THE ASSOCIATION BETWEEN CLINICAL MEASURES OF MOVEMENT QUALITY WITH FUNCTIONAL PERFORMANCE MEASURES

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment for the requirements of the degree of Master of Arts in the Department of Exercise and Sport Science (Athletic Training).

Chapel Hill
2015

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ABSTRACT

Alicia Yamamoto: The Association between Clinical Measures of Movement Quality with Functional Performance Measures
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The purpose of this study was to examine the association between clinical measures of movement quality as it pertains to injury risk with functional performance measures. This study examined the associated of movement quality screenings with performance variables of speed, agility, lower body power, and core power tested through a 40-yard sprint, modified t-test, single-leg triple hop, and seated rotational medicine ball throw, respectively. This study used a correlational design.

Movement quality was assessed using both dynamic (jump-landing) and slow-controlled (double and single leg squats) tasks. Movement errors were assessed during both the jump-landing and squat tasks using a standardized scoring rubric. Higher scores indicated more movement errors, hence worse movement quality. The participants were then asked to complete a 40-yard sprint, modified t-test, single-leg triple hop, and seated rotational medicine ball in a randomized order. Spearman's order-rank correlations were used to determine the association between movement quality during the jump-landing and squat tasks with each of the functional performance measures.

Dynamic movement quality, assessed using the LESS, was significantly associated with agility (modified t-test), lower body power (single-leg triple hop), and core power (seated rotational medicine ball throw). However, no such relationship was observed between movement quality assessed during the slow, more controlled squat tasks with functional performance measures. Movement quality during a more dynamic, max effort test is strongly associated with functional measures of performance. While movement quality during a more slow-controlled task is important for assessing neuromuscular characteristics associated with high injury risk movement patterns, these measures are not associated with functional measures of performance. Therefore, there is a need to assess movement quality across a continuum of tasks ranging from slow-controlled global body movements to high-energy, max effort specific tasks when examining an individual for both injury risk factors and performance associations.

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LIST OF ABBREVIATIONS

MKSI – Musculoskeletal Injury

LESS – Landing Error Scoring System

Fusionetics - FUSX

FMS – Functional Movement System

SEBT – Star Excursion Balance Test

IPP – Injury prevention program

CHAPTER 1

INTRODUCTION

Lower extremity injuries account for approximately two-thirds of all injuries seen in collegiate athletics.[1] It has been shown that these injuries can result in emotional distress,[2] long-term disabilities,[3] can ultimately contribute to significant US health care costs,[4] and decrease individual and team performance.[5] The cost for initially managing these injuries and their residual effects has become astronomical. For example, health care costs of anterior cruciate ligament (ACL) reconstructions are estimated at $1 billion per year[6]. Similar trends can be seen with other common lower extremity injuries.[5] Preventing lower extremity injuries is important for lowering overall cost, as well as limiting the amount of emotional distress,[2] long-term disabilities,[3] and both individual and team performance decrements that result from injury.[5]

In an attempt to reduce injury rates and its negative effects, several movement assessment tools have been proposed to clinicians. These tools can be utilized to predict the risk of lower extremity injuries to the hip, knee, hamstring, groin, and ankle,[4] as well as global movement quality of the body.[7] In addition, these screening tools can be utilized as a basis for implementation of corrective exercises based on the identified risk factors such as muscle imbalances or neuromuscular dysfunction. Furthermore, these programs could theoretically aid in improving athletic performance if efficient movement is attained. In the current literature, research has primarily focused on how an acute assessment is related to injury risk factors.[8] For example, the LESS (Landing Error Scoring System) is a jump-landing task that found poor movement patterns (increased medial knee displacement, decreased hip and knee flexion, etc) are associated with anterior cruciate ligament (ACL) injuries and patella femoral pain syndrome (PFPS).[9] In addition, higher composite scores, signifying poorer biomechanics, are associated with higher-risk biomechanics for sustaining a lower extremity injury.[9] The jump-landing task, however, is only specific to identifying individuals with increased risk of lower extremity injuries such as ACL injury and PFPS. Other research has focused on the Functional Movement Screen (FMS), a more global movement quality screen and incorporates upper extremity motion as well to include the whole kinetic chain.[7,10-12] The FMS utilizes seven different tasks to assess fundamental movement patterns: an active straight leg raise, shoulder mobility, trunk stability push-up, rotary stability quadruped, deep squat, hurdle step, and in-line lunge.[7,10-12] With regards to injury risk, Kiesel et al found that a FMS score less than or equal to 14, out of a possible 21, was associated with a significantly greater risk of injury during a competitive season in NFL players.[12] The composite score of the FMS, however, has been found to have a sensitivity of only 0.12 for serious musculoskeletal (MSKI) injuries.[7]

Although there are no studies that associate an acute movement screening with athletic performance ability, there is some evidence that IPP's, based on acute movement screening results, may improve performance. One study implementing an ACL IPP based on the LESS test on females found increases in performance variables such as speed, agility, aerobic fitness, and vertical jump height.[13] Moreover, proper delivery of IPPs, focusing on correcting high-risk kinematic and kinetic risk factors, has been shown to reduce the risk of lower extremity injuries by 65-85%.[14]

A novel-screening tool, which is becoming popular in professional sports organizations, is called Fusionetics. Similar to all other movement assessments, this tool looks at global movement quality to identify injury risk and theoretically athletic performance ability. Although no research currently exists on Fusionetics as an entire test battery, it does use two tests supported by research, and observes for unilateral difference.[15,16] Similar to the FMS, Fusionetics utilizes seven various tasks including a 2-leg squat, 2-leg squat with a heel lift, 1-leg squat, push-up, shoulder movement, trunk/lumbar spine movement, and cervical spine movements. The composite score of Fusionetics, out of 100, is theorized to be more sensitive than the FMS in predicting injury risk and athletic performance, because it is graded on a larger scale, and may identify asymmetries between limbs. One feature that sets this program apart from others is that an IPP is automatically generated per individual testing results. This can reduce time and make delivery of an IPP more efficient. The creation of an IPP to mitigate high-risk kinematic and kinetic risk factors is a major objective of any screening tool.

In an attempt to reduce injury risk and gauge athletic performance, several movement screening tools have been proposed. The evidence produced, thus far, seems promising for its ability to associate an acute screening assessment with injury risk; and for its ability to generate IPP's to reduce injury risk and improve performance. However, to our knowledge, no data exists that correlates screening tools with athletic performance, which is one of their main boasts. Furthermore, because Fusionetics is a novel screening tool, there are no studies that investigate its efficacy.

Therefore, the purpose of this study is to determine if there is an association between global movement quality and athletic performance ability using both the LESS and Fusionetics.

Independent Variables:

1. LESS Composite score (out of 22)
2. Fusionetics Sectional Total Error Scores
    a. Movement Efficiency (ME) Total Error Score (out of 60)
    b. Squat Total Error Score (out of 40)
    c. Upper Quarter Total Error Score (out of 20)

Dependent Variables:

1. Modified T-Test time (seconds)
2. 40-yard sprint time (seconds)
3. Seated rotational medicine ball throw distance (feet)
4. Single-leg triple hop distance (feet)

Research Questions:

1. What is the association between total LESS score and performance?
    a. What is the association between the total LESS score and agility?
    b. What is the association between the total LESS score and lower extremity power?
    c. What is the association between the total LESS score and core power?
    d. What is the association between the total LESS score and speed?

2. What is the association between Fusionetics sectional total error scores and performance?
    a. Squat Total Error Score
        i. What is the association between the squat total error score and agility?
        ii. What is the association between the squat total error score and lower extremity power?
        iii. What is the association between the squat total error score and core power?
        iv. What is the association between the squat total error score and speed?

