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Assessment of core stability: developing practical models

Andy Waldhelm
Louisiana State University and Agricultural and Mechanical College, awaldh1@lsu.edu

ASSESSMENT OF CORE STABILITY: DEVELOPING PRACTICAL MODELS

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Andy Waldhelm
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ABSTRACT

Core stability is a concept in the health and fitness professions which became popular in the early 1990s. Professionals such as physicians, physical therapists, biomechanists, and chiropractors use the concept to educate patients on the recovery from or prevention of injuries. Despite its popularity, core stability remains a generalized term, which is poorly understood and it lacks a universal definition and gold standard assessment. This makes it difficult to identify the role of core stability in athletic injury prevention and performance. To better assess core stability, the objective for this dissertation was to construct a reliable core stability index using measurements which best define and evaluate core stability.

The purpose of our first experiment was to introduce and determine the intra-rater reliability of clinical measurements which may relate to core stability. Following a literature review 35 tests were identified and evaluated. The 35 tests assess five different components of core stability: strength, endurance, flexibility, motor control, and function. Intraclass correlation coefficients were calculated to establish intra-rater reliability. There were highly reliable tests in each of the five groups. Overall, core endurance tests were the most reliable measurements, followed by the flexibility, strength, motor control, and functional tests.

Experiment 2 was divided into two parts. The first objective was to determine the relationships between three clinical assessments associated with core stability and the 35 core stability test introduced in Experiment 1. The clinical assessments consisted of the Star Excursion Test and the Frontal Plane Projection Angel (FPPA) of the knee during a single leg squat and drop. Pearson correlation coefficient analysis was performed to determine the relationships between the assessments and the core stability related tests. Overall the relationship

between the clinical assessments and core stability related tests had low correlations. Therefore, the three clinical assessments we selected may not thoroughly assess core stability.

In the second part of Experiment 2 an index was developed that thoroughly evaluates core stability. The participants and their results from part one of Experiment 2 were used to create the index. Physiological factors of each test, principal component analysis, and correlation coefficients were analyzed to select the tests included in the index. Five tests were selected as relevant variables and included into the index: sit up test, trunk extension strength, left hip extension strength, left hip extension active range of motion, and left single leg balance test with vision.

The results in this study are beneficial to the practice of assessing core stability as well as the fields of sports medicine, occupational medicine, and fitness. Core stability is a complex concept that is composed of different components including strength, endurance, flexibility, and motor control. In the present study, a core stability index was developed which helps define and evaluate core stability, but more work is need to validate the index.

CHAPTER1: INTRODUCTION

Core stability is a concept used in the health and fitness professions which became popular in the early 1990s. Physicians, physical therapists, biomechanists, and chiropractors use the concept to educate patients on the recovery from or prevention of injuries. It is further used by fitness professionals in relation to the improvement of physical fitness and athletic performance. Despite its popularity, core stability remains a generalized term, which is poorly understood and described (Panjabi, 1992). Furthermore, it lacks a universal definition, and currently there is not a gold standard assessment of core stability. This makes it difficult to identify or measure the role of core stability in athletic performance (Nesser, Huxel, Tincher, & Okada, 2008) and determine its relationship to athletic injuries (Heiderscheit & Sherry, 2007). In this chapter, a history of the concept of core stability and an introduction of two experiments that may help define and thoroughly evaluate core stability is provided.

Background Information

Low back pain is a major health concern in the United States. One of the factors associated with developing low back pain is improper or excessive vertebral mobility in the lumbar spine (Pope & Panjabi, 1985). From the theory of spinal hypermobility, or instability, the concepts of lumbar stabilization and core stability were developed. These concepts are used to describe the ability to limit the amount of movement in the region of the body that connects the upper and lower extremities.

In the earliest literature on spinal stability, Morris, Lucas, and Bresler (1961) questioned how the lumbar spine was able to absorb large loads without failure. They hypothesized the trunk played an essential role in the protection of the spine from injury. They believed the spine was an elastic column supported by the paraspinal muscles and protected by two chambers: the thoracic and abdominal cavities. The muscles of the trunk transformed the walls of these chambers into rigid structures capable of accepting part of the force produced by the heavy loads, while maintaining a stable spine.

In the 1970s, spinal stability became of greater interest as it was hypothesized the trunk muscles played an important role in the protection of the spine and pelvis when performing activities (Farfan, 1975). Farfan (1975) discussed how the coordinated activation of the abdominal musculature minimized the amount of torque and shear stress placed on the lumbar spine. Furthermore, Farfan (1975) explained how the abdominal muscles positioned the spine and pelvis to maximize power output. This ability is extremely important in actions that occur in the transverse plane, such as a baseball swing or a hockey slap shot.

In the 1990s, a formal description of the individual components of the spinal stabilizing system was introduced. Panjabi (1992) described three components, which together function to stabilize the spine during both dynamic and static tasks: passive (ligamentous), active (musculotendenous), and neural control components.

The passive component consists of the vertebrae, intervertebral discs, zygapophyseal joints, and ligaments of the spine (O'Sullivan, Manip-Phyty, Twomey, & Allison, 1997). It has been observed that the passive structures of the spine alone are highly unstable, with the thoracolumbar spine buckling under a load of 20 N (Morris, Lucas, & Bresler, 1961). Furthermore, it has been observed that an isolated lumbar spine would buckle under 88 N of stress (Crisco, Panjabi, Yamamota, & Oxland, 1992). Panjabi (1992) agreed, as he stated the passive component provides the least amount of stability of the three system components. It is only at the end ranges of motion, where the ligaments become stretched, that the passive component was critical in achieving stability. These same ligaments may be classified under the neural control component, since the mechanoreceptors within them provide information on vertebral position and movements. Although the roles of the passive structures are small in comparison to the other components, the intervertebral discs play a significant role in the stability of the spine. The discs aid in movement and transmit forces along the vertebrae (Walsh & Lotz, 2004). In addition, it has been observed that injury to the intervertebral discs can occur and cause the spine to be less stable. Saal (1992) stated that repetitive movements and torsional stress to the lumbar intervertebral discs and facet joints could lead to degeneration. This can potentially develop into spinal joint failure, since the intervertebral discs are responsible for load transmission within the intervertebral segments.

The active component is comprised of muscles which surround the core (Panjabi, 1992). Hodges (2004) stated that the active system contributes to core stability by the muscles' force generating capacity. Willson, Dougherty, Ireland, and Davis (2005) introduced three mechanisms whereby the active component contributes to core stability: intra-abdominal pressure, spinal compressive forces, and hip and trunk muscle stiffness. The first mechanism, intra-abdominal pressure, is achieved by the activation of the abdominal muscles, namely the transversus abdominis (Hodges, 1999), the diaphragm, the pelvic floor muscles (Willson et al., 2005), and tension of the thoracolumbar fascia (Tesh, Dunn, & Evans, 1987). Intra-abdominal pressure creates a pressured-filled cavity anterior to the spine, causing a force against the apex of the lordosis of the lumbar vertebrae. This limits the segmental movement of the vertebrae when performing activities (Hodges & Richardson, 1996). Increased intra-abdominal pressure may decrease the compressive loads on the spine and could reduce the risk for injury (Daggfeldt & Thorstensson, 2003). According to Gardner-Morse and Stokes (1998), spinal compression is achieved by antagonistic coactivation of the abdominal muscles. They estimated that antagonistic coactivation of the trunk flexor and extensor muscles will increase compressive loading by a maximum of 21% during a task requiring 40% of maximum effort. According to Willson et al. (2004), the last mechanism in which the active component contributes to core stability is to produce stiffness in the hip and trunk muscles. They stated that unless the trunk is loaded, the muscles in the hips and trunk are virtually inactive, and the passive structures are required to be the main core stabilizers.

The final component involved in core stability is the neural control component. Panjabi (1992) suggested that for spinal stabilization to occur, the neural control component must receive information, determine specific requirements, and then initiate the active component. Hodges (2004) stated that the central nervous system (CNS) continually interprets information sent by afferent nerves from the peripheral mechanoreceptors. The CNS then compares this information to what is considered "appropriate stability or posture" and stimulates muscle activity in a precise manner to maintain stability. Aruin and Latash (1995) proposed two subcomponents of the neural control component. The first subcomponent, feedforward, is the anticipatory adjustment of the core to movement or perturbations (Aruin & Latash, 1995). Since the first subcomponent's efficacy is suboptimal, a second subcomponent, feedback, is required. The feedback subcomponent is a corrective response, which is initiated by the peripheral mechanoreceptors (Aruin & Latash, 1995). The neural control component uses both feedforward (anticipatory) and feedback (reaction) mechanisms to retain and restore stability (Aruin & Latash, 1995). Classifying an action as solely feedforward or feedback control is difficult, since at times, a combination of the two is employed (Riemann & Laphart, 2002).

The actual term "core stability" did not become popular in scientific literature until the end of the 20th century. This was initiated by the popularity of core stability exercise programs in the practice of physical rehabilitation (McGill, 2001) and fitness (Bliss & Teeple, 2005). Furthermore, as the term core stability developed from lumbar or spinal stability, the anatomical makeup grew. It now may include the pelvis, hips, and shoulder girdles (Bliss & Teeple, 2005; Kibler, Press, & Sciascia, 2006).

In the field of physical rehabilitation, McGill (2001) reported that the goal of a core stability program is to train the muscles of the core in order to maintain a sufficient amount of spinal stability. He claimed muscle strength may not be the optimal goal of a rehabilitation core stability program. He suggested that core endurance is more important in the prevention of and recovery from injury. Conversely, it has been proposed that core strength programs will improve stability and coordination of the deep abdominal muscles, which can reduce low back injuries (Faries & Greenwood, 2007).

Researchers are now discovering that aspects of core stability may play an important role in the prevention and rehabilitation of injuries in the extremities. Ireland, Willson, Allantyne, and Davis (2003) observed that females who demonstrated core weakness, namely the hip abductors and external rotators, were more likely to suffer from patellofemoral pain. They concluded that individuals with a weaker core were unable to prevent excessive knee valgus and internal rotation moments during activities. This may encourage lateral tracking of the patella and pain. Similar observations by Leetun, Ireland, Willson, Ballantyne, and Davis (2004) observed an increased risk of injury in college athletes who demonstrated significant core weakness. They noted the importance of a proximal stabilization program to prevent lower extremity injuries in athletes.

Historically, most of the research studying core stability has focused on the relationship between core stability and athletic injuries. Hibbs, Thompson, French, Wrigley, and Spears

(2008) stated, “compared to the information available on core stability and low back pain, there is far less research available on the benefits of core training for elite athletes and how core training should be performed to optimize sporting performance.” Much of the theory linking core stability to athletic performance is based on the concept that athletic power is generated and then transferred from the body’s trunk or core (Santana, 2003). Furthermore, Santana (2003) stated that the core’s muscular layout is in a crisscross design, which resembles a *serape*, a colorful blanket worn by people in Mexico and other Latin American countries (Logan & McKinney, 1977). From this piece of clothing, the concept of the Serape Effect was developed. The Serape Effect is important during ballistic movements, as the muscles of the Serape Effect (the rhomboids, the serratus anterior, the external obliques, and the internal obliques) add to the internal forces. These forces are then transferred from the large muscles of the lower extremities, trunk, and pelvis to the smaller muscles of the upper extremities (Logan & McKinney, 1977). The Serape Effect has been observed more in skilled athletes when compared to non-skilled athletes (Logan & McKinney, 1977).

Nesser, Huxel, Tincher, and Okada (2008) performed one of the few investigations which studied the relationship between core stability and athletic performance. They tested 29 National Collegiate Athletic Association Division I football players and compared four core stability endurance tests with athletic performance tests. The athletic performance measurements included a countermovement vertical jump test, a shuttle run, 20- and 40-yard sprints, and one repetition maximum bench press, squat, and power clean. The authors observed only weak to moderate correlations between core stability and performance measurements. Nesser and colleagues presented two possible explanations for the weak relationships: the use of nonspecific measurements of core stability, or core stability only played a minor role in the performance tests they measured.

Core stability is a common term used in medical and fitness fields, but despite its popularity, core stability remains a novel concept with many debatable issues. One of the major issues surrounding core stability is the lack of a standard core stability assessment. Hibbs, Thompson, French, Wrigley, and Spears (2008) indicated that the lack of a gold standard for measuring core stability may explain the lack of literature on the relationship between core stability and athletic performance. Therefore, two experiments are introduced in this document to help define and develop a standard evaluation of core stability.

Experiments

Several tests and measurements are available which claim to assess a component of core stability. Core stability components which have been measured include strength, endurance, flexibility, motor control, and function. Leetun and associates (2004) assessed the core strength and endurance of 140 collegiate athletes with the objective of identifying individuals who were at risk for injuries. They recorded maximum isometric hip abductor and external rotation strength and the muscular endurance capabilities of the anterior, posterior, and lateral trunk muscles. They observed that individuals with stronger core muscles were less likely to sustain a lower extremity injury. Assessing the reliability of core flexibility measurements as part of a preseason screen, Gabbe, Bennell, Wajswelner, and Finch (2004) used the sit and reach test and a goniometer to measure the range of motion of the trunk and hips. They found moderate to very good reliability for all tests. Parkhurst and Burnett (1994) assessed motor control of the core when they attempted to identify the relationship between lower back proprioception and injury. Along with two other tests, they used a trunk reposition test to measure low back proprioception.

They observed significant relationships between impaired lower back proprioception and injury. Another option in assessing core stability is to observe an individual performing a functional movement or activity. Kibler, Press, and Sciascia (2006) suggested evaluating the ability to perform a one leg squat or single leg balance activity. They claim deviations or difficulty performing such an activity may suggest core stability impairment.

Given the number of available core stability measurements, the reliability of these tests can vary. Bohannon et al. (1986) observed very high intra-rater reliability for isometric trunk strength during a single session reliability study. Unlike Bohannon, Moreland, Finch, Stratford, Balsor, and Gill (1997) found low inter-rater reliability when measuring trunk isometric forces. Testing core muscular endurance of athletes, Evans, Refshauge, and Adams (2007) observed high to very high intra-rater reliability. Similarly, Gabbe, Bennell, Wajswelmer, and Finch (2004) found high to very high test-retest reliability of four core flexibility measurements. Using a single limb dynamic balance assessment to evaluate core motor control, Cachupe, Shifflett, Kahanov, and Wughalter (2001) reported very high reliability during a single day testing session. Loudon, Wiesner, Goist-Foley, Asjes, and Loudon (2002) reported moderate to very high intra-rater reliability when performing five functional tests on individuals with knee pain.

With these reliability differences, the objective of the first study was to introduce, measure, and compare the reliability of several core stability related measurements, all of which can be performed in a clinical setting. As part of the first experiment, thorough review of the literature was performed and 35 different measurements were identified as they potentially could be related to core stability. These measurements were then classified into five groups: strength, endurance, flexibility, motor control, and function. Based on previous studies, we expected to observe moderate to high intra-rater reliability with all tests. Furthermore, of the five groups of tests, we anticipated the core endurance tests would be the most reliable.

As mentioned earlier, functional assessments are techniques used to evaluate core stability. Although functional assessments are commonly used in clinical settings, we believe they may not directly evaluate specific components of core stability. One of the most popular functional assessments used is the Star Excursion Test (Bliss & Teeple, 2005). The Star Excursion Test is a functional assessment used to evaluate lumbopelvic control and balance, hip stability, and hip strength (Bliss & Teeple, 2005). Similarly, other functional assessments are available to evaluate core stability, including a single limb squat and drop tests. During the single leg squat test, standing balance, lower extremity coordination and core strength during a closed chain activity are assessed (Kibler, Press, & Sciascia, 2006). In addition to the single leg squat, the more dynamic single leg drop test has been used in the clinical setting to evaluate neuromuscular control of the trunk and lower extremity (Russell, Palmieri, Zinder, & Ingersoll, 2006).

There are two aspects to our second experiment. The objective for part one of this study is to determine the relationships between three clinical assessments associated with core stability and 35 measurements related to core stability. The three clinical assessments analyzed were the Star Excursion Test, the single leg squat, and the single leg drop tests. We hypothesize that the relationships between the three core stability assessments and the measurements related to core stability will be minimal. The objective for part two of Experiment 2 is to construct a core stability index using measurements which best define and evaluate core stability.

References

Aruin, A. S., & Latash, M. L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research, 103,* 323-332.

Bliss, L. S., & Teeple, P. (2005). Core stability: The centerpiece of any training program. *Current Sports Medicine Reports, 4*, 179-183.

Bohannon, R. W. (1986). Test-retest reliability of hand-held dynamometry during a single session strength assessment. *Physical Therapy, 66*, 206-209.

Cachupe, W. J., Shifflett, B., Kahanov, L., & Wughalter, E. H. (2001). Reliability of Biodex Balance System Measure. *Measurement in Physical Education and Exercise Science, 5*, 97-108.

Crisco, J. J., Panjabi, M. M., Yamamoto, I., & Oxland, T. R. (1992). Euler stability of the human ligamentous lumbar spine. *Clinical Biomechanics, 7*, 27-32.

Daggfeldt, K., & Thorstensson, A. (2003). The mechanics of back-extensor torque production about the lumbar spine. *Journal of Biomechanics, 36*, 815-825.

Evans, K., Refshauge, K. M., & Adams, R. (2007). Trunk muscle endurance tests: reliability and gender differences in athletes. *Journal of Science and Medicine in Sports, 10*, 447-455.

Farfan, H. F. (1975). Muscular mechanism of the lumbar spine and the position of power and efficiency. *Orthopaedic Clinics of North America, 6,* 135-144.

Faries, M. D., & Greenwood, M. (2007). Core Training: stabilizing the confusion. *Strength and Conditioning Journal, 29,* 10-25.

Gabbe, B. J., Bennell, K. L., Wajswelner, H., & Finch, C. F. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5*, 90-97.

Gardner-Morse, M. G., & Stokes, A. F. (1998). The effects of abdominal muscle coactivation on lumbar spine stability. *Spine, 23*, 86-92.

Heiderscheit, B., & Sherry, M. (2007). What effect do core strength and stability have on injury prevention and recovery? In D. MacAuley & T.M. Best (Eds.), *Evidence-based Sports Medicine,* (2nd ed., pp. 59-72). Hoboken, NJ: Blackwell Publishing.

Hibbs, A. E., Thompson, K. G., French, D., Wrigley, A., & Spears, I. (2008). Optimizing performance by improving core stability and strength. *Sports Medicine, 38,* 995-1008.

Hodges, P. W. (1999). Is there a role for the transverse abdominis in lumbo-pelvic stability? *Manual Therapy, 4,* 74-86.

Hodges, P. W. (2004). Lumbopelvic stability: a functional model of biomechanics and motor control. In C. Richardson, Hodges, P.W., & Hides, J. (Eds.), *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain* (2nd ed., pp. 13-28). Edinburgh, UK: Churchill Livingstone.

Hodges, P. W., & Richardson, C. A. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain. *Spine, 21*, 2640-2650.

Ireland, M. L., Willson, J. D., Ballantyne, B. T. & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 33,* 671-676.

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine, 36*, 189-198.

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine & Science in Sports & Exercise, 36,* 926-934.

Logan, G. A., & McKinney, W. C. (1977). The serape effect. In G. A. Logan & W. C. McKinney (Eds.), *Anatomic Kinesiology* (2nd ed., pp. 197-208). Dubuque, IA: Wm. C. Brown & Company Publishers.

Loudon, J. K., Wiesner, D., Goist-Foley, H. L., Asjes, C.,& Loudon, K. L. (2002). Intrarater reliability of functional performance tests for subjects with patellofemoral pain syndrome. *Journal of Athletic Training, 37,* 256-261.

McGill, S. M. (2001). Low back stability: from formal description to issues for performance and rehabilitation. *Exercise and Sports Sciences Reviews, 29,* 26-31.

Morris, J. M., Lucas, D. B., & Bresler, B. (1961). Role of the trunk in stability of the spine. *The Journal of Bone and Joint Surgery (Amer. Volume), 43-A*, 327-351.

Nesser, T. W., Huxel, K. C., Tincher, J. L., & Okada T. (2008). The relationship between core stability and performance in Division I football players. *Journal of Strength and Conditioning Research, 22,* 1750-1754.

O'Sullivan, P. B., Manip Phyty, G. D., Twomey, L. T., & Allison, G. T. (1997). Evaluation of specific stabilization exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine, 22*, 2959-2967.

Panjabi, M. M. (1992). The stabilizing system of the spine: Part 1. Function, dysfunction, adaptation, and enhancement. *Journal of Spinal Disorders, 5*, 383-389.

Parkhurst, T. M., & Burnett, C. N. (1994). Injury and proprioception in the lower back. *Journal of Orthopaedic & Sports Physical Therapy, 19*, 282-295.

Pope, M. H., & Panjabi, M. M. (1985). Biomechanical definitions of spinal instability. *Spine, 10,* 255-256.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part 1: The physiologic basis of functional joint stability. *Journal of Athletic Training, 37,* 71-79.

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41,* 166-171.

Saal, J. A. (1992). The new back school prescription: Stabilization training part II. *Occupational Medicine, 7*, 33-42.

Santana, J. C. (2003). The serape effect: a kinesiological model of core training. *Strength and Conditioning Journal, 25,* 73-74.

Tesh, K. M., Dunn, T. S., & Evans, J. H. (1987). The abdominal muscles and vertebral stability. *Spine, 12*, 501-508.

Walsh, A. J. L., & Lotz, J. C. (2004). Biological response of the intervertebral disc to dynamic loading. *Journal of Biomechanics, 37,* 329-337.

Willson, J. D., Dougherty, C. P., Ireland, M. L., & Davis, I. M. (2005). Core stability and its relationship to lower extremity function and injury. *Journal of the American Academy of Orthopaedic Surgeons, 13*, 316-325.

CHAPTER 2: METHODS

Experiment 1

The methods described in this section were developed to introduce and determine the intra-rater reliability of 35 core stability related measurements.

Participants and Rater

Fifteen active, right lower extremity dominate college-age males (age: 21.2 ± 1.3 yr, weight: 74.1 ± 13.4 kg, height: 1.76 ± 0.1 m), who were recruited from a local university, volunteered for the study. Lower extremity dominance was determined by asking the participants, “If you were to kick a soccer ball as hard as you could, which leg would you use?” whereby the chosen leg was classified as the dominate leg. All participants reported the absence of any orthopedic injury to their trunk and extremities within the past year. The participants provided informed consent, as approved by Institutional Review Board, Louisiana State University, prior to data collection. A physical therapist with seven years of clinical experience, with an assistant, performed the testing.

Procedures

A test-retest design was used to assess the intra-rater reliability for 35 core stability related measurements. All participants were required to attend two testing sessions, scheduled at least seven days apart. For both sessions, all tests were performed in random order, between and within the testing categories, except for the endurance tests. The endurance tests were performed last, due to their fatigue-inducing nature, and were randomized. The evaluator demonstrated all tests and the participant performed a practice trial to become familiar with the procedure and the equipment used in each test. Each participant’s age, weight, and height were recorded prior to session one. A five minute treadmill walk with self selected speed was performed as warm-up before each testing session.

Strength Tests

The strength tests included eight isometric tests and an isoinertial test. The isometric tests were performed on a Biodex System 3 Pro (Biodex Medical Systems, Inc., Shirley, NY) and followed modified procedures described by Essendrop, Schibye, and Hansen (2001) and Nadler, Malanga, DePrince, Stitik, and Feinberg (2000). Maximal isometric strength for trunk flexion and extension, bilateral hip extension, abduction, and external rotation were performed. The average of three force measurements was recorded, whereby the participants held each contraction for five seconds. Trunk flexion (Figure 2.1) and extension (Figure 2.2) were performed in the standing position, pelvis stabilized, and without upper extremity support. The attachment was placed two inches below the participant's sternal notch for trunk flexion, and between the scapulas for trunk extension. Similarly, bilateral hip extension (Figure 2.3) and abduction (Figure 2.4) forces were collected in the standing position, without upper extremity support. The attachment was placed two inches above the posterior knee joint line for extension, and two inches above the lateral knee joint line for abduction. Bilateral hip external rotation force was measured with the participant in sitting, hips and knees flexed at 90°, and without upper extremity support. The attachment of the Biodex was placed two inches above the medial malleolus.

The isoinertial strength test included a timed sit-up test, with the objective of performing as many full sit-ups as possible within one minute. The protocol for the sit-up test was developed by the American Alliance of Health, Physical Education, Recreation, and Dance (AAHPERD, 1980). The test was initiated in the hook-lying position, with participant's arms held across the chest, knees flexed at 90°, and feet secured. To complete a full sit-up, the participant's scapulas touched the mat in the lying position and, in the upright position, the elbows made contact with the knees.

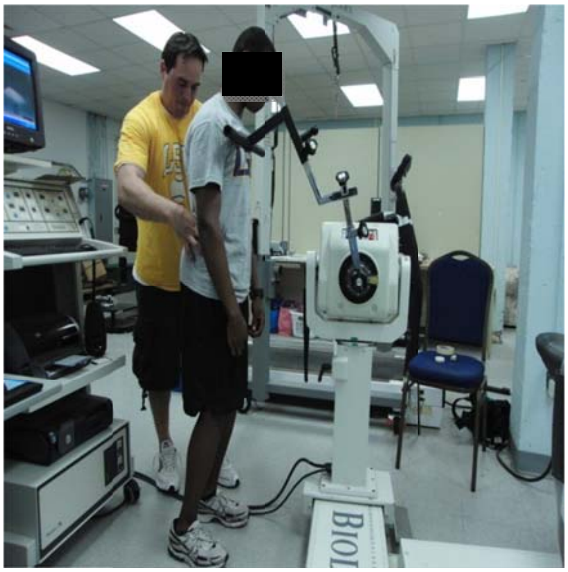

Figure 2.1. Trunk flexion strength test

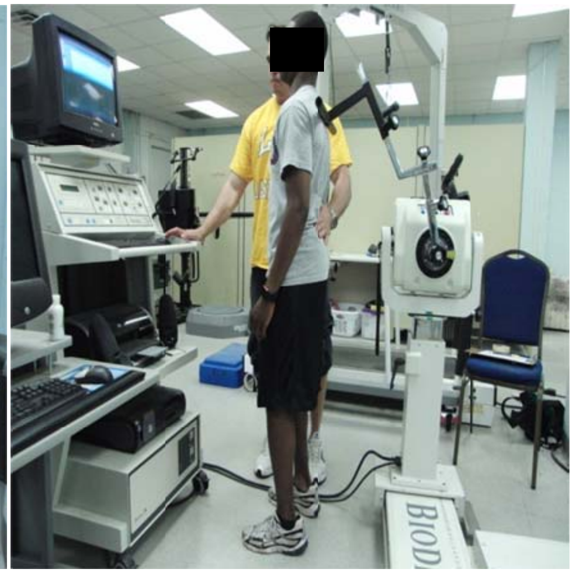

Figure 2.2. Trunk extension strength test

Figure 2.3. Hip extension strength test

Figure 2.4. Hip abduction strength test

Endurance Tests

Four core endurance tests following protocols established by McGill, Childs, and Liebenson (1999) were performed. The endurance tests included the trunk flexion test (Figure 2.5), trunk extension test (Figure 2.6), and bilateral side bridge tests. The objective of each endurance test was to hold a specific static position or a posture for as long as posible. The trunk flexion endurance test began with the participant in hook-lying position, with the trunk manually supported at 60° of trunk flexion. The participant's knees and hips were flexed at 90°, arms crossed over chest and feet secured. After the support was removed, the participant held the position as long as possible. The trunk extension endurance test was performed with the participant lying prone on a treatment table with the pelvis, hips, and knees secured to the treatment table. The participant's trunk and upper extremities were supported by the seat of a chair located directly in front, and at same height as the treatment table. The chair was removed and the individual held a horizontal body position for as long as possible with arms crossed over the chest. The test was discontinued when the participant fell below the horizontal position or below the level of the treatment table. The side bridge tests were performed in the side lying position on a treatment table. The participant's knees were extended, with the top foot placed in front of the lower foot. Participants supported their weight only on their lower elbow and feet while lifting their hips off the mat. The test was stopped when hips returned to the mat.

Figure 2.5. Trunk flexion endurance test

Figure 2.6. Trunk extension endurance test

Flexibility Tests

Active range of motion measurements for the trunk and hips, as well as a sit and reach test, were included in the group of core flexibility tests. Active range of motion measurements for trunk flexion, extension, rotation, and hip extension were based on Norkin and White (1995). Trunk flexion and extension range of motion were measured by first recording the distance between C7 and S1while standing upright (neutral length). To locate C7 and S1, the vertebrae were palpated and marked with a pen. The participant forward flexed as far as possible with the pelvis stabilized. The length between C7 and S1 was re-measured and the difference in lengths (neutral and flexed) was recorded as the trunk flexion flexibility. Similarly, for trunk extension, the participant bent backward as far as possible with the pelvis stabilized. The distance between C7 and S1 was measured and the length decrease from the neutral measurement was documented as trunk extension flexibility. Similarly, trunk rotation flexibility was measured by asking the participant to sit on a chair with the feet on the floor and the trunk and head in neutral position. The participant rotated the trunk and head as far as possible in both directions. A 30 cm plastic goniometer was positioned, so the fulcrum was above the center of the participant's head. The stationary arm was positioned parallel to the imaginary line between the iliac crests, and the movement arm aligned with an imaginary line between the acromial processes of the shoulders.

Bilateral hip extension flexibility was measured with the participant in the prone position, knees extended, and pelvis stabilized. In neutral position, the fulcrum of a 30 cm plastic goniometer was positioned over the greater trochanter, the stabilizing arm was positioned along the lateral midline of the pelvis, while the movement arm was aligned with the lateral midline of the femur. Following maximal active hip extension, the movement arm was realigned with the femur and the change in degrees from neutral was recorded.

Active hip internal and external rotation flexibility were measured using the method described by Ellison, Rose, and Sahrmann (1990). The participant was in the prone position with the testing hip in neutral and knee flexed at 90°. The non-testing leg was placed at 30° of hip abduction, with the knee extended and pelvis stabilized. In the starting position, a 30 cm plastic goniometer was positioned with the stabilizing arm aligned vertically, while the movement arm was aligned along the shaft of the tibia. Following maximal active hip internal and external rotation, the movement arm was realigned with the shaft of the tibia and the change in degrees from the starting position was recorded.

Finally, the sit and reach test was performed using the methods described in the American College of Sports Medicine guidelines (2000). The participant sat with the shoes on and feet resting against a traditional sit and reach box. The participant's knees were extended and stabilized by the examiner, whereby he was requested to lean and reach as far as possible along the measurement scale with one hand placed on top of the other with palms down. The furthest distance reached along the scale was recorded to the nearest 0.5 cm and the average of two trials was documented.

Motor Control Tests

The group of motor control tests included a passive reposition test for each hip and a single limb balance assessment, with and without vision. The passive hip reposition tests were performed using protocols modified from those described by Zazulak, Hewett, Reeves, Goldberg, and Cholewicki (2007), who performed repositioning tests of the lumbar spine. The purpose of the repositioning tests is to evaluate kinesthetic awareness. The objective of the reposition tests was for the participant to stop the passively moving thigh at a target hip range of motion. The hip repositioning tests were performed on the Biodex System 3 Pro using the Passive Mode. The lower extremity was moved between 10° of hip flexion and extension at a rate of 2° per second. The blindfolded participant was in a standing position; for safety, they were allowed to use the upper extremities for support. The hip attachment was positioned two inches above the knee to allow the testing limb to be off the ground. The participant's thigh was first passively moved from neutral (starting position) to a randomized target position and held for five seconds. The thigh was then returned to the neutral position. The participant's thigh was again passively moved and the participant attempted to manually stop their limb at the target position using the emergency stop button. The angle between the resulting and the target position (in degrees) was recorded and the average of two trials for each limb was documented.

The Single Limb Athletic Test performed on the Biodex Balance System SD (Biodex Medical Systems, Inc., Shirley, NY) was used to assess single limb balance (Figure 2.7), as it measures the center of pressure during a single leg stance. The Single Limb Athletic Test is a dynamic stability test performed without upper extremity support, on an unstable platform that is free to move in the anterior-posterior and medial-lateral axes simultaneously. The platform resistance force ranges from 1 (the hardest) to 12 (the easiest). Level 10 was selected after a pilot study reviled it was safe and participants required the hip strategy to maintain balance. Four different conditions were performed: right leg with vision, left leg with vision, right leg blindfolded, and left leg blindfolded. Each test was performed for three, ten seconds long trials and the overall stability index was record for each of the four tests. The overall stability index is the average change in the center of pressure for both the anterior-posterior and medial-lateral axes over the three trials.

Figure 2.7. Single leg balance test

Functional Tests

Three functional tests formed the last group of tests and included a bilateral squat test, a timed single leg hop test, and a single leg hop test for distance. The protocol for the bilateral squat followed the methods introduced by Loudon, Weisner, Goist-Foley, Asjes, and Loudon (2002). The goal of the test is to perform the maximum number of squats during a 30 sec period. The test was initiated with the participant sitting in a chair without armrests, with the hips and knees flexed at 90°. To perform one repetition, the participant rose to full knee extension and returned to the chair. Arms were kept crossed over the chest during the test and the number of repetitions performed was recorded. The timed and distance single limb hop tests were performed according to the protocol described by Reid, Birmingham, Stratford, Alcock, and Griffin (2007). The objective of this test is to hop as quickly as possible over a distance of 9.14 meters on a single leg. The participant performed one trial of the timed hop test on each limb. The single leg hop for distance test was performed by hopping as far as possible and landing on the same leg. For a successful trial, the participant was required to hold the landing position for at least two seconds and the distance hopped was measured from toe to toe. Three hops from each leg were performed and the most successful hop was recorded.

Table 2.1. Groups of tests related to core stability

Strength	**Endurance**	**Flexibility**	**Motor Control**	**Functional**
Trunk flexion	Trunk flexion	Sit and Reach	Right SLB vision	Squat
Trunk extension	Trunk endurance	Trunk flexion	Left SLB vision	Right hop distance
Right hip extension	Right Side Bridge	Trunk extension	Right SLB blindfold	Left hop distance
Left hip extension	Left Side Bridge	Right trunk rotation	Left SLB blindfold	Right hop timed
Right abduction		Left trunk rotation	Right hip reposition	Left hop timed
Left abduction		Right hip extension	Left hip reposition	
Right hip ER		Left hip extension		
Left hip ER		Right hip IR		
		Left hip IR		
		Right hip ER		
		Left hip ER		

Note: ER - External Rotation; IR – Internal Rotation; SLB - Single leg balance test

Statistical Analyses

At the completion of testing, all results were analyzed using SPSS for Windows (version 17.0; SPSS Inc, Chicago, IL). Descriptive statistics (mean and standard deviation) were used to report the daily testing results. The testing results were first evaluated using coefficient of variation and differences between the two testing sessions. Additionally, intraclass correlation coefficient (ICC 2,1) for the average of two trials was used to estimate repeatability and 95% confidence intervals (CI) were provided. The ICC (2,1) was performed using the following equation (Shrout & Fleiss, 1979):

$$ICC(2,1) = (BMS - EMS)/(BMS + (k-1)EMS)$$

where BMS = between mean square, EMS = residual mean square, and k = number of trials. ICC (2,1) was used, since it includes the variability of measurements for any session on any participant (Shrout & Fleiss, 1979). Munro and Page's (1993) ICC classification system was used for determining acceptable reliability. This system classified ICC values as little, if any (0.00 − 0.25), low (0.26 − 0.49), moderate (0.50 − 0.69), high (0.70 − 0.89), and very high (0.90 − 1.00). 95% CI with $\alpha = .05$ was developed using the following equation (McGraw & Wong, 1996):

$$CI = (F_L - 1)/(F_L + (k - 1))$$

where $F_L = F_{obs}/F_{tabled}$ for the lower limit, and $F_L = F_{obs} \times F_{tabled}$ for the upper limit, F_{obs} = row effects (session), F_{tabled} = the $(1 - .5\alpha) \times 100^{th}$ percentile of the distribution with $n - 1$ representing the numerator, and $(n - 1)(k - 1)$ representing the denominator degrees of freedom, respectively.

Experiment 2, Part 1

The methods described in this section were used to determine the relationships between three clinical assessments associated with core stability and 35 core stability related measurements, which were introduced in Experiment 1.

Participants

Thirty-six healthy, active, college-age participants (18 males, 18 females, age: 21.0 ± 1.2 yr, weight: 69.4 ± 13.2 kg, height: 1.7 ± 0.1 m), who were recruited from a local university, volunteered for the study. Participants who reported an orthopedic injury to their trunk or extremities within the past year were not invited to participate in the study. Three females were classified as left lower extremity dominate. Lower extremity dominance was determined as described above. To eliminate any confusion from lower extremity dominance, the results for the three females who were identified as left lower extremity dominate were switched. Therefore, when a test is labeled as right or left, the right side will be considered the dominate side. The participants provided informed consent as approved by Institutional Review Board, Louisiana State University, prior to testing.

Procedures

Testing was performed in a laboratory setting. All tests were first demonstrated by the evaluator and the participant performed a practice trial to become familiar with the procedure and the equipment used in each test. No verbal encouragement was given to the participant during the tests. The clinical assessments associated with core stability were performed first and in a random order, followed by the 35 core stability related measurements. The core stability related measurements were also performed in random order, between and within the testing categories, except for the endurance tests. The endurance tests were performed last due to their fatigue-inducing nature and were randomized. Each participant's age, weight, height, and dominate leg length (anterior superior iliac spine to lateral malleolus) were recorded and a five minute warm-up was performed on a treadmill before testing begun.

Star Excursion Test

The Star Excursion Test is a clinical test used to assess neuromuscular control of the trunk, pelvis, and lower extremities, for the purpose of injury prevention and rehabilitation (Gribble & Hertel, 2003). Although several methods of performing the Star Excursion Test have been presented, this study implemented a protocol modified from those described by Kinzey and Armstrong (1998). The layout of the test includes two pairs of perpendicular lines (Figure 2.8). The first pair of lines was in the horizontal and vertical directions, while the second set of lines was placed at 45° angle to the horizontal and vertical lines. A box, large enough for the participant to stand in, was placed centrally at the intersection of the four lines. The test was initiated with the participant standing inside the starting box. Without the foot making contact with the ground, the participant reached as far as possible in one of the four diagonal directions, and then returned to the starting box. The diagonal directions are marked by the second set of perpendicular lines. The furthest distance reached was marked along the line and then measured from the center using a tape measure. The participant progressed in all four directions with each leg as a part of one trial. Three trials were performed, with a three-minute rest period between trials.

The participant was instructed to perform the maximum reach using any method possible without moving the stabilizing foot. The average length of three trials for each of the four directions and each leg was recorded resulting in eight scores. The total score was calculated as the sum of all eight scores. To adjust the test to an individual's leg length, the total score was divided by eight times the participant's leg length and multiplied by 100. This provided an outcome which was a percentage of the participant's leg length. This adjustment has been described by Gribble and Hertel (2003).

Figure 2.8. Star Excursion Test

Single Leg Squat and Drop Tests

Single leg squat and drop tests are used to help identify athletes who are at risk for lower extremity injuries (Willson, Ireland, & Davis, 2006). It is hypothesized enhanced core stability will provide greater control of the femur, which decreases knee valgus angle (hip adduction and internal rotation), during athletic activities may reduce the number of low extremity injuries (Russell, Palmieri, Zinder, & Ingersoll, 2006; Zeller, McCrory, Kibler, & Uhl, 2003). The single leg squat test requires control of the body over a planted leg, and is used to screen for poor hip strength and trunk control (Zeller et al., 2003). Similarly, the single leg drop test is a dynamic test requiring control of the lower extremity and trunk upon landing, thus limiting excessive forces placed on the lower extremity that may result in injuries (Zhang, Bates, & Dufek, 2000).

Most extant studies that focused on lower extremity kinematics of a single leg squat or a drop have been performed in a laboratory setting, using expensive three-dimensional motion analyses equipment. These methods are typically not available in a clinical setting. Recently a two-dimensional method that allows measuring knee valgus angle, the Frontal Plane Projection Angle (FPPA), was introduced. This method can be performed in a clinical setting, and requires only a digital camera and photo editing software.

In this study the FPPA of the knee was measured using the method described by Willson, Ireland, and Davis (2006) for the single leg squat and the single leg drop. To measure the FPPA of the knee, three markers were placed on the dominant leg: at the mid-thigh between the anterior superior iliac spine and the midpoint of the tibiofemoral joint (mid thigh marker), the midpoint of the tibiofemoral joint (knee marker), and between the midpoint of the medial and lateral malleoli (ankle marker). To develop the anatomical alignment FPPA of the knee (Figure 2.9a), the participant stood on one leg facing a digital camera (AIPTEK INC., Irving, CA). The

FPPA is formed by the line between the markers of the mid-thigh and knee, and the line between the markers of the knee and ankle. The FPPA of the knee was analyzed during a single leg squat (Figure 2.9b) and a single limb drop (Figure 2.9c) from a height of 50.8 cm. The single limb squat was performed to 45° of knee flexion, with an object (bicycle pump) notifying the participant when they have reached 45°. The average of three FPPAs for the single limb squat and drop was compared to the anatomical alignment FPPA. The differences between the FPPA of the single limb squat and the anatomical alignment and between the FPPA of the drop and anatomical alignment were recorded.

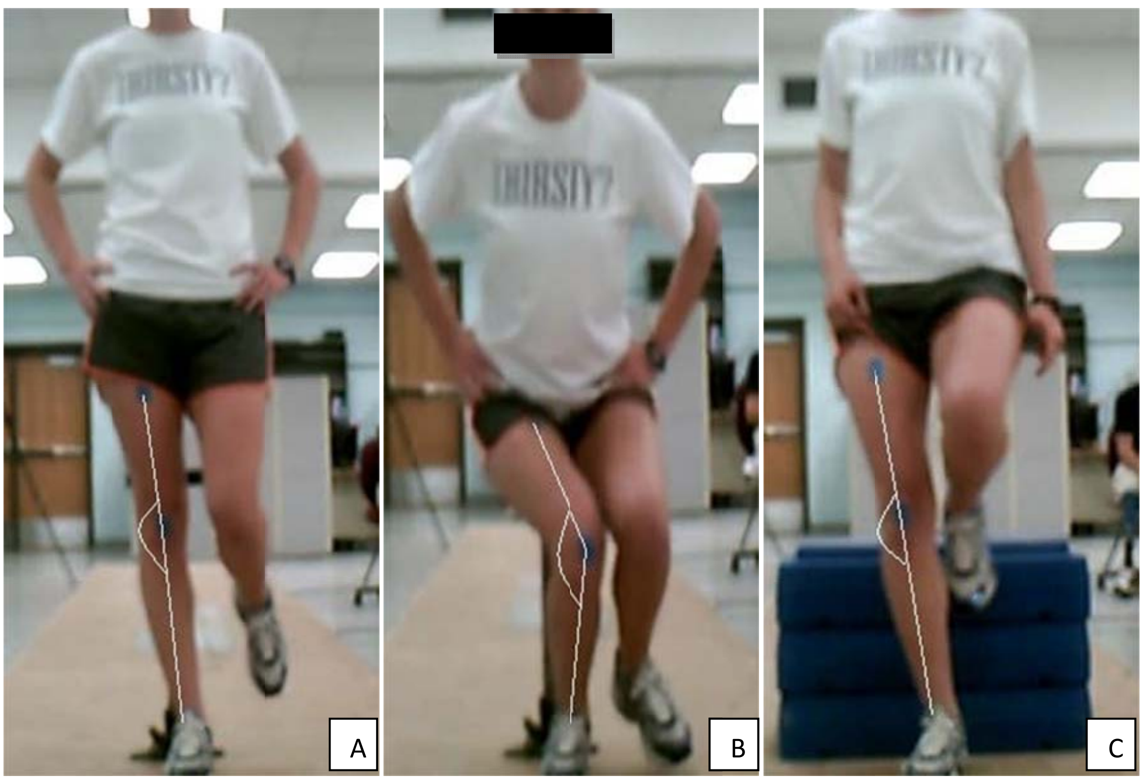

Figure 2.9. Frontal Plane Projection Angle of the Knee: a) anatomical alignment, b) squat, and c) drop

Core Stability Related Measurements

The 35 core stability related measurements described in Experiment 1 were used in this study with one addition. Since females were included, the eight maximal isometric strength measurements were adjusted fo body weight.

Statistical Analyses

Results were analyzed using SPSS for Windows (version 17.0; SPSS Inc, Chicago, IL). Baseline statistics (mean, standard deviation, range, and coefficient of variation) were used to report the individual results for each clinical assessment and core stability related measurement. Analysis of variance with repeated measures was used to detect possible trends between trials for the eight isometric strength tests and the single leg squat and drop assessments. Correlation analyses within the clinical assessments and between the clinical assessments and the core stability related measurement were evaluated using the Pearson correlation coefficient. Statistical significance was set at $\alpha < .05$.

Experiment 2, Part 2

The methods used in the second part of Experiment 2 were designed to develop an index that thoroughly evaluates core stability. The results from part one of Experiment 2 were used to create the index. Four core stability related measurements, right hip abduction strength, left hip reposition test, and timed right and left hop tests, were omitted following their poor reliability observed in Experiment 1.

Development of the Core Stability Index

To construct the core stability index, relevant measurements were first selected. Results from Experiment 1, principal component analysis, and correlation coefficients were analyzed to select the tests to be included in the index. Principal component analysis is used to reduce a large number of interrelated variables while retaining as much variation from the original data set as possible (Jolliffe, 2002). This was accomplished by transforming the data set into a set of new uncorrelated variables − the principal components (Jolliffe, 2002). These new variables are then ordered, whereby the first few components include the most of the variation from all of the original variables. Although, principal component analysis is typical used for model reduction, the present study used the principal component analysis as a tool to assist in selecting the measurements used in the index. The minimal number of principal components which collectively accounted for at least 50% of the total variation were extracted. Within these extracted principal components, core stability related measurements that had correlation coefficients greater than 0.5 were selected for further analyses using Pearson's Correlation. The analyses of the significant correlations within the extracted principal components will further assist in the selection of measurements that make up the core stability index. SPSS (version 17.0; SPSS Inc, Chicago, IL) was used for statistical analysis with significance set at $\alpha < 05$.

References

ACSM. (2000). *Guidelines for exercise testing and prescription*(6th ed.). Baltimore: Lippincott, Williams, & Walkins.

Ellison J. B., Rose S. J., & Sahrmann S. A. (1990). Patterns of hip rotation range of motion: a comparison between healthy subjects and patients with low back pain. *Physical Therapy, 70,* 537-541.

Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength tests for the trunk, hands, and shoulders. *International Journal of Industral Ergonomics, 28,* 379-387.

Gribble, P. A., & Hertel, J. (2003). Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science, 7,* 89-100.

Jolliffe, I. T. (2002). *Principal Component Analysis* (2nd ed.). New York: Springer.

Kinzey, S. J., & Armstrong, C. W. (1998). The reliability of the Star-Excursion Test in assessing dynamic balance. *Journal of Orthopaedic & Sports Physical Therapy, 27,* 356-360.

Loudon, J. K., Wiesner, D., Goist-Foley, H. L., Asjes, C.,& Loudon, K. L. (2002). Intrarater reliability of functional performance tests for subjects with patellofemoral pain syndrome. *Journal of Athletic Training, 37,* 256-261.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal datatbase. *Archives of Physical Medicine and Rehabilitation, 80,* 941-944.

McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods, 1,* 30-46.

Munro, B. H., & Page, E. B. (1993). *Statistical Methods for Health Care Research* (2nd ed.). Philadelphia: J.B. Lippincott.

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik, T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female follegiate athletes. *Clinical Journal of Sport Medicine, 10*, 89-97.

Norkin, C. C., & White, D. J. (1995). *Measurement of Joint Motion: A Guide to Goniometry* (2nd ed.). Philadelphia: F.A. Davis.

Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Physical Therapy, 87,* 337-349.

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41,* 166-171.

Shrout, P. E., & Fleiss J. L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin, 86,* 420-428.

Willson, J. D., Ireland, M. L., & Davis, I. (2006). Core strength and lower extremity alignment during single leg squats. *Medicine & Science in Sports & Exercise, 38,* 945-952.

Zazulak B. T., Hewett T. E., Reeves N. P., Goldberg B., & Cholewicki, J. (2007). The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *American Journal of Sports Medicine, 35,* 368-373.

Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *The American Journal of Sports Medicine, 31,* 449-456.

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise, 32*, 812–819.

CHAPTER 3: RESULTS

Experiment 1

Descriptive results of mean, standard deviation, coefficient of variation, and relative difference of all dependent variables between the two testing sessions are presented in Table 3.1. The overall coefficient of variation (CV) ranged from 6% to 87% in session one and 5% to 80% in session two. CV for the strength tests ranged from 16% to 42% in session one and 14% to 46% in session two. Endurance tests in session one had CV that ranged from 35% to 52%, and 29% to 46% in session two, respectively. CV ranged from 8% to 66% in session one and 7% to 62% in session two for the flexibility tests. For the motor control tests CV ranged from 24% to 87% and 28% to 80% in session one and two, respectively. For the functional tests, session one had CV ranging from 6% to 15%, whereas it was 5% to 11% in session two.

The relative difference between sessions for all core stability measurements ranged from 0% to 41.4%. The lowest relative difference for the strength tests was observed for left hip external rotation (0.4%), while the highest corresponded to trunk extension (19.4%). For the endurance tests, left side bridge had the smallest relative difference (0.3%), while right side bridge had the largest difference (8.9%), about half what observed in strength tests. The relative differences for the flexibility tests ranged from left hip internal rotation (1.4%) to trunk extension (11.0%), similar to that of the endurance tests. For the motor control tests, very little relative difference was observed for the left hip reposition test between sessions. The highest relative difference of the group was observed for the right hip reposition test (41.4%), twice as that of the strength tests. The functional tests had the lowest range of relative differences of the five groups. They ranged from the squat test (0.4%) to the left hop for distance test (4.3%), about half of that comparing to the endurance and flexibility tests.

Table 3.1. Descriptive statistics for core stability measurements (n = 15)

	Session 1			Session 2			Relative
Strength Tests	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Difference**
Trunk flexion (N)	57.75	19.5	34%	63.49	29.1	46%	9.9%
Trunk extension (N)	72.31	30.6	42%	86.31	39.6	46%	19.4%
Right hip extension (N)	59.42	18	30%	69.19	27.1	39%	16.4%
Left hip extension (N)	68.29	17.1	25%	69.29	19.8	29%	1.5%
Right abduction (N)	69.89	20.5	29%	73.62	15.5	21%	5.3%
Left hip abduction (N)	63.33	18	28%	72.71	17	23%	14.8%
Right hip ER (N)	56.89	11	19%	55	12.1	22%	3.3%
Left hip ER (N)	54.07	16.1	30%	54.31	17.2	32%	0.4%
Sit up test	45.6	7.33	16%	49.13	7.01	14%	7.7%
Endurance Tests							
Trunk flexion (s)	57.87	29.1	50%	58.6	17	29%	1.3%
Trunk extension (s)	83.27	29.4	35%	81.27	25	31%	2.4%
Right side bridge (s)	82.2	32.2	39%	74.87	25.2	34%	8.9%
Left side bridge (s)	77.2	39.9	52%	76.93	35.7	46%	0.3%
Flexibility Tests							
Sit and reach (cm)	4.2	2.77	66%	4.62	2.87	62%	10.0%
Trunk flexion (cm)	12.42	1.51	12%	13.39	1.58	12%	7.8%
Trunk extension (cm)	5.98	1.03	17%	6.64	0.99	15%	11.0%
Right trunk rotation (deg)	91.93	8.9	10%	89.33	6.15	7%	2.8%
Left trunk rotation (deg)	89.2	7.26	8%	88.07	5.35	6%	1.3%
Right hip extension (deg)	27.53	7.73	28%	29.67	6.11	21%	7.8%
Left hip extension (deg)	27.4	7.37	27%	28.73	8.51	30%	4.9%
Right hip IR (deg)	45.47	10	22%	46.8	8.61	18%	2.9%
Left hip IR (deg)	47.6	10.1	21%	48.26	6.86	14%	1.4%
Right hip ER (deg)	47.8	6.28	13%	50	9.09	18%	4.6%
Left hip ER (deg)	48.33	6.57	14%	52	9.96	19%	7.6%
Motor Control Tests							
Right SLB vision	1.63	0.77	47%	1.29	0.52	40%	20.9%
Left SLB vision	1.833	0.77	42%	1.55	0.58	37%	15.4%
Right SLB blindfold	5.2	1.27	24%	4.37	1.57	36%	16.0%
Left SLB blindfold	4.94	1.57	32%	4.77	1.35	28%	3.4%
Right hip reposition (deg)	2.27	1.97	87%	1.33	1.06	80%	41.4%
Left hip reposition (deg)	2.26	1.16	51%	2.26	1.66	73%	0.0%
Functional Tests							
Squat test	30.07	4.65	15%	30.2	4.44	15%	0.4%
Right hop distance (cm)	148.93	10.1	7%	151.6	7.45	5%	1.8%
Left hop distance (cm)	145.62	8.88	6%	151.91	8.76	6%	4.3%
Right hop timed (s)	3.08	0.43	14%	2.98	0.26	9%	3.2%
Left hop timed (s)	3.14	0.42	13%	3.02	0.33	11%	3.8%

Note: SD - Standard Deviation; CV - coefficient of variation (SD/Mean); Relative differences are calculated as |Mean 2 – Mean 1|× 100%/ Mean 1: ER - External rotation; IR - Internal rotation; S.L.B. - Single leg balance test

The intra-rater reliabilities of the individual parameters are presented in Table 3.2. The overall intra-rater reliability for all core stability measurements ranged from none (.00) to very high (.98). Negative ICC was the result of very small BMS (between mean squares) comparing to greater RMS (residual mean square) in the ICC calculation, means very unreliable results in the test-retest arrangement. Nineteen (54%) of the thirty-five measurements were considered to have high (0.70 to 0.89) or very high (0.90 to 1.00) reliability, twelve (34%) of the tests were considered to have moderate (0.50 to 0.69) reliability, while four (11%) of the tests were considered to have low (0.26 to 0.49) reliability.

All strength tests, except the right hip abduction test (ICC = .45), were observed to have moderate to very high reliability, with the sit up test having the highest (.92). The endurance tests were observed to have moderate to very high reliability (.66 − .96) with the left side bridge test having the highest (.96). The flexibility tests were observed to have moderate to very high reliability (.62 − .98), with the traditional sit and reach test having the highest reliability (.98). The motor control measurements were observed to have moderate to high reliability (.52 − .90), with the exception of the left hip reposition test was not reliable (.00). The functional tests were observed to have the greatest amount of discrepancy (.42-.90) among the five groups. Within the group, right (.45) and left (.42) hop tests for time had low reliability, the squat test had moderate reliability (.55), where right (.91) and left (.92) hop test for distance had very high reliability.

Table 3.2. Intra-rater reliability for core stability measurements (n = 15)

Strength Tests	ICC (2,1)	95% CI
Trunk flexion *	.62	0.00 − 0.87
Trunk extension #	.81	0.43 − 0.94
Right hip extension #	.73	0.19 − 0.91
Left hip extension *	.68	0.05 − 0.89
Right hip abduction ^	.45	0.00 − 0.82
Left hip abduction *	.61	0.00 − 0.95
Right hip ER #	.71	0.15 − 0.90
Left hip ER #	.85	0.55 − 0.95
Sit up test +	.92	0.77 − 0.97
Endurance Tests		
Trunk flexion *	.66	0.01 − 0.89
Trunk extension #	.79	0.38 − 0.93
Right side bridge #	.74	0.30 − 0.92
Left side bridge +	.96	0.87 − 0.99
Flexibility Tests		
Sit and reach +	.98	0.95 − 0.99
Trunk flexion #	.71	0.13 − 0.90
Trunk extension #	.79	0.37 − 0.93
Right trunk rotation *	.67	0.01 − 0.89
Left trunk rotation *	.69	0.07 − 0.90
Right hip extension *	.64	0.00 − 0.88
Left hip extension #	.84	0.52 − 0.95
Right hip IR #	.74	0.22 − 0.91
Left hip IR *	.65	0.00 − 0.88
Right hip ER *	.62	0.00 − 0.87
Left hip ER *	.68	0.03 − 0.89
Motor Control Tests		
Right SLB vision #	.87	0.60 − .096
Left SLB vision #	.76	0.27 − 0.92
Right SLB blindfold +	.90	0.72 − 0.97
Left SLB blindfold #	.80	0.41 − 0.93
Right hip reposition *	.52	0.00 − 0.84
Left hip reposition &	.00	0.00 − 0.55
Functional Tests		
Squat test *	.55	0.00 − 0.85
Right hop distance +	.91	0.74 − 0.97
Left hop distance +	.92	0.76 – 0.97
Right hop timed ^	.45	0.00 − 0.81
Left hop timed ^	.42	0.00 − 0.81

Note : + - Very High Reliability (0.90 − 1.00), # - High Reliability (0.7 − 0.89); * - Moderate Reliability (0.50 − 0.69); ^ - Low Reliability (0.26 − 0.49); None, & - Little Reliability (0.00 − 0.25); ER- External rotation; IR- Internal rotation; SLB - Single leg balance test;

Experiment 2, Part 1

Mean, standard deviation, minimum and maximum values, and coefficient of variation for each of the core stability related measurements and clinical assessments associated to core stability are presented in Table 3.3. The overall coefficient of variation (CV) ranged from .035 to .714 for the 35 core stability related measurements, while CV for the three clinical assessments ranged from .055 to 12.9. As a group, the motor control tests were observed to have the largest CV ranging from .309 to .714, and the functional tests had the smallest range, .035 to .181. Strength tests CV ranged from .106 to .416, whereas endurance tests ranged from .378 to .638, and flexibility tests from .077 to .687. There was no significant differences observed between the average values record for each trial for the eight isometric strength tests and the single leg squat and drop assessments.

Table 3.4 reports low coefficient of determination (R^2) between the clinical assessments associated with core stability and the core stability related measurements, ranging from .00004 to .194. The coefficients of determination between the Star Excursion Test and the thirty-five tests ranged from R^2 = .0001 to R^2 = .179. Significant relationships were observed between the Star Excursion Test and trunk flexion flexibility (R^2 = .179), trunk extension strength (R^2 = .177), and right single leg hop tests for distance (R^2 = .127). Coefficients of determination (R^2) ranged from .00003 to 0.194 between the single leg squat test and the core stability related measurements. The relationship between the single leg squat and trunk flexion endurance test (R^2 = .127) was the only significant correlation within the group. Overall, the coefficients of determination between the single leg drop test and the core stability related measurements were the weakest, ranging from R^2 = .00004 to .068, of the three clinical tests and there was no statistically significant relationship observed..

Among the clinical assessments, there was a significant relationship between the single leg squat and drop tests (R^2 = .384). There were low, non-significant relationship between the Star Excursion Test and the single leg squat (R^2 = .001) and single leg drop tests (R^2 = .033).

Table 3.3. Experiment 2, part 1 descriptive statistics (n = 36)

	Mean	Standard Deviation	Min-Max	CV
Strength Tests				
Trunk flexion (N/kg)	.709	.253	.31 – 1.44	.367
Trunk extension (N/kg)	.999	.416	.34 – 2.31	.416
Right hip extension N/kg)	.690	.245	.36 – 1.45	.355
Left hip extension (N/kg)	.761	.212	.40 – 1.28	.279
Right hip abduction (N/kg)	.821	.212	.48 – 1.45	.258
Left hip abduction (N/kg)	.800	.176	.50 – 1.32	.220
Right hip ER (N/kg)	.679	.156	.38 – 1.08	.106
Left hip ER (N/kg)	.645	.164	.37 – 0.99	.254
Sit – up test (Repetitions)	44.0	9.00	26 – 65	.204
Endurance Tests				
Trunk flexion (s)	53.1	33.9	12 – 161	.638
Trunk extension (s)	87.4	33.0	24 – 174	.378
Right side bridge (s)	70.6	31.8	23 – 163	.450
Left side bridge (s)	69.6	35.4	32 – 202	.509
Flexibility Tests				
Sit and reach (cm)	9.21	6.32	-8.26 – 24.8	.687
Trunk flexion (cm)	12.9	3.59	7.62 – 20.3	.278
Trunk extension (cm)	6.01	2.26	2.54 – 12.7	.376
Right trunk rotation (deg)	93.9	7.27	70 – 110	.077
Left trunk rotation (deg)	94.0	7.81	75 – 108	.083
Right hip extension (deg)	24.4	5.81	15 – 36	.238
Left hip extension (deg)	23.6	5.51	12 – 35	.233
Right hip IR (deg)	49.9	10.1	25 – 75	.202
Left hip IR (deg)	50.7	10.4	30 – 71	.205
Right hip ER (deg)	55.7	8.71	40 – 75	.156
Left hip ER (deg)	55.1	8.27	40 – 71	.150
Motor Control Tests				
S.L.B. Vision right	1.61	1.15	.13 – 7.11	.714
S.L.B. Vision left	1.63	1.02	.40 – 6.35	.626
S.L.B. Blindfolded right	5.11	1.58	2.30 – 10.70	.309
S.L.B. Blindfolded left	5.03	1.58	2.70 – 9.00	.314
Right hip reposition (deg)	2.38	1.28	0.00 – 5.50	.538
Left hip reposition (deg)	2.43	1.29	0.00 – 5.00	.530
Functional Tests				
Squat test (Repetitions)	28.4	4.83	21 – 40	.170
Right hop distance (cm)	148	5.16	78.7 – 200.7	.035
Left hop distance (cm)	145	5.28	68.6 – 200.7	.036
Right hop timed (s)	3.40	.586	2.38 – 4.91	.172

Left hop timed (s)	3.47	.628	2.53 − 5.15	.181
Clinical Assessments				
Star Excursion Test (%)	104	5.77	91.96 − 118.04	.055
Single leg squat (°)	-5.72	8.19	-17.3 − 19.3	1.43
Single leg drop (°)	.612	7.90	-12.0 − 19.0	12.9

Note: CV - coefficient of variation (Standard Deviation/Mean); ER - External rotation; IR - Internal rotation; S.L.B. - Single leg balance test; S.L. - Single leg

Table 3.4. Coefficients of determination (R^2) between core stability related measurements and clinical assessments (n = 36)

	Star Excursion Test	S.L. Squat Test	S.L. Drop Test
Strength Tests			
Trunk flexion	.024	.004	.000
Trunk extension	**.177**	.012	.003
Right hip extension	.019	.006	.032
Left hip extension	.081	.009	.020
Right hip abduction	.082	.002	.000
Left hip abduction	.093	.001	.004
Right hip ER	.000	.020	.003
Left hip ER	.069	.056	.023
Sit up test	.008	.015	.001
Endurance Tests			
Trunk flexion	.000	**.194**	.068
Trunk extension	.001	.060	.054
Right side bridge	.019	.005	.001
Left side bridge	.021	.000	.007
Flexibility Tests			
Sit and reach	.016	.004	.010
Trunk flexion	**.179**	.000	.005
Trunk extension	.013	.001	.001
Right trunk rotation	.062	.002	.003
Left trunk rotation	.016	.004	.000
Right hip extension	.073	.005	.012
Left hip extension	.099	.003	.004
Right hip IR	.000	.008	.012
Left hip IR	.038	.001	.006
Right hip ER	.070	.001	.000
Left hip ER	.011	.005	.003
Motor Control Tests			
S.L.B. Vision right	.003	.014	.001
S.L.B. Vision left	.000	.017	.003
S.L.B. Blindfolded right	.054	.012	.009
S.L.B. Blindfolded left	.051	.001	.023
Right hip reposition	.000	.006	.044
Left hip reposition	.051	.007	.004
Functional Tests			
Squat test	.035	.002	.003

Right hop distance	**.127**	.025	.009
Left hop distance	.060	.028	.004
Right hop timed	.044	.044	.032
Left hop timed	.016	.011	.005
Clinical Assessments			
Star Excursion Test	1	.001	.038
Single leg squat	.001	1	**.384**
Single leg drop	.038	**.384**	1

Note: **Bold** - significant at the 0.05 level; ER - External rotation; IR - Internal rotation; S.L.B. - Single leg balance test; S.L. - Single leg

Experiment 2, Part 2

The principal components analysis of all 31 core stability related measurements resulted in the extraction of four components, which cumulatively explained 54.32% of the total variance of all tests (Table 3.5).

Table 3.5. Eigenvalues (λ) and the percentage of explained variance for ten principal components (λ%)

Component	λ	Cumulative λ%
1	6.149	19.8
2	4.829	35.4
3	3.007	45.1
4	2.854	54.3
5	2.061	60.9
6	1.733	66.5
7	1.454	71.2
8	1.323	75.5
9	1.111	79.1
10	1.017	82.3

Correlation coefficients of all reliable core stability related measurements for the four extracted principal components are presented in Table 3.6. In principal component 1, eleven measurements were observed to have correlation coefficients greater than 0.5, whereas principal component 2 had seven such tests. Two measurements in principal components 3 and 4 were observed to have correlation coefficient greater than 0.5.

Table 3.6. Correlation coefficients of all core stability related measurements for extracted principal components, eigenvalues (λ), and the percentage of explained variance (λ%)

Core Stability Test	**1**	**2**	**3**	**4**
Sit up	**.768**	.087	-.194	.119
Right side bridge	**.724**	.288	-.374	.055
Left hip abduction	**.707**	.043	.215	-.049
Right hop for distance	**.694**	.334	.370	.262
Squat test	**.688**	.083	-.422	-.111
Left hip ER strength	**.654**	.014	-.056	-.156
Left side bridge	**.647**	.379	-.421	.144
Left hop for distance	**.618**	.427	.280	.369
Left hip extension strength	**.540**	-.031	.286	-.521
Trunk flexion endurance	**.528**	.204	-.428	-.142
Right hip extension strength	**.513**	-.276	.323	-.300
Left Single limb vision	.373	**-.784**	.090	.122
Right single limb vision	.305	**-.746**	.062	.334
Right single limb blindfold	.345	**-.710**	.372	.247
Left single limb blindfold	.324	**-.677**	.321	.331
Left hip ER AROM	-.173	**.564**	.360	.301
Left hip IR AROM	-.277	**.544**	.338	-.126
Right hip IR AROM	-.199	**.514**	.458	-.281
Left trunk rotation AROM	.263	.455	.283	.376
Trunk extension endurance	.371	.419	-.370	-.248
Trunk extension strength	.259	.081	**.565**	-.463
Trunk flexion strength	.456	-.063	**.506**	-.408
Right hip extension AROM	-.003	.365	.008	**.610**
Left hip extension AROM	.008	.263	.121	**.563**
Sit and reach	.058	.406	.076	-.414
Right trunk rotation AROM	.200	.222	.329	.328
Right hip ER strength	.491	.073	-.287	.027
Right hip ER AROM	-.165	.492	.194	.265
Right hip reposition	-.325	.166	-.192	-.062
Trunk extension AROM	-.089	-.209	-.101	-.026
Trunk flexion AROM	.093	.182	.212	-.286

Note: ER - external rotation; IR - internal rotation; AROM - active range of motion

Correlation coefficients ranged from .034 (right side bridge and trunk flex endurance) to.932 (right hop for distance and left hop for distance) for tests selected from principal component 1 (Table 3.7). The sit up test was significantly correlated ($p < .05$) to ten of the eleven tests selected from principal component 1, with the exception being left hip extension strength. For tests with correlation coefficients greater than .5 in principal component 2, correlation coefficients ranged from -.192 (right single leg balance test blindfolded and left hip external rotation active range of motion) to .870 (right and left single leg balance test with vision). The left single leg balance test with vision was significantly correlated ($p < .05$) to all seven tests selected from principal component 2 (Table 3.8). The two tests selected from principal component 3, trunk extension and flexion strength, were observed to be significantly correlated ($r = .704$). Similarly, right and left hip extension active range of motion, selected from principal component 4, were significantly correlated ($r = .655$).

Table 3.7. Correlation matrix of tests with correlation coefficient (*r*) greater than 0.5 in principal component 1

	Sit up	**RSB**	**LHab**	**Rhop**	**squat**	**LHer**	**LSB**	**Lhop**	**LHe**	**Tflxe**	**RHe**
Sit up	**1.000**										
RSB	**.623**	**1.000**									
LHab	**.440**	**.385**	**1.000**								
Rhop	**.540**	**.494**	**.544**	**1.000**							
Squat	**.686**	**.592**	**.391**	.319	**1.000**						
LHer	**.394**	.271	**.580**	.306	**.441**	**1.000**					
LSB	**.516**	**.908**	**.370**	**.456**	**.487**	**.375**	**1.000**				
Lhop	**.536**	**.497**	**.374**	**.932**	.300	.214	**.487**	**1.000**			
LHe	.246	.184	**.391**	.286	**.382**	**.429**	.039	.152	**1.000**		
Tflxe	**.334**	.034	**.376**	.302	**.455**	**.387**	-.094	.144	**.650**	**1.000**	
RHe	**.419**	**.601**	.145	.124	**.509**	**.457**	**.642**	.227	.263	.050	**1.000**

Note: **Bold** - correlation significant at the 0.05 level; RSB - right side bridge; LHab - left hip abduction strength; LHer - left hip external rotation strength; LSB - left side bridge; Lhop - left hop for distance; LHe - left hip extension strength; TFlxe - Trunk flexion endurance; RHe - right hip extension strength

Using the results from Experiment 1, results from the principal component analysis, and correlation coefficients between tests in each principal component, five tests were selected as relevant variables: sit up test, trunk extension strength, left hip extension strength, left hip extension active range of motion, and left single leg balance test with vision. Our initial model for our core stability index:

$$Y = a_1X_1 + b_1X_2 + c_1X_3 + d_1X_4 + e_1X_5$$

Where Y = core stability score, X_1 = Sit up test, X_2 = trunk extension strength, X_3 = left hip extension strength, X_4 = left hip active range of motion, and X_5 = left single leg balance test with vision.

Table 3.8. Correlation matrix of tests with correlation coefficient (*r*) greater than 0.5 in principal component 2

	LSLvision	**RSLvision**	**RSLblind**	**LSLblind**	**LHER**	**LHIR**	**RHIR**
LSLvision	**1.000**						
RSLvision	**.870**	**1.000**					
RSLblind	**.790**	**.754**	**1.000**				
LSLblind	**.663**	**.633**	**.780**	**1.000**			
LHER	**-.389**	-.292	-.192	-.201	**1.000**		
LHIR	**-.403**	**-.379**	-.239	**-.436**	**.386**	**1.000**	
RHIR	**-.476**	**-.431**	-.246	**-.434**	.277	**.818**	**1.000**

Note: **Bold** - correlation significant at the 0.05 level; LSLvision - left single leg balance test with vision; RSLvision - right single leg balance test with vision; RSLblind - right single leg balance test blindfolded; LSLblind - left single leg balance test blindfolded; LHER - left hip external rotation active range of motion; LHIR - left hip internal rotation active range of motion; RHIR - right hip internal rotation active range of motion

CHAPTER 4: DISCUSSION

Experiment 1

The purpose of this study was to introduce, measure, and compare the reliability of 35 measurements identified as related to core stability, which examine five different components contributing to core stability. Core endurance tests were the most reliable measurements among the five groups, and flexibility tests were the second most reliable, followed by strength, motor control, and functional assessments.

Some descriptive results observed in this study compared favorably to previous parameters reported in the literature, but not all. Moreland, Finch, Stratford, Balsor, and Gill (1997) evaluated trunk strength and endurance of thirty-nine healthy workers. Four of the six tests in their report were similar to measurements in the present study. In the current work, a corresponding outcome was observed only when performing the trunk flexion endurance test, 63 to 59 s, which could result from the use of the same protocol. However, three of the four tests had very different results. Compared to the results reported by Moreland et al., our observations were lower (trunk flexion 232/58 N; trunk extension: 281/72N). The disparity in trunk strength could be due to differences in testing instrumentation and testing positions. Moreland and associates used a hand-held dynamometer to record trunk strength, whereas here the Biodex System 3 Pro was employed. The Biodex is a more stabile measuring device than the hand-held dynamometer; therefore, it could have contributed to the lower observed scores. Participants in the Moreland et al. study performed their trunk flexion strength test in a hook-lying position at thirty degrees of trunk flexion. This position is more stable since the feet were secure, which could allow participants to exert more force compared to the test performed in the present study. Furthermore, with trunk flexion at 30 °, the abdominal muscles are shorter and can produce more force compared to the neutral posture used here. Earlier studies have observed changes in muscle length affect muscle force n several different muscles (Leedham & Dowling, 1994; Lunnen, Yack, & LeVaeu, 1981; Wickiewicz, Roland, Powell, & Edgerton, 1983). Similar to trunk flexion, trunk extension strength was measured with participant's pelvis and lower extremities stabilized to a treatment table. Their trunk extended beyond the treatment table, thus allowing their participants to use the treatment table for stability while they exerted force. In contrast, the present study implemented a more functional testing position to test both trunk flexion and extension strength. The participants stood in a neutral posture, knees slightly bent, feet flat on floor, and pelvis stabilized by a spotter to avoid movement. The third test with different results was trunk extension endurance test (94 s comparing to our results of 83). The testing protocol and position were identical in both studies, but the use of female participants in Moreland et al. study may have contributed to their greater scores. Unlike trunk flexor endurance, females have been observed to have longer trunk extension endurance times compared to men (McGill et al., 1999).

Three other core stability related measurements that resulted in different outcomes from previous studies included hip internal and external active range of motion and the squat test. Testing active hip internal and external range of motion as part of a lower extremity screen, for which Gabbe, Bennell, Wajswelner, and Finch (2004) recorded less degrees of flexibility compared to the present study (internal rotation 27°/46°, external rotation 22°/78°). The most noticeable difference between the two studies was the participant's testing position. Gabbe and associates performed their range of motion tests in the sitting position, while the prone position was chosen in the present work. The sitting position requires the participant to move against gravity, whereas in the prone position, gravity assists the movement. Furthermore, in the sitting position the hip flexibility could be limited by a mechanical block of the joint. Significant differences in hip internal and external rotation range of motion due to testing position have been documented in earlier research (Simoneau, Hoenig, Lepley, & Papanek, 1998). Loudon, Wirsner, Goist-Foley, Asjes, and Loudon (2002) performed the squat test on eleven healthy adults as a part of a functional performance assessment. Using the same protocol, the participants in their study performed a less number of squats (20 compared to 30). This could be due to different populations tested in the studies. Loudon et al. used volunteers who were mostly female and had a mean age of 30, while participants in the present study were all male and had an average age of 21, and could thus be in better physical condition. Thus, the differences between the observations reported here and those found in literature can be explained by different testing protocols and testing populations.

Despite the differences in the testing scores, many of the core stability related measurements used in this study had similar reliability compared to earlier studies. Testing core endurance, Evens, Refshauge, and Adams (2007) had similar high intra-rater reliability on two of three tests. Similar results were observed with the side bridge tests, right ICC= .82 to .74 and left ICC= .85 to .96. Intra-rater reliability did differ between trunk flexion endurance reported by Evens et al. and present results, ICC= .95 to .66. Although the methodology was identical, Evans et al. reported a much longer average endurance time, 350 s to 58 s, compared to the results reported here. Furthermore, trunk flexion endurance results were in agreement with previous studies (McGill, Childs, & Liebenson, 1999; Moreland et al., 1997). For example, Gabbe et al. (2004) reported comparable sit and reach intra-rater reliability, ICC= .97 to .98. This can be contributed to the simplicity of the testing equipment and protocol. In addition, Cachupe, Shifflett, Kahanov, and Wughalter (2001) also recorded similar reliability for the single leg balance test, ICC .81, compared to ICC, which ranged from .76 to .90 for the four tests performed here. Both tests used comparable protocols and participants.

While some of the core stability related measurements had similar reliability, other tests were observed to have lower reliability when compared to earlier reports. Compared to current observations, Essendrop, Schibye, and Hansen (2001) found greater intra-rater reliability for trunk flexion strength, ICC= .62 to .97, and trunk extension strength, ICC= .81 to .93. However, differences in reliability could be contributed to the testing position. Both studies tested participants in standing position with the pelvis stabilized, but Essendrop and associates also stabilized their participants' shoulders. Although this position could isolate the trunk muscles, it limits the need for muscle coordination, which is essential in functional and athletic activities. Loudon et al. (2002) also had a different reliability outcome when compared to the present study. The reliability of the squat test they performed was greater, ICC= .55 to .79, compared to the results observed here. Having only two to three days between sessions and the testing order not changing could contribute to the greater reliability. The differences in intra-rater reliability could be explained through descriptive statistics, (i.e. testing protocol).

There were differences observed between the relative differences and the ICC of several measurements. For example, the squat test had a small relative difference, 0.4%, but only moderate reliability, ICC= .55. The opposite was observed for trunk extension strength, where a high relative difference was recorded, 19.4%, but the measurement had high reliability, ICC= .81. Disparity in the range of the scores may contribute to the inconsistencies between the relative difference and ICC. With a small range, the relative difference may also be small, but the tests may not be reliable and vice versa.

The current observations provided valuable information on the reliability of several core stability related measurements. Nevertheless, caution must be taken when attempting to generalize the results beyond the population of healthy, college-aged males without recent orthopedic injury. Although inter-rater reliability was not performed, four tests with poor reliability were identified, which will prevent similar problems occurring in future testing Furthermore, many of the measurements used in the present study could be performed using a different protocol or instrumentation.

Overall, the results in this study are beneficial to the practice of assessing core stability. Core stability is a complex concept that relates to different components, including strength, endurance, flexibility, motor control, and function. Therefore, partial evaluation will result in an incomplete assessment of core stability. The current results showed that the reliability of core stability related measurements could vary. It is especially true when a thorough evaluation of core stability is performed. In this work, the intra-rater reliability of 35 core stability related measures was indentified. Some of the observed results were slightly lower than previous studies, but this could be due to the testing positions that required the participant to be in a functional posture, which were deliberately selected. Future studies will explore how the reliable of core stability related measures correlate with athletic performance or injury.

Experiment 2, Part 1

In support of the initial hypothesis, the overall relationships between the three clinical assessments associated with core stability and 35 core stability related measurements were minimal and varied between assessments. The Star Excursion Test had significant correlations with three core stability related measurements (trunk extension strength, trunk flexion active range of motion, and the right single leg hop test for distance), which was more than the other two assessments. The single leg squat only had one significant correlation with trunk flexion endurance test, while the single leg drop had none. The single leg squat and drop tests had significant relationship with each other, but this may be contributed to the use of the same instrumentation when measuring the knee valgus angle. There was virtually no correlation between the Star Excursion Test and the single limb squat and drop tests. Thus, it can be assumed the Star Excursion Test evaluates different components or aspects of stability compared to the other clinical assessments.

Examining the methods of each assessment, the Star Excursion Test may be more complex than the two other clinical assessments, requiring the individual to disturb their equilibrium by reaching outside of their base of support and returning to the starting position (Kinzey & Armstrong, 1998). Furthermore, performing the Star Excursion Test may require different physiological contributions to enable lower extremity coordination, flexibility, strength, and postural control, as compared to the single leg squat and drop tests.

The Star Excursion Test was observed to have significant¸ yet low correlations with trunk extension strength, trunk flexion active range of motion, and the right single leg hop test for distance. To the authors' knowledge, the contribution of these individual components with the Star Excursion Test have not previously been examined. The essential role of the trunk extensor muscles during single leg stance with lower extremity movement may explain the significant correlation found between trunk extensor strength and the Star Excursion Test. Hodges and Richardson (1997) observed an anticipatory contraction of the abdominal and multifidus muscles before lower extremity movement. This feed forward mechanism allows for the stabilization of the spine before a perturbation is introduced. Therefore, the trunk extensor muscles may stabilize the trunk and spine during the Star Excursion Test, thus allowing for maximum reach distance.

Trunk flexion active range of motion may be important as the individual reaches in the two posterior directions of the Star Excursion Test. Actively flexing the trunk causes the re-positioning of the individual's center of gravity, which may create a more stable base and lead to a longer reach. Although actively flexing the trunk when performing the Star Excursion Test may be required, excessive or maximum trunk flexion would be discouraged, since it may result in a less stabile position. Neuromuscular control of the lower extremity when landing and performing the Star Excursion Test may be similar, thus resulting in the significant relationship between the two. It has been reported that trunk and hip control play a critical role in the performance on the Star Excursion Test and upon landing on a single leg (Gribble & Hertel, 2003; Hewett et al., 2005).

The single leg squat had a significant correlation with the trunk flexion endurance test only. Similar to the Star Excursion Test, the significant relationship may be a result of the abdominal muscles attempting to stabilize the trunk and spine in preparation for a movement. To add to this theory, the objective of the endurance test was to stabilize the entire body while attempting to hold a posture for as long as possible. It has been suggested that trunk and hip strength are important when performing a single leg squat (Willson, Ireland, & Davis, 2006). Unlike the results reported here, Willson et al. (2006) found significant correlations between the FPPA (Frontal Plane Projection Angle) during a single leg squat and trunk extension strength and single leg squat and hip external rotation strength. Differences in observations may be a result of the use of different instrumentation and testing positions. Willson et al. used a hand-held dynamometer to measure maximum isometric force, while the Biodex System 3 Pro was employed in this study. Second, they tested for trunk extension strength in the prone position, while in the current experiments the individual was tested when standing, which may require more control and stability. Claiborne, Armstrong, Gandhi, and Pincivero (2006) observed a significant relationship between hip abduction strength and knee valgus direction during a single limb squat. Instrumentation could again be the reason for the different outcome when compared to the present study. Claiborne et al. (2006) tested hip abduction strength isokineticly, rather than isometrically, as was the case here. Furthermore, they also assessed knee valgus direction using three-dimensional analyses, compared to present two-dimensional analysis.

The single leg drop test did not have a significant correlation with any of the 35 core stability related measurements. The single limb drop test is a new assessment with the majority of the prior research investigating landing mechanics and landing differences between male and female participants (Joseph et al., 2008; Russell, Palmieri, Zinder, & Ingersoll, 2006). Similar to the single limb squat, hip strength was believed to play a vital role in lower extremity control during landing (Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008). Although, we did not observe significant correlation between the hip strength and the single leg drop, early research suggests that they may be related. Lawrence et al. (2006) observed that individuals with greater hip external rotation strength, along with knee flexor and extensor strength, had a significant decrease in knee valgus angle and vertical ground reaction force. Disparity in results may be explained by differences in instrumentation and participants. Lawrence et al. (2006) used a handheld dynamometer to assess hip external rotator isometric strength, while the present study used the more stable Biodex System 3 Pro. Furthermore, Lawrence et al. (2006) used only female participants, while both males and females were used in this study.

The three clinical assessments used in this study, although important in identifying an individual who may be at risk of injury, may not be the best tools for assessing core stability. Core stability is a complex concept and is thus difficult to evaluate. The current results indicate that the three clinical assessments do not measure the same physical characteristics as our 35 core stability related measurements. Thus, we suggest that, in order to truly assess core stability, individual components of core stability, such as trunk strength or endurance, must be taken into consideration.

There were differences in the methodology and results between Experiment 1 and Experiment 2, part 1. Females were utilized in Experiment 2, part 1 and not in Experiment 1. This may have resulted in higher flexibility scores and lower endurance outcomes in Experiment 2, part 1. Furthermore, since females participated in Experiment 2, part 1, isometric strength was adjusted for body weight.

As stated before, caution must be taken when attempting to generalize the results beyond the population of healthy, college-aged individual without recent orthopedic injury. In this study, males and females were grouped together, which may have affected the result of the clinical assessments. It has been observed that males and females use different techniques and strategies when performing a single limb squat and drop (Russell, Palmieri, Zinder, & Ingersoll, 2006; Zeller, McCrory, Kibler, & Uhl, 2003).

Future studies, a core stability index will be developed, using only four or five measurements, which thoroughly evaluates core stability. It was expected that this index will enable identification of individuals at risk of injuries, as well as enable them to improve athletic, work, and functional performance.

Experiment 2, Part 2

The objective for the second part of Experiment 2 was to, based on the experimental measurements, create an index that better defines and evaluates core stability. Using results from Experiment 1, principal component analysis, and correlation coefficients, five tests were selected: sit up test, trunk extension strength, left hip extension strength, left hip extension active range of motion, and left single leg balance test with vision. The reasons behind selection of these specific tests are presented and discussed below.

The sit up was the first test selected for inclusion in the index. It is commonly used in several fitness assessments and programs to evaluate abdominal strength and endurance (Jackson et al., 1998). It was believed that abdominal strength and endurance was correlated to lower back pain and injury, and that this type of assessment may help identify at-risk individuals (Hall, Hetzler, Perrin, & Weltman, 1992). Although, the relationship between lower back pain and abdominal strength and endurance is widely accepted, there is a lack of documented evidence (Jackson et al., 1998). In the present study, the sit up test had the highest correlation coefficient within principal component 1. Furthermore, it had significant correlation with nine of the other ten tests extracted from principal component 1, including three of the four core endurance tests and all three functional tests. The sit up test was also observed to have very high intra-rater reliability in Experiment 1.

Another major factor believed to contribute to chronic lower back pain is trunk extensor weakness (Mayer, Smith, Keeley, & Mooney, 1985). Therefore, trunk extensor strength was included in the index. Several studies have observed that individuals with lower back pain or dysfunction demonstrated significant weakness of the trunk extensor muscles compared to non-symptomatic individuals (Bayramoglu et al., 2001; Lee, Obi, & Nakamura, 1995; McNeill, Warwick, Anderson, & Schultz, 1980). Trunk extension strength was observed to have a greater correlation coefficient of the two tests extracted from principal component 3. Trunk extension strength also had significant correlation with the other test and was observed to have high intra-rater reliability.

Hip extension weakness has been linked to functional impairments in older adults (Brown, Sinacore, & Host, 1995), as well as lower back pain and lower extremity injury in athletes (Nadler, Malanga, DePrince, Stitik, & Feinberg, 2000). Furthermore, hip extensor muscle imbalance has been associated with lower back pain in collegiate athletes (Nadler et al., 2001), which may be corrected with a core strengthening program (Nadler et al., 2002). Therefore, the third test in the developed index is left hip extension strength. It was the only test extracted from principal component 1 not to have a significant correlation with the sit up test. Furthermore, to account for hip muscle imbalance, we believe a coefficient may be added in the future using a ratio of the weaker hip extensor strength over the stronger hip extension strength. Although left hip extensor strength was only observed to have moderate intra-rater reliability, its relationship to injury and function was deemed valuable and must be included in the index.

Left hip extension active range of motion was the fourth test included in the index. It has been associated with postural dysfunction, but its association to injuries, pain, or functional limitations is mostly unknown (Godges, MacRae, & Engelke, 1993; Heino, Carter, & Godges, 1990). A number of authors observed a relationship between limited hip range of motion and groin pain in athletes, but whether hip stiffness is a precursor to groin pain remains unclear (Verrall, Hamilton, et al., 2005; Verrall, Slavotinek, et al., 2007). Despite the uncertainly of the role of hip extension range of motion in injury prevention, having a range of motion test in the index is deemed as a necessity. Right hip extension active range of motion had a greater correlation coefficient of the two tests extracted from principal component 4, but the left hip extension active range of motion was observed to have greater intra-rater reliability and was thus selected.

The last test included in the index was the left single leg balance test with vision. It had a greater correlation coefficient of the seven tests extracted from principal component 2 and was significantly correlated with the other six tests, including the three other single leg tests. Another factor in the selection of the left single leg balance test was that the left or non-dominate leg acts as the stabilizing limb in an activity such as kicking a football. Single limb balance has been used in several different capacities; for example, to predict falls in the elderly (Vellas et al., 1997), identify individuals at risk for lower extremity injury (Trojian & McKeag, 2006), and as a return to play criteria for an injured athlete (Guskiewicz & Perrin, 1996). Single limb stance requires many factors, including feedback from vestibular, visual, and proprioceptive sensor, as well as the coordination of trunk and lower extremity muscles (Guskiewicz & Perrin, 1996). Finally, the left single leg balance test with vision had high intra-rater reliability in Experiment 1.

Given the reasoning above, it was believed that the five most valuable measurements were selected for inclusion in the index, as they collectively thoroughly assess and define core stability. Unfortunately, the present index was not validated or verified as a part of the present study. This being the first attempt in using this core stability equation, it was anticipated that there will be several changes to the index as the work on data collection and analysis continues, extending the sample to other populations. It has been stated that years of debate and countless modifications may be needed before an index is validated and can be used to predict certain events (Whittlesey & Hamill, 2004). Therefore, in the near future, experiments with a different population, preferably world-class athletes or individuals with a history of injury, will be conducted.

The results of this research are beneficial to the study of core stability as well as the fields of sports medicine, occupational medicine, and fitness. Core stability is a popular concept used to help individuals prevent and recover from injuries, as well as improve athletic performance. Despite its popularity, core stability is an overused term that is not clearly defined or assessed. Therefore, this study introduced an index that contributes to the definition and evaluation of core stability.

Many physiological factors contribute to core stability including muscle strength and endurance, flexibility, and motor control. Furthermore, to prevent and recover from injuries and improve performance, core stability programs are utilized in rehabilitation and fitness centers to improve muscle strength, endurance, flexibility, and motor control. Therefore, in defining core stability, it is the ability of the core to use muscular strength and endurance, flexibility, and motor control to maintain proper body position and alignment in order to prevent injury, while performing at an optimal level. Similar to its definition, to assessing core stability measurements must be included that evaluate strength, endurance, flexibility, and motor control. The index introduced meets that criteria and therefore we believe it is a thorough assessment of core stability. Although the index was not verifies or validated in this project, future studies will be performed using different populations to aid in the validation process.

Limitations

Several concerns regarding the ability to generalize the results of this study were identified. Not testing the validity of the core stability index was most significant limitation of the dissertation. Despite not validating the index, the present study will assist medical and fitness professions perform a thorough assessment of core stability in the future. Sampling bias may have affected outcomes of both experiments, given that all participants were recruited from the same university. Therefore, the results of the present study may be limited to a population of healthy, college-aged individuals without recent orthopedic injury. Although for Experiment 1, inter-rater reliability was not performed, four tests that had low reliability were identified. Therefore, the conclusions from Experiment 1 were used to limit the number of tests analyzed when constructing the core stability index in the second part of Experiment 2. Measuring intra-rater reliability was an important initial study, but an inter-rater reliability study will be conducted in the future, when the current index is validated.

Future Directions

The results of this study provided a description of core stability and highlighted the difficulties encountered when attempting to assess core stability. A core stability index was developed, but not validated. Therefore, the next stage in the ongoing research will be to assess the core stability related measurements, and comparing results of different populations. Inclusion of different population will allow the index to be modified by adding or subtracting a specific test, or by changing the coefficients in the equation. Ideally, once fully developed, this index will have the ability to identify impairments that may affect performance and recognize individuals who are at risk for injury. In later studies, a training study is planned, which will examine how exercise affects core stability or which training program can enhance core stability more reliably and significantly.

References

Bayramoglu, M., Akman, M. N., Klnc, S., Cetin, N., Yavuz, N., & Ozker, R. (2001). Isokinetic measurement of trunk muscle strength in women with chronic low-back pain. *American Journal of Physical Medicine & Rehabilitation, 80,* 650-655.

Brown, M., Sinacore, D. R., & Host, H. H. (1995). The relationship of strength to function in the older adult. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 50,* 55-59.

Cachupe, W. J., Shifflett, B., Kahanov, L., & Wughalter, E. H. (2001). Reliability of Biodex Balance System Measure. *Measurement in Physical Eduaction and Exercise Science*, *5,* 97-108.

Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during single leg stance. *Journal of Applied Biomechanics, 22,* 41-50.

Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength tests for the trunk, hands, and shoulders. *International Journal of Industral Ergonomics, 28,* 379-387.

Evans, K., Refshauge, K. M., & Adams, R. (2007). Trunk muscle endurance tests: reliabiltiy and gender differences in athletes. *Journal of Science and Medicine in Sports, 10,* 447-455.

Gabbe, B. J., Bennell, K. L., Wajswelner, H., & Finch, C. F. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5,* 90-97.

Godges, J. J, MacRae, P. G., & Engelke, K. A. (1993). Effects of exercise on hip range of motion, trunk muscle performance, and gait economy. *Physical Therapy, 73.* 468-477.

Gribble, P. A., & Hertel, J. (2003). Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science, 7,* 89-100.

Guskiewicz, K. M., & Perrin, D. H. (1996). Research and clinical applications of assessing balance. *Journal of Sports Rehabilitation, 5,* 45-63.

Hall, G. L., Hetzler, R. K., Perrin, D., & Weltman, A. (1992). Relationship of timed sit-up test to isokinetic abdominal strength. *Research Quarterly for Exercise and Sport, 63,* 80-84.

Heino, J. G., Carter, C. L., & Godges, J. J. (1990). Relationship between hip extension range of motion and postural alignment. *Journal of Orthopedic and Sports Physical Therapy*, *12*, 243-247.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt Jr., R. S., Colosimo, A. J., McLean, S. G. et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine, 33,* 492-501.

Hodges, P. W., & Richardson, C. A. (1997) Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy, 77,* 132-142.

Jackson, A. W., Morrow, J. R., Brill, P. A., Kohl, H. W., Gordon, N. F., & Blair, S. N. (1998). Relations of sit-up and sit-and-reach tests to low back pain in adults. *Journal of Orthopedic and Sports Physical Therapy, 27,* 22-26.

Joseph, M., Tiberio, D., Baird, J. L., Trojian, T. H., Anderson, J. M., Kraemer, W. J. et al.

(2008).Knee valgus during drop jumps in National Collegiate Athletic Association Division I female athletes: the effect of a medial post. *American Journal of Sports Medicine, 36,* 285-289.

Kinzey, S. J., & Armstrong, C. W. (1998). The reliability of the Star-Excursion Test in assessing dynamic balance. *Journal of Orthopaedic & Sports Physical Therapy, 27,* 356-360.

Lawrence, R. K., Kernozek, T. W., Miller, E. J., Torry, M. R., & Reuteman, P. (2008). Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics, 23,* 806-813.

Lee, J. H., Ooi, Y., & Nakamura, K. (1995). Measurement of muscle strength of the trunk and the lower extremities in subjects with history of low back pain. *Spine, 20,* 1994-1996.

Leedham, J. S., & Dowling, J. J. (1994). Force-length, torque-angle and EMG-joint angle relationships of the human in vivo biceps brachii. *European Journal of Applied Physiology and Occupational Physiology, 70,* 421-426.

Loudon, J. K., Wiesner, D., Goist-Foley, H. L., Asjes, C., & Loudon, K. L. (2002). Intrarater reliability of functional performance tests for subjects with patellofemoral pain syndrome. *Journal of Athletic Training, 37,* 256-261.

Lunnen, J. D., Yack, J., & LeVeau, B. F. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy, 61,* 190-195.

Mayer, T. G., Smith, S. S., Keeley, J., & Mooney, V. (1985).Quantification of lumbar function: Part 2: sagittal plane trunk strength in chronic low-back pain patients. *Spine, 10,* 765-772.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal datatbase. *Archives of Physical Medicine and Rehabilitation, 80,* 941-944.

McNeill, T., Warwick, D., Anderson, G., & Schultz, A. (1980). Trunk strengths in attempted flexion, extension, and lateral bending in healthy subjects and patients with low-back disorders. *Spine, 5,* 529-538.

Moreland, J., Finch, E., Stratford, P., Balsor, B., & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *Journal of Orthopaedic & Sports Physical Therapy, 26,* 200-208.

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik, T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clinical Journal of Sports Medicine, 10,* 89-97.

Nadler, S. F., Malanga, G. A., Feinberg, J. H., Prybicien, M., Stitik, T. P., & DePrince, M.

(2001). Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. *American Journal of Physical Medicine & Rehabilitation, 80,* 572-577.

Nadler, S. F., Malanga, G. A., Bartoli, L. A., Feinberg, J. H., Prybicien, M., & DePrince, M. (2002). Hip muscle imbalance and low back pain in athletes: influence of core strengthening. *Medicine and Science in Sports & Exercise, 4,* 9-16.

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C.D. (2006). Sex differences in Valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41,* 166-171.

Simoneau, G. G., Hoenig, K. J., Lepley, J. E., & Papanek, P. E. (1998). Influence of hip position and gender on active hip internal and external rotation. *Journal of Orthopedic and Sports Physical Therapy, 28,* 158-164.

Trojian, T. H., & McKeag, D. B. (2006). Single leg balance test to identify risk of ankle sprains. *British Journal of Sports Medicine, 40,* 610-613.

Vellas, B. J., Wayne, S. J, Romero, L., Baumgartner, R. N., Rubenstein, L. Z., & Garry, P. J. (1997). One-leg balance is an important predictor injurious falls in older persons. *Journal of the American Geriatrics Society, 45,* 928-930.

Verrall, G. M., Hamilton, I. A., Slavotinek, J.P., Oakeshott, R.D., Spriggins, A.J., Barnes, P.G., et al. (2005). Hip joint range of motion reduction in sports-related chronic groin injury diagnosed as pubic bone stress injury. *Journal of Science and Medicine in Sport, 8,* 77-84.

Verrall, G. M., Slavotinek, J. P., Barnes, P. G., Esterman, A., Oakeshott, R. D., & Spriggins, A. J. (2007). Hip joint range of motion restrictions precedes athletic chronic groin injury. *Journal of Science and Medicine in Sport, 10,* 463-466.

Whittlesey, S. N., & Hamill, J. (2004). Computer simulation of human movement. In D. G. Robertson, G. E., Caldwell, Hamill, J, Kamen, G., & Whittlesey, S. N. (Eds.), *Research methods in biomechanics* (pp. 211-225). Champaign, IL: Human Kinetics.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. Clinical Orthopaedics & Related Research, 179, 275-283.

Willson, J. D., Ireland, M. L., & Davis, I. (2006). Core strength and lower extremity alignment during single leg squats. *Medicine & Science in Sports & Exercise, 38,* 945-952.

Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *The American Journal of Sports Medicine, 31,* 449-456.

MASTER REFERENCE LIST

ACSM. (2000). *Guidelines for exercise testing and prescription*(6th ed.). Baltimore: Lippincott, Williams, & Walkins.

Aruin, A. S., & Latash, M. L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research, 103,* 323-332.

Bayramoglu, M., Akman, M. N., Klnc, S., Cetin, N., Yavuz, N., & Ozker, R. (2001). Isokinetic measurement of trunk muscle strength in women with chronic low-back pain. *American Journal of Physical Medicine & Rehabilitation, 80,* 650-655.

Bliss, L. S., & Teeple, P. (2005). Core stability: The centerpiece of any training program. *Current Sports Medicine Reports, 4*, 179-183.

Bohannon, R. W. (1986). Test-retest reliability of hand-held dynamometry during a single session strength assessment. *Physical Therapy, 66*, 206-209.

Brown, M., Sinacore, D. R., & Host, H. H. (1995). The relationship of strength to function in the older adult. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 50,* 55-59.

Cachupe, W. J., Shifflett, B., Kahanov, L., & Wughalter, E. H. (2001). Reliability of Biodex Balance System Measure. *Measurement in Physical Education and Exercise Science, 5*, 97-108.

Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during single leg stance. *Journal of Applied Biomechanics, 22,* 41-50.

Crisco, J. J., Panjabi, M. M., Yamamoto, I., & Oxland, T. R. (1992). Euler stability of the human ligamentous lumbar spine. *Clinical Biomechanics, 7*, 27-32.

Daggfeldt, K., & Thorstensson, A. (2003). The mechanics of back-extensor torque production about the lumbar spine. *Journal of Biomechanics, 36*, 815-825.

Ellison J. B., Rose S. J., & Sahrmann S. A. (1990). Patterns of hip rotation range of motion: a comparison between healthy subjects and patients with low back pain. *Physical Therapy, 70,* 537-541.

Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength testsfor the trunk, hands, and shoulders. *International Journal of Industrial Ergonomics, 28,* 379-387.

Evans, K., Refshauge, K. M., & Adams, R. (2007). Trunk muscle endurance tests: reliability and gender differences in athletes. *Journal of Science and Medicine in Sports, 10*, 447-455.

Farfan, H. F. (1975). Muscular mechanism of the lumbar spine and the position of power and efficiency. *Orthopaedic Clinics of North America, 6,* 135-144.

Faries, M. D., & Greenwood, M. (2007). Core Training: stabilizing the confusion. *Strength and Conditioning Journal, 29,* 10-25.

Gabbe, B. J., Bennell, K. L., Wajswelner, H., & Finch, C. F. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5*, 90-97.

Gardner-Morse, M. G. & Stokes, A. F. (1998). The effects of abdominal muscle coactivation on lumbar spine stability. *Spine, 23*, 86-92.

Godges, J. J, MacRae, P. G., & Engelke, K. A. (1993). Effects of exercise on hip range of motion, trunk muscle performance, and gait economy. *Physical Therapy, 73.* 468-477.

Gribble, P. A., & Hertel, J. (2003). Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science, 7,* 89-100.

Guskiewicz, K. M., & Perrin, D. H. (1996). Research and clinical applications of assessing balance. *Journal of Sports Rehabilitation, 5,* 45-63.

Hall, G. L., Hetzler, R. K., Perrin, D., & Weltman, A. (1992). Relationship of timed sit-up test to isokinetic abdominal strength. *Research Quarterly for Exercise and Sport, 63,* 80-84

Heiderscheit, B., & Sherry, M. (2007). What effect do core strength and stability have on injury prevention and recovery? In D. MacAuley & T.M. Best (Eds.), *Evidence-based Sports Medicine,* (2nd ed., pp. 59-72). Hoboken, NJ: Blackwell.

Heino, J. G., Carter, C. L., & Godges, J. J. (1990). Relationship between hip extension range of motion and postural alignment. *Journal of Orthopedic and Sports Physical Therapy*, *12*, 243-247.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt Jr., R. S., Colosimo, A. J., McLean, S. G. et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine, 33,* 492-501.

Hibbs, A. E., Thompson, K. G., French, D., Wrigley, A., & Spears, I. (2008). Optimizing performance by improving core stability and strength. *Sports Medicine, 38,* 995-1008.

Hodges, P. W. (1999). Is there a role for the transverse abdominis in lumbo-pelvic stability? *Manual Therapy, 4,* 74-86.

Hodges, P. W. (2004). Lumbopelvic stability: a functional model of biomechanics and motor control. In C. Richardson, Hodges, P.W., & Hides, J. (Eds.), *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain* (2nd ed., pp. 13-28). Edinburgh, UK: Churchill Livingstone.

Hodges, P. W., & Richardson, C. A. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain. *Spine, 21*, 2640-2650.

Hodges, P. W., & Richardson, C. A. (1997) Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy, 77,* 132-142.

Ireland, M. L., Willson, J. D., Ballantyne, B. T. & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 33,* 671-676.

Jackson, A. W., Morrow, J. R., Brill, P. A., Kohl, H. W., Gordon, N. F., & Blair, S. N. (1998). Relations of sit-up and sit-and-reach tests to low back pain in adults. *Journal of Orthopedic and Sports Physical Therapy, 27,* 22-26.

Jolliffe, I. T. (2002). *Principal Component Analysis* (2nd ed.). New York: Springer.

Joseph, M., Tiberio, D., Baird, J. L., Trojian, T. H., Anderson, J. M., Kraemer, W. J. et al. (2008). Knee valgus during drop jumps in National Collegiate Athletic Association Division I female athletes: the effect of a medial post. American Journal of Sports Medicine, 36, 285-289.

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine, 36*, 189-198.

Kinzey, S. J., & Armstrong, C. W. (1998). The reliability of the Star-Excursion Test in assessing dynamic balance. *Journal of Orthopaedic & Sports Physical Therapy, 27,* 356-360.

Lawrence, R.K., Kernozek, T.W., Miller, E.J., Torry, M.R., & Reuteman, P. (2008). Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics, 23,* 806-813.

Lee, J. H., Ooi, Y., & Nakamura, K. (1995) Measurement of muscle strength of the trunk and the lower extremities in subjects with history of low back pain. *Spine, 20,* 1994-1996.

Leedham, J. S., & Dowling, J. J. (1994). Force-length, torque-angle and EMG-joint angle relationships of the human in vivo biceps brachii. *European Journal of Applied Physiology and Occupational Physiology, 70,* 421-426.

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine & Science in Sports & Exercise, 36,* 926-934.

Logan, G. A., & McKinney, W. C. (1977). The serape effect. In G.A. Logan & W.C. McKinney (Eds.), *Anatomic Kinesiology* (2nd ed., pp. 197-208). Dubuque, IA: Wm. C. Brown & Company Publishers.

Loudon, J. K., Wiesner, D., Goist-Foley, H. L., Asjes, C., & Loudon, K. L. (2002). Intrarater reliability of functional performance tests for subjects with patellofemoral pain syndrome. *Journal of Athletic Training, 37,* 256-261.

Lunnen, J. D., Yack, J., & LeVeau, B. F. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy, 61,* 190-195.

Mayer, T. G., Smith, S. S., Keeley, J., & Mooney, V. (1985).Quantification of lumbar function: Part 2: sagittal plane trunk strength in chronic low-back pain patients. *Spine, 10,* 765-772.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal datatbase. *Archives of Physical Medicine and Rehabilitation, 80,* 941-944.

McGill, S. M. (2001). Low back stability: from formal description to issues for performance and rehabilitation. *Exercise and Sports Sciences Reviews, 29,* 26-31.

McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods, 1,* 30-46.

McNeill, T., Warwick, D., Anderson, G., & Schultz, A. (1980). Trunk strengths in attempted flexion, extension, and lateral bending in healthy subjects and patients with low-back disorders. *Spine, 5,* 529-538.

Moreland, J., Finch, E., Stratford, P., Balsor, B., & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *Journal of Orthopaedic & Sports Physical Therapy, 26,* 200-208.

Morris, J. M., Lucas, D. B., & Bresler, B. (1961). Role of the trunk in stability of the spine. *The Journal of Bone and Joint Surgery (Amer. Volume), 43-A*, 327-351.

Munro, B. H., & Page, E. B. (1993). *Statistical Methods for Health Care Research* (2nd ed.). Philadelphia: J.B. Lippincott.

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik, T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female follegiate athletes. *Clinical Journal of Sport Medicine, 10*, 89-97.

Nadler, S. F., Malanga, G. A., Feinberg, J. H., Prybicien, M., Stitik, T. P., & DePrince, M. (2001). Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. *American Journal of Physical Medicine & Rehabilitation, 80,* 572-577.

Nadler, S. F., Malanga, G. A., Bartoli, L. A., Feinberg, J. H., Prybicien, M., & DePrince, M. (2002). Hip muscle imbalance and low back pain in athletes: influence of core strengthening. *Medicine and Science in Sports & Exercise, 4,* 9-16.

Nesser, T. W., Huxel, K. C., Tincher, J. L., & Okada T. (2008). The relationship between core stability and performance in Division I football players. *Journal of Strength and Conditioning Research, 22,* 1750-1754.

Norkin, C. C., & White, D. J. (1995). *Measurement of Joint Motion: A Guide to Goniometry* (2nd ed.). Philadelphia: F.A. Davis.

O'Sullivan, P. B., Manip Phyty, G. D., Twomey, L. T., & Allison, G. T. (1997). Evaluation of specific stabilization exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine, 22*, 2959-2967.

Panjabi, M. M. (1992). The stabilizing system of the spine: Part 1. Function, dysfunction, adaptation, and enhancement. *Journal of Spinal Disorders, 5*, 383-389.

Parkhurst, T. M., & Burnett, C. N. (1994). Injury and proprioception in the lower back. *Journal of Orthopaedic & Sports Physical Therapy, 19*, 282-295.

Pope, M. H., & Panjabi, M. M. (1985). Biomechanical definitions of spinal instability. *Spine, 10,* 255-256.

Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Physical Therapy, 87,* 337-349.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part 1: The physiologic basis of functional joint stability. *Journal of Athletic Training, 37,* 71-79.

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41,* 166-171.

Saal, J. A. (1992). The new back school prescription: Stabilization training part II. *Occupational Medicine, 7*, 33-42.

Santana, J. C. (2003). The serape effect: a kinesiological model of core training. *Strength and Conditioning Journal, 25,* 73-74.

Shrout, P. E., & Fleiss J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin, 86,* 420-428.

Simoneau, G. G., Hoenig, K. J., Lepley, J. E., & Papanek, P. E. (1998). Influence of hip position and gender on active hip internal and external rotation. *Journal of Orthopedic and Sports Physical Therapy, 28,* 158-164.

Tesh, K. M., Dunn, T. S., & Evans, J. H. (1987). The abdominal muscles and vertebral stability. *Spine, 12*, 501-508.

Trojian, T. H., & McKeag, D. B. (2006). Single leg balance test to identify risk of ankle sprains. *British Journal of Sports Medicine, 40,* 610-613.

Vellas, B. J., Wayne, S. J, Romero, L., Baumgartner, R. N., Rubenstein, L. Z., & Garry, P. J. (1997). One-leg balance is an important predictor injurious falls in older persons. *Journal of the American Geriatrics Society, 45,* 928-930.

Verrall, G. M., Hamilton, I. A., Slavotinek, J. P., Oakeshott, R. D., Spriggins, A. J., Barnes, P.G., et al. (2005). Hip joint range of motion reduction in sports-related chronic groin injury diagnosed as pubic bone stress injury. *Journal of Science and Medicine in Sport, 8,* 77-84.

Verrall, G. M., Slavotinek, J. P., Barnes, P. G., Esterman, A., Oakeshott, R. D., & Spriggins, A. J. (2007). Hip joint range of motion restrictions precedes athletic chronic groin injury. *Journal of Science and Medicine in Sport, 10,* 463-466.

Walsh, A. J. L., & Lotz, J. C. (2004). Biological response of the intervertebral disc to dynamic loading. *Journal of Biomechanics, 37,* 329-337.

Whittlesey, S. N., & Hamill, J. (2004). Computer simulation of human movement. In D. G. Robertson, G. E., Caldwell, Hamill, J, Kamen, G., & Whittlesey, S. N. (Eds.), *Research methods in biomechanics* (pp. 211-225). Champaign, IL: Human Kinetics.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. Clinical Orthopaedics & Related Research, 179, 275-283.

Willson, J. D., Dougherty, C. P., Ireland, M. L., & Davis, I. M. (2005). Core stability and its relationship to lower extremity function and injury. *Journal of the American Academy of Orthopaedic Surgeons, 13*, 316-325.

Willson, J. D., Ireland, M. L., & Davis, I. (2006). Core strength and lower extremity alignment during single leg squats. *Medicine & Science in Sports & Exercise, 38,* 945-952.

Zazulak B. T., Hewett T. E., Reeves N. P., Goldberg B., & Cholewicki, J. (2007). The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *American Journal of Sports Medicine, 35,* 368-373.

Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *The American Journal of Sports Medicine, 31,* 449-456.

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise, 32*, 812–819.

APPENDIX A: REVIEW OF RELEVANT LITERATURE

MEASUREMENT OF CORE STABILITY AND ITS IMPACT ON ATHLETIC PERFORMANCE

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By

Andy Waldhelm

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M.P.T., Nova Southeastern University, 2002

Table of Contents

CHAPTER 1: INTRODUCTION

Core stability is a new concept which has gained popularity in the health and fitness professions. Physicians, physical therapists, biomechanics, chiropractors, and personal trainers now use core stability to educate patients/clients on how to recover from and prevent low back pain and how to improve physical fitness or athletic performance. Core stability, also referred to as lumbar stabilization, spinal stability, lumbo-pelvic hip stability, and trunk stability, is often used to describe the ability to limit the amount of movement in the region of the body which connects the upper and lower extremities.

It is believed spinal stability was first introduced by Knutsson in 1944, when he viewed a retrodisplacement of vertebrae during trunk flexion on a radiograph (as cited in Panjabi, 1992, p. 383). Later, Morris, Lucas, and Bresler (1961) questioned how the lumbar spine was able to absorb large loads without failure. They concluded that the components of the trunk played an essential role in allowing the spine to withstand large loads without injury. In the 1970s, spinal stability became of great interest, as it was hypothesized that the trunk muscles played an important role in the protection and effectiveness of the spine and pelvis (Farfan, 1975).

The actual term "core stability" did not become popular in scientific literature until the turn of the 21st century. This was initiated by the popularity of core stability exercise programs in the practice of physical rehabilitation (McGill, 2001) and fitness (Bliss & Teeple, 2005). In the field of physical rehabilitation, McGill (2001) reported that the goal of a core stability program was to train the muscles of the core in order to maintain a sufficient amount of spinal stability. Researchers are now discovering that core stability may play an important role in the prevention and rehabilitation of injuries in the extremities. Ireland, Willson, Allantyne, and Davis (2003) observed that females who demonstrated core weakness, namely the hip abductors and external rotators, were more likely to suffer from patellofemoral pain. They concluded that individuals with a weaker core were unable to prevent excessive knee valgus and internal rotation moments during activities. This may encourage lateral tracking of the patella and pain. Similar observations by Leetun, Ireland, Willson, Ballantyne, and Davis (2004) observed an increased risk of injury in college athletes who demonstrated significant core weakness. They noted the importance of a proximal stabilization program in order to prevent lower extremity injuries in athletes.

Historically, most of the research studying core stability has focused on the relationship between core stability and athletic injuries. Hibbs, Thompson, French, Wrigley, and Spears (2008) stated, "compared to the information available on core stability and low back pain, there is far less research available on the benefits of core training for elite athletes and how core training should be performed to optimize sporting performance." Much of the theory linking core stability to athletic performance is based on the idea that athletic power is generated and then transferred from the body's trunk, or core (Santana, 2003). One of the few investigations which has studied the relationship between core stability and athletic performance was performed by Nesser, Huxel, Tincher, and Okada (2008). They tested 29 National Collegiate Athletic Association Division I football players and compared four core stability endurance tests with athletic performance tests. The authors observed only weak to moderate correlations between core stability and performance measurements.

An important issue regarding core stability is that it remains a generalized and poorly understood term (Panjabi, 1992). It lacks a universal definition and typically, the exact location of the core on the human body can vary considerably (Willson, Dougherty, Ireland, & Davis, 2005). Because a universal definition does not exist, there is not a standard assessment of core stability, which makes it difficult to measure the importance of core stability in athletic performance (Nesser, Huxel, Tincher, & Okada, 2008). Therefore, the objective of the review is to locate, define, and describe the components of core stability, establish how to thoroughly assess core stability, explain the relationship between core stability and athletic performance, and discuss future research.

CHAPTER 2: DESCRIPTION OF CORE STABILTY

Core stability is a concept used within several industries, including the health and medical professions. Whether it is used to predict the risk of low back injury among workers (Luoto, Heliovaara, Hurri, & Alaranta, 1995) or to determine how to improve one's golf game (Tsai et al., 2004), the definition of core stability has been known to vary throughout the scientific literature. The objectives of this section are to provide a clear understanding of the core's location on the body, define stability as it relates to core stability, and explain the biomechanical components that relate to core stability.

2.1. Location of the Core

In the 1960s and 1970s, researchers began studying stability of the middle region of the human body, or trunk. Morris, Lucas, and Bresler (1961) were among the first researchers who identified the trunk, thorax and abdomen as important elements in the stability of the lumbar spine. Later, Aspden (1989) illustrated the importance of posture to spinal stability by introducing a new mathematical model in which the spine resembled an arch. Using this model, Aspden observed that calculations from earlier measurements of compressive stresses on the spine were over-estimated. Today, individuals continue to study the stability of the trunk, but the stability of several anatomical structures are now included; it is not simply limited to the lumbar spine. The so-called core may include any structures that link the upper extremities to the lower extremities. In this section, we will discuss studies that attempt to elaborate on the anatomical makeup of the core. We will not elaborate on the function of each structure, as the functions will be discussed later in the chapter.

Bliss and Teeple (2005) introduce a simple description of the anatomical structures which form the core. They state that the core includes the musculature surrounding the lumbopelvic region. These muscles include the abdominals, the gluteals, the paraspinals, the hip abductors and external rotators, and the diaphragm. Kibler, Press, and Sciascia (2006) later propose a more detailed definition of the core's anatomy. Their definition includes all the musculoskeletal structures of the spine, hips, pelvis, proximal lower limb, and abdomen. Like Bliss and Teeple, Kibler and colleagues include the abdominal muscles--transverse abdominus, internal and external obliques, and rectus abdominus--as well as the diaphragm and the muscles of the hips (glutei, hip rotators) and pelvis. Unlike Bliss and Teeple, Kibler and coworkers include the quadratus lumborum, the multifidi, and the thoracolumbar fascia as part of the posterior segment of the core. Furthermore, they state that the pelvic floor muscles should be included in the anatomy of the core, since they help provide a base of support for the spine and trunk muscles. Kibler et al. also include the prime movers of the extremities--latissimus dorsi, upper and lower trapezium, pectoralis major, hamstrings, quadriceps, and the iliopsaos--since they attach to the core. In addition to most of the structures mentioned earlier, Willson, Dougherty, Ireland, and Davis (2005) include the intrinsic muscles of the spine (erector spinae) to their description of the core. They state that the intrinsic muscles help enhance the motor control components of the core stability, which would not be possible if one only included the large global muscles.

Bliss and Teeple (2005), Kibler et al. (2006), and Willson et al. (2005) all contributed to develop a descriptive location of the core and all the structures involved. Therefore, we propose the following summary of the location of the core: the core is the mid-section of the body that links the lower extremities to head, neck, and upper extremities through the thorax and lumbar-pelvic regions. It consists of all the muscular and neurological structures that make this linkage anatomically possible, while functionally effective and efficient.

2.2. Definition of Stability as Applied to the Core

The term stability has many definitions in scientific literature. This is certainly the case when studying human movement and physiology. For instance, there are several studies on the stability of the human gait pattern (Bhatt, Wening, & Pai, 2006; Buzzi & Ulrich, 2004; Cromwell & Newton, 2004) and cardiac rhythm stability (Leger & Thivierge, 1998; Malik, 1998; Stein, Rich, Rottman, & Kleiger, 1995). Furthermore, there are different classifications of stability, including dynamic stability and static stability. As Reeves, Narendra, and Cholwicki (2007) so aptly stated, "Stability depends on the system and the task being performed." We will first discuss how stability has been defined and used in different anatomical structures and joints, then discuss how it is defined and used in core stability.

The terms stable or unstable have been used to describe several different body parts, such as the ankle, knee, shoulder, and the lumbar spine. Wikstrom, Tillman, Chmielewski, and Borsa (2006) define the dynamic stability of the knee and ankle as "the ability to maintain normal movement patterns while performing high level activities without unwanted episodes of giving way." Looking at the upper extremity, Borsa, Laudner, and Sauers (2008) described both a static and dynamic stability of the shoulder complex. At the glenohumeral joint, they defined passive stability as the ability of the passive structures to resist the displacement of the humeral head from the glenoid, while dynamic stability is the ability of the rotator cuff and scapular stabilizing muscles to maintain the humeral head centered on the glenoid fossa. Borsa et al. used the end result of a subluxation or dislocation to define both passive and dynamic stability of the shoulder. A subluxation or dislocation may be a common injury of the glenohumeral joint, but it is uncommon in the knee (not including a patellar dislocation) or ankle. This helps illustrate that the definition of stability may differ from body part to body part, or a different description of stability may be required when referring to different locations on the body. The term stability, in addition to its use in joints of the extremities, it has also been applied to the spine and pelvis.

In studying the stability of the spine, one must determine if they are studying static or dynamic stability and then observe the behavior of the vertebrae. Much like the shoulder, when studying the stability of the spine, one must determine if a perturbation results in the displacement of the vertebrae past its physiological range (Reeves, Narendra, & Cholwicki, 2007). Lucus and Bresler (1961) may have been the first to test the concept of static spinal stability when they observed that the isolated thoracolumbar spine will buckle under a compress load of 20 N. Crisco, Panjabi, Yamamoto, and Oxland (1992) later isolated the lumbar spine and calculated an average compress load of 88 N before the spine became unstable. These experiments help demonstrate the concept of static stability of the spine, which is defined as the ability of a loaded structure to maintain static equilibrium (Bergmark, 1989). If stability is not upheld, then any small changes in equilibrium will cause the structure to "collapse" (Bergmark, 1989). This definition of stability may not be accurate to describe core stability, since the spine has been observed to accept loads up to18000 N during power lifting (Cholewicki & McGill, 1996).

Since the spine is a mobile system with the ability to change position in three axes, a different definition of stability is needed. White and Panjabi (1978) used the term "clinical stability of the spine" to better explain how the spine accepts loads. They define "clinical stability" as the "ability of the spine under physiological loads to limit patterns of displacement so as not to damage or irritate the spinal cord or nerve roots and, in addition, to prevent incapacitating deformity or pain due to structural change." Further contributing to the notion of dynamic stability of the spine, Cholewicki and McGill (1996), using a lumbar spine model, observed that the stability of the lumbar spine increased during high demanding tasks and decreased during low demanding tasks. Their observations did not support the hypothesis that the spine maintains a constant level of stability. Furthermore, their observations led to a term known as significant stability, which states that individuals must maintain a significant amount of stability during activities through low yet continuous muscle activation (McGill, Grenier, Kavcic, & Cholewicki, 2003). After explaining how stability is used to describe different body parts, we will attempt to describe how stability is used in the concept of core stability.

Hodges (2004) may have been first to study the concept of core stability in his composite model of lumbopelvic stability. Hodges defines the term lumbopelvic stability as the "dynamic process of controlling static position in the functional context, but allowing the trunk to move with control in other situations." Hodges also describes three interdependent hierarchy levels of lumbopelvic stability: the control of whole-body equilibrium, control of lumbopelvic orientation, and intervertebral control. The control of whole-body equilibrium is important when the trunk is repositioned in order to move the center of mass (COM). Hodges warns that if whole-body equilibrium is not maintained, control of the lumbopelvic orientation and intervertebral control cannot be maintained. Lumbopelvic orientation controls the curvature and posture of the spine and pelvis during activities (Hodges, 2004). Lumbopelvic orientation is extremely important, as it is the level in which buckling can occur if not controlled (Hodges, 2004). The last level in the hierarchy is intervertebral control, which controls both translation and rotation of each individual vertebra (Hodges, 2004). This level is not independent of the lumbopelvic orientation and can also be exposed to segmental buckling (Hodges, 2004).

Later definitions of core stability took a simpler but similar approach to defining stability as compared to Hodges (2004). Bliss and Teeple (2005) define dynamic stabilization of the spine as the ability to use muscular strength and endurance to maintain a neutral spine posture and then control the spine beyond the neutral zone when performing activities. Willson, Dougherty, Ireland, and Davis (2005) define core stability as the ability of the lumbopelvic-hip complex to return to equilibrium following a perturbation without buckling of the vertebral column. Last, Kibler, Press, and Sciascia (2006) state that the ability to control the position and motion of the trunk over the pelvis and leg to produce, transfer, and control force and motion to the terminal segment during kinetic chain activities is core stability.

Stability has been defined differently, and different definitions reflect the system or movement being studied. Furthermore, when studying core stability a pinpoint definition has yet to be developed since core stability is important in both injury prevention and physical performance. Therefore, we propose core stability is the ability to resist external mechanical perturbations in order to maintain the anatomical integrity of the core and to support the functionality of the entire body.

2.3. Components of Core Stability

We have discussed the location of the core and the definition of core stability; now we will describe the functional components which contribute to core stability. Panjabi (1992) introduced three interdependent subsystems, all capable of compensating for one another if there is an injury or impairment, which create the spinal stabilizing system. The three subsystems include the passive musculoskeletal subsystem, the active musculoskeletal subsystem, and the neural and feedback subsystem, also referred to as the neural control subsystem (Panjabi, 1992). This section will describe each of these spinal stabilization subsystems and discuss how they may contribute to core stability.

2.3.1. Passive Component

The passive component consists of the vertebrae, intervertebral discs, zygapophyseal joints, and ligaments of the spine (O'Sullivan, Manip Phyty, Twomey, & Allison, 1997). The passive structures of the spine alone are highly unstable, with the thoracolumbar spine buckling under 20 N (Lucas & Bresler, 1961) and the isolated lumbar spine buckling under 88 N (Crisco, Panjabi, Yamamota, & Oxland, 1992). Panjabi (1992) agrees, as he states the passive component provides the least amount of stability of the three components. In fact, in the neutral position the passive component does not provide significant stability. It is only at the end-ranges of motion that the ligaments become stretched and limit spinal movement (Panjabi, 1992). Furthermore, these same ligaments can be classified under the neural control component, which will be discussed later, due to the fact that they provide information on vertebral position and movements (Panjabi, 1992). In agreement with Panjabi, Willson, Dougherty, Ireland, and Davis (2005) claim the contribution of the passive component is small and is the product of the interaction of a load placed on the bony architecture and the compliance of the soft tissue. Although some claim the roles of the passive structures are small in comparison to the other components, the intervertebral discs play a significant role in the stability of the spine since the discs aid in movement and transmit forces along the vertebrae (Walsh & Lotz, 2004). In addition, it has been noted that injury to the intervertebral discs can occur and cause the spine to be less stable. Saal (1992) states that repetitive movements and torsional stress to the lumbar intervertebral discs and facet joints can lead to degeneration, which may develop into spinal joint failure since the intervertebral discs are responsible for load transmission within the intervertebral segments.

The passive component of the core includes ligaments, vertebrae, intervertebral discs and joints of the spine. The primary role of this component is to limit spinal motion at the end-ranges and transmit forces between the vertebrae. Although the role of the passive component is small, injury to the passive structures can cause joint failure and instability.

2.3.2. Active Component

The active component consists of muscles and thoracolumbar fascia, which surround the core (Panjabi, 1992). Hodges (2004) states that the active system contributes to core stability by the force generating and transfer capability of the muscles and fascia. Both Panjabi and Hodges suggest that although the active system is of significant importance to spinal stability, it cannot act alone and therefore must be included in the neural control component.

Willson, Dougherty, Ireland, and Davis (2005) included a detailed description of the role of the active component in their description of core stability. They introduced three mechanisms in which the active component contributes to core stability: intra-abdominal pressure, spinal compressive forces, and hip and trunk muscle stiffness. The first mechanism, intra-abdominal pressure, which is the amount of pressure within the abdominal cavity, is achieved by activation of the abdominal muscles, namely the transversus abdominis (Hodges, 1999), the diaphragm, the pelvic floor muscles (Willson et al., 2005), and tension of the thoracolumbar fascia (Tesh, Dunn, & Evans, 1987). Intra-abdominal pressure functions in spinal stability by creating a pressure-filled cavity anterior to the spine, causing a force against the apex of the lordosis of the lumbar vertebrae and limiting the segmental movement when performing activities (Hodges & Richardson, 1996). Furthermore, increases in intra-abdominal pressure may decrease the compressive loads on the spine and may reduce the risk for injury (Daggfeldt & Thorstensson, 2003). Gardner-Morse and Stokes (1998) illustrate the second mechanism of stability, as they conclude that antagonistic coactivation of the abdominal muscles will increase spinal stability by increasing the compressive forces placed on the spine. They estimate that antagonistic coactivation of the trunk flexor and extensor muscle increase compressive loading by a maximum of 21% during a 40% effort task, with the external obliques providing the greatest gains. The last mechanism in which the active component contributes to core stability, according to Willson et al. (2005), is to produce stiffness in the hip and trunk muscles. They stated that unless the trunk is loaded, the muscles in the hips and trunk are virtually inactive and the passive structures are required to be the main stabilizers of the core.

The active component of the core plays a vital role in core stability, but different muscles assist in different ways. The muscles of the trunk can be divided into two muscle systems: local and global muscles (Bergmark, 1989). Bergmark describes the local muscles as deep muscles that have their origin or insertion at the vertebrae. Their roles are to control the curvature of the spine and provide sagittal and lateral stiffness (Bergmark, 1989). The major local muscles include the transverse abdominis, the lumbar multifidus, and the posterior fibers of the internal obliques (O'Sullivan, Manip Phyty, Twomey, & Allison, 1997). These muscles, specifically the lumbar multifidi, have large percentages of type I fibers (58-69%) and larger type I fiber size, which help their supportive capabilities (Richardson, 1999). The global muscles are large, superficial muscles which do not attach directly to the vertebrae (Bergmark, 1989). These muscles generate movement in the trunk, balance external loads, and transfer loads from the thorax to the pelvis (Hodges, 2004). These muscles include the erector spinae muscles, the internal (all but the posterior fibers) and external obliques, the rectus abdominal muscles, and the lateral segments of the quadratus lumborum (Bergmark, 1989). The thoracolumbar fascia, specifically the posterior layer, may be included with the global muscles since it plays an important role in the transferring of forces between the spine, pelvis, and legs (Vleeming, Pool-Goudzwaard, Stoeckart et al., 1995).

The posterior layer of the thoracolumbar fascia covers the posterior muscles of the trunk from the sacral region through the thoracic region (Vleeming, Pool-Goudzwaard, Stoeckart et al., 1995). The posterior layer of the thoracolumbar fascia is further divided into two lamina: superficial and deep. The superficial lamina is continuous with the latissimus dorsi and gluteus maximus and partially connected to the external oblique and the trapezius. The deep lamina's main connection is to the sacrotuberous ligament. Contraction and stretching of the gluteus maximus and latissimus dorsi muscles can conduct and transfer contralateral forces through the posterior layer of the thoracolumbar fascia during activities (Vleeming et al., 1995). Although the local and global muscles are located and function differently, it is of vital importance that they work together in order to create and uphold stability of the spine (Hodges, 2004).

The active component contributes to core stability in three ways: intra-abdominal pressure, spinal compressive forces, and hip and trunk muscle stiffness (Willson, Dougherty, Ireland, & Davis, 2005). The muscles of the active component have been classified as either local or global, and although the roles of these groups differ, they must work together in order to achieve a stable core. Finally, as important as the functions of the active component are to core stability, stabilization could not occur without the activity of the neural control component, which will be discussed in the next section.

2.3.3. Neural Control Component

The final component involved in core stability is the neural control component. Panjabi (1992) suggests that for spinal stabilization to occur, the neural control component must receive information from a number of transducers, determine specific requirements for stability, and then initiate contraction of the active component. Hodges (2004) states that the central nervous system (CNS) continually interprets information sent by afferent nerves from the peripheral mechanoreceptors, compares this information to what is considered “appropriate stability or posture”, and stimulates muscle activity in a precise manner to maintain control of the spine. Although Panjabi and Hodges’ statements are accepted in the literature, they describe simply one of the mechanisms which contribute to the neural control component. Aruin and Latash (1995) proposed two subcomponents of the neural control component. The first subcomponent (feedforward) is the anticipatory adjustment of the core to movement or perturbations (Aruin & Latash, 1995). Since the first subcomponent’s efficacy is suboptimal, a second subcomponent (feedback) is required. The feedback subcomponent is a corrective response, which is initiated by the peripheral receptors (Aruin & Latash, 1995). The neural control component acts collectively, using both feedforward (anticipatory) and feedback (reaction) mechanisms to retain and restore stability (Aruin & Latash, 1995), but classifying an action as solely feedforward or feedback control is difficult, since at times a combination of the two is used (Riemann & Laphart, 2002).

The feedforward control of core stability results from advanced preparation before a movement occurs or before a load is placed on the trunk (Hodges, 2004). This advanced preparation is initiated at higher levels of motor control: cerebral cortex, cerebellum, and basal ganglia (Riemann & Laphart, 2002). The motor cortex allows for the initiating and managing of complex voluntary movements (Riemann & Laphart, 2002). The cerebellum is responsible for the planning and adjustment of coordinated movement, while the basal ganglia are thought to be involved in high-order aspects of motor control (Riemann & Laphart, 2002).

The feedforward control mechanism can best be demonstrated by studies which show the activation of trunk muscles occurring before movement of both the upper and lower extremities and when an expected load is placed on the trunk. Friedli, Hallett, and Simon (1984) observed activation in trunk (rectus abdominis, erector spinae) and leg muscles (quadriceps, biceps femoris) before voluntary movement at the elbow occurred in conditions where the trunk was supported and not supported and with or without a load placed on the upper extremity. Activation of trunk muscles before voluntary movement of the lower extremity has also been observed. Hodges, Richardson, and Hasan (1997) witnessed activity of the transverses abdominis, the rectus abdominis, internal obliques, and external obliques muscles before voluntary hip flexion, abduction, and extension. The transverses abdominis muscles preceded all other muscles for all three hip movements (Hodges et al., 1997). Other studies have shown delayed activity of the transverses abdominis muscles as a repertory mechanism in individuals with pain in the low back (Hodges & Richardson, 1998) and groin (Cowan et al., 2004). When an expected load is placed on the trunk, the CNS can activate the trunk muscle in anticipation of the load. Moseley, Hodges, and Gandevia (2003) observed activation of the deep lumbar mulifidus muscles in six of the seven participants as an expected weight was dropped into a bucket they were holding. In order to maintain stability in the core, the neural control component must have the ability to prepare the active component for movement and for an expected load.

The feedback mechanism of the neural component provides proprioceptive information on the whereabouts and movements of the core and other joints (Ebenbichler, Oddsson, Kollmitzer, & Erim, 2001). As with stability, proprioception is a term with several different meanings in the scientific literature; therefore, we use Riemann and Lephart's (2002) definition which states that proprioception describes afferent information from internal peripheral areas that contribute to postural control, stability, and conscious sensations. The sensory structures which provide proprioceptive information are called mechanoreceptors and are located in the muscles, tendons, ligaments, and joint capsules. Four common mechanoreceptors are the Ruffini receptors, Pacini receptors, muscle spindles, and the Golgi tendon organs. The Ruffini receptors and Pacini receptors are both located in ligaments and joint capsules. The Ruffini receptors are thought to be stretch receptors, while the Pacini receptors are activated by compression (Hogervorst & Brand, 1998). The muscle spindles are located in muscle fibers and provide information relating to muscle length and change in muscle length (Riemann & Lephart, 2002). The Golgi tendon organs are located in the musculotendinous junction and provide information muscle tension (Riemann & Lephart, 2002). To test proprioception, a joint or postural repositioning test is commonly used. Gill and Callaghan (1998) studied the ability of individuals with and without low back pain to reproduce a postural position in both standing and four-point kneeling. The study showed that individuals without low back pain were more accurate in repositioning in both the standing (2.25°) and four point kneeling positions (2.43°) (Gill & Callaghan, 1998). Therefore, pain may impair the proprioceptive input, which is an important aspect of the neural component of core stability.

To further demonstrate feedback control of core stability, we examine the actions that occur when an unexpected load or perturbation impacts the core. It has been observed that muscle activation differs in situations when an unexpected load is placed on the body, compared to an expected load (Mosley, Hodges, & Gandevia, 2003), with the major difference being a lack of the pre-activation of postural muscles (Cresswell, Oddsson, & Thorstensson, 1994). When an unexpected load or perturbation is placed on the body, a response mechanism is activated to restore stability (Ebenbichler, Oddsson, Kollmitzer, & Erim, 2001). This reaction can be initiated at the reflex level using the monosynaptic stretch reflex (Hodges, 2004) or using more complex automatic postural responses, which are equal to the magnitude, type, and direction of the perturbation (Ebenbichler et al., 2001). Small perturbations can initiate the "ankle strategy", where muscles around the ankle are recruited to restore equilibrium, while larger perturbations require the "hip strategy", which imposes specific hip movements to reestablish an upright posture (Ebenbichler et al., 2001).

In summary, the neural control component of core stability uses both feedforward and feedback control to initiate and maintain core stability and equilibrium. Impairments, such as pain, can cause disruption to both the feedforward and feedback systems, which may lead to loss of stability.

2.4. Summary

The objectives of this chapter were to identify the core's location on the body using anatomical structures, define stability as it relates to the core stability, and explain the functional components that make up stability. The location of the core can include any neural and muscular-skeletal structure which connects the upper and lower extremities. Stability may be defined in several different ways and may require a different definition depending of the system or movement being studied. When studying core stability, a pinpoint definition may not be available, but the main focus of a description should include the ability to control both whole body and thoraco-lumbopelvic equilibrium in both static and dynamic activities without injury. There are three interdependent subsystems which create the spinal stabilizing system: the passive musculoskeletal subsystem, the active musculoskeletal subsystem, and the neural control subsystem. The passive component includes ligaments, vertebrae, intervertebral discs, ribs, pelvis, and bones of the hips and shoulders. Their primary role is to provide structure and limit motion at the end-ranges. Although the role of the passive component is small, injury to the passive structures can cause joint failure. The active component contributes to core stability in three ways: intra-abdominal pressure, spinal compressive forces, and hip and trunk muscle stiffness. The muscles of the active component can be classified as either local or global muscles, depending on their location and their function, but both groups must work together in order to achieve a stable core. Finally, in order to maintain stability, the neural control component must receive information, determine specific requirements for stability, and then initiate contraction of the active component. In addition, the neural control component uses both feedforward and feedback mechanisms, collectively, to maintain stability. After describing where, what, and how core stability is achieved, the next chapter will discuss how to test core stability.

CHAPTER 3: MEASURING CORE STABILITY

Testing stability in human movement can be challenging. As with defining stability, measurements for stability can vary depending on the type of movement or joint being studied. For instance, Gill and colleagues (2001) measured trunk sway of multiple standing positions to determine postural balance. To study gait stability, Menz, Lord, St. George, and Fitzpatrick (2004) measured walking speed, walking cadence, step length, and rhythmic acceleration patterns of the head and pelvis. Similar to postural and gait stability, there are many measuring tools used to test the stability of a single joint. Harter, Osternig, Singer, James, Larson, and Jones (1988) used five different parameters to test the stability of the knee joint. They used a subjective questionnaire on knee function, a knee arthrometer to record objective measurements of knee ligamentous laxity, a knee joint position sense test, an orthopaedic clinical examination, and isokinetic muscle testing of the knee extensors and flexors. Like knee joint stability, several measurements have been developed to evaluate the specific properties of the core and to evaluate core stability in functional movements. Therefore, the objectives of this section are to introduce measurements which quantify both specific properties of core stability, including core strength, core endurance, core flexibility and core proprioception, and describe measurements which indirectly assess core stability during functional activities.

3.1. Core Strength Tests

Core strength is an important aspect of core stability. Core strength is vital to the prevention of injuries and the enhancement of performance (Bless and Teeple, 2005). Core strength measurements are common throughout the literature (Biering-Sorensen, 1984; Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Ireland, Willson, Ballantyne, & Davis, 2003; Nadler, Malanga, DePrince, Stitik, & Feinberg, 2000). Initial tests were developed to establish a relationship between muscle weakness and injury (Biering-Sorensen, 1984; Ireland et al., 2003; Nadler et al., 2000), but more recently core strength tests have been used to develop an association between core strength and athletic performance (Tsai, Sell, Myers et al., 2004) and functional tests (Willson, Ireland, & Davis, 2006). There are three common techniques used to evaluate core strength: isometric testing, isokinetic testing, and isoinertial testing.

Isometric testing tests muscular strength when a body segment is stationary (Franklin, Whalcy, & Howley, 2000). The results are recorded by a dynamometer which must be stabilized to achieve accurate results (Ireland, Willson, Ballantyne, & Davis, 2003). All movements of the trunk and hip have been measured isometrically and this section will describe methods to test each movement. In an early study, Biering-Sorensen (1984) measured maximum isometric strength of trunk flexion and extension, along with other core stabilization tests, to uncover possible risk factors for low back dysfunction in individuals between the ages of thirty and sixty-nine. The participants performed the test, which was recorded using a strain-gauge dynamometer, in the standing position, and the maximum contraction was performed for at least ten seconds. Later, Nadler, Malanga, DePrince, Stitik, and Feinberg (2000) used mean and maximum isometric force of the hip abductors and extensors to establish a relationship between side-to-side strength asymmetry and lower extremity and low back injuries in female college athletes. Special dynamometer anchoring stations were used to accurately measure muscle force, and the force was maintained for two to four seconds.

More recently, Ireland and associates (2003) used isometric measurements of the hip abductors and external rotators to study the relationship between weak hip muscles and patellofemoral pain in females. They used hand-held dynamometers with stabilizing straps to perform each test, and the peak force was recorded after five seconds of maximum effort. The peak force was then normalized to body weight. Willson et al. (2006) demonstrated the ability to test trunk lateral flexors when they studied the association between core strength and the ability to perform a single leg squat. They measured peak isometric torque of the trunk flexors and extensors; lateral flexors, hip abductors and external rotators; and knee flexors and extensors. Similar to Ireland et al. (2003), a hand-held dynamometer with stabilizing straps was used to measure five seconds of maximum isometric torque.

Illustrating the ability to test trunk isometric force in the transverse plane, DeMichele et al. (1997) studied different training frequencies on improvements in maximum isometric trunk torque. Testing was performed on a special rotary torso restraint system at seven different angles. Furthermore, good intra-rater reliability for trunk flexion and extension isometric force (Essendrop, Schibye, & Hansen, 2001) and hip flexion, extension, abduction, and adduction isometric force (Bohannon, 1986) has been observed. In summary, isometric core strength can be recorded on multiple movements of the trunk and hip, at different angles, and with good reliability. Force should be recorded for at least two seconds but can be recorded for longer than ten seconds. Furthermore, peak and mean isometric values are commonly used, but each measurement should be normalized. Although the example in this section normalized force to body weight, this may not be the most accurate method, since muscle strength increases at a lower rate than body size (Jaric, 2002). It has been suggested that adjusting for body mass using the allometric scaling method, in which the exponent force generated by a muscle to body mass is 0.67, is a better method (Jaric, Radosavljevic-Jaric, & Johansson, 2002). Finally, isometric force is typically measured using a hand-held dynamometer with a stabilizing device, which is more cost-effective and requires less time to perform than the isokinetic test, which will be discussed in the following section.

One limitation of isometric testing is that testing occurs only at a single angle. Isokinetic testing measures muscle torque at a constant velocity though a preset range of motion (Willson, Dougherty, Ireland, & Davis, 2005). Similar to isometric testing, isokinetic testing can be performed on several trunk and hip movements. Claiborne, Armstrong, Gandhi, and Pincivero (2006) studied the relationship between hip and knee strength and movement of the knee when performing a single leg squat. They measured concentric and eccentric muscle strength of the hip adductors/abductors, extensors/flexors, and internal/external rotators, as well as knee flexors/extensors at 60° per second. To demonstrate testing and reliability of isokinetic measurements of the trunk, Delitto, Rose, Crandell, and Strube (1991) measured trunk flexor and extensor torque. Furthermore, they demonstrated that isokinetic testing can occur at different velocities, as they tested at 60°, 120°, and 180° per second. They concluded that isokinetic testing was a sensitive and reliable measurement of trunk function. Isokinetic testing, although requiring expensive equipment and time consuming, is an effective method to measure core strength. Isokinetic testing can measure muscle torque of the core, both concentrically and eccentrically, and at different speeds. Although not mentioned specifically in any study introduced in this section, muscle torque should be normalized to body mass.

The last measure of core strength we will introduce is isoinertial testing, which measures muscle capacity at a constant resistance (Willson, Dougherty, Ireland, & Davis, 2005). One of the most commonly accepted core isoinertial strength tests is the curl-up test of the Canadian Standardized Test of Fitness. In this test, the participant performs their maximum number of curl-ups at a constant tempo, twenty-five repetitions per minute (Willson et al., 2005). When the participant can no longer maintain the pace, the test is stopped. Similar to the curl-up test, an isoinertial test called the extensor dynamic endurance test was described by Moreland, Finch, Stratford, Balsor, and Gill (1997). For this test, the participant lies prone over a 30° foam wedge and extends the trunk to neutral then back to the starting position. The test is performed at a constant tempo, twenty-five repetitions per minute, and the test is stopped if the participant can no longer keep the pace.

Other isoinertial strength tests involve specialized equipment which can measure torque, displacement, and velocity of curtain trunk movements. Szpaiski, Michel, and Hayez (1996) introduced a dynamometric device which they used to measure velocity and displacement of trunk movement in the sagittal plane. They chose to set the resistance at 50% of the participant's maximum isometric force. Parnianpour, Li, Nordin, and Kahanovitz (1989) created a database of normal measurements when performing an isoinertial test on a device called the B200 Isostation (Isotechnologies, Inc., Carrboro, North Carolina). This specific device allows for testing in the sagittal, frontal, and transverse plane. Other tests commonly classified as isoinertial tests which indirectly measure core strength, such as the single limb squat and the repetitive lifting test, will be discussed later in this chapter in the functional tests section. Isoinertial tests measure core strength against a constant resistance. This resistance can be one's own body weight or external resistance provided by special instruments.

Core strength can be determined using an isometric test, an isokinetic test, or an isoinertial test. An isometric test is a static test where force is recorded by a dynamometer, which must be stabilized. Although the test is static, measurements may be measured at different angles, and isometric tests are quicker and more cost efficient than other testing methods. Isokinetic testing measures core strength at a constant velocity. Although they require expensive instrumentation, measurements for most core movements can be recorded in both concentric and eccentric movements and at different velocities. We believe the velocity of the isokinetic test should be task specific. For instance, isokinetic studies on shoulder rotator strength of baseball pitchers are performed at fast velocities, 300 deg/sec (Mikesky, Edwards, Wigglesworth, & Kunkel, 1995) and 240 deg/sec (Hinton, 1988). Last, for both isometric and isokinetic tests, strength measurements should be adjusted for body mass. Isoinertial strength tests measure core strength at a constant resistance. The resistance can be the participant's own body weight or a set resistance on special devices. Similar to the isokinetic tests, the set resistance should be task-specific. Core strength is just one of four measurable properties of core stability; the next section will discuss how to measure core endurance.

3.2. Core Endurance Tests

Core endurance tests have been used in the literature to introduce relationships between core stability and injury (Leetun, Ireland, Willson, Ballantyne & Davis, 2004) and between core stability and performance (Latikka, Battie, Videman, & Gibbons, 1995). Although other authors have classified core endurance tests as isometric tests (Willson, Dougherty, Ireland, & Davis, 2005), we will define a core endurance test as a test in which the participate maintains an unsupported, static trunk position for a period of time. Although there are numerous endurance tests to select from, the four core endurance tests that will be described in this section are the Sorensen test for back trunk extensors, the prone bridge, the side or lateral bridge, and the trunk flexor endurance test.

The Sorensen test was found to be the most reported back endurance test in the literature (Moreau, Green, Johnson, & Moreau, 2001). This test assesses the posterior muscles of the trunk (Willson, Dougherty, Ireland, & Davis, 2005). It is performed by having the participant lie prone and hold the unsupported trunk horizontal, while the pelvis and low extremities are stabilized on a treatment table (Moreau et al., 2001). The test is stopped when the participant can no longer maintain a horizontal position or after 240 seconds. On an average women perform better on the Sorensen test, mean endurance time ranging from 142.0 to 220.4 seconds, compared to men, mean endurance time ranging from 84.0 to 195.0 seconds (Moreau et al., 2001).

Similar to the Sorensen test, the prone bridge test measures the endurance of the posterior core muscles, but also tests the endurance of the anterior core muscles (Bliss & Teeple, 2005). The prone bridge test is performed by having the participant lie prone and then push up with their elbows and toes (Bliss & Teeple, 2005). The participant attempts to support their body weight on only their elbows and toes, with their pelvis in a neutral position and their body straight (Bliss & Teeple, 2005). Schellenber, Land, Chan, and Burnham (2007) observed the mean of the prone bridge to be 72.5 seconds in individuals without low back pain, but the variability was high. They also observed the prone bride to have good test–retest reliability.

To measure the lateral core muscles, including the abdominal obliques (Bliss &Teeple, 2005) and the quadratus lumborum (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004), the side or lateral bridge test, which was described by McGill, Childs, and Liebenson (1999), should be used. The participant is positioned in a side-lying position with their top lower extremity resting directly on the bottom lower extremity (Leetun et al., 2004). The hips are at zero degrees of flexion and the knees in full extension (Leetun et al., 2004). The participant is asked to raise the hips off the table using their feet and bottom elbow (Leetun et al., 2004). The test is stopped when the participant can no longer keep this position (Leetun et al., 2004). In men, McGill and associates (1999) reported average endurance for right lateral bridge to be 94 seconds and left lateral bridge to be 97 seconds, with woman scoring slightly lower, 72 and 77 seconds, respectively.

Finally, to assess the endurance of the anterior core muscles, McGill, Childs, and Liebenson (1999) describe the trunk flexor endurance test. To perform this test, the participant is positioned at 60° of trunk flexion, usually supported with a foam wedge, hips and knees flexed at 90°, and the feet stabilized (Bliss & Teeple, 2005). The wedge is removed, and the participant attempts to hold this position of 60° of trunk flexion for as long as possible (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004). Mean flexion endurance time was greater for females, 149 seconds, than men, 144 seconds (McGill et al., 1999).

The objective of this section was to introduce four core endurance tests, which can help assess core stability. We defined a core endurance test as a test in which the participant maintains an unsupported, static trunk position for a period of time. Using the four tests we described, one can test the endurance of the anterior, posterior, and lateral muscles of the core. The Sorensen test is used to assess trunk extensor endurance but does not test the muscles of the pelvis or hips, since they are supported. The prone bridge test evaluates both posterior and anterior core muscles, including muscles of the hips and pelvis, but particular attention must be placed on pelvic position, since the inability to maintain the pelvis neutral calls for the termination of the test. The side or lateral bridge test assesses the endurance of the lateral muscles of the core. Similar to the prone bridge, special attention must be placed on posture to correctly terminate the test. The final test, the trunk flexor endurance test, evaluates the endurance of the anterior core muscles. When conducting this test, the evaluator must recognize not only changes in trunk angle, but also changes in hip and knee angles, since changes in hip and knee angles also call for termination of the test. Since we have introduced core strength and endurance tests, the next section will focus on how to evaluate the flexibility and range of motion of the core.

3.3. Core Flexibility Test

Inflexibility has been related to pain and impaired performance. Studies have observed poor core flexibility to be related to low back pain (Lindsay & Horton, 2002) as well as hip and knee pain (Reid, Burnham, Saboe, & Kushner, 1987). Although there is debate on the importance of flexibility in athletic performance (Craib, Mitchell, Fields, Cooper, Hopewell, & Morgan, 1996; Godges, Macrae, Longdon, & Tinberg, 1989), most athletic activities require a minimal amount of core flexibility to be successful. In this section we will describe six common clinical methods used to test core flexibility, as well as a method using a lightweight triaxial electrogonimeter.

Core flexion flexibility tests are commonly used in the clinical setting, and two time-efficient tests are the fingertip to floor test and the sit and reach test. To perform a fingertip-to-floor test the participant stands, without shoes, feet shoulder-width apart and knees straight (Merritt, McLean, Erickson, & Offord, 1986). The participant is asked to bend forward and reach their toes, and this position is held for fifteen seconds (Merritt et al., 1986). After one practice trial, the second test was recorded using the distance from the middle finger to the floor (Merritt et al., 1986). Despite a simple protocol, Merritt and colleagues (1986) reported this test to have low inter-examiner and intra-examiner reproducibility. The sit-and-reach test is another frequently used test to measure core flexion flexibility. To perform the sit-and-reach test the participant sits on the floor with their knees extended and their feet together, up against a sit-and-reach box (Craib, Mitchell, Fields, Cooper, Hopewell, & Morgan, 1996). The participant then reaches as far as possible for their toes with their hands together (Craib et al., 1996). Four trials are performed, with each position held for two seconds or more, and the greatest distance of the four trials is used (Craib et al., 1996). The sit-and-reach test has been shown to have good inter-reader and intra-reader reliability (Gabbe, Bennell, Wajswelner, & Finch, 2004).

The next two core flexibility tests, Modified Schober and Moll Test and Loebl Test, have several components, which test different trunk movements. Merritt, McLean, Erickson, and Offord (1986) describe both these tests in great detail. The Modified Schober and Moll Test measures the flexibility of trunk flexion, extension, and lateral flexion using a measuring tape (Merritt et al., 1986). The Loebl Test measures trunk flexion and extension using an inclinometer (Merritt et al., 1986). Merritt et al. (1986) reported all tests except the Moll extensor test to be reliable. Unlike the fingertip-to-floor or the sit-and-reach test, these tests measure only trunk movements and do not allow the hamstrings or arm lengths to have an impact on the results.

Since neither the Modified Schober and Moll Test or the Loebl Test measure trunk rotation, we will introduce a test described by Craib, Mitchell, Fields, Cooper, Hopewell, and Morgan (1996) to evaluate trunk rotation flexibility. For this test, the participant sits in a chair with their pelvis against the backrest and their knees stabilized. The participant holds a bar behind their head, against their shoulders, and slightly above both scapulas. The participant actively rotates the trunk, and the rotational angle is measured from the back of the chair to the bar resting on the shoulder opposite of the rotation with a goniometer. To our knowledge, reliability measurements have not been established for this test.

The final clinical test we will introduce is the passive straight leg raise, which measures hamstring length (Hsieh, Walker, & Gillis, 1983). The participant lays supine with their hips and knees extended (Craib, Mitchell, Fields, Cooper, Hopewell, & Morgan, 1996). An assistant lifts one of the participant's lower extremities, with the knee extended, up towards the participant's head, while the other lower extremity remains flat on the table (Craib et al., 1996). When the participant experiences excessive discomfort in the elevated lower extremity, the angle between the edge of the table and the midline of the thigh is measured using a goniometer (Hsieh et al., 1983). The passive straight leg raise has been shown have good intra-rater and inter-rater reliability (Gabbe, Bennell, Wajswelner, & Finch, 2004).

To this point, we have only described core flexibility tests which used simple measurement tools such as a measuring tape or a goniometer. Now we will present a device which can measure instantaneous three-dimensional motion of the trunk. Lindsay and Horton (2002) used the Lumbar Motion Monitor (Wellness Design, Chattanooga Group Inc., Hixson TN), which is a lightweight triaxial electrogoniometer to measure spine motion in golfers with and without low back pain. This device can measure trunk flexion, extension, side bending, and rotation without interfering with the golf swing. Furthermore, this device not only measures range of motion but also angular velocity and acceleration.

Several different tests used to measure core flexibility were introduced in this section, as well as a method using a lightweight triaxial electrogoniometer. Although we did not detail hip range of motion measurements, there are several resources available, including the work of Craib, Mitchell, Fields, Cooper, Hopewell, and Morgan (1996), which describes these procedures. The fingertip-to-floor test is a simple test used to measure core flexion flexibility, but it has a low reproducibility and is limited if a subject touches the floor. The sit-and-reach test is another common test used to test trunk flexion flexibility, but requires a special box and special attention must be placed on maintaining the knees in extension. The Modified Schober and Moll Test and the Loebl test allow for measurement of core flexibility for several movements, unlike the fingertip-to-floor or the sit-and-reach test. Furthermore, they do not allow hamstring or upper extremity length to factor in the measurements. Since the Modified Schober and Moll Test and the Loebl Test does not measure trunk rotation flexibility, a test described by Craib, Mitchell, Fields, Cooper, Hopewell, and Morgan (1996) was presented, but to the author's knowledge, reproductivity measurements have not yet been established. Next, the straight leg raise was introduced, which measures hamstring length and has been shown to have good reliability. Last, a device, the Lumbar Motion Monitor, was described. It is a lightweight triaxial electrogoniometer, which records range of motion, angular velocity, and angular acceleration. After discussing methods to test core strength, endurance, and flexibility, we will now explain how to evaluate the proprioceptive perceptions of the core.

3.4. Proprioceptive Tests

Proprioception is a term that is not clearly defined in the literature. As mentioned in the neural control component section, proprioception is a feedback mechanism which provides information on the location and movement of joints and limbs, also known as kinesthesia, to the central nervous system (Lephart, Princivero, & Rozzi, 1998). Furthermore, as described in the neural component section, injury or pain may impair proprioceptive feedback and cause functional limitations (Lephart et al., 1998).

Assessment of proprioception is more commonly measured in joints of the extremities, such as the shoulder or knee, compared to the core. Lephart, Warner, Borsa, and Fu (1994) studied joint position and kinesthesia in healthy, unstable, and surgically repaired shoulders. The study used a special device which passively moved the shoulder joint through internal and external rotation at 0.5 deg/sec. The blindfolded participants pressed a signaling button when they first experienced movement and the amount of time to detect movement was recorded. For position sense, the device passively positioned the shoulder in internal or external rotation and this joint angle was held for ten seconds. To reposition the shoulder, the participant used a switch to control the device to passively relocate his shoulder, and angle displacement was recorded. They observed a significant difference in both joint position sense and kinesthesia between the affected and unaffected shoulders of the unstable group, but no differences were reported for the healthy and surgically repaired group. Unlike Lephart and colleagues (1994), Barrack, Skinner and Buckley (1989) tested only change in position when they compared differences in the proprioception between knees of individuals who suffered an ACL tear and healthy controls. They used a similar device to that of Lephart et al. (1994). They reported a significantly greater difference in the ability to sense change in joint position between the healthy knee and a knee which was surgically repaired, compared to both knees of the controls.

Trunk or core proprioception assessment is not as common as in the extremities. It is believed that Pankhurst and Burnett (1994) were the first to study proprioception in the low back, as they investigated the relationship between low proprioception and a history of low back pain. They measured proprioception using three different measurements--passive motion threshold, directional motion perception, and repositioning accuracy--in three different planes--sagittal, frontal, and transverse. Similar to the studies on the shoulder and knee, the passive motion threshold is the smallest motion a subject can identify. During the passive motion threshold test the participant had to identify in which direction the motion occurred, which constituted the directional motion perception test. The position accuracy test required the participant to be passively placed in a position for five seconds and then returned to neutral. The participant was asked to return to this position and the repositioning error was recorded. They observed a moderate correlation ($r = .40$) between history of low back pain and low back proprioception.

Later, Gill and Callaghan (1998) evaluated lumbar proprioception in individuals with and without low back pain. Their assessment of lumbar propioception involved the participant reproducing a target posture 10 times in thirty seconds, with a computer screen providing visual feedback on position, in standing and four-point kneeling. They observed the group with low back pain to be less accurate when repositioning than the control group.

Proprioception is a neural feedback mechanism which provides information on location and movement of joint and limbs, and both of these properties should be measured when assessing proprioception. Testing of proprioception is less common in the core compared with the extremities, but measurements are available. These measurements, though, require special instrumentation and could be difficult to perform clinically. We have discussed methods of testing four properties of core stability: strength, endurance, flexibility, and proprioception. In the next section we will introduce functional methods which indirectly measure core stability.

3.5. Functional Tests

Up to this point we have described tests which measure individual aspects of core stability. In this section, tests which measure core stability through functional movements and activities will be explained. There are several different tests and screens which indirectly measure core stability; the tests we will describe are the five tests described by Loudon, Wiesner, Goist-Foley, Asjes, and Loudon (2002), the star-excursion test, the single limb squat, the Sahrmann core stability test, and a functional movement screen for firefighters.

Loudon, Wiesner, Goist-Foley, Asjes, and Loudon (2002) presented five tests, which they called a functional performance test. Although they used these test to investigate the reliability of the measurements in individuals with and without knee pain, we believe they are also good functional measures for core stability. The first test they describe is the anteromedial lunge. For this test, the participant stands behind a start line and performs a maximum forward lunge, with the lunging knee flexing to at least 90°, across the midline. The lunge is measured from the start line to the location where the heel of the lunging leg touches the ground. The participant must maintain good balance and posture during the lunge, and the maximum length of three trials for each limb is recorded. The second test is the step-down test. To perform the step-down test, the participant stands on an eight inch high step and steps forward and down to the floor with a single leg. The lowering limb only brushes the floor and returns to the step, insuring the stable limb performs the task. This movement is performed as many times as possible for thirty seconds, and both limbs are evaluated. The third test is the single-leg press, which is performed on a Total Gym (Fitness Quest Inc., Canton, OH) at level seven. The participant begins the test in single limb stance, with the knee fully extended, then bends the knee to 90° and returns to full knee extension. This movement is considered one repetition, and the participant performs as many as possible in thirty seconds. Again, both limbs are tested. The fourth test is the bilateral squat test, which is initiated by the participant standing evenly over both legs, in full knee extension, and feet shoulder-width apart. The participant performs as many squats as possible, to 90° of bilateral knee flexion, in thirty seconds. The last test Loudon et al. (2002) described was the balance and reach test. Similar to the anteromedial lunge test, the participant starts behind a start line and reaches straight forward with a single limb, as far as possible, until the heel touches the floor. The maximum of three trials is recorded, and then a marker is placed at 80% of the maximum distance. The participant then lunges past the 80% of maximum marker as many times as possible within thirty seconds. Only lunges that pass the 80% marker are counted, and both limbs are measured.

Similar to two of the tests just described by Loudon, Wiesner, Goist-Foley, Asjes, and Loudon (2002) are the star-excursion test and the single limb squat. The star-excursion test is a common clinical test used to measure dynamic balance and resembles the previously mentioned balance and reach test. There are different methods to the star-excursion test, but we will describe the method used by Kinsey and Armstrong (1998) when they evaluated the test's intra-rater reliability. The layout of the test includes two sets of perpendicular lines: One set is the horizontal and vertical lines, and the other set is placed 45° from the horizontal and vertical lines. A box large enough for a participant to place his feet in is placed centrally in the intersection of the 4 lines. The test begins with the participant standing inside the starting box. The participant reaches for one of the four diagonal directions: right-anterior, right-posterior, left-anterior, and left-posterior. These diagonal directions are marked by the second set of perpendicular lines. The participant reaches as far as possible, but the reaching foot is not to touch the ground. The farthest point reached is marked and then measured from the center. The test is performed five times for each direction with each leg, and rest time between trials is given. The average of the five trials for each direction is used. Kinsey and Armstrong (1998) reported moderate intra-rater reliability for the star-excursion balance test. The single limb squat resembles the single leg press described by Loudon et al. (2002), but the individual's body weight is not supported. During the single limb squat, an individual performs a partial squat, 45° (Claiborne, Armstrong, Gandhi, & Pincivero, 2006) or 60° (Willson, Ireland, & Davis, 2006) of knee flexion. Unlike the other tests we have described, quality of movement is studied, such as the knee position during the squat (Claiborne et al., 2006), using motion analyses equipment. This type of equipment is not available in most clinical settings, therefore subjective measurements are commonly used (Kibler, Pressm & Sciascia, 2006). The star-excursion test and the single limb squats are two more examples of functional tests to indirectly study core stability. Although in a clinical setting, the star-excursion test produces more objective observations, both tests can reveal impairments in core stability.

The last two functional tests to be described in this section include a test which uses a biofeedback unit, which are popular in clinical settings, and a test designed specifically for a curtain occupation. The Sahrmann core stabilizing test uses a Stabilizer Pressure Biofeedback Unit (Chattanooga Group, Inc., Hixson, TN) which is placed under a participant's lumbar spine while they are lying supine, as described by Stanton, Reaburn, and Humphries (2004). The cuff is inflated to 40 mm Hg and the participant performs five levels of activity, each level increasing in difficulty. The participant must keep the pressure cuff reading 10 mm Hg from baseline throughout the activity to progress to the next level. The final functional test is a functional movement screen introduced by Peate, Bates, Lunda, Francism and Bellamy (2007), which was specifically created for firefighters. This test involves seven functional movements which correspond to a firefighter's activity. The screen includes a hurdle step-over, a lunge, a deep squat, active straight leg raise, and a stability push up, all activities which require core stabilization (Peate et al., 2007).

There are several functional tests that require core stability to perform, and in this section we described ten different functional tests. The five tests in the study performed by Louden, Wiesner, Goist-Foley, Asjes, and Loudon (2002) included an anteromedial lunge, step-down, single-leg press, bilateral squat, and balance and reach tests. One important benefit is that these tests could all be performed in a clinical setting and have objective measures. Therefore, a therapist can evaluate pre- and post-treatment outcomes. The star-excursion test is also a common clinical test used to measure dynamic balance in four different directions. Although there are different methods to the test, we described the method used by Kinsey and Armstrong (1998). During the single limb squat test we described, an individual performs a partial squat, but unlike the other tests, the quality of movement is evaluated, not distance or repetitions.

Therefore, in clinical settings only subjective observations or estimates are recorded. The Sahrmann core stabilizing test uses a pressure biofeedback cuff, which is placed under a participant's lumbar spine while they perform different activities in the supine position. The cuff is inflated to 40 mm Hg and must remain within 10 mm Hg of baseline as they progress through the five levels of activity, with each level increasing in difficulty. The final functional test is a functional movement screen which was specifically created for firefighters. This test involves seven functional movements which correspond to a firefighter's activity. In our opinion this is the best type of function test one can perform, since it involves activities which resemble those that will be needed to perform a task or occupation.

3.6. Summary

The objectives of this section were to describe tools which quantify both specific properties of core stability and measures of functional activities which require core stability. The three types of core strength measures are isometric test, isokinetic tests, and isoinertial tests. Isometric tests are static tests where force is recorded by a dynamometer, which must be stabilized, and measurements can be performed at different angles. These measurements are quick and reliable and can be performed with somewhat inexpensive equipment. Isokinetic testing measures core strength at a constant velocity, but it requires expensive instrumentation. Isokinestic measurements for most core movements can be recorded for both concentric and eccentric movements, at different task specific velocities, but these tests can be time consuming. Isoinertial strength tests measure core strength at a constant resistance. Some of the isoinertial tests do not require special equipment and are performed quickly, while others require special devices and are time consuming. Core endurance tests are tests in which the participant maintains an unsupported, static trunk position for a period of time. Using the four tests we described, one can analysis the endurance of the anterior, posterior, and lateral muscles of the core. When performing core endurance tests, the examiner must study any changes in pelvis, hip and knee position, since changes in posture signal the termination of the test. Several methods to measure core flexibility or range of motion were explained. All measures of trunk and hip flexibility or range of motion can be measured using inexpensive tools such as a tape measure, goniometer, or an inclinometer. More expensive equipment, such as the triaxial electrogoniometer we described, is available and can measure other variables such as angular velocity and acceleration. Core proprioceptive tests evaluate the ability of an individual to reposition in a target posture or joint angle and to identify movement in the core. These measurements are not commonly performed clinically since they require special instrumentation. Last, functional tests, which require core stability to perform, were introduced. All tests can be performed clinically with objective measures, except for the single limb squat. Special attention should be given to the functional movement screen, since this test measures movements which are required to perform a specific task. We believe that these types of screens should be performed initially, before tests for different components of core stability are performed. The initial screen will determine if impairment exists, while the core strength, endurance, flexibility, and proprioception tests will isolate the impairment. After describing several different methods of measuring core stability, the next chapter will explain the relationships between core stability and athletic performance.

CHAPTER 4: RELATIONSHIP BETWEEN CORE STABIITY AND ATHLETIC PERFORMANCE

Historically, much of the research studying core stability has focused on the relationship between core stability and injuries. Although many exercise regimens and performance enhancement training protocols include core stability exercises, little research has been performed on the impact and relationship between core stability and athletic performance (Hibbs, Thompson, French, Wrigley, & Spears, 2008). Much of the theory on the importance of the core for maximum athletic performance centers on the notion that the core is the link between the trunk and the extremities and an athlete is only as strong as his or her weakest link (Bliss & Teeple, 2005). This statement will be better explained in the first section of this chapter when we discuss the Serape Effect. Later, we will examine the available literature focusing on the relationship between core stability and athletic performance and finally introduce the key elements which should be included when constructing a core stability training program.

4.1. The Serape Effect

Much of the theory linking core stability to athletic performance is generated by the idea that athletic power is generated and then transferred from the body's trunk or core (Santana, 2003). Furthermore, in his description of the core, Santana (2003) states the core's muscular layout reveals a crisscross design, which resembles a serape. A serape is a colored blanket worn by people in Mexico and other Latin American countries (Logan & McKinney, 1977). It hangs around the neck and shoulders and crosses diagonally on the anterior aspect of the trunk (Santana, 2003). From this piece of clothing and due to the fact the Serape Effect has been observed more in skillful athletes compared to non-skilled athletes, the term was created to help illustrate the importance of the core in athletic performance (Logan & McKinney, 1977).

The concept of the Serape Effect states that during ballistic movements the muscles of the

Serape Effect add to the internal forces, and these internal forces transfer from the large muscles of the lower extremities, trunk, and pelvis to the smaller muscles of the upper extremities (Logan & McKinney, 1977). The Serape Effect is observed during the preparatory phase of ballistic movements (Logan & McKinney, 1977), which includes the pre-stretching of the core muscle, and creates the ability to provide these muscles with the optimal length-tension for maximum force production (Santana, 2003). The Serape Effect involves four pairs of trunk muscles: the rhomboids, the serratus anterior, the external obliques, and the internal obliques (Logan & McKinney, 1977).

The Serape Effect is observed during the preparatory phase of ballistic movements, where the four pairs of core muscles are pre-stretched for maximum force production. The Serape Effect initiated the idea that the core is an essential part of athletic movements and must be enhanced in order to improve performance (Konin, Beil, & Werner, 2003). Since we have identified the foundation of the relationship between core stability and athletic performance, we will now examine evidence for and against a relationship between the two.

4.2. Core Stability and Athletic Performance

Most of the scientific literature on core stability studies the relationship between core stability and injuries, and only in the past decade has attention been placed on the relationship between core stability and athletic performance (Santana, 2003). Hibbs, Thompson, French, Wrigley, and Spears (2008) state, “Compared to the information available on core stability and low back pain, there is far less research available on the benefits of core training for elite athletes and how core training should be performed to optimize sporting performance.” They further indicate the lack of a gold standard for measuring core stability and strength when performing daily tasks and sporting movements may explain the lack of literature on the relationship between core stability and athletic performance. The objective of this section is to review the available literature on the association between core stability and athletic performance and review the effects of core stability training and impairment on athletic performance.

One of the first studies linking core stability and athletic performance was performed by Craib, Mitchell, Fields, Cooper, Hopewell, and Morgan (1996). They studied the association between trunk and lower extremity flexibility and running economy in sub-elite competitive distance runners. Running economy was measured by calculating the runners' submaximal VO_2, while active flexibility measurements of trunk rotation, trunk side bending, hip external rotation, ankle dorsiflexion, and ankle plantar flexion were recorded. A sit-and-reach test and a straight leg raise test were also performed. Their main observation was a positive and significant correlation between hip external rotation ($r= 0.53$) and dorsiflexion ($r= 0.65$) flexibility tests and running economy. Therefore, greater aerobic capacity was found in individuals with greater hip external rotation and dorsiflexion ability. Although Craib and associates' (1996) objective may not have been to study the association between core stability and athletic performance, they were one of the first to successfully link the two. Of course, they only tested one component of core stability as they observed a positive and significant relationship between the ability to externally rotate the hip and running economy. Some years later, Tsai, Sell, Myers, McCrory, Laudner, Pasquale, and Lephart (2004) studied the relationship between hip strength and golf performance. They compared isometric hip adduction and abduction strength of three different groups of golfers, who were grouped by ability levels. Furthermore, they examined hip strength and self-reported golf driving distance. They found left hip abduction strength was significantly different among the groups, with the best golfers demonstrating greater left hip abductor strength. They also observed a mild relationship between left hip abductor strength and golf handicap (r = -.334) and left hip abductor strength and driving distance (r = -.320). Similar to Craib, Mitchell, Fields, Cooper, Hopewell, and Morgan (1996), Tsai et al. (2004) may have indirectly linked core stability to athletic performance, but they found some interesting results. They observed increased left hip abduction strength in the group of superior golfers and a mild relationship between left hip abduction strength and golf handicap. A point of interest is the negative relationship between left hip abduction strength and driving distance. One would predict a positive relationship between the two, with increased hip strength leading to increased driving distance, but this was not observed in this particular study. Therefore, driving distance may not be a strong indicator of golf performance, or since the driving distance was self-reported, some golfers may have over-estimated their driving distance. In the two studies we identified, the main objective was not to link core stability to athletic performance, but they demonstrated how these studies could be accomplished. We will now review a paper whose intention was to develop a relationship between core stability and athletic performance.

One of the few investigations which directly studies the of the relationship between core stability and athletic performance was performed by Nesser, Huxel, Tincher, and Okada (2008), who tested twenty-nine National Collegiate Athletic Association Division I college football players. The authors measured core stability using four isometric position hold tests, or what we defined as a core endurance test. The tests included the trunk flexor endurance test, trunk extensor test, and bilateral side bridging tests. Several athletic performance measurements were used, including a countermovement vertical jump test, a shuttle run, twenty and forty yard sprints, and one repetition maximum bench press, squat, and power clean. The authors observed only weak to moderate correlations between core stability and the performance measurements. Some of the relationships between core stability and performance included the bench press (r = -0.217), vertical jump (r = 0.591), 40 yard sprint (r = -0.604), and squat (r =-.470). Nesser et al. listed two possible explanations for the weak relationships: the use of nonspecific measurements of core stability and core stability plays only a minor role in the performance tests they measured. We believe the first explanation has more merit. This study uses only the endurance core stability tests and does not include tests for strength, flexibility, neuromuscular control, and overall function. We believe the role of core stability in athletic performance may only be known when all aspects of core stability are used in the assessment. Furthermore, the athletic performance tests used do not evaluate true sport ability, therefore specific sport assessments such as golf driving distance and baseball or softball pitch velocity should be used in the future.

Initially we introduced studies which analyzed the association between core stability and athletic performance, now we evaluate how improved or impaired core stability effects athletic performance. Thompson, Blackwell, Kepesidis, and Myers-Cobb (2004) studied the effects of core stabilization training on swing speed of seventeen older golfers. The eight week core stability intervention included static and dynamic exercises using mats, foam rollers, stability balls, elastic cables, and medicine balls. The authors observed an average increase of driver swing speed of 6.3 km/hr in the exercise group (N=1l), compared to an average decrease in swing speed of 1.2 km/hr the control group (N=6). Although they had a small number of total participants and an unbalanced number of participants in each group, Thompson et al. (2004) were able to observe positive influence from a core stabilization program on driver swing speed. Future studies should examine the effect of core stability on driving distance, driving accuracy, and the golfer's handicap. Furthermore, this study did not have a true core stability assessment, so it is unknown if the core stability intervention had an influence on core stability directly.

Limiting their core stabilization intervention, Stanton, Reaburn, and Humphries (2004) investigated the effect of a six week Swiss ball training regimen on maximal aerobic power and running economy of eighteen young male athletes. Unlike Thompson, Blackwell, Kepesidis, and Myers-Cobb (2004), Stanton et al. (2004) included a pre- and post-core stability assessment. They used the Sahrmann core stability test, which was described earlier. They observed a significant improvement in core stability but not in the maximal aerobic power and running economy. The authors concluded that a lack of improved performance may be associated with the current training level of the participants, poor selection of exercise regimen and/or the insignificant load of the exercise protocol. In addition to the authors' conclusions, we would like to emphasize that the core stability test that was used is commonly found in a rehabilitation setting rather than a sports performance environment. So although the participants improved on a rehabilitation core stability assessment following a six week Swiss ball exercise program, scores on an athletic performance core stability test may have not improved.

Similar to Stanton, Reaburn, and Humphries (2004), Tse, McManus, and Masters (2005) did not observe a significant effect from a core stability intervention on a series of performance tests of college-aged rowers. Their intervention consisted of an eight week (2 times a week) progressive core stabilization program and a circuit program. The circuit program was also performed by the control group. They observed a significant improvement on two of the four core stability tests in the core stability group, compared to the control group. Their tests were the same four core endurance tests used by Nesser, Huxel, Tincher, and Okada (2008). Interestingly, they also observed a significant improvement in the back extensor endurance test in the control group, compared to the core stability group. There was not a significant difference in the functional performance tests, which included a vertical jump, broad jump, 10-m shuttle run, 40-

m sprint, medicine ball toss, and 2000-m maximal rowing ergometer test, between the groups. Similar to Stanton et al. (2004), Tse and associates (2005) explained that the lack of improvement in performance could be related to the prior conditioning level of the participants, short duration of the exercise program, and the use of testing measurements, which could not detect small amounts of improvements.

In a recent study testing the effects of a core stability program on long distance running performance, Sato and Mokha (2009) observed improved 5000-m running times in recreational and competitive runners. A control group (n = 8) and an experimental group (n = 12) were formed, each consisting of both recreational and competitive runners, and each group performed their normal running protocol. In addition, the experimental group performed five popular core stabilization exercises four times a week for six weeks. Sato and Mokha (2009) used the Star Excursion Balance Test to measure core stability before and following the six week training program. Both groups improved their Star Excursion Balance Test scores, and although no significant interaction was found, the core stability group improved by 11.67cm. The training group also improved their 5000-m run times by an average of 47 sec, compared to an average 17 sec in the control group. This difference in improvements was a statistically significant interaction. The authors theorized that the training frequency of four days a week, which was more often than previous studies, may have contributed to the improved running times. Furthermore, the participants stated that performing the exercises provided feedback on correct posture, which they carried over to their running. One possible explanation for the differences in improvements, which the authors did not address, is the fact that the training group had a slower initial running time. There was an average difference of nearly one and one-half minutes per mile between the groups, which was statistically significant and may have had a greater impact on the improved running time, compared to the core stability training.

Unlike the previous studies which studied how improving core stability effects athletic performance, Abt, Smoliga, Brick, Jolly, Lephart, and Fu (2007) studied the relationship between impaired core stability and cycling mechanics. They hypothesized that a decrease in core stability would lead to changes in cycling mechanics and pedal force. They evaluated cycling mechanics prior to and following a core fatigue workout. They observed changes in kinematic variables, which included an increase in frontal plane knee motion and sagittal plane knee and ankle motion, without loss of pedal force or work. The authors concluded that fatigue caused compensatory kinematic changes in order to produce the desired power output.

This section reviewed literature on the association between core stability and athletic performance and the effects of core stability training and impairment on athletic performance. The evidence presented is contradictory, with the evidence not fully explaining the importance of core stability. The available literature remains limited, and it continues to question core stability evaluation techniques and sport-specific core stability training protocols and interventions. Although we were unable yet to clearly demonstrate the importance of core stability on athletic performance, core stability training continues to be a common practice in sport enhancement programs; therefore, in the next section we will discuss the important components of a core stability training program.

4.3. Core Stability Training

In theory, core stability and balance are important aspects of sports due to the three-dimensional movement patterns involved in most athletic events (Hibbs, Thompson, French, Wrigley, & Spears, 2008), although the relationship between core stability and athletic performance has not yet been established. Likewise, the effects of core stability training on athletic performance are in the developmental phase of research. But despite the lack of scientific evidence, core stability training is a common practice in sports performance enhancement programs. Although there are several exercises which claim to improve core stability, how does one determine which exercises should be included in a core stability program? The purpose of this section is to discuss the differences between core stability exercise programs, what should be included in a core stability program, and how to progress through this program.

It has been stated that core stability in sports performance differs from core stability in a rehabilitation setting (Hibbs, Thompson, French, Wrigley, & Spears, 2008). Hibbs et al. (2008) explain that in the rehabilitation setting, the goal of core stability training is to allow an individual with low back pain to perform everyday tasks without pain, while in a sports performance setting, the goal of core stability training is to allow the athlete to improve on a technique which could improve performance. Faries and Greenwood's (2007) definition of core stability, in terms of a rehabilitation setting, is the ability to stabilize the spine for the purpose of preventing injury. Therefore, the goal of core stability training is to achieve significant strength, endurance, and recruitment patterns which will prevent injuries. In the sports performance setting, Willardson (2007) suggests that improving core stability will provide a more secure foundation, which will allow for greater force production in the upper and lower extremities. Furthermore, Willardson (2007) explains that core stability is a dynamic concept, which attempts to adjust to changes in posture and loads; therefore, exercises to improve core stability should replicate movement patterns of a given sport. Unlike a rehabilitation goal of core stability, the goal of core stability in the sports performance setting is to develop a foundation which will lead to greater power and more efficient use of the upper and lower extremities (Hibbs et al., 2008) when performing sports specific movement patterns (Willardson, 2007).

When designing a core stability training program for sports enhancement, the program should contain exercises for both the global and local muscles (Bliss & Teeple, 2005), with the goals of improving endurance, strength, flexibility and motor control of these muscles (Faries & Greenwood, 2007). Comerford (as cited in Hibbs, Thompson, French, Wrigley, & Spears, 2008, p. 999) lists three sub-areas of importance when developing a core stabilization program. The first is a low-threshold stability exercise program, which allows the central nervous system to modify and efficiently control the recruitment of the local and global muscles in order to avoid muscle recruitment imbalances. The second is a high-threshold, overload training program of the global stabilizer muscles in order to produce hypertrophy and lead to a greater and more stable foundation. The last is a high-threshold strength training program of the global mobilizing muscles, resulting in maximal force being produced in the upper and lower extremities. Like Comerford, Hibbs et al. (2008) include low-threshold and high-threshold exercises in their core stability program to improve joint stability, muscle function, and movement function. But unlike Comerford, Hibbs et al. (2008) include exercises to improve joint range and muscle extensibility. Stephenson and Swank (2004) state that flexibility exercises should be included because a flexible spine may reduce the chance of injury caused by an unexpected load. There may not be much debate on the development or contents of a core stability program, but attempting to progress through a program could be difficult.

The progression of core stability may be more important and may lead to much more debate than the construction of a core stability program. McGill (2001) states that muscle control and flexibility training should precede all other core training, due to the possibility of the spine buckling during normal activity. McGill's (2001) notion could be classified as a progression in a rehabilitation core stability program and therefore may not represent how to proceed through a sports-specific core stabilization program. Others (Stephenson & Swank, 2004; Willardson, 2007) suggest core exercises should first be performed in a stable environment and then progress to an unstable environment. An example of this would be to first perform a chest press on a flat bench and then progress to performing the exercise on a Swiss ball. Bliss and Teeple (2005), who incorporate many different ideas, may have the best description for how to progress though a core stability program. They state that an athlete must first demonstrate the neuromuscular control of their core muscles on both stable and unstable surfaces. Then the athlete can perform multidirectional exercises, especially in the transverse plane, which is vital to athletic activities. Next, proprioception training should be used to improve their ability to react to postural perturbations. Last, power exercises, such as plyometrics, and sports-specific exercises should be performed to enhance muscle activation.

The objectives of this section were to explain possible differences in a core stability program in rehabilitation and a sports enhancement setting and to describe how to develop and progress a sports enhancement core stability program. The ultimate goal of core stability training in a rehabilitation setting is to help prevent injuries, while in a sports performance setting, the goal is to generate and transfer force to the upper and lower extremities. A sports enhancement core stability program should include exercises which benefit both local and global muscles and include both low and high-threshold exercise. The progression of the sports enhancement core stability program can be a difficult challenge. Interestingly, a sports enhancement program can be initiated with exercises similar to a rehabilitation program. Once neuromuscular control is established, the athlete can then progress to exercises on an uneven surface, multidirectional exercises, and finally to power and sports-specific exercises.

4.4. Summary

The objectives of this chapter were to explain the Serape Effect, examine the literature on the relationship between core stability and athletic performance, and discuss what is involved in a core stability training program. The available literature remains limited on the importance of core stability on athletic performance due in part to a lack of a global definition of core stability and a true core stability measurement. Although the evidence does not clearly explain the relationship of core stability to athletic performance, it continues to question how core stability is evaluated and if sports-specific core stability training is effective. There is a difference between the goals of core stability training in a rehabilitation setting, compared to a sports enhancement setting. Core stability training in a rehabilitation setting is used to help recover and prevent future injuries, while in a sports enhancement setting, core stability training is performed to generate and transfer force to the upper and lower extremities. A sports enhancement core stability program should include exercises which benefit both the local and global muscles and include both low- and high-threshold exercises. The progression of the program should first develop neuromuscular control, then progress to multidirectional exercises, and finally to power and sports-specific interventions. As we have now defined and described the components of core stability, established how to assess core stability, and explained the relationship between core stability and athletic performance, we will now detail future projects and research.

CHAPTER 5: FUTURE DIRECTION

To review, we first identified the location of the core, defined stability as it relates to core stability and identified the three components of core stability. The location of the core is the mid-section of the body that links the lower extremities to the head, neck, and upper extremities through the thorax and lumbar-pelvic regions and consists of all the muscular and neurological structures that make this linkage anatomically possible. We define core stability as the ability to resist external mechanical perturbations in order to maintain the anatomical integrity of the core and to support the functionality of the entire body. The three components of core stability include the passive musculoskeletal component, the active musculoskeletal component, and the neural component. We then identified measurements which quantify both specific properties of core stability, including core strength, core endurance, core flexibility, and core proprioception, and described measurements which indirectly assess core stability during functional activities. Last, we explained the Serape Effect, which in theory, links core stability to athletic performance by the idea that athletic power is generated and then transferred from the body's trunk or core. We examined the literature on the relationship between core stability and athletic performance and discussed what is involved in a core stability training program. Now we will explain future directions and projects to be developed to better understand the relationship between core stability and athletic performance.

5.1. Aim 1. Create and determine the reliability of a comprehensive core stability test.

It has been suggested that a major reason for the inability to determine the impact core stability plays in athletic performance is the absence of a true assessment of core stability (Nesser, Huxel, Tincher, & Okada, 2008). The objective is to develop a core stability assessment which evaluates all four individual components of core stability which were discussed: strength, endurance, proprioceptive, and flexibility. It is our hope that this assessment will be the foundation for all future core stability assessments. Furthermore, we will determine the reliability of the test. We hypothesize that the strength and endurance tests will produce high test-retest correlations, as were observed in isometric tests for the hips (Agre, Magness, Hull, Wright, Baxter, Patterson et. al., 1987) and trunk (Essendrop, Schibye, and Hansen, 2001) and four trunk endurance tests (McGill, Childs, and Liebenson, 1999). We will also observe moderate to high flexibility test-retest reliability, as observed by Gabbe, Bennell, Wajswelner, and Finch (2004), who tested the range of motion of the hips and trunk. Although to the author's knowledge, a test-retest evaluation of the ability to reposition the trunk and hips has not yet been performed, we believe our proprioception test of core repositioning has similar results to those of Deshpande, Connelly, Culham, and Costigan (2003), who observed high reposition reliability of the ankle.

5.2. Aim 2. Evaluate how individual core stability tests correlate to the functional core stability tests.

Every individual component of the core stability test mentioned in Aim 1 is significant, yet we believe the contribution of each component is not equal. Therefore, we will assess the importance of each individual core stability test by comparing the individual core stability tests to the functional core stability tests, which measure two or more individual components. We hypothesize the strength and proprioception components will be the major contributors to the functional core tests, since these two components are typically tested and improved following a sports injury (Roberts, Ageberg, Andersson, & Friden, 2007) or to improve athletic performance (Chimera, Swanik, Swanik, & Straub, 2004; Wooden, Greenfield, Johanson, Litzelman, Mundrane, & Donatelli, 1992). Discovering the level of contribution for each individual component will allow us to develop a more accurate weighted scoring system for our core stability evaluation.

5.3. Aim 3. Validate the core stability test using a proven intervention.

Last, we will attempt to validate our core stability test, both individual and functional components, by using an abdominal belt, which has been observed to increase intra-abdominal pressure and spinal stability (Cholewicki, Juluru, Radebold, Panjabi, & McGill, 1999). We hypothesize that every individual and functional core test will improve with the abdominal belt except flexibility, which has been observed not to change following external stabilization (Dekutoski, Schendel, Ogilvie, Olsewski, Wallace, & Lewis, 1994). Furthermore, the validation will allow us to test our grading system described in Aim 2, to ensure we stress the importance of the major contributors.

REFERENCES

Abt, J. P, Smoliga, J. M, Brick, M. J., Jolly, J. T., Lephart, S. M., & Fu, F. H. (2007). Relationship between cycling mechanics and core stability. *Journal of Strength and Conditioning Research, 21,* 1300-1304.

Agre, J. C., Magness, J. L., Hull, S. Z., Wright, K. C., Baxter, T. L., Patterson, R., & Stradel, L. (1987). Strength testing with a portable dynamometer: reliability of the upper and lower extremities. *Archives of Physical Medicine and Rehabilitation, 68,* 454-458.

Aruin, A. S. & Latash, M. L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research, 103,* 323-332.

Aspden, R. M. (1989). The spine as an arch: a new mathematical model. *Spine, 14,* 266-274.

Barrack, R. L., Skinner, H.B., & Buckley, S.L. (1989). Proprioception in the anterior crucicate deficient knee. *The American Journal of Sports Medicine, 17,* 1-6.

Bergmark, A. (1989). Stability of the lumbar spine: A study in mechanical engineering. *Acta Orthopaedica Scandinavica Supplementum, 230*, 1-54.

Bhatt, T., Wening, D. J., & Pai, Y. C. (2006). Adaptive control of gait stability in reducing slip related backward loss of balance. *Experimental Brain Research, 170,* 61-73.

Biering-Sorensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine, 9,* 106-119.

Bliss, L. S., & Teeple, P. (2005). Core stability: The centerpiece of any training program. *Current Sports Medicine Reports, 4*, 179-183.

Bohannon, R. W. (1986). Test-retest reliability of hand-held dynamometry during a single session of strength assessment. *Physical Therapy, 66,* 206-209.

Borsa, P. A., Laudner, K. G., & Sauers, E. L. (2008). Mobility and stability adaptations in the shoulder of the overhead athlete: A theoretical and evidence-based perspective. *Sports Medicine, 38*, 17-36.

Buzzi, U. H., & Ulrich, B. D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8*, 241-254.

Chimera, N. J., Swanik, K. A., Swanik, B., & Straub, S. J. (2004). Effects of plyometric training on muscle-activation strategies and performance in female athletes. J*ournal of Athletic Training, 39,* 24-31.

Cholewicki J. & McGill, S. M. (1996). Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain. *Clinical Biomechanics (Bristol, Avon), 11*, 1-15.

Cholewicki, J., Juluru,K., Radebold, A., Panjabi, M. M., & McGill, S. M. (1999). Lumbar spine stability can be augmented with an abdominal belt and/or increased intra-abdominal pressure. *European Spine Journal, 8,* 388-395.

Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during single leg stance. *Journal of Applied Biomechanics, 22,* 41-50.

Cowan, S. M., Schache, A. G., Brukner, P., Bannell, K. L., Hodges, P. W., Coburn, P., et al. (2004). Delayed onset of transverses abdominus in long-standing groin pain. *Medicine & Science in Sports & Exercise, 36*, 2040-2045.

Craib, M. W., Mitchell, V. A., Fields, K. B., Cooper, T. R., Hopewell, R., & Morgan, D. W. (1996). The association between flexibility and running economy in sub-elite male athletes. *Medicine and Science in Sports and Exercise, 28,* 737-743.

Cresswell, A. G., Oddsson, L., & Thorstensson, A. (1994). The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research, 98,* 336-341.

Crisco, J. J., Panjabi, M. M., Yamamoto, I., & Oxland, T. R. (1992). Euler stability of the human ligamentous lumbar spine. *Clinical Biomechanics, 7*, 27-32.

Cromwell, R. L., & Newton, R. A. (2004). Relationship between balance and gait stability in healthy older adults. *Journal of Aging and Physical Activity, 12,* 90-100.

Daggfeldt, K., & Thorstensson, A. (2003). The mechanics of back-extensor torque production about the lumbar spine. *Journal of Biomechanics, 36*, 815-825.

Dekutoski, M. B., Schendel, M. J, Ogilvie, J. W., Olsewski, J. M., Wallace, L. J., & Lewis, J. L. (1994). Comparison of in vivo and in vitro adjacent segment motion after lumbar fusion. *Spine, 19,* 1745-1751.

Delitto, A., Rose, S. J., Crandell, C. E., & Strube, M. J. (1991). Reliability of isokinetic trunk muscle performance. *Spine, 16,* 800-803.

DeMichele, P. L., Pollock, M. L., Graves, J. E., Foster, D. N., Carpenter, D., Grazarella, L. et al. (1997). Isometric torso rotation strength: effect of training frequency on its development. *Archives of Physical Medicine and Rehabilitation, 78,* 64-69.

Deshpande, N., Connelly, D. M., Culham, E. G., & Costigan, P. A. (2003). Reliability and validity of ankle proprioception measures. *Archives of Physical Medicine and Rehabilitation, 84,* 883-889.

Ebenbichler, G. R., Oddsson, L. I. E., Kollmitzer, J., & Erim, Z. (2001). Sensory-motor control of the lower back: implications for rehabilitation. *Medicine & Science in Sports & Exercise, 33*, 1889-1898.

Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength tests for the trunk, hands, and shoulders. *International Journal of Industrial Ergonomics, 28,* 379-387.

Farfan, H. F. (1975). Muscular mechanism of the lumbar spine and the position of power and efficiency. *Orthopaedic Cinics of North America, 6,* 135-144.

Faries, M. D., & Greenwood, M. (2007). Core Training: stabilizing the confusion. *Strength and Conditioning Journal, 29,* 10-25.

Franklin, B. A., Whalcy, M. H., & Howley, E. T. (Eds.). (2000). *ACSM's guidelines for exercise testing and prescription (6th ed.)*. Philadelphia: Lippincott, Williams, & Wilkins.

Friedli, W. G., Hallett M., & Simon, S. R. (1984). Postural adjustments associated with rapid voluntary arm movements 1. Electromyographic data. *Journal of Neurology, Neurosurgery, and Psychiatry, 47*, 611-622.

Gabbe, B., Bennell, K., Wajswelner, H., & Finch, C. (2004). Reliability of common lower extremity musculoskeletal screening tools. *Physical Therapy in Sports, 5,* 90-97.

Gardner-Morse, M. G., & Stokes, A. F. (1998). The effects of abdominal muscle coactivation on lumbar spine stability. *Spine, 23*, 86-92.

Gill, J., Allum, J. H. J., Carpenter, M. G., Held-Ziolkowska, M., Adkin, A. L., Honegger, F., et al. (2001). Trunk sway measures of postural stability during clinical balance test: effect of age. *Journal of Gerontology, 56A,* M438-M447.

Gill, K. P., & Callaghan, M. J. (1998). The measurement of lumbar proprioception in individuals with and without low back pain. *Spine, 23*, 371-377.

Godges, J. J., Macrea, H., Longdon, C., & Tinberg, C. (1989). The effects of two stretching procedures on hip range of motion and gait economy. *Journal of Orthopaedic and Sports Physical Therapy, 7,* 350-357.

Harter, R. A., Osternig, L. R., Singer, K. M., James, S. L., Larson, R. L., & Jones, D. C. (1988). Long-term evaluation of knee stability and function following surgical reconstruction for anterior cruciate ligament insufficiency. *The American Journal of Sports Medicine, 16,* 434-443.

Hibbs, A. E., Thompson, K. G., French, D., Wrigley, A., & Spears, I. (2008). Optimizing performance by improving core stability and strength. *Sports Medicine, 38,* 995-1008.

Hides, J. (Ed.). *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain* (2nd ed., pp. 13-28). Edinburgh, UK: Churchill Livingstone.

Hinton, R. Y. (1988). Isokinetic evaluation of shoulder rotational strength in high school baseball pitchers. *The American Journal of Sports Medicine, 16, 274-279.*

Hodges, P. W. (1999). Is there a role for the transverse abdominis in lumbo-pelvic stability? *Manual Therapy, 4,* 74-86.

Hodges, P. W. (2004). Lumbopelvic stability: a functional model of biomechanics and motor control. In C. Richardson, Hodges, P.W., & Hides, J. (Ed.), *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain* (2nd ed., pp. 13-28). Edinburgh, UK: Churchill Livingstone

Hodges, P. W., & Richardson, C. A. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain. *Spine, 21*, 2640-2650.

Hodges, P. W., & Richardson, C. A. (1998). Delayed postural contraction of transversus abdominus associated with movement of the lower limb in people with low back pain. *Journal of Spinal Disorders, 11*, 46-56.

Hodges, P. W., Richardson, C. A., & Hasan, Z. (1997). Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy, 77*, 132-144.

Hogervorst, T., & Brand, R. A. (1998) Current concepts review: mechanoreceptors in joint function. *Journal of Bone and Joint Surgery, 80-A,* 1365-1378.

Hsieh, C. Y., Walker, J. M., & Gillis, K. (1983). Straight-leg-raising test. Comparison of three instruments. *Physical Therapy,* ***63***, 1429–1433.

Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 33,* 671-676.

Jaric, S. (2002). Muscle strength testing: use of normalization for body size. *Sports Medicine, 32,* 615-631.

Jaric, S., Radosavljevic-Jaric, S., & Johansson, H. (2002). Muscle force and muscle torque in humans require different methods when adjusting for differences in body size. *European Journal of Applied Physiology, 87,* 304-307.

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine, 36*, 189-198.

Kinzey, S. J. & Armstrong, C. W. (1998). The reliability of the star-excursion test in assessing dynamic balance. *Journal of Orthopaedic & Sports Physical Therapy, 27,* 356-360.

Konin, J. G., Beil, N., & Werner, G. (2003). Facilitating the serape effect to enhance extremity force production. *Functional Rehabilitation, 8,* 54-56.

Latikka, P., Battie, M. C., Tideman, T., & Gibbons, L. E. (1995). Correlations of isokinetic and psychophysical back lift and static back extensor endurance test in men. *Clinical Biomechanics, 10,* 325-330.

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine & Science in Sports & Exercise, 36,* 926-934.

Leger, L., & Thivierge, M. (1998). Heart rate monitors: validity, stability, and functionality. *Physician and Sportsmedicine, 16*, 143-151.

Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports Medicine, 25,* 149-155.

Lephart, S. M., Warner, J. J. P., Borