purpose of this study was to determine the association between movement assessment performance and head impact biomechanics.

Specific Aims & Hypotheses

Specific Aim 1. To test the hypothesis that Division I college football players with poorer preseason movement assessment performance will demonstrate more severe head biomechanics (linear and rotational acceleration) than those with better preseason movement assessment performance (as measured by Fusionetics and Landing Error Scoring System).

Hypothesis 1: Linear and rotational accelerations will be greater in football players with poor movement assessment performance compared to those with good movement assessment performance

Specific Aim 2. To test the rating agreement between Fusionetics (poor, moderate, good) and Landing Error Scoring System (poor, moderate, good) movement assessment performance scales.

Hypothesis 2: The Fusionetics movement assessment classification (poor, moderate, good) will agree strongly with the Landing Error Scoring System movement assessment classification (poor, moderate, good).

Specific Aim 3. To test the hypothesis that preseason-to-postseason changes in movement assessment performance are associated with head impact frequency in college football players.

> *Hypothesis 3:* College football players sustaining a relatively high head impact frequency will demonstrate a decline in movement assessment performance as measured on the Fusionetics and Landing Error Scoring System movement assessments.

Clinical Significance

Implementing functional movement assessment screenings in the collegiate setting is feasible and in some cases, already established. We use these tools to identify musculoskeletal injury risk but there may be additional benefit to screenings. If functional movement assessments can identify those who will display more severe or frequent head impacts, we can correct their movement patterns and hopefully, decreased incidence of concussion.

CHAPTER 2

LITERATURE REVIEW

Introduction

Concussions are a subset of traumatic brain injuries (TBI) and have been part of our society for hundreds of years. Over the past decade, concussion has sparked media attention due to its unknown and hypothesized long-term effects. The National Athletic Trainers' Association describes concussion as a trauma-induced alteration in mental status that may or may not involve loss of consciousness. [2] External biomechanical forces are applied to the head or body that cause microstructural injuries in the brain that are not visible using conventional imaging techniques such as x-ray, computerized tomography (CT) or magnetic resonance imaging (MRI). Microstructural injury to the brain leads to physiological dysfunctions that exist as ionic shifts, metabolic changes, or impaired neurotransmission. [27] These dysfunctions present as various physical, emotional, and cognitive symptoms. A multifaceted approach should be used to diagnose and manage concussion due to the symptom variation and limitations using conventional imaging techniques. Clinical tests that are used to diagnose mild TBI assess symptoms, mental status, eye tracking, muscle strength, motor control and cognitive function. [2] Common symptoms fall into a physical, emotional, or cognitive category. They include headache, dizziness, nausea, difficulty remembering, irritability and more. Eighty to 90% of injuries resolve in approximately two weeks but some can last for up to several months. [15, 28] Concussion variation makes diagnosis difficult. Each injury presents in different ways. The multifaceted approach to diagnosis helps bridge gaps in concussion evaluation.

Concussion Epidemiology

In the United States, traumatic brain injuries are common and expensive. [1, 3] The emergency department sees approximately 1.1 million traumatic brain injuries per year. [1] In 2010, 623 visits to the emergency department per 100,000 people were related to traumatic brain injury (4.8% of all injuries) and the costs of traumatic brain injuries can reach over $60 billion per year. [1, 3] The majority of traumatic brain injuries (80%) are diagnosed as mild, and only 16% of mild TBIs are treated in a hospital. [3] Most mild TBIs are treated by a primary physician and do not need to be seen in the emergency department. This makes determining the total number of mild TBIs difficult.

An estimated 1.6 to 3.8 million TBIs occur in sport and recreational activities annually. [29] Concussion makes up 6.2% of all injuries sustained in the National Collegiate Athletics Association (NCAA). [4] Football has the highest concussion rates in all sports and has contributed to 36% of concussions sustained in the NCAA. [4, 15, 16] In football, the concussion rate is 603 injuries per 10,000 athlete-exposures. Wrestling has the second highest concussion rate of 86 injuries per 10,000 athlete-exposures. [4] Player contact is the most common mechanism of injury, accounting for 86.7% of concussions sustained in competition. [4] Contact occurs while blocking, tackling or being blocked or tackled. Direct blows by another player’s body or the ground may cause injuries. Indirect contact may result when a blow to the body causes shearing forces at the head. With over 3 million youth football players, 1 million high school football players and 100,000 collegiate football players in the United States today, concussion is a major public health concern. [29]

In football, many head impacts occur that do not result in head injury. These are known as subconcussive impacts, which are believed to cause subconcussive injuries to the brain. [16] A subconcussive injury causes microstructural injuries to the brain but do not result in symptoms of a concussion. [16] The subconcussive effects on short- and long- term neurological health is still unknown. Concussion history has been associated with risk for other injuries. [19, 20]

Links to musculoskeletal injury

Concussion has been linked to musculoskeletal injuries, especially in the lower extremity. [5, 19, 20] Posture, voluntary movement, and reactions to a changing environment are important during sport and activity. During activity, the brain must collect and synthesize visual and somatosensory information from multiple areas to produce and coordinate movement. [30] Neuromuscular reflexes starting in the brain, travel to the upper and lower extremities. [30] Damage to these areas or the connections between these areas can result from concussion. The inability to maintain posture or react quickly during sports may put athletes at greater risk for musculoskeletal injury.[19] The link between concussion and lower extremity musculoskeletal injury could exist in retired National Football League (NFL) players. Of approximately 2,500 retired NFL players, 60% reported a history of at least one concussion and 71% reported a history of at least one lower extremity musculoskeletal injury sustained during play. [19] It is difficult to determine if concussion leads to lower extremity injuries or if lower extremity injury leads to concussion due to the limitation of retrospective questionnaires on retired NFL players.

The order between concussion and lower extremity was made more clear in a study that showed concussed collegiate athletes were 2 times more likely to sustain a lower extremity injury post-concussion versus pre-concussion. [20] Other studies have shown concussed collegiate athletes are approximately 2 times more likely to sustain an acute lower extremity injury during a 90-day period following their return to play as compared to non-concussed sport and aged matched athletes. [5, 20]

Concussion management may also play a role in musculoskeletal injury after concussion. Current concussion management protocols call for cognitive and physical rest until the individual is asymptomatic. [28] This normally takes two weeks but can take much longer. [15] Discontinuing all activity until symptoms resolve is the common treatment for two reasons. Evidence from animal studies have shown delayed recovery in concussed rats with early physical activity after injury. [28] Energy from the brain that is required to repair the neuronal damage from the concussion is taken away which slows recovery. [28] The second reason is to eliminate the possibility of sustaining Second Impact Syndrome. [28] Second Impact Syndrome occurs when a concussed individual receives another blow to the head before their initial symptoms resolve. Brain swelling increases intracranial pressure and leads to brain stem failure. Due to the fatality of Second Impact Syndrome, concussed patients must rest until asymptomatic. [31] Once asymptomatic, rehabilitation includes a return to play progression of physical activity, but some concussions include vestibular and visual impairments that are neglected during the return to play progression. [32] Damage to the vestibular system or its connections to the brain may alter balance, proprioception, or vision. Without correcting these problems, athletes may return to the playing field before they have functional visual, vestibular and somatosensory systems that are needed to coordinate movement. An athlete's inability to coordinate movement may lead to a musculoskeletal injury, or another head injury.