Research Hypotheses:

1. LESS Score
   a. We hypothesize that there is a linear relationship between total LESS scores and T-test agility times.
   b. We hypothesize that there is an inverse relationship between total LESS scores and single-leg triple hop distance.
   c. We hypothesize that there is an inverse relationship between total LESS scores and seated rotational medicine ball throw distance.
   d. We hypothesize that there is a linear relationship between total LESS scores and 40-yard sprint times.
2. Fusionetics Sectional Total Error Scores
   a. ME Total Error Score
      i. We hypothesize that there is an inverse relationship between ME total error score and T-test agility times.
      ii. We hypothesize that there is a linear relationship between ME total error score and single-leg triple hop distance.
      iii. We hypothesize that there is a linear relationship between ME total error score and seated rotational medicine ball throw distance.
      iv. We hypothesize that there is an inverse relationship between ME total error score and 40-yard sprint times.
   b. Squat Total Error Score

i. We hypothesize that there is an inverse relationship between squat total error score and T-test agility times.
ii. We hypothesize that there is a linear relationship between squat total error score and single-leg triple hop distance.
iii. We hypothesize that there is a linear relationship between squat total error score and seated rotational medicine ball throw distance.
iv. We hypothesize that there is an inverse relationship between squat total error score and 40-yard sprint times.

c. Upper Quarter Total Error Score

i. We hypothesize that there is an inverse relationship between upper quarter total error score and T-test agility times.
ii. We hypothesize that there is a linear relationship between upper quarter total error score and single-leg triple hop distance.
iii. We hypothesize that there is a linear relationship between upper quarter total error score and seated rotational medicine ball throw distance.
iv. We hypothesize that there is an inverse relationship between upper quarter total error score and 40-yard sprint times.

Delimitations:

1. The subjects were women between the ages of 18 and 25 participating on the varsity soccer, volleyball, field hockey, tennis, lacrosse, and basketball teams at the collegiate level.
2. Exclusion criteria for subjects will limit subjects to have no lower extremity injuries in the last 6 months that has kept them out of sport participation for 4 days consistently, no lower extremity surgeries in the last year, and are not currently injured or experiencing pain greater than general muscle soreness.
3. The same investigator performed all measurements.

Limitations:

1. Measurements only apply to collegiate varsity athletes. Findings may only be applied to this population.
2. Activity levels of the athletes may differ due to the nature of the teams.

Assumptions:

1. All measurements are reliable and valid.
2. All subjects will be capable of and put their best effort in completing the LESS test, Fusionetics test, modified t-test, single-leg triple hop, seated rotational medicine ball throw, and 40-yard sprint.
3. Activity levels of all subjects were similar.

CHAPTER 2

REVIEW OF LITERATURE

INTRODUCTION

The majority of injuries seen in sport are sustained in the lower extremities.[1] Injury prevention programs (IPPs) have been developed to help reduce the occurrence of these injuries and have been created based off kinematic and kinetic risk factors shown to pre-dispose an individual to lower extremity injuries, such as the ACL.[14] Several movement assessment screens have been utilized to help identify individuals who display movement patterns associated with a higher risk of injury.[4,9,12,17-20] The purpose of this review is to give background information on lower extremity and global movement assessment screens commonly used to identify at-risk movement quality addressed in IPPs. Additionally, this review will provide information on what the focus of IPPs currently is, and where the focus of IPPs is heading.

EPIDEMIOLOGY

Lower extremity musculoskeletal injuries are prevalent in collegiate athletics, as well as recreational sport, military, and general population.[21-24] Over a 16-year period, the National Collegiate Athletic Association (NCAA) tracked injury and exposure rates of 15 sport activities.[1] In 16 years, 182,000 injuries and over 1 million exposures were recorded.[1] Approximately two-thirds of these injuries were sustained to the lower extremity, including the low-back and trunk.[1] Over 50% of these lower extremity injuries in athletic participation recorded were sustained from a non-contact mechanism of injury.[25] Similarly, in recreational sport activities and exercise participation the National Center for Injury Prevention and Control estimated that 10,000 Americans per day seek medical treatment and 50-80% of these injuries are to the lower extremity.[21-23] In addition, in a military setting 40% of all noncombat musculoskeletal injuries (MSKI) were attributed to the lower extremity.[24] In total, it has been found that approximately 66% of athletic injuries are to the lower extremity, and 75-80% of these injuries are a result of a non-contact mechanism of injury.[21,22,26-29]

Initial costs for managing these injuries are becoming astronomical at every level of athletic participation. In a 5-year span at the professional level the National Basketball Association (NBA) spent $400 million dollars in medical costs, Major League Baseball (MLB) spent $320 million dollars, and the National Football League (NFL) spent the most at $705 million dollars in medical costs. In the same amount of time the NCAA spent $675 million dollars in medical costs. In just one year MSKI in the Military accounted for 2.4 million medical visits to military medical treatment facilities resulting in $548 million dollars spent on medical costs. With these injuries are associated costs for not only the initial management of the injury, but the cost of managing any residual long-term disabilities as well.[2,3,21] One such injury frequently associated with long-term disabilities is an acute rupture of the ACL.[4] Osteoarthritis following acute traumatic knee injuries is one of the long-term disabilities that have extensively studied.[21,30] Posttraumatic osteoarthritis (PTOA) has been found to be the most common and costly long-term disability among the U.S. Military and other populations of varying levels of physical activity.[21,31] PTOA resulting from hip, knee, and ankle injuries was estimated to result in a financial burden of $3.06 billion dollars annually.[32] In a span of 8 years the cost of osteoarthritis has risen from $184.3 billion dollars to $281.5 billion dollars. The prevalence of lower extremity injuries sustained in non-contact sport activity, as well as the associated costs and long-term disabilities, suggest an obvious need to implement a program designed to help prevent lower extremity injuries.[1] Movement quality graded through movement assessment screens has been the primary focus of research and has provided the foundational information for IPPs.

MOVEMENT ASSESSMENT SCREENS

Functional Movement Screen (FMS)

The FMS was developed to qualitatively screen athletes for intrinsic injury-risk factors by having the subjects perform seven movements and documenting if each movement is completed with or without compensation.[17] The seven different tasks to assess fundamental movement patterns include an active straight leg raise, shoulder mobility, trunk stability push-up, rotary stability quadruped, deep squat, hurdle step, and in-line lunge.[7,10-12] Once the screen is completed a score is tallied and utilized to help predict an individual's risk of injury.[12] The score is determined using a 4-point ordinal scale to obtain a possible total score of 21. With this screen, the higher an individual's total score is the lower his or her risk of injury.[12] For each individual test a score of 1 corresponds to an inability to perform the movement asked, a score of 2 corresponds to the ability to perform the movement but with a compensation, and a score of 3 corresponds to the ability to correctly complete the movement without compensations.[17] Kiesel et al found that a FMS score less than or equal to 14 was associated with a significantly greater risk of injury during a competitive season in NFL players.[12] O'Connor et al found the same findings in Marine Officer Candidates, however their study only identified a sensitivity of 0.45 for overuse injuries and a sensitivity of 0.12 and for more severe injuries.[7] Furthermore, it has been found the FMS is not a useful tool for determining possible athletic capabilities making the FMS less enticing to athletes and coaches.[33,34]

Landing Error Scoring System (LESS) Test

Comparatively, the LESS has been proven to have both intra-rater and inter-rater reliability and biomechanical validity for identifying high-risk movement patterns in individuals specifically at risk for anterior cruciate ligament (ACL) injury and patella femoral pain syndrome (PFPS).[9,35] The LESS test is a jump-landing task where the subject is asked to stand on a 30-cm high box and instructed to jump a distance of 50% of their height in front of them and immediately jump as high as they can upon landing.[9] This test includes a checklist of movement impairments to be assessed during a jump-landing task; these impairments include assessing knee / hip / trunk flexion, lateral trunk flexion, medial knee displacement (MKD), ankle plantarflexion, stance width, and toe in or out.[9] With this screen 17 jump-landing characteristics are evaluated and scored through video analysis. The higher the total number out of 17 the more at-risk the individual is to injury.[35] The LESS-RT (real time) is a modified LESS test that allows a clinician to utilize the screen with patients without need for video analysis.[35] With the

LESS-RT the clinician only has to observe 10 jump-landing characteristics.[35] A study done on the reliability of the LESS-RT found good inter-rater reliability that compares favorably to the LESS making this a clinically useful movement assessment screen.[35] However, no research to our knowledge has been done associating the LESS with athletic performance outcomes.

Fusionetics

Fusionetics is a novel movement assessment screen that analyzes global movement quality. It utilizes seven different tasks to assess fundamental movement patterns including a 2-leg squat, 2-leg squat with a heel lift, 1-leg squat, push-up, shoulder movement, trunk/lumbar spine movement, and cervical spine movements. Each individual task score accounts for specific compensations seen while performing the task and if those compensations occur asymmetrically. The individual scores are then added to generate an overall composite score out of 100. Based on the compensations and asymmetries displayed during the tasks a list of corrective exercises is generated for the individual. Coinciding with the corrective exercises are suggested sets, repetitions, and times per week the individual should complete each exercise. The corrective exercises are also prioritized based on higher-risk movement patterns that were identified. This makes the program useful clinically. The composite score of Fusionetics is theorized to be more sensitive than the FMS because it identifies asymmetries between limbs and is graded on a larger scale. However, Fusionetics is a novel screening tool used to assess global movement quality and no research to our knowledge has been done on its' reliability or association with performance.

INJURY PREVENTION PROGRAMS and COMPLIANCE

Several IPPs have been developed focusing on correcting poor movement quality identified through movement assessment screen.[4,25,40,41] While the duration and volume of IPPs implemented on athletic populations for research vary, many programs consistently utilize exercises within the same categories including: stretching, lower extremity and core strengthening, plyometrics, and balance.[13,42-44] Several of the IPPs researched utilizing this structure have had positive results by decreasing an individuals' risk of injury.[13,25,42,43,45] Mandelbaum et al developed a 20 minute warm-up formatted injury prevention and performance enhancement program.[42] Subjects were instructed to complete the program 3 times per week while in pre-season and 1 time per week while in-season.[42] The program consisted of 3 basic jogging warm-up activities, 5 stretching techniques for the lower extremity and trunk, 3 lower extremity strengthening exercises, 5 plyometric exercises, and 3 agility activities.[42] The results of a one-year follow-up to the study indicated an 88% reduction of injury.[42] Similarly, Olsen et al developed a warm-up that took approximately 15-20 minutes to complete and was to be performed before every practice for the first 15 sessions and then once per week for the duration of the season.[25] The program consisted of 8 basic running warm-up activities, 2 agility activities, 5 balance exercises, and 5 strength and power exercises.[25] The results of the study found a relative injury risk reduction of 81% in individuals that participated in the intervention program.[25] Similar stretching, strengthening, and balance methods were utilized by Bell et al in a program they developed utilizing basic principles in the National Academy of Sports Medicine corrective exercise strategies textbook.[43]

Although poor movement quality has been found to place an individual at a biomechanical disadvantage for lower extremity injuries, and IPPs have been developed to address muscle groups associated with poor movement quality, coaches and athletes are still not compliant with IPPs.[46] Compliance consequences result from both lack of implementation[46] as well as adherence to IPPs.[44] However, it has been suggested that the key to success of an IPP is proper implementation and adherence to the training program.[47] A study done on soccer players in various club levels found that the risk of injuries was 68-72% lower in athletes that completed at least 70% or more of the IPP as compared to those with lower adherence.[44] Low compliance through both implementation and adherence of IPPs by coaches and athletes is theorized to be due to the additional time completing an IPP would require.[13] Because coaches have a limited amount of training time with their athletes, the focus of their training time needs to be on enhancing performance.[13] Nonetheless, a study done on professional soccer players found significant associations between low season injury rates and increased performance.[5] In this study, the team that decreased the frequency and severity of injuries had a statistically better chance of improving team performance.[5]

Recent research has found increases in performance variables after implementation of IPPs for the ACL.[5,13,48] DiStefano et al. found that after a 9-week intervention period of implementing an ACL IPP addressing static flexibility, balance, strengthening, agility, and plyometric exercise on both limbs, individuals were able to improve balance ability and power assessed through vertical jump height.[13] Similarly, Noyes et al. found that after a 6-week intervention period of implementing an ACL IPP addressing flexibility, lower extremity and core strengthening, and jump training, individuals displayed increases in speed, agility, and VO_2 max.[48] These studies, however, did not utilize subjects that specifically display movement quality errors that indicate a need for an IPP.[13,48]

CONCLUSION

The prevalence of non-contact, lower extremity injuries sustained in sport activity, as well as the associated cost and long-term disabilities with injury, indicate a need to implement an injury prevention program.[1,3,4,49-51] Injury prevention programs implemented for lower extremity injuries, such as for the ACL, have been shown to be approximately 65-85% effective.[14] However, coaches and athletes are not complaint with IPPs.[13,46] In Utah, it was found that only approximately 19% of soccer coaches have implemented IPPs.[46] It has been suggested that if the focus of IPP research is redirected toward their effectiveness in performance gains, coaches and athletes would be more compliant with implementation of these programs.[13,46,48] ACL IPPs that focus on flexibility, balance, strengthening, agility, and plyometric exercise have found increases in performance measures, although none of these studies have utilized subjects that specifically display "poor" movement quality.[13,46,48] It is suggested that individuals that display poor movement quality identified through movement assessment screens would benefit from these programs.[48] However, to our knowledge no study has been done directly linking "poor" movement quality during a screening assessment to performance. Therefore, the purpose of this study is to determine the association between individuals' LESS and Fusionetics scores and performance during tests for agility, power, and speed.

CHAPTER 3

METHODS

EXPERIMENTAL DESIGN

We used simple correlation analyses to evaluate 1) relationships between total LESS scores and performance on the t-test, single-leg triple hop, seated rotational medicine ball throw, and 40-yard sprint and 2) relationships between total and sectional error scores of FUSX tests and performance on the t-test, single-leg triple hop, seated rotational medicine ball throw, and 40-yard sprint. Specifically the predictor variables of the LESS composite score and FUSX total error scores and the criterion variables of time (seconds) for the t-test and 40-yard sprint and distance (feet) for single-leg triple hop and seated rotational medicine ball throw were used to evaluate these relationships.

SUBJECTS

Twenty-five female subjects from the university setting volunteered for this study. The subjects' ages ranged from 18-25 years of age. Subjects were included in the study if they reported participating in physical activity for at least thirty minutes per day, three days per week. Subjects also had to be a current varsity sport athlete participating on the soccer, volleyball, field hockey, lacrosse, tennis, and basketball teams. Subjects were excluded from the study if she 1) suffered a lower extremity injury in the last six months that kept her out of sport participation for 4+ days consistently 2) had undergone a lower extremity surgery in the past year or 3) was currently injured or currently experiencing pain more than general muscle soreness as perceived by the individual.

PROCEDURE

All subjects were required to attend a single testing session lasting approximately 1 hour and 45 minutes. Prior to data collection, subjects read and signed an informed consent from approved by the Institutional Review Board at the University of North Carolina Chapel Hill. Subjects were also required to complete a health and activity questionnaire to ensure compliance with the study's inclusion criteria, injury history, and to obtain height and weight. Subjects were required to wear athletic shoes, shirts, and shorts that allowed the patella to be completely visible. After ensuring all required forms were completed and inclusion criteria was met, the subjects were asked to perform the LESS and Fusionetics screening tools in a randomized order to obtain a movement quality score for both tests.

Landing Error Scoring System (LESS) Test

Subjects were instructed on and performed a jump-landing task. Subjects were asked to stand on a 30-cm high jumping box that was placed 50% of their height away from a landing target marked with athletic tape. Subjects were instructed to jump off of the jumping block onto the landing target and to jump as high as they could once they landed from the box. Specific emphasis was placed on both subjects' feet leaving the box simultaneously, as well as immediately trying to jump as high as they could once they landed from the box. Subjects were not provided any feedback on landing technique unless they were performing the task incorrectly. Subjects were given a maximum of 5 practice trials prior to data collection. Each subject performed 5 jump-landing tasks and were given a one minute rest period between trials to avoid fatigue.

Fusionetics (Global Movement Efficiency) Assessment

2-Leg Squat

Subjects were instructed on and performed a 2-legged squat. Subjects were instructed to stand with feet shoulder-width apart and pointed straight forward with arms fully extended directly over their head. The subjects were instructed to squat down as if they were trying to sit in a chair. The subject was asked to complete a total of 15 squats as the researcher observed 5 squats from the front, side, and rear view. An expert rater and a beginner rater researcher then recorded compensations that occurred. From the front view, compensations included if the feet turned out or flattened and if the knees moved into valgus or varus. From the side view, compensations included an excessive forward lean, if the low back arched or rounded, and if the arms fell forward. From the rear view, compensations included heel lifts or an asymmetrical weight shift occurred.

2-Leg Squat with Heel Lift

Subjects were instructed to perform a 2-legged squat with a 2-inch wood block placed directly underneath their heels. As with previous task, subjects were instructed to stand with feet shoulder-width apart and pointed straight forward with arms fully extended directly over their head. The subjects were instructed to squat down as if they were trying to sit in a chair. The subject was asked to complete a total of 15 squats as the researcher observed 5 squats from the front, side, and rear view. The researcher then recorded compensations that occurred. From the front view, compensations included if the feet turned out or flattened and if the knees moved into valgus or varus. From the side view, compensations included an excessive forward lean, if the low back arched or rounded, and if the arms fell forward. From the rear view, compensations included heel lifts or an asymmetrical weight shift occurred.

1-Leg Squat

Subjects were instructed on and performed a 1-legged squat. Subjects were instructed to stand on one foot with their hands placed on their hips. The subjects were instructed to squat down as if they were trying to sit in a chair. The subject was asked to complete a total of 5 squats per leg as the researcher observed from the front. The researcher then recorded compensations that occurred. Possible compensations included if the feet flattened, the knees moved into valgus or varus, or if they displayed an uncontrolled trunk including trunk flexion, rotation, and/or hip shift, or a loss of balance occurred.

Push-Up

Subjects were instructed to assume a push-up position with feet, hips, shoulders, and hands properly aligned at chest level and approximately shoulder-width apart. The subjects were instructed to lower themselves toward the ground with their chest approximately 3-5 inches away from the floor and then to return to start position. The subject was asked to complete 10 push-ups while the researcher observed for compensations from the side. Possible compensations included the head moving forward, scapular winging, low back arching, stomach protruding, or knees bending.

Shoulder Movement

The subjects were instructed to stand with posterior side flat against a wall. The subjects were instructed to complete shoulder flexion, internal rotation, external rotation, and horizontal abduction with both arms independently. From the side the researcher observed for compensations during the movements including an inability to bring their hand to the wall during flexion, external rotation, and horizontal abduction, and an inability to bring their hand to the mid-line of their trunk during internal rotation.

Trunk / Lumbar Spine Movements

The subjects were instructed to stand upright in a neutral position. The subjects were instructed to complete trunk lateral flexion and rotation. From the front the researcher observed for compensations during the movements including an inability to reach the lateral joint line of the knee during lateral flexion and an inability to rotate their shoulder to the midline of their trunk during rotation.

Cervical Spine Movement

The subjects were instructed to stand with their posterior side flat against the wall. The subjects were instructed to complete lateral flexion and rotation. The researcher observed for compensations from the front including an inability to side-bend half the distance to the shoulder during lateral flexion and an inability to rotate their chin to their shoulder during rotation.

After completing the movement quality screenings, subjects were asked to complete a 10-minute jog around the indoor track at a self-selected pace.
Subjects were then taken through the performance tests. Performance tests were completed in a randomized order.

Performance Assessments

T-Test

Four cones were laid out in a T pattern. A base set of timing gates was utilized for timing of the t-test. The leg of the T was 10 yards in length from the timing gates. The crosspiece of the T was 10 yards in length. The subject was instructed to begin at the base. The subject was instructed to sprint to the cone in the middle of the crosspiece, side-shuffle to the left cone, side-shuffle to the far right cone, side-shuffle back to the middle cone, and then backpedal to the base cone and to begin the test on the verbal instruction of “go”. Each subject performed the T-test 3 times shuffling to the left and right alternating between sides. The subject was given a minute rest period between trials to avoid fatigue.

Single-Leg Triple Hop

For the single-leg triple hop, the subject was instructed to jump on one leg three times consistently as far forward as possible. The distance was recorded from the edge of the starting line to the placement of the subject’s heel on the last jump. Each subject performed the test 3 times on the right and left limb alternating between each side and was given a 30 second rest period between trials to avoid fatigue.

Seated Rotational Medicine Ball Throw

For the seated rotational medicine ball throw, subjects were given a 2.7-kg medicine ball. Subjects were seated on a plyometric box with their feet flat on the floor and facing perpendicular to the direction they threw the medicine ball. Subjects were instructed to forward flex at their hips and abdomen while rotating to either the left or right side.[52] Subjects were instructed to rotate and throw the medicine ball as far as they can. Each subject performed the test 3 times to the right and left alternating between each side and were given a 30 second rest period between trials to avoid fatigue.

40-yard Sprint

For this test, two sets of timing gates were laid out 40-yards apart. The subject was instructed to sprint the 40-yards as fast as possible all the way through the second set of timing gates. Timing began on the first movement and stopped after the subject hit the 40-yard mark. Each subject performed the test 3 times and was given a minute rest period between trials to avoid fatigue.

DATA REDUCTION

LESS Scoring Criteria

1. Knee flexion angle at initial contact:
   a. If the knee flexed to an angle greater than 30 degrees, the subject was marked YES.
   b. If the knee was not flexed to an angle greater than 30 degrees, the subject was marked NO.
2. Hip flexion angle at initial contact:
   a. If the thigh was flexed on the trunk, the subject was marked YES.
   b. If the thigh was in line with the trunk and the hips were not flexed the subject was marked NO.
3. Trunk flexion angle at initial contact:
   a. If the trunk was flexed on the thigh, the subject was marked YES.
   b. If the trunk was vertical or extended on the hips, the subject was marked NO.
4. Ankle Plantarflexion at initial contact:
   a. If the foot landed toe to heel, the subject was marked with YES.
   b. If the foot landed heel to toe or flat, the subject was marked with NO.
5. Knee valgus angle at initial contact:
   a. If the patella moved medially past the great toe, the subject was marked YES.
   b. If the patella did not move medially past the great toe, the subject was marked with NO.

6. Lateral trunk flexion angle at initial contact:
    a. If the midline of the trunk was flexed to the left or right of the body, the subject was marked YES.
    b. If the midline of the trunk was not flexed to the left or right of the body, the subject was marked NO.
7. Stance width – Wide:
    a. If the foot landed wider than shoulder width, the subject was marked YES.
    b. If the foot did not land wider than shoulder width, the subject was marked NO.

See Appendix 1 for LESS scoring criteria.

Movement Efficiency Scoring Criteria

1. 2-Leg Squat
    a. Foot Turn-Out
        i. If a foot deviated laterally so that the medial borders were no longer parallel, the foot that deviated was marked.
        ii. If neither foot deviated laterally so that the medial borders remained parallel, the subject was not identified as having the compensation.
    b. Foot Flattens
        i. If a foot displayed the medial longitudinal arch moving toward the ground and / or touching the ground, the foot that moved was marked.

ii. If neither foot moved so that the medial longitudinal arch remained in place, the subject was not identified as having the compensation.

c. Knee Valgus

i. If the patella of a knee deviated medially past the great toe, the knee that deviated was marked.

ii. If the patella of either knee did not deviate medially past the great toe, the subject was not identified as having the compensation.

d. Knee Varus

i. If the patella of a knee deviated laterally past the third toe, the knee that deviated was marked.

ii. If the patella of either knee did not deviate laterally past the third toe, the subject was not marked as having the compensation.

e. Forward Lean

i. If the torso flexed forward so that it was no longer parallel with the lower leg, the subject was marked YES for having the compensation.

ii. If the torso remained parallel with the lower leg, the subject was not marked as having the compensation.

f. Low Back Arch

i. If the lumbar spine moved into excessive extension out of neutral alignment, the subject was marked YES for having the compensation.

ii. If the lumbar spine remained in neutral alignment, the subject was not marked for having the compensation.

g. Low Back Round

i. If the lumbar spine moved into excessive flexion out of neutral alignment, the subject was marked YES for having the compensation.

ii. If the lumbar spine remained in neutral alignment, the subject was not marked for having the compensation.

h. Arms Fall Forward

i. If the arms fell forward past the ears or the elbows flexed, the subject was marked YES for having the compensation.

ii. If the arms remained in line and the elbows did not flex, the subject was not marked for having the compensation.

i. Heel of Foot Lifts

i. If a heel lifted up and no longer made contact with the ground, the heel that lifted was marked.

ii. If both heels remained in contact with the ground, the subject was not marked for having the compensation.

j. Asymmetrical Weight Shift

i. If the hips and pelvis laterally deviated from the midline of the body, the side it deviated to was marked.

ii. If the hips and pelvis remained in line, the subject was not marked for having the compensation.

2. 2-Leg Squat with Heel Lift

    a. Foot Turn-Out

        i. If a foot deviated laterally so that the medial borders were no longer parallel, the foot that deviated was marked.

        ii. If neither foot deviated laterally so that the medial borders remained parallel, the subject was not identified as having the compensation.

    b. Foot Flattens

        i. If a foot displayed the medial longitudinal arch moving toward the ground and / or touching the ground, the foot that moved was marked.

        ii. If neither foot moved so that the medial longitudinal arch remained in place, the subject was not identified as having the compensation.

    c. Knee Valgus

        i. If the patella of a knee deviated medially past the great toe, the knee that deviated was marked.

        ii. If the patella of either knee did not deviate medially past the great toe, the subject was not identified as having the compensation.

    d. Knee Varus

        i. If the patella of a knee deviated laterally past the third toe, the knee that deviated was marked.

        ii. If the patella of either knee did not deviate laterally past the third toe, the subject was not marked as having the compensation.

e. Forward Lean

    i. If the torso flexed forward so that it was no longer parallel with the lower leg, the subject was marked YES for having the compensation.

    ii. If the torso remained parallel with the lower leg, the subject was not marked as having the compensation.

f. Low Back Arch

    i. If the lumbar spine moved into excessive extension out of neutral alignment, the subject was marked YES for having the compensation.

    ii. If the lumbar spine remained in neutral alignment, the subject was not marked for having the compensation.

g. Low Back Round

    i. If the lumbar spine moved into excessive flexion out of neutral alignment, the subject was marked YES for having the compensation.

    ii. If the lumbar spine remained in neutral alignment, the subject was not marked for having the compensation.

h. Arms Fall Forward

    i. If the arms fell forward past the ears or the elbows flexed, the subject was marked YES for having the compensation.

    ii. If the arms remained in line and the elbows did not flex, the subject was not marked for having the compensation.

i. Asymmetrical Weight Shift

   i. If the hips and pelvis laterally deviated from the midline of the body, the side it deviated to was marked.

   ii. If the hips and pelvis remained in line, the subject was not marked for having the compensation.

3. 1-Leg Squat

   a. Foot Flattens

      i. If a foot displayed the medial longitudinal arch moving toward the ground and / or touching the ground, the foot that moved was marked.

      ii. If neither foot moved so that the medial longitudinal arch remained in place, the subject was not identified as having the compensation.

   b. Knee Valgus

      i. If the patella of a knee deviated medially past the great toe, the knee that deviated was marked.

      ii. If the patella of either knee did not deviate medially past the great toe, the subject was not identified as having the compensation.

   c. Knee Varus

      i. If the patella of a knee deviated laterally past the third toe, the knee that deviated was marked.

      ii. If the patella of either knee did not deviate laterally past the third toe, the subject was not marked as having the compensation.

   d. Uncontrolled Trunk

i. If pelvis hiking / dropping on stance leg, lateral flexion, or rotation occurred, the side that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

e. Loss of Balance

i. If the hands come off the hips or the non-stance leg touches the ground, the side that caused the compensations was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

4. Push Up

a. Head Moves Forward

i. If the head moved toward the ground out of alignment, the subject was marked YES for having the compensation.

ii. If the head remained in alignment, the subject was not marked for having the compensation.

b. Winging Scapula

i. If the shoulder blades excessively moved up toward the ceiling or head, the subject was marked YES for having the compensation.

ii. If the shoulder blades did not move excessively up toward the ceiling or head, the subject was not marked for having the compensation.

c. Low Back Arching / Stomach Protruding

i. If the lumbar spine moved into excessive extension out of neutral alignment and the stomach moved toward the ground, the subject was marked YES for having the compensation.

ii. If the lumbar spine and stomach remained in line, the subject was not marked for having the compensation.

d. Knees Bend

i. If the knees were unable to maintain alignment with the body, the subject was marked for having the compensation.

ii. If the knees were able to maintain alignment with the body, the subject was not marked for having the compensation.

5. Shoulder Movement

a. Flexion

i. If cervical spine protraction, shoulder elevation, lumbar spine excessive extension out of neutral alignment, elbow flexion, or back / glut lost contact with the wall, the side that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensation.

b. Internal Rotation

i. If shoulder elevation, shoulder blade protraction or anterior tilting occurred away from the wall, or the hand / forearm did not reach an optimal position, the side that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensation.

c. External Rotation

i. If cervical protraction, shoulder elevation, lumbar spine excessive extension out of neutral alignment, back / glut lost contact with the wall, or the hands did not get within an ideal distance from the wall, the side that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

d. Horizontal Abduction

i. If cervical protraction, shoulder elevation, shoulder blade protraction or anterior tilting away from the wall, elbow flexion, lumbar spine excessive extension out of alignment, back / glut lost contact with the wall, or the hands did not get within an ideal distance from the wall, the side that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

6. Trunk / Lumbar Spine Movement

a. Lateral Flexion

i. If shoulder elevation, cervical spine hyperextension / flexion / rotation, lumbar spine excessive extension out of neutral alignment, hip flexion or lateral shift, knee flexion, medial longitudinal arches touched ground, or heels lifted off the floor, the direction of the flexion that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

b. Rotation

i. If shoulder elevation, head laterally flexed / rotated / forward movement, lateral flexion of trunk, thoracic spine flexion, lumbar spine excessive extension out of neutral alignment, pelvis shifting / rotation, knee flexion / valgus, medial longitudinal arches touched ground, or heels lifted off the floor, the direction of the rotation that caused the compensations was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

7. Cervical Spine Movement

a. Lateral Flexion

i. If shoulder elevation, head movement away from wall, hyperextension, or cervical flexion / rotation, the direction of flexion that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

b. Rotation

i. If shoulder elevation, shoulder / head movement away from wall, or hyperextension / flexion / lateral flexion of the cervical spine occurred, the direction of the rotation that caused the compensation was marked.

ii. If none of the aforementioned compensations occurred with either side, the subject was not marked for having the compensations.

See Appendix 2 for Movement Efficiency Scoring Criteria.

For each subject, the times for each trial of the t-test for both the right and left sides and 40-yard sprint were averaged independently. Averages were also taken for both the right and left sides of the seated rotational medicine ball throws and single-leg triple hops independently.

APPENDIX 1

Item #	LESS item	Operational definition	Camera View
1	Knee flexion angle at initial contact	At the time point of initial contact, if a knee is flexed less than 30 degrees, score Asymmetrical Heel-Toe/Toe-Heel , score ERROR. If both knees are flexed more than 30 degrees, score NO ERROR.	Sagittal plane
2	Hip flexion angle at initial contact	At the time point of initial contact, if a thigh is in line with the trunk then a hip is not flexed and score ERROR If both thighs are flexed on the trunk, score NO ERROR.	Sagittal plane
3	Trunk flexion angle at initial contact	At the time point of initial contact, if the trunk is vertical or extended on the hips, score ERROR. If the trunk is flexed on the hips, score NO ERROR.	Sagittal plane
4	Ankle plantar-flexion angle at initial contact	At the time point of initial contact, if a foot lands heel to toe or flat foot, score ERROR. If both feet land toe to heel, score NO ERROR.	Sagittal plane
5	Asymmetrical foot contact	If one foot lands before the other or if one foot lands heel to toe or foot flat and the other lands differently (i.e. toe to heel), score ERROR. If the feet land symmetrically, score NO ERROR.	Sagittal plane and Frontal plane
6	Asymmetrical TIMING	If one foot lands before the other, score ERROR. If the feet land at the same time, score NO ERROR.	Sagittal plane and frontal plane
7	Asymmetrical Heel-Toe/Toe-Heel	If one foot lands heel to toe or foot flat and the other lands toe to heel, score ERROR. If the feet land symmetrically, score NO ERROR.	Sagittal plane and frontal plane
8	Lateral trunk flexion angle at initial contact	At the time point of initial contact, if the midline of the trunk is flexed to the left or the right side of the body, score ERROR. If the trunk is not flexed to the left or right side of the body, score NO ERROR.	Frontal plane
9	Medial knee position at initial contact	At the time point of initial contact, draw a line straight down from the center of the patella. If the line is medial to the midfoot, score ERROR. If the line goes through the midfoot, score NO ERROR.	Frontal plane

10-11	Stance width	Once the entire foot is in contact with the ground, draw a line down from the tip of each shoulder. If a line falls inside a foot, score ERROR for greater than shoulder width. If a line falls outside of a foot, score ERROR for less than shoulder width. If both lines fall on the feet, score NO ERROR. ***If a foot is internally or externally rotated, grade the stance width based on heel placement.	Frontal plane
12-13	Foot position	At the point of maximum rotation between initial contact and maximum knee flexion, if a foot is externally or internally rotated more than 30 degrees, then score ERROR. If the feet are not internally or externally rotated more than 30 degrees between the time period of initial contact to max knee flexion, score NO ERROR.	Frontal plane
14	Knee flexion displacement	If a knee does not flex more than 45 degrees from initial contact to maximum knee flexion, score ERROR. If the knees do not flex more than 45 degrees, score NO ERROR.	Sagittal plane
15	Hip flexion displacement	If a thigh does not flex more on the trunk from initial contact to maximum knee flexion angle, score ERROR. If a thigh flexes more on the trunk from initial contact to maximum knee flexion, score NO ERROR.	Sagittal plane
16	SMALL Trunk flexion displacement	If the trunk does not flex more from the point of initial contact to maximum knee flexion, score ERROR. If the trunk does flex more from the point of initial contact to maximum knee flexion, score NO ERROR.	Sagittal plane
17	EXCESSIVE Trunk flexion displacement	If the trunk flexes past parallel with the lower leg, score ERROR. If the trunk appears parallel with the lower leg or less, score NO ERROR.	Sagittal plane
18	Maximum medial knee position	At the point of maximal medial knee position, draw lines straight down from the center of each patella. If a line runs through the great toe or is medial to the great toe, score ERROR. If both lines are lateral to the great toe, score NO ERROR.	Frontal plane
19	Asymmetrical LOADING	If subject appears to have a weight-shift, or be loading one side more than the other, score ERROR. If weight seems to be loaded evenly across both limbs, score NO ERROR.	Frontal plane
20	Wobble	Watch landing REAL-TIME. If one or both of subject's knees appears to "wobble", or demonstrate quick varus/valgus motion, score ERROR. If no wobble is present, score NO ERROR.	Frontal plane

21	Joint displacement	Watch the sagittal plane motion at the trunk, hips, and knees from initial contact to maximum knee flexion angle. If the subject goes through large displacement of the trunk, hips, and knees then score SOFT. If the subject goes through some trunk, hip, and knee displacement but not a large amount, then score AVERAGE. If the subject goes through very little, if any trunk, hip, and knee displacement, then score STIFF.	Sagittal plane
22	Overall impression	Score EXCELLENT if the subject displays a soft landing and no frontal plane motion at the knee. Score POOR if the subject displays a stiff landing and at least some frontal or transverse plane lower extremity motion OR large frontal or transverse plane lower extremity motion. All other landings score AVERAGE.	Sagittal plane and Frontal plane

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APPENDIX 2

Movement Efficiency Item	View	Region	Compensation	Presence of Compensation	Operational Definition
Double Leg Squat	Front	Foot / Ankle	Foot Turn-Out	R / L	Feet deviate laterally so medial borders are no longer parallel
			Foot Flattens	R / L	Medial longitudinal arch touches floor
		Knee	Valgus	R / L	Knee deviates medially past the great toe
			Varus	R / L	Knee deviates laterally past the third toe
	Side	Low Back / Hip	Forward Lean	Y / N	Torso no longer parallel with lower leg
			Low Back Arch	Y / N	Excessive extension in reference to neutral alignment
			Low Back Round	Y / N	Excessive flexion in reference to neutral alignment
		Shoulder	Arms Fall Forward	Y / N	Arms fall forward past the ears or elbow flexion occurs
	Back	Foot / Ankle	Heel of Foot Lifts	R / L	Heels no longer touch floor
		Low Back / Hip	Asymmetrical Weight Shift	R / L	Hips and pelvis laterally deviate from midline of body

Movement Efficiency Item	View	Region	Compensation	Presence of Compensation	Operational Definitions
Double Leg Squat with Heel Lift	Front	Foot / Ankle	Foot Turn-Out	R / L	Feet deviate laterally so medial borders are no longer parallel
			Foot Flattens	R / L	Medial longitudinal arch touches floor
		Knee	Valgus	R / L	Knee deviates medially past the great toe
			Varus	R / L	Knee deviates laterally past the third toe
	Side	Low Back / Hip	Forward Lean	Y / N	Torso no longer parallel with lower leg
			Low Back Arch	Y / N	Excessive extension in reference to neutral alignment
			Low Back Round	Y / N	Excessive flexion in reference to neutral alignment
		Shoulder	Arms Fall Forward	Y / N	Arms fall forward past the ears or elbow flexion occurs
	Back	Low Back / Hip	Asymmetrical Weight Shift	R / L	Hips and pelvis laterally deviate from midline of body

Movement Efficiency Item	**View**	**Region**	**Compensation**	**Presence of Compensation**	**Operational Definition**
Single Leg Squat	Front	Foot / Ankle	Foot Flattens	R / L	Medial longitudinal arch touches floor
		Knee	Valgus	R / L	Knee deviates medially past the great toe
			Varus	R / L	Knee deviates laterally past the third toe
		Low Back / Hip	Uncontrolled Trunk	R / L	Hips do not remain level or squared
			Loss of Balance	R / L	Hands leave hips or non-stance leg touches floor

STATISTICAL ANALYSIS

All data analyses were performed using SPSS version 13.0 (SPSS, Inc. Chicago, IL). Spearman's rank-order correlations were run to examine the relationships between the LESS total error score and Fusionetics movement efficiency total error score (number of errors totaled from all 7 tasks incorporated in screen), squat total error score (number of errors totaled from the 2-leg squat, 2-leg squat with heel lift, and 1-leg squat), and upper quarter total error score (number of errors totaled from push-ups, shoulder movements, trunk movements, and cervical movements) independently with performance levels for each dependent variable. Statistical significance was set a-priori at $p < 0.05$.

RESEARCH DESIGN RUBRIC

Question	Description	Data Source	Method
1a.	What is the association between lower extremity movement quality and agility?	IV: • LESS score DV: • T-test time (seconds)	Spearman rho correlation
1b.	What is the association between lower extremity movement quality and lower extremity power?	IV: • LESS score DV: • SL Triple Hop Distance (feet)	Spearman rho correlation
1c.	What is the association between lower extremity movement quality and core power?	IV: • LESS score DV: • Med Ball Throw Distance (feet)	Spearman rho correlation
1d.	What is the association between lower extremity movement quality and speed?	IV: • LESS score DV: • 40-yard sprint time (seconds)	Spearman rho correlation
2a.	What is the association between global movement quality and agility?	IV: • ME Total Error score • Squat Total Error score • UQ Total Error Score DV: • T-time test (sec)	Spearman rho correlation
2b.	What is the association between global movement quality and lower extremity power?	IV: • ME Total Error score • Squat Total Error score • UQ Total Error Score DV: • SL Triple Hop Distance (feet)	Spearman rho correlation

2c.	What is the association between global movement quality and core power?	IV: • ME Total Error score • Squat Total Error score • UQ Total Error Score DV: • Med Ball Throw Distance (feet)	Spearman rho correlation
2d.	What is the association between global movement quality and speed?	IV: • ME Total Error score • Squat Total Error score • UQ Total Error Score DV: • 40-yard sprint time (seconds)	Spearman rho correlation

CHAPTER 4

MANUSCRIPT

INTRODUCTION

Lower extremity injuries account for approximately two-thirds of all injuries seen in collegiate athletics.[1] Approximately three-fourths of these injuries are being sustained through non-contact mechanisms of injury, suggesting that there are underlying neuromuscular dysfunctions and muscle imbalances pre-disposing these individuals to injury.[28,29,53] These factors have been identified through screening tools developed to assess an individuals' movement quality through both slow-controlled and high-energy, dynamic movement assessment screens.[4] Furthermore, studies have shown that injury prevention programs (IPPs) addressing poor movement quality have reduced lower extremity injuries by 65-85%.[14] Unfortunately, compliance with implementing IPPs is low.[46] It has been theorized that low compliance from both coaches and athletes is due to a limited amount of time available for training, and that the focus of their training time needs to be on enhancing performance.[13] Redirecting the focus of IPPs from improving movement quality and reducing injury rates to how these changes may also effect performance enhancement may increase coaches' and athletes' interest and compliance of these programs. However, there is little research examining the association between movement quality with functional performance measures. Therefore, the purpose of this study was to examine the association between clinical measures of movement quality with functional performance measures.

METHODS

Subjects

25 varsity female athletes from the university setting volunteered for this study (n= 4 soccer, n= 2 volleyball, n= 3 field hockey, n= 6 lacrosse, n= 7 tennis, n= 3 basketball). Subjects were excluded from the study if she 1) suffered a lower extremity injury in the last six months that kept her out of sport participation for 4+ days consistently 2) had undergone a lower extremity surgery in the past year or 3) was currently injured or currently experiencing pain more than general muscle soreness as perceived by the individual. Prior to data collection, subjects read and signed an informed consent from approved by the Institutional Review Board at the University of North Carolina Chapel Hill. Subjects were also required to complete a health and activity questionnaire to ensure compliance with the study's inclusion criteria, injury history, and to obtain height and weight. Subjects were required to wear athletic shoes, shirts, and shorts that allowed the patella to be completely visible.

Procedures

All subjects were required to attend a single testing session lasting approximately 1 hour and 45 minutes. After ensuring all required documentation were completed and inclusion criteria were met, the subjects were asked to perform a series of dynamic (jump-landing) and slow-controlled (double and single leg squats) movement tasks. The

Landing Error Scoring System (LESS) was used to evaluate movement quality during the dynamic jump-landing task. A similar scoring criteria was used to evaluate movement quality during the double leg (DLS) and single leg squat (SLS) tasks. The specific movement error criteria for both LESS and squat evaluations will be discussed further in the Data Reduction/Analysis section.

Movement quality during the dynamic task was evaluated as subjects performed 5 trials of a standardized jump-landing task. Subjects jumped forward from a 30-cm high box at a distance half of their height, marked with white athletic tape on the ground. Subjects were instructed to jump forward with their heels landing past the tape, and then to immediately jump as high as they could following their landing. Subjects were instructed to leave the box and land with both feet simultaneously and were allowed a maximum of five practice trials to ensure they were completing the task correctly.

A Microsoft Kinect v2.0™ sensor (The Microsoft Corporation, Redmond Washington, USA) was positioned 10 feet in front of the subject to record all jump-landing trials. Unlike previous dual-view camera systems (anterior and side views) that have been used to record jump-landing trials for LESS scoring, the Kinect-based system requires a single video and depth sensor to evaluate LESS scores. LESS scoring operational definitions have been previously described[9], and are provided in APPENDIX 3.

Movement quality during the slow-controlled squat tasks was evaluated as the subject's performed a series of DLS and SLS. First, subjects were instructed on and performed a DLS. Subjects were instructed to stand with feet shoulder-width apart and pointed straight forward with arms fully extended directly over their head. The subjects were instructed to squat down as if they were trying to sit in a chair. The subject was asked to complete a total of 15 squats as the researcher observed 5 squats from the front, side, and rear view. The subjects were then asked to complete the DLS with their heels lifted onto a 4-cm wood block with the same instructions as the DLS with their heels on the ground. The final lower body task required was a SLS on each limb. Subjects were instructed to stand on one foot with their hands placed on their hips. The subjects were instructed to squat down as if they were trying to sit in a chair. The subject was asked to complete a total of 5 squats per leg while being observed from the front.

Movement errors were identified in real-time by a member of the research team (AY) as participant's performed the double and single leg squat tasks. Double leg and single leg squat error operational definitions have been described and can be found in Appendix 4.

Subjects were then instructed to complete a functional and/or dynamic self-directed warm-up to prepare for the functional performance tests. In a randomized fashion, subjects were then asked to complete three 40-yard dash trials, three “T”-tests cutting to the right and left alternating sides in-between each trial (six total trials), as well as three seated rotational medicine ball tosses and single-leg triple hops to the right and left alternating sides in-between trials. Subjects were given at least a one-minute rest break in-between task trials and a two-minute rest break in-between tasks to ensure readiness and avoid fatigue. Subjects were given more rest time upon request, however, no participant required additional rest time.

For the 40-yd sprint, two sets of timing gates (TF100, Trac Tronix, Lenexa, Kansas, United States) were laid out 40-yards apart. The subject was instructed to sprint the 40-yards as fast as possible all the way through the second set of timing gates. Timing began on the first movement and stopped after the subject hit the 40-yard mark. Each subject completed 3 trials and the average of the trials was used for data analysis.

The previously described timing gate system was used for timing of the “T”-test. Four cones were laid out in a “T” pattern. The longitudinal leg of the “T” was 10 yards in length from the timing gates to the intersection of the “T” cross-piece. The crosspiece of the “T” was also 10 yards in length. The subject was instructed to begin at the base. The subject was instructed to sprint to the cone in the middle of the crosspiece, side-shuffle to the left cone, side-shuffle to the far right cone, side-shuffle back to the middle cone without any foot cross-over, and then backpedal to the base cone and to begin the test on the verbal instruction of “go”. Each subject performed the “T”-test 3 times shuffling to the left and right alternating between sides. Both the single-leg triple hop and seated rotational medicine ball throw began at a starting point marked with athletic tape. For the single-leg triple hop, the subject was instructed to jump on one leg three times consistently as far forward as possible. The distance was recorded from the edge of the starting line to the placement of the subject's heel on the last jump. Each subject performed the test 3 times on the right and left limb alternating between each side.

For the seated rotational medicine ball throw, subjects were given a 2.7-kg medicine ball. Subjects were seated on a 47-cm high plyometric box with their feet flat on the floor and facing perpendicular to the direction they threw the medicine ball. Subjects were instructed to forward flex at their hips and abdomen while rotating to either the left or right side.[52] Subjects were instructed to rotate and throw the medicine ball as far as they can. Each subject performed the test 3 times to the right and left alternating between each side. The averages of each side were used for data analysis.

Data Reduction:

Landing Error Scoring System (LESS).

All jump-landing trials were evaluated from data collected by the Kinect sensor using Physimax software. To objectively score the LESS, the Microsoft Kinect v2.0™ sensor streamed video data to a Lenovo Thinkpad Laptop CPU (The Lenovo Corporation, Morrisville, NC, USA) running a web-based PhysiMax™ application (PhysiMax, Tel Aviv, Israel). The PhysiMax™ application autonomously scores the LESS from the depth camera video data streamed to the CPU the from the Kinect v2.0™ sensor. The Kinect v2.0™ sensor is capable of establishing a 3-dimensional rigid body segment link model from the sensor's data stream. The established rigid body segments of interest included the thorax, pelvis, thigh, shank, and foot. Three degree of freedom segmental linkages (anatomical joint estimates) between the thorax-pelvis, pelvis-thigh, thigh-shank, and shank-foot interfaces established the L5-S1, hip, knee, and ankle joints respectively. Using both linear and angular kinematic data from the 3-dimensional rigid body segment link model the PhysiMax application autonomously scored the first (trials 1, 2, 3) of the 5 jump-landings based on the operationally defined LESS error criterion (Appendix 3). We have evaluated the validity of Kinect-based LESS scores as compared to expert raters and have observed strong correlations between Kinect based and expert rater LESS scores.

The Landing Error Scoring System (LESS) is a standardized clinical movement assessment tool for identifying improper movement patterns during the jump landing tasks. The LESS uses a binary system (0,1) to evaluate landing technique based on nine jump landing characteristics: knee flexion angle, knee valgus angle, trunk flexion angle, ankle plantar-flexion angle, foot position, stance width, foot contact (heel or toe first), overall joint motion, and overall impression of landing "quality". A higher LESS score indicates a greater number of landing errors committed, and thus poor jump landing technique.

The LESS has been shown to be both a reliable (intra-rater: $ICC_{2,k}$=.90, SEM=1.08; inter-rater: $ICC_{2,1}$=.83, SEM=1.50) tool to assess landing errors in large populations of subjects efficiently.[54,55] In addition to being reliable, predictive and concurrent validity of the LESS has also been established.[54-56] The LESS and an electromagnetic motion analysis tool yield comparable conclusions about specific landing errors, such as knee flexion, knee valgus torque, and vertical ground reaction forces.[54] [9]Predictive validity of the LESS has been established in prospective research that has been conducted comparing LESS scores between ACL-injured and non-injured individuals.[56] The results revealed that ACL-injured subjects demonstrated less knee flexion motion and less flexion in all lower extremity joints compared to the non-injured subjects.

Statistical Analyses

All data analyses were performed using SPSS version 13.0 (SPSS, Inc. Chicago, IL). Spearman's rank-order correlations were run to examine the relationships between the movement quality scores (LESS Score and Squat Score) with the averages of each functional performance measure (40 yard sprint, "T"-test to right, "T"-test to left, triple hop on right leg, triple hop on left leg, medicine ball throw to right, medicine ball throw to left). Statistical significance was set a-priori at $p < 0.05$.

RESULTS

Data was analyzed on 24 of the 25 subjects who volunteered for the study. Means and standard deviations for movement quality and functional performance measures are listed in Tables 1 and 2, respectively. Dynamic movement quality assessment using LESS scores were significantly associated with the following functional performance measures: "T"-test to the right and left, triple hop on right and left leg, and medicine ball throw to the right and left (Table 3). In agreement with our hypothesis, each of the significant associations indicated that higher LESS scores (poor movement quality) was associated with decreased functional performance on measures of power and agility.

However, there were no significant association between the LESS and 40-yard sprint time.

In contrast to our hypothesis, movement quality assessed during slow and controlled tasks, such as the double and single leg squat, was not associated with functional performance. There were also no significant associations between the total number of errors during the double and single leg squat tasks with any of the functional performance measures (Table 1). Thus, movement quality during more slow and controlled movements does not appear to influence our measures of power, speed or agility. Performance and movement quality descriptives are provided in Tables 2 and 3, respectively.

Table 1 – Movement Quality and Functional Performance Measure Associations

	LESS Score		Squat Total Error	
	r	p	r	p
"T"-Test R Avg	.491	.025*	-.156	.457
"T"-Test L Avg	.543	.006*	-.237	.255
Med Ball R Avg	-.467	.021*	.335	.101
Med Ball L Avg	-.426	.038*	.237	.254
Triple Hop R Avg	-.419	.042*	-.004	.984
Triple Hop L Avg	-.451	.027*	-.020	.926
40-yd Sprint Avg	.366	.079	.112	.594

Table 2 – Performance Descriptives

	Mean	Std. Deviation
"T"-Test R Avg	10.45	0.57
"T"-Test L Avg	10.46	0.61
Med Ball R Avg	22.16	2.74
Med Ball L Avg	22.18	3.28
Triple Hop R Avg	16.85	1.62
Triple Hop L Avg	17.49	1.50
40-yd Sprint Avg	5.74	0.39

Table 3 – Movement Quality Descriptives

	Mean	Std. Deviation
LESS	4.9	2.0
Total Squat	14.2	3.7
Double Leg Squat	5.9	2.1
Double Leg Squat with Heel Lift	2.0	1.7
Single Leg Squat R	3.2	0.9
Single Leg Squat L	3.3	0.8

DISCUSSION

The most important findings from this study indicate that dynamic movement quality, assessed using the LESS, is associated with lower extremity agility ("T"-test), lower extremity power (single-leg triple hop), and lumbo-pelvic-hip (core) power (medicine ball throw) in collegiate division 1 female athletes. However, no such relationship was observed between movement quality assessed during slow and controlled tasks with functional performance measures of lower extremity agility, lower extremity power, core power, and speed.

Previous research examining the relationship between movement quality and functional performance is mixed. Similar studies have been performed utilizing the Functional Movement Screen (FMS), which also uses slow, low-energy movement tasks to assess movement quality. Lockie et al. completed a study with similar methods to examine the relationship between the FMS with a 5-m sprint, 10-m sprint, 20-m sprint, 5-0-5 test, modified "T"-test, vertical jump, standing long jump, and lateral jump.[57] This study found that a higher-scoring hurdle step, in-line lunge, and active straight-leg raise (implying better movement) was related to poorer agility seen in the 505 and modified "T"-test.[57] This study also only found that a higher-scored left-leg active straight leg raise was related to a poorer unilateral vertical and standing broad jump.[57] Overall, this study found minimal relationships between FMS and athletic performance.[57] Similarly, Okada et al. investigated the relationship between the FMS with a backward medicine ball throw, "T"-run, and single-leg-squat.[33] Minimal significant relationships were found between individual FMS tasks with athletic performance tests.[33] The significant relationships found were ambiguous, with only the right shoulder mobility negatively correlated with the medicine ball throw, and only the left in-line lunge and right shoulder mobility being positively correlated to the agility "T"-test.[33] This would indicate that a higher FMS score was associated with a lower medicine ball distance and a slower "T"-test time, respectively. Parchmann and McBride had contrasting results in their study that looked at the association of the FMS in golfers with a 10-m sprint, 20-m sprint, vertical jump, modified t-test, and a sport-specific task of club head velocity.[34] This study found that no significant relationships existed between both the overall FMS score or any of the individual FMS tests with any athletic performance tests.[34] While these studies have mixed findings, overall there have been very minimal associations found between assessments of movement quality with functional performance measures. The findings of our study are in agreement with previous investigations. The slow and controlled assessments of movement quality used in our study show no associations with functional performance measures.

The dynamic assessment of movement quality used in our study, however, showed strong associations with lower extremity agility, lower extremity power, and core power. Although this is the first study to directly investigate the relationship between dynamic movement quality assessed through the LESS with athletic performance, previous studies have found that you can improve both dynamic movement quality and performance through implementation of neuromuscular training through an injury prevention program.[58,59] After implementing a 10-15 minute prevention program, 3 to 4 times per week for an entire season on youth soccer players, DiStefano et al found that subjects who had LESS scores of 6 or higher in the beginning of the season achieved the greatest improvements at the end of the season.[58] Similarly, Myer et al used baseline knee abduction moments during a drop-vertical jump to assess changes after implementation of a neuromuscular training program.[59] This study also found that individuals that displayed a higher risk for injury achieved greater improvements.[58] While these are more indirect investigations, these findings suggest that movement quality assessed during more explosive, maximal effort tasks do appear to influence functional performance. Our findings coincide with this concept in that individuals with poor movement quality during maximal effort dynamic tasks have reduced functional performance. Furthermore, they extend this previous work as a direct association was analyzed between dynamic movement quality and functional performance.

The mixed findings between dynamic versus slow-controlled movement quality with performance suggest that associations between movement quality and functional performance may be task dependent.[33,34,60] A recent study investigating the biomechanics of firefighters during functional tasks found that they are not strongly related to the biomechanics of slow and controlled movement screens, such as the FMS.[60] Specificity of testing may be important when considering the relationship between movement quality and functional performance measures. In this study, we observed several significant associations between movement quality assessed with a dynamic, maximal performance task (LESS). Specifically, we observed there was a strong, positive correlation between the LESS and the “T”-test to both sides indicating a higher LESS score (poorer movement quality) was associated with slower t-test times. Additionally, there was a strong, inverse correlation between the LESS and the seated rotational medicine ball throws to both sides, as well as the single-leg triple hops on both legs. This indicates that poorer movement quality was also associated with shorter distances achieved. However, we did not observe such relationships when assessing movement quality during slow and controlled squatting tasks, even though movement quality criteria and basic movement patterns were nearly identical to those during the LESS.

The implications of this study show that movement quality is an important factor associated with various measures of functional performance including agility, core power, and lower extremity power. This is an important finding to stress to coaches and athletes to get a better relative advantage for implementing injury prevention programs designed to improve movement quality. Both the LESS and assessments using squat related tasks have been shown to successfully predict injury risk.[7,9,11,35,61,62] However, these findings should not suggest that the LESS is a preferred movement quality assessment over other tasks that are slow and controlled. Rather, it may suggest a need for a more comprehensive assessment of movement quality across a range of speeds and loads as suggested by McGill at el[60] in their study of firefighters. Furthermore, a secondary analysis of our data shows no significant associations between LESS scores and movement quality during the squat tasks implying that these are independent assessments of movement quality. Although both are related to injury risk, squats are associated with identifying neuromuscular dysfunctions, muscular imbalances, and joint mobility restrictions, which can successfully guide corrective exercise interventions to improve movement quality. Our findings strengthen the value of functional movement quality assessments as we see that more dynamic movement quality tests are not only associated with injury risk, but also associated with functional performance. Therefore, we recommend that a continuum of movement quality tests are utilized, including both the jump-landing and squats, creating a battery of tests to assess movement quality as it relates to both injury risk and athletic performance. These findings provide insight into the importance of improving dynamic movement quality to not only reduce injury risk, but also enhance performance. Previous research has shown that implementation of an IPP improves dynamic movement quality and results in improved performance variables.[13,58] Now that a direct association between dynamic movement quality and agility, lower extremity power, and core power have been identified, it is reasonable to suggest that implementation of an IPP will also result in improvement of these variables.

Associations between dynamic movement quality and functional performance were limited to power and agility as we did not observe an association with speed (40-yard sprint). A lack of association may suggest that speed is not associated with movement quality or that perhaps there is a need for a more task specific assessment of movement quality to see such a relationship. The findings of this study are also limited to just females in the division 1 college athlete population. While combining both males and females in the same study may limit results due to the innate variability of performance between the two groups, there is a need to replicate this study in males, as well as varying levels of athletics. Future studies should try to incorporate individuals that exemplify better movement quality with a low risk of injury. The results of our investigation are also limited to the movement screens and performance tasks utilized for our study.

Because our results suggest that specificity of task selection may better identify movement errors seen in performance variables, future studies should incorporate different performance tests to better assess the relationship of movement quality with agility, power, and speed.

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