Movement assessments

Movement assessments are clinical tools to evaluate movement quality. These tests are designed to identify people who are at greater risk for musculoskeletal injury due to different movement compensations or asymmetries. [24] Movement assessments incorporate fundamental, dynamic movements to assess stability and mobility. [33] Examples of common movement assessments include the Functional Movement Screen (FMS), Star Excursion Balance Test (SEBT), Y Balance Test, Landing Error Scoring System (LESS), and Fusionetics. Each test utilizes different movements but all incorporate natural movement patterns used in sport and activity. [34] The next paragraphs will discuss each of these assessments in detail.

The FMS is a screening system that uses seven simple yet dynamic movement patterns to identify movement compensations or imbalances in an individual. [33] The ability of someone to perform these movements is based on proprioception and kinesthesia. Errors in movement are scored on a zero to three scale with three being performance of the movement pattern without any compensation. A two is awarded for ability to complete the movement with compensations, a one is awarded to an individual who cannot perform the movement pattern, and a zero is given if at any time during the movement pattern the patient has pain. [33] Once problems are distinguished, clinicians can recommend programs to correct imbalances and asymmetries. The FMS has fair to excellent inter-rater reliability with an intraclass correlation coefficient (ICC) of 0.37 to 0.98 and clinicians with more training in the scoring system have greater intra-rater reliability (ICC=0.95) than those with less experience (ICC=0.37). [33] The FMS testing kit is inexpensive and training clinicians in scoring the test is not difficult. No certification or specified training is required to administer the test. The variability in training or testing experience may be a limitation of this assessment.

The SEBT is comprised of eight dynamic balance tests where the individual must maintain postural stability in single leg stance. A single leg squat is performed while the opposite limb moves in anterior, posterior, lateral, and medial directions to challenge the patient's mobility, stability, proprioception and neuromuscular control. The SEBT has excellent intra-rater and inter-rater reliability with ICCs between 0.84 and 0.87. [26] After conducting a study on the reliability of the SEBT, Hyong and Kim suggested using the Y Balance Test instead of the SEBT because it is shorter and yields similar results in quantifying dynamic balance.

The Y Balance test was designed as a modification to the SEBT. Instead of testing single leg balance in eight positions, it only evaluates the anterior, posterolateral, and posteromedial directions. The Y Balance Test is sensitive for detecting decreased mobility and asymmetries, especially in the ankle. Good to excellent intra-rater reliability and inter-rater reliability were found (ICC=0.67-0.96). [35] The Y Balance test can be used for mass screenings and time sensitive evaluations as compared to the SEBT. Both the SEBT and the Y Balance test are inexpensive and easily conducted in most settings. Limitations to these assessments are the exclusion of upper extremity movement patterns.

The LESS utilizes jump-landing biomechanics to assess lower extremity injury risk. [36] The individual jumps from a box height, equal to half of their height, to an area on the ground in front of the box and then jumps vertically as high as they can.

Biomechanical errors, such as genu valgum and trunk flexion, are noted when the individual lands on the ground. A review of recent studies on the LESS showed it had good to excellent inter-rater reliability (ICC=0.81). [36, 37] Real time assessments of the LESS have shown good inter-rater reliability and precision ($ICC_{2,1}$=0.79). [37] Researchers have used the LESS to predict to non-contact ACL injuries in collegiate and high school athletes, but have had little success. Smith et. al. screened 3,876 college and high school athletes and found no differences in the LESS scores of those who went on to suffer non-contact ACL injuries and their matched controls. [38] Combing force plates for people to jump onto while doing the LESS provide more information about the individual's movement quality but are not feasible in many cases due to cost. The LESS provides a dynamic movement pattern more likely seen in sporting activities.

Fusionetics was designed to perfect human movement by evaluating movement quantity and quality then implementing corrective exercise programs specific to an individual's movement deficiencies. [22] Limited range of motion has been associated with increased injury risk. Decreased glenohumeral internal rotation has been shown to cause shoulder pain. [39] Functional movement patterns such as, the overhead squat, single leg squat, and push up are assessed as well as glenohumeral, lumbar and cervical range of motion. Real time scoring of this movement assessment allows for increased efficiency as compared to video analysis. Programs are edited and assigned based on the individual's muscular weakness, imbalances and the supervision level needed during exercise. The programs can be found online and are easily accessible through the use of a smartphone application. Videos and descriptions of each exercise are listed next to the assigned program. Fusionetics centralizes information to ensure continuity of care.

The purpose of movement assessments is to decrease risk of injury and enhance performance. [33] Assessing range of motion, strength, balance, and proprioception through an overhead squat or jump landing identify the participant's weaknesses. Those weaknesses can be addressed to avoid compensations that cause insufficient movement and decreased performance. [33] Movement assessments are used as a pre-participation screen and return to play tool. [33]

Movement assessment as an injury predictor

Poor movement quality determined from a movement assessment is said to translate onto the playing field. The assessments are constructed to pick up on muscular imbalances, decreased flexibility, and balance deficits that are associated with increased injury risk. Poor scores on the FMS, LESS, SEBT, and Y Balance are associated with greater risk of musculoskeletal injury.

Joint laxity and loss of range of motion have been shown to be predictors of injury in the lower extremity. [21, 40, 41] Decreased dorsiflexion causes a more erect posture during drop-landing tasks, increasing forces distributed at the knee. [42] The SEBT test for example, is designed to pick up on decreased range of motion of the ankle, knee or hip. [43] Hamstring to quadriceps strength ratio and hip adductors to hip abductors flexibility ratio has been a predictor of injuries to the lower extremity. [21, 40] The hamstrings protect against anterior tibial translation. Proper activation and strength of the hamstrings reduce anterior translation, which will reduce load placed on the anterior cruciate ligament. [44] The hurdle on the FMS and single leg squat on Fusionetics assess hamstrings and quadriceps co-contraction. Movement assessments can detect joint laxity, decreased range of motion, and muscular strength that put individuals at risk of lower extremity injury.

Muscular asymmetries may be indicative of injury risk as well. The FMS is scored between 0 and 21, where 21 is awarded if you can perform all seven movement patterns without any compensations. A score of 14 or lower is associated with greater musculoskeletal injury risk. [24, 25, 45] Asymmetries on the Y Balance Test put athletes at a 2.5 times greater risk of sustaining lower extremity injury. [26] If poor movement patterns can be identified using these assessments then hopefully the movement patterns can be corrected before an injury occurs.

Head impact biomechanics

There are a number of ways to study the biomechanics related to head injury. Early studies impacted animals in the head and observed that concussion was related to excessive linear and rotational head acceleration experienced from the impact.[46-48] Human cadaveric heads were used later to confirm that the linear acceleration of the head created intracranial pressure differences within the skull. These pressure differences allowed the brain to move within the skull causing tensile and shear strain damage to the brain tissue. [49-52] Technological advancements now allow researchers to use complex computer simulations or finite element models to replicate the dynamic response of the skull and brain from impacts. [53-57] Finite element models require biomechanical inputs collected from real world situations. Sports, and especially football, provide an environment to study the biomechanics of concussion because of the number of head impacts and head injury that occur regularly.

Football and hockey helmets have been used to measure head impacts. The Head Impact Telemetry [58] System (Simbex, NH; Sideline Response System, Chicago, IL) was created to measure the head impact biomechanics football players experience while competing. [58] The HIT System records the frequency, location, and magnitude of impacts sustained to the head. An encoder with six single-axis accelerometers is inserted between the padding of a commercially available Riddell Speed, Revolution, and Flex helmet. [59] The accelerometers make contact with the head to measure head acceleration, not helmet acceleration. For this reason a properly fitting helmet is important to the accuracy of the HIT System. [60] During games and practices a sideline computer (SRS) records and stores data from the accelerometers instantaneously. Linear acceleration is measured in real time and rotational acceleration and impact location are calculated later. [59, 61]

Instrumented helmets have been widely studied to determine head impact exposure in football players. [6, 7, 59, 62-64] Exposure to head impact is dependent on player position. Linebackers, offensive linemen, and defensive linemen receive significantly higher numbers of impacts per season and per game as compared to quarterbacks, wide receivers, running backs, and defensive backs. [7, 62, 63] Frequency of head impacts is also dependent on session type, being practice or competition. Players experience two times more head impacts per game (14.3) than per practice (6.3). [6, 7, 64] An individual player can sustain up to 1,400 head impacts per season. [6]

Head impact magnitude is measured by linear and rotational acceleration. An injury threshold has not been clearly defined but some studies showed that impacts exceeding 70-75g of linear acceleration can cause concussion. [59] Through finite element model simulations, impact severity based on linear acceleration categorized by less than 66g as mild, 66-106g as moderate, and greater than 106g as severe were associated with a 25%, 50% and 80% risk of concussion. Similar risks for concussion, through finite element models were determined by categorizing rotational acceleration less than 4,600 rad/s^2 as mild, 4,600-7,900 rad/s^2 as moderate, and greater than 7,900 rad/s^2 as severe. [10, 53, 65] Most impacts sustained in football are low magnitude (20g of linear acceleration). [62, 63] Although offensive and defensive linemen receive the highest number of impacts, they receive the lowest magnitude of impacts as compared to other position groups. [62] The repetitive subinjurous impacts are of growing health concern due to the potential long-term effects. Research is continuing to focus on the consequences of repetitive head trauma. Head impact biomechanics is utilized in defining how often low magnitude impacts, or subconcussive impacts are occurring on the field.

The gForce Tracker [54] (Artaflex Inc., Markham, ON, Canada) and X2 Mouthguard [66] (X2 Biosystems, Seattle, WA) are also measurement tools in head impact biomechanics. The gForce Tracker (GFT) measures 6 degrees of freedom head kinematics to obtain linear acceleration, rotational velocity, impact location, and severity. [54] The GFT does not calculate rotational acceleration and was found to overestimate linear acceleration during impacts in football helmets. [54, 67] Further research is needed in the GFT in football helmets. The X2 Mouthguard has a 3-axis linear accelerometer and a 3-axis angular rate sensor. It is a custom fitted mouth guard to the upper dentition. The X2 measures peak linear and angular acceleration. [66] The X2 is dependent on the athlete keeping their mouth guard in throughout the practice or competition. Athletes who call plays on the field, such as quarterbacks and linebackers, may not be compliant with wearing a mouth guard. The X2 may be costly to replace if mouth guards are frequently lost.

Continuing to study head impact biomechanics systems, such as the HIT System or GFT, can help us learn what external forces to the head cause internal injuries. In regards to location of impact, temporal impacts are said to increase risk of injury, although more information is needed. Looking at all of the data from the HIT System will increase sensitivity of its ability to predict injury. [59]

Poor movement screen and head impact biomechanics

Concussion has been linked to lower extremity injury. Poor performance on movement assessments has also been linked to lower extremity injury. Athletes with poor movement quality may be at risk for higher magnitude impacts or more frequent impacts due to their insufficient movement patterns. Is there a link between concussion and poor performance on movement assessments? Dorrien's study found no relationship between concussion history and FMS performance. [68] While they compared those without a concussion history to those with a concussion history, it would be interesting to see if there is any changes to movement screen scores pre and post concussion. Repetitive concussive or subconcussive impacts throughout the season may alter efferent pathways and effect voluntary movement patterns. By assessing an athlete's movement patterns pre- and post-season, we can look for changes caused by impacts sustained over the course of the season. The purpose of this study is to determine the association between movement assessment performance and head impact biomechanics.

Methodological considerations

Implementing a movement assessment in preseason screenings is dependent on several factors. Team size, feasibility, and costs play a role in the decision. The LESS is an appropriate choice for a football program because it is performed quickly, has good inter-rater reliability, and has little equipment. Current research shows the reliability of a marker-less motion capture system assessing kinematics. A depth camera (Microsoft Kinect sensor version 1; Microsoft Corporation; Redmond, WA) records human kinematics. The LESS is recorded by the Kinect camera then scored by the PhysiMax Athletic Movement Assessment software (PhysiMax Technologies Ltd.; Tel Aviv, Israel). Virtual markers assess dynamic movement using proprietary algorithms to calculate joint angle, velocity and acceleration. [20] Significant agreement exists between expert LESS scorers and the PhysiMax for 14 of 21 LESS items. [20] The PhysiMax had moderate reliability ($\kappa=0.48\pm0.40$) and with Prevalence and Bias Adjusted Kappa statistics a higher reliability ($PABA\kappa=0.71\pm0.27$). [20] The PhysiMax showed repeatability and agreement with a marker-based system and true joint angle. [69] Employing the use of the PhysiMax makes LESS testing more efficient.

Similarly to the LESS, Fusionetics is also time efficient and requires little equipment. Fusionetics offers a clinical tool to assess movement patterns in collegiate football players because it encompasses both upper and lower body movement. Fusionetics and the LESS identify deficiencies and asymmetries in someone's movement patterns and range of motion. In contrast, the FMS test requires more training in the scoring of the test, does not create prevention programs that address someone's deficiencies, and does not measure range of motion. The SEBT and Y Balance test focus on one movement pattern and do not incorporate the upper extremity. Fusionetics and the LESS are well suited for working with a football team, because they are the most time efficient and can accommodate a large roster of players. The clinician can supervise many athletes at once with the use of Fusionetics' mobile app and its videos. Fusionetics can also measure range of motion, which has been shown to be a predictor of injury in previous studies. [21] The LESS test provides a more dynamic movement pattern to expose weaknesses.

We will employ the HIT System because it provides large amounts of data in a real world application. [70] A strong correlation (r^2=0.90) between the HIT System and gold standard reference accelerometers inside a Hybrid III dummy head form was found in a laboratory setting. [61] The HIT System was shown to be accurate (r^2= 0.710-0.981) in testing rotational acceleration from impacts to the back and sides of the helmet. [61]

As discussed earlier, proper helmet fitting is important in maintaining the accuracy of the HIT System to measure head impact kinematics. Contact between the head and encoder must take place at all times to ensure accurate measurements. However, the encoders can cause discomfort to players especially those with smaller helmets. [60] Accuracy of the HIT System is also location dependent. Impacts to the facemask are less accurate (r^2=0.415) compared to impacts to the helmet shell, which had less than 6% error. [61] This can be attributed to helmet decoupling from the head during facemask impacts, and the encoder losing sufficient contact with the head. This is important to note in the application of the HIT System, because many football players do not have a properly fitting helmet. Given the its limitations, and the creation of additional head impact monitoring devices, the HIT System is still the best way to measure on-field head impact biomechanics. By incorporating Fusionetics and LESS testing and the HIT System into a football program, we can determine if poor performance on movement assessments is associated with concussive or subconsussive impacts on the football field.

CHAPTER 3

METHODOLOGY

Study Design

A prospective cross-sectional study design compared good and poor movers' head impact biomechanics over the course of one NCAA Division 1A football season. All participants underwent preseason and postseason movement assessments. Head impact biomechanics for participants were tracked using the HIT System. Changes in movement assessment score from preseason to postseason were also assessed. For Specific Aim 1, the independent variable was movement category and dependent variables were head impact biomechanics. For Specific Aim 2, the independent variables were LESS movement category and Fusionetics movement category. For Specific Aim 3, the independent variables were time and impact exposure group and the dependent variables were movement scores (Table 3.1).

Participants

We recruited 44 male collegiate football players (mass= 109.0 ± 20.8 kg, age= 20.0 ± 1.3 yr). Participants were included if they did not have a current injury making them unable to complete preseason movement testing and excluded if they sustained a significant lower or upper extremity injury during the 2016 season, such that they did not complete the season. Exclusion from comparison of preseason and postseason testing occurred if the subject sustained a significant injury throughout the season that resulted in time loss greater than 4 weeks. The university institutional review board approved this research study and all participants provided informed consent prior to participation in the study.

Instrumentation

Landing Error Scoring System

The LESS is a jump-landing task used to assess dynamic movement patterns. A depth camera (Microsoft Kinect sensor version 1; Microsoft Corporation; Redmond, WA) recorded human kinematics while participants performed the LESS. PhysiMax Athletic Movement Assessment software (PhysiMax Technologies Ltd.; Tel Aviv, Israel) scored each completed LESS trial. Each trial was assessed for errors or compensations at the feet, knees or trunk. Descriptions of the errors can be found in Table 3.2. Total number of errors was averaged over 3 trials to give the subject their final LESS movement score.

Fusionetics Movement Efficiency Test

The Fusionetics Movement Efficiency Test comprised of an overhead squat, overhead squat with heel lift, single leg squat, pushup, glenohumeral range of motion, lumbar spine range of motion, and cervical spine range of motion. Errors at the feet, knees, trunk, shoulders and cervical spine were identified. Descriptions of these errors can be found in Table 3.3. Individual scores for each movement pattern were given along with a total movement score calculated by Fusionetics proprietary algorithm.

Head Impact Telemetry System

The HIT System measured the frequency, location, and magnitude of impacts sustained to the head while football players competed in games and practices. An encoder with six single-axis accelerometers was inserted between the padding of a commercially available Riddell Revolution (sizes: M, L, or XL), Speed (sizes: M, L, or XL), and Flex football helmet. This study used a recording threshold of 10 g. The accelerometers collected data at 1kHz for a period of 40ms; 8ms are pre-trigger and 32ms of data collected post-trigger. A radiofrequency telemetry link transmitted time-stamped data from the accelerometers to a sideline computer. The system can collect data from as many as 64 players over the length of the football field. In the event players were out of range from the sideline computer, data from 100 separate impacts could be stored in the on-board memory built. The data were reduced and processed by a proprietary algorithm. The HIT System calculated the peak linear acceleration, and rotational acceleration, Gadd Severity Index, Head Injury Criterion, and head impact location.

Procedures

Participants underwent functional movement assessments prior to the start of preseason. One clinician administered Fusionetics and LESS testing. Participants performed a standardized warmup prior to all functional movement assessment testing. The warm up included cycling for 5 minutes on a stationary bike at 80 RPM, dynamic stretching of the hamstrings, quadriceps, hip flexors, glutes, calves, and shoulders, and static stretching of the hamstrings, quadriceps, hip flexors, glutes, iliotibial band, leg adductors, and latissimus dorsi. Upper and lower extremity dynamic and static stretches were completed one time for 30 seconds each. Movement quality was then assessed with the LESS followed by Fusionetics. All participants completed the same order of movement assessments.

Participants performed 6 LESS trials, 3 practice and 3 collected trials. The participant started on a 30cm box, jumped horizontally, without any upward motion, into a target landing area located at a distance of 50% of their height from the front of the box. The participant then immediately performed a maximal vertical jump after landing in the target area. Participants were not coached on form. A Kinect camera was placed 11 feet from the front of the box, and measured participant's landing and jumping kinematics.

After completing the LESS testing participants moved on to the Fusionetics movement assessment. This assessment began with participants performing an overhead squat. They were instructed to perform 5 to 8 repetitions with their arms overhead, squatting as low as they could. The overhead squat was repeated with the addition of a heel lift. Next, participants completed 3 to 5 repetitions of a single leg squat on each leg. They were instructed to squat to the approximate height of a chair with their arms and opposite leg positioned wherever felt comfortable. The push up test consisted of 3 to 5 push-ups with their hands in a comfortable position. Glenohumeral range of motion consisted of flexion, horizontal abduction, internal rotation and external rotation. Lumbar spine range of motion consisted of rotation and lateral flexion. Cervical spine range of motion consisted of rotation and lateral flexion. Glenohumeral, lumbar spine and cervical spine range of motion were all performed from a standing position. Three trials were performed. Fusionetics test components were administered in the same order each time for convenience. We do not believe there was a test order effect.

Participants wore helmets instrumented with the HIT System. Each player had a unique identification number assigned to their HIT System sensor. Helmets were properly fitted by professional equipment managers at the beginning of the season to ensure accelerometers made contact with the head to measure head acceleration, not helmet acceleration. During games and practices the HIT System recorded, calculated, and stored linear acceleration, rotational acceleration, and impact location data from the accelerometers in real-time.

Data from the HIT System were collected over the 2016 season and included 74 practices and 13 competitions. The HIT System was programmed to begin collecting data when a practice or competition began, and programmed to stop at the session completion. This reduced our chances for including possible impacts sustained outside of competition or practice.

Data Reduction

Fusionetics movement assessment scores were used to categorize participants into one of three movement quality groups: 1) good (score exceeding 75), 2) moderate (scores ranging from 50 to 75), and 3) poor (scores below 50). The software predetermines Fusionetics grouping cutoffs. Additionally, LESS errors were also used to categorize participants into one of three movement quality groups: 1) good (<5 errors), 2) moderate (6-7 errors), and 3) poor (greater than 7 errors). [23]

Statistical Analysis

Only impacts with a peak resultant linear acceleration greater than 10 g were included in the analyses. We applied natural logarithmic transformations to our linear and rotational acceleration data to conform to the assumptions of data normality for Specific Aim 1A. For Specific Aim 1, separate random intercepts general linear mixed models were performed for peak linear and rotational acceleration (Hypothesis 1). The independent variable for these analyses was functional movement quality (good, moderate, and poor) and player was treated as a repeating factor. Separate independent samples T-test assessed the cumulative sum of linear and rotational acceleration differences between good and moderate movers scored by Fusionetics. We performed a Kappa analysis of measurement agreement (Hypothesis 2) between Fusionetics and the LESS in determining functional movement quality (good, moderate, poor). Lastly, we evaluated the association between impact frequency and change in functional movement quality for Fusionetics and the LESS with a regression (Hypothesis 3). All analyses were carried out in SAS (version 9.4, SAS Institute Inc., Cary, NC). Statistical significance was set *a priori* with an alpha less than 0.05.

Table 3.1. Statistical Analysis Summary

Aim	Objective	Data Source	Comparison	Methods
1A	To test the hypothesis that Division I college football players with poorer preseason movement assessment performance will demonstrate more severe head biomechanics (linear and rotational acceleration) than those with better preseason movement assessment performance (as measured by Fusionetics and Landing Error Scoring System).	IV: Movement category DV: Head impact biomechanics	Functional movement category: 1. Good 2. Moderate 3. Poor Head impact biomechanics: 1. Linear acceleration 2. Rotational acceleration	Linear Mixed Model with random intercepts
2	To test the rating agreement between Fusionetics (poor, moderate, good) and Landing Error Scoring System (poor, moderate, good) movement assessment performance scales.	IV: LESS movement category and Fusionetics movement category	Functional movement category: 1. Good 2. Moderate 3. Poor	Kappa agreement
3	To test the hypothesis that preseason-to-postseason changes in movement assessment performance are associated with head impact frequency in college football players.	IV: Impact frequency DV: Change in functional movement quality	Impact frequency Change in functional movement quality	Regression

Table 3.2. Description of Landing Error Scoring System Errors

Item	Description	View	# of Errors
Stance width	Landing in a very narrow or wide stance	Front	+1
Max foot-rotation position	Feet are moderately externally rotated or slightly internally rotated	Front	+1
Initial foot-contact symmetry	1 foot lands before the other or 1 foot lands heel-to-toe and the other lands toe-to-heel	Front	+1
Max knee-valgus angle	Small amount of knee valgus (+1) or large amount of knee valgus (+2)	Front	+1-2
Amount of lateral trunk flexion	Leaning right or left so the trunk is not vertical	Front	+1
Initial landing of feet	Landing heel-to-toe or with a flat foot	Side	+1
Amount of knee-flexion displacement	Small amount (+2) or average amount (+1) of knee-flexion displacement	Side	+1-2
Amount of trunk-flexion displacement	Small amount (+2) or average amount (+1) of trunk-flexion displacement	Side	+1-2
Total joint displacement	Large displacement of trunk and knees (0); average amount of trunk and knee displacement (+1); small amount of trunk and knee displacement (+2)	Side	0-2
Overall impression	Soft landing and no frontal-plane motion at knee (0); Stiff landing and /or large frontal-plane motion at knee (+2); all other landings (+1)	N/A	0-2

Table 3.3. Description of Fusionetics Movement Efficiency Test Errors

Test	Description of Errors	View
Overhead Squat	Foot flattens, foot turns out, knee valgus, knee varus	Front
	Excessive forward lean, low back arches, low back rounds, arms fall forward	Side
	Heels lift, asymmetrical weight shift	Rear
Overhead Squat with Heel Lift	Foot flattens, foot turns out, knee valgus, knee varus	Front
	Excessive forward lean, low back arches, low back rounds, arms fall forward	Side
	Heels lift, asymmetrical weight shift	Rear
Single Leg Squat	Foot flattens, knee valgus, knee varus, uncontrolled trunk flexion, loss of balance	Front
Push Up	Head moves forward, scapular winging, low back arches/stomach protrudes, knees bend	Side
Glenohumeral Motion	Flexion: unable to bring hand to wall; Internal Rotation: unable to bring hand to midline of trunk; External Rotation: unable to bring hand to wall; Horizontal Abduction: unable to bring hand to wall	Side
Trunk Motion	Lateral Flexion: unable to reach lateral joint line of knee; Trunk Rotation: unable to rotation shoulder to midline of trunk	Side
Cervical Spine Motion	Lateral Flexion: unable to side-bend half the distance to shoulder; Rotation: unable to rotate chin to shoulder	Front

CHAPTER 4

Introduction

An estimated 1.6 to 3.8 million traumatic brain injuries occur in sport and recreational activities annually. [1] Concussions are a subset of traumatic brain injuries that are defined as a trauma-induced alteration in mental status. [2] A multifaceted approach is used to diagnose concussion due to the complexity of the injury. Several clinical tests are established for diagnosis but none to determine who is at risk of sustaining the injury.

Football has one of the highest concussion rates sustained in the National Collegiate Athletics Association due to the high head impact frequency players sustain during participation. [4, 5] Research has identified factors influencing head impact frequency and severity in order to understand their relationship to concussion risk. These factors include, but are not limited to, event type, [4, 6, 7] collision anticipation, [8, 9] and play type. [10] Previous studies suggest peak linear accelerations exceeding 70 to 75 g may be associated with greater concussion risk. [11] However, there is no definitive head injury threshold. [71, 72] Understanding concussion injury mechanics is of growing concern due to the potential long-term neurological consequences associated with concussions and repetitive head impacts that do not result in any clinically diagnosed concussion (subconcussive impacts). [12-14] Given these long-term implications, studying head impacts using innovative head impact monitoring systems will allow for a better understanding of these phenomena, and may identify mechanisms by which injury risk can be reduced.

While the long-term effects of concussion and subconcussive impacts remains largely unknown, studies on the acute effects of concussion have focused almost entirely on its clinical manifestation including symptoms, balance, and neurocognition. [2, 15-18] The clinical measures used to assess these manifestations may be limited. For example, lingering deficits in dynamic balance, voluntary movement, and reaction times—required for adapting to changing environments in sport participation—remain impaired beyond recovery in static balance testing. [19, 20] Given this, it is not surprising concussion has been linked to increasing musculoskeletal injury risk. Concussed athletes are two times more likely to sustain a musculoskeletal injury post-concussion versus pre-concussion. [5, 19, 20] Concussed athletes are also more likely to sustain a musculoskeletal injury after returning to play as compared to their non-concussed counterparts. Given the published link between concussion and neuromuscular control, it is possible repetitive head impacts could negatively influence functional movement.

Movement assessments are used to clinically evaluate functional movement quality, and could help inform the relationship between movement quality and risk for concussion or head impacts. [21] They are employed in many clinical settings to identify movement compensations including muscular imbalances, decreased flexibility and balance deficits associated with musculoskeletal injury risk. [21] Such mechanisms that label an individual as a poor mover, may also put them at greater concussion risk. Deficits to the neuromuscular system, causing movement compensations, may be similar to those sustained after head impact. Fusionetics is a movement assessment incorporating upper and lower extremity movement patterns to identify injury risk. [22] The Landing Error Scoring System is a dynamic movement assessment of jump landing biomechanics. [23] Fusionetics and the LESS categorize movement quality as good, moderate, and poor. These two evaluations are commonly employed but to date there are no research studies to determine if Fusionetics and the LESS demonstrate agreement with each other. Scientific inquiry has established an association between concussion history and increased musculoskeletal injury risk.

Data support the notion that functional movement screening can identify patients at a higher musculoskeletal injury risk. [21, 23, 25, 26, 45] Studying the association of functional movement and head impact biomechanics is a feasible and necessary progression in understanding the links between concussion and musculoskeletal injury risk. Therefore, the overall purpose of this study was to determine the association between movement assessment performance and head impact biomechanics.

Methods

A prospective cross-sectional study design compared participants head impact biomechanics over the course of one NCAA Division 1A football season. All participants underwent preseason and postseason movement assessments. Changes in movement assessment scores from preseason to postseason were also assessed.

Participants

We recruited 44 male collegiate football players (mass= 109.0 ± 20.8 kg, age= 20.0 ± 1.3 yr). Table 4.1 provides a breakdown for each position group. Participants were included if they did not have a current injury making them unable to complete preseason movement testing and wore a Riddell helmet brand that accommodates a HIT System encoder. Exclusion from comparison of preseason and postseason testing occurred if the subject sustained a significant injury throughout the season that resulted in time loss greater than 4 weeks. The university institutional review board approved this research study and all participants provided informed consent prior to participation in the study.

Instrumentation

Landing Error Scoring System

The LESS is a jump-landing task used to assess dynamic movement patterns. A depth camera (Microsoft Kinect sensor version 1; Microsoft Corporation; Redmond, WA) recorded human kinematics while participants performed the LESS. PhysiMax Athletic Movement Assessment software (PhysiMax Technologies Ltd.; Tel Aviv, Israel) assessed for errors or compensations at the feet, knees or trunk and scored each completed LESS trial (see Table 3.2). PhysiMax has shown good agreement with expert LESS raters ($PABA\kappa=0.71\pm0.27$). [20] Scores range from 0 to 17. Lower scores indicate better movement quality. Additionally, LESS errors categorized participants into one of three movement quality groups: 1) good (<5 errors); 2) moderate (6-7 errors); and 3) poor (> 7 errors). [23] Total number of errors was averaged over 3 trials to give the subject their final LESS movement score.

Fusionetics Movement Efficiency Test

The Fusionetics Movement Efficiency Test comprised of an overhead squat, overhead squat with heel lift, single leg squat, push up, glenohumeral range of motion, lumbar spine range of motion, and cervical spine range of motion. Errors at the feet, knees, trunk, shoulders and cervical spine were identified (see Table 3.3). Individual scores for each movement pattern were given along with a total movement score calculated by Fusionetics proprietary algorithm. Scores range from 0 to 100. Higher scores indicate better movement quality. Fusionetics movement assessment scores categorized participants into one of three movement quality groups: 1) good (score exceeding 75); 2) moderate (scores ranging from 50 to 75); and 3) poor (scores below 50). The software predetermined Fusionetics grouping cutoffs.

Head Impact Telemetry System

The HIT System measured the frequency, location, and magnitude of impacts sustained to the head while football players competed in games and practices. An encoder with six single-axis accelerometers was inserted between the padding of a commercially available Riddell Revolution (sizes: M, L, or XL), Speed (sizes: M, L, or XL), and Flex football helmet. This study used a recording threshold of 10 g. The accelerometers collected data at 1kHz for a period of 40ms; 8ms are pre-trigger and 32ms of data collected post-trigger. A radiofrequency telemetry link transmitted time-stamped data from the accelerometers to a sideline computer. The system can collect data from as many as 64 players over the length of the football field. In the event players were out of range from the sideline computer, data from 100 separate impacts could be stored in the encoder's on-board memory. The HIT System's proprietary algorithm reduced, processed, and calculated the peak linear and rotational acceleration, Gadd Severity Index, Head Injury Criterion, and head impact location. Cumulative peak linear and rotational acceleration were defined as the sum of the peak linear and rotational accelerations associated with each individual head impact sustained over the course of the season. [9]

Procedures

Participants underwent functional movement assessments prior to the start of preseason. Participants performed a standardized warm up prior to all functional movement assessment testing. The warm up included cycling for 5 minutes on a stationary bike at 80 RPM, dynamic stretching of the hamstrings, quadriceps, hip flexors, glutes, calves, and shoulders, and static stretching of the hamstrings, quadriceps, hip flexors, glutes, iliotibial band, leg adductors, and latissimus dorsi. Upper and lower extremity dynamic stretches were completed for 10 yards and upper and lower extremity static stretches were completed one time for 30 seconds each. Movement quality was then assessed with the LESS followed by Fusionetics. All participants completed the same order of movement assessments. The same clinician administered both assessments for all participants.

Participants performed 6 LESS trials, 3 practice and 3 collected trials. The participant started on a 30cm box, jumped horizontally, without any upward motion, into a target landing area located at a distance of 50% of their height from the front of the box. The participant then immediately performed a maximal vertical jump after landing in the target area. Participants received no coaching on their form. A Kinect camera was placed 11 feet from the front of the box, and measured participant’s landing and jumping kinematics.

After completing the LESS testing participants moved on to the Fusionetics movement assessment. This assessment began with participants performing an overhead squat. They were instructed to perform 5 to 8 repetitions with their arms overhead, squatting as low as they could. The overhead squat was repeated with the addition of a heel lift. Next, participants completed 3 to 5 repetitions of a single leg squat on each leg. They were instructed to squat to the approximate height of a chair with their arms and opposite leg positioned wherever felt comfortable. The push up test consisted of 3 to 5 push-ups with their hands in a comfortable position. Glenohumeral range of motion consisted of flexion, horizontal abduction, internal rotation and external rotation. Lumbar spine range of motion consisted of rotation and lateral flexion. Cervical spine range of motion consisted of rotation and lateral flexion. Glenohumeral, lumbar spine and cervical spine range of motion were all performed from a standing position. Three trials were performed. Fusionetics test components were administered in the same order each time for consistency with pre- and post-season testing.

Participants wore helmets instrumented with the HIT System. Players had a unique identification number assigned to their HIT System sensor. Professional equipment managers properly fitted the helmet at the beginning of the season to ensure the accelerometers made contact with the head to measure head acceleration, not helmet acceleration. During games and practices the HIT System recorded, calculated, and stored linear acceleration, rotational acceleration, and impact location data from the accelerometers in real-time.

The HIT System collected data over the 2016 season and included 74 practices and 13 competitions. The HIT System was programmed to begin collecting data when a practice or competition began, and programmed to stop at the session completion. This reduced our chances for including possible impacts sustained outside of competition or practice.

Statistical Analysis

Only impacts with a peak resultant linear acceleration greater than 10 g were included in the analyses. [61, 63, 65] We applied natural logarithmic transformations to our linear and rotational acceleration data to conform to the assumptions of data normality for Specific Aim 1. For Specific Aim 1, separate random intercepts general linear mixed models were performed predicting peak linear and rotational acceleration from functional movement quality (good, moderate, and poor) (Hypothesis 1). Next, we performed a Kappa analysis to test the measurement agreement (Hypothesis 2) between Fusionetics and the LESS in determining functional movement quality category (good, moderate, poor). Lastly, we evaluated the effect of impact frequency on change in functional movement quality for Fusionetics and the LESS between pre and postseason with a regression (Hypothesis 3). All analyses were carried out in SAS (version 9.4, SAS Institute Inc., Cary, NC). Statistical significance was set *a priori* with an alpha less than 0.05.

Results

Forty-four participants underwent preseason movement testing (Table 4.2). Thirty-eight of those participants completed postseason movement testing. Six players completed preseason movement testing but did not complete postseason movement testing for the following reasons: two sustained season ending injuries, two had injuries that made them unable to complete movement testing at the time of testing, and two did not attend postseason movement testing. Over the course of the 2016 football season, we collected 29,747 head impacts (11.56 impacts/game/player and 8.76

impacts/practice/player). All impacts included exceeded our study's post-processing threshold of 10g.

Preseason movement screening and movement assessment agreement

Forty-four participants were classified into the poor, moderate, and good movement categories based off Fusionetics and LESS testing. No one tested poor for Fusionetics, while there were 25 moderate movers, and 19 good movers. Using the LESS, there were 18 poor movers, 18 moderate movers, and 8 good movers. Fusionetics and LESS had poor agreement on categorizing an individual's preseason movement quality as good, moderate, or poor movers (κ=0.0435 (95%CI, -0.1166 to 0.2036), p <0.001).

Head impact biomechanics

There were no effects of preseason movement assessment group on the two HIT System impact outcomes: linear acceleration and rotational acceleration (see Table 4.3).

Preseason to postseason movement assessment change and head impact frequency

Participants increased an average of 1.2 ± 7.5 points in their Fusionetics score from preseason to postseason, but the frequency of impacts did not significantly predict preseason to postseason score changes on Fusionetics ($F_{1,36} = 0.22$, $p = 0.643$). Participants increased an average of 0.2 ± 2.5 points in their LESS score from preseason to postseason, but the frequency of impacts did not significantly predict preseason to postseason score changes on the LESS ($F_{1,36} < 0.01$ $p = 0.988$).

Discussion

Given the link between concussion and musculoskeletal injury, as well as functional movement assessment performance and musculoskeletal injury, we sought to determine functional movement assessments' ability to predict head impact biomechanics in collegiate football players. Utilizing functional movement assessments to detect those at risk of concussion is the next step in this research. We found that an athlete's movement abilities as assessed by Fusionetics and LESS did not predict impact severity over the course of the season. Dorrien et. al. had similar findings to our study, that there was no relationship between concussion history and Functional Movement Screen (FMS) score. [68] Both our study and Dorrien et. al. used collegiate athletes. A possible limitation of the studies is the samples. The samples are made up of elite athletes who complete the same training program year-round. The functional movement assessments chosen may not be sensitive enough to detect neurological and neuromuscular differences within the sample. A greater range of scores may be found in high school athletes who do not complete the same training program and have variability in skill.

We believe we found no differences in Fusionetics movement categories because none of our participants scored less than 50, testing as "poor." Differences may be found if the participants were normally distributed between Fusionetics movement categories. Also, lack of reliability data for this clinician scoring Fusionetics is a limitation of this study. LESS scores above 5 result in increased risk of anterior cruciate ligament injury. [23] Studies have also shown incidence of stress fractures increases 15 percent with every 1-point increase in LESS score. [73] These devastating and limiting injuries are less commonly seen in football. Future research should incorporate movement assessments that predict injuries frequently sustained in football.

Compensations seen on Fusionetics and LESS may not translate to the field when players must cover longer distances or utilize their visual and sensory systems during impacts. Players are at greater risk of more severe head impact biomechanics when closing distances are greater than 10 yards. [10] Breakdown of form, coupled with increased speed, may result in greater impact magnitude. Decreased visual and sensory performance are also linked to more severe head impact biomechanics. [65] Fusionetics and LESS do not require advanced visual and sensory performance and therefore, may not translate to the field. Movement assessments are performed in a controlled environment, unlike the unanticipated, fast paced playing field.

Sport specific outcomes should be considered when choosing a movement assessment. We chose Fusionetics because it incorporated the upper extremity and cervical spine and involves slower movements to reveal neuromuscular deficits. We chose LESS because it was a more dynamic movement pattern and predicts risk of musculoskeletal injury. [23, 73] Fusionetics and LESS had poor agreement on a participant's movement assessment category. This may be due to the innate differences between tests. Fusionetics incorporates the upper extremity, while LESS does not. The LESS was found to predict anterior cruciate ligament injury in soccer players. [23] Unlike soccer, football incorporates the upper extremity. Deficits and compensations at the upper extremity that may result in head impacts may not be picked up on the LESS. The LESS is a more dynamic lower extremity test because it requires a jump landing. LESS categorized 18 participants as poor movers, while Fusionetics did not categorize anyone as poor. A large part of Fusionetics involves a double leg squat. This movement pattern is trained by division I football players year-round, possibly inflating Fusionetics scores. Although movement assessments are designed to evaluate the same components of lower extremity muscular imbalances, and range of motion and balance deficits, the outcomes were not the same. This begs the question of which assessment is correctly identifying football players at greater risk of musculoskeletal injury, if any? Our study did not track musculoskeletal injuries sustained throughout the season to determine if either were successful at predicting musculoskeletal injury.

We found no significant difference in change in functional movement assessment score and head impact frequency over the course of one season. Our results show little change in Fusionetics score (1.2 ± 7.5 points) and LESS score (0.2 ± 2.5 points) from preseason to postseason. The lack of a control group is a limitation of this study. A control group could determine if there was any change in movement assessment score preseason to postseason without sustaining head impacts.

Recent studies have shown concussed athletes are twice as likely to sustain a lower extremity injury post-concussion versus pre-concussion and twice as likely to sustain a lower extremity injury within 90 days of their return to play as compared to their non-concussed counterparts. [5, 20] Given the link between concussion and neuromuscular control, we hypothesized movement assessment score would decrease after sustaining head impacts throughout the season. The gross movement patterns that Fusionetics and LESS incorporate may not be sensitive enough to the changes that occur after head impacts. As previously discussed, research has found no association between FMS score and concussion history. [68] The FMS is also comprised of gross upper and lower extremity movement patterns that may not detect slight changes in neuromuscular control. Previous studies have found subtle gait changes and static postural control insufficiencies in those with a history of concussion. [74, 75] These changes may be too subtle and specific to be detected in functional movement assessments. Adding force plates to LESS may detect changes after head impacts.

The data supports current research that a large percent of our impacts sustained were classified as mild, being 95.5 percent of linear acceleration and 99.1 percent of rotational acceleration. [6, 63] Current research is studying the long-term effects of these subconcussive impacts. The little change in functional movement assessment score from preseason to postseason may not capture the long-term effects and later stages of brain injury that repetitive head impacts may have.

The use of multiple movement assessments allows the clinician to gather more information on an athlete's movement quality but it not always feasible. Advantages of LESS are its time efficiency. Trials are quickly performed and inclusion of the Kinect camera and PhysiMax software made data retrieval easy. LESS accommodates the large size of football programs. Fusionetics identifies movement compensations and creates corrective exercises to address muscular imbalances, decreased flexibility and asymmetries. Fusionetics has the ability to assess functional movement quality, nutrition, and recovery. It is very user friendly and directed towards overall sports performance. Although the test took longer, Fusionetics is better suited for a football program because it yields more information. Functional movement assessments' reliability and validity are frequently studied in relation to itself but rarely in relation to another assessment. Due to the lack of agreement found in our study, it would be interesting to see what functional movement assessments agree with one another, if any. We must continue looking for preseason movement assessment tools that can predict head impact biomechanics in hopes of identifying those at greater risk of concussion. If compensatory movement patterns can be corrected before contact practices begin, we may reduce the incidence of concussion.

Table 4.1. Participants by position group

	n	Mass (kg)	Age (yr)
Bigs[a]	17	132.8 ± 6.9	20.3 ± 1.2
Big Skill[b]	8	104.8 ± 4.4	20.3 ± 1.6
Skill[c]	13	88.3 ± 5.2	19.6 ± 1.3
Special Teams[d]	3	96.0 ± 8.0	19.7 ± 0.6
Total	44	109.0 ± 20.8	20.0 ± 1.3

[a] Bigs: Offensive Linemen, Defensive Linemen

[b] Big Skill: Quarterback, Linebackers, Tight Ends

[c] Skill: Defensive Backs, Running Backs, Wide Receivers

[d] Special Teams: Kicker, Long Snappers

Table 4.2. Descriptives of preseason movement assessment scores

		95% CI		Range	
Movement assessment	Mean	Lower	Upper	Lower	Upper
Fusionetics Total ME Score[a]	73.1	70.5	75.5	55.9	90.3
Overhead Squat	61.7	57.8	65.8	33.3	94.5
Overhead Squat with Heel Lift	84.3	81.3	86.8	48.2	94.5
Single Leg Squat	45.7	39.7	52.0	2.8	97.2
Push Up	87.9	84.2	91.5	60.0	100.0
Glenohumeral Range of Motion	86.2	81.7	90.2	50.0	100.0
Trunk Range of Motion	71.0	61.2	79.9	0.0	100.0
Cervical Spine Range of Motion	85.8	78.8	92.4	0.0	100.0
LESS[b]	6.8	6.0	7.4	12.0	2.0

[a] Fusionetics is scored 0 to 100; higher scores indicate better performance

[b] LESS is scored 0 to 17; lower scores indicate better performance

Table 4.3. Descriptive statistics for head impact severity by functional movement assessment group

	Linear acceleration (g)				Rotational acceleration (rad/s^2)			
		95% CI				95% CI		
	Mean	U	L	p^a	Mean	U	L	p^a
Fusionetics								
Good mover[c]	22.1384	23.2621	21.0689	(Ref)	892.524	937.994	849.258	(Ref)
Moderate mover	22.6904	23.6868	21.7359	0.453	931.820	972.763	892.601	0.193
LESS		Global Test[b]		0.442		Global Test[b]		0.793
Good mover[c]	21.8526	23.5690	20.2613	(Ref)	936.581	1012.29	866.532	(Ref)
Moderate mover	22.9986	24.1951	21.8613	0.264	909.719	958.60	863.332	0.534
Poor mover	22.1855	23.3409	21.0872	0.739	909.650	958.60	863.332	0.533

[a] p values are relative to the reference category used by the random intercepts general mixed linear model analysis

[b] Global Test refers to the omnibus model evaluating the null hypothesis of no differences between any categories for this variable

[c] The reference category

Table 4.4. Average movement assessment score by position group

	n	Fusionetics	LESS
Bigs[a]	17	73.3 ± 9.9	9.9 ± 2.4
Big Skill[b]	8	71.9 ± 10.4	5.4 ± 3.3
Skill[c]	16	72.4 ± 7.6	7.1 ± 2.1
Special Teams[d]	3	78.6 ± 3.8	7 ± 1.7
Total	44	73.1 ± 8.8	6.8 ± 2.4

[a] Bigs: Offensive Linemen, Defensive Linemen
[b] Big Skill: Quarterback, Linebackers, Tight Ends
[c] Skill: Defensive Backs, Running Backs, Wide Receivers
[d] Special Teams: Kicker, Long Snappers

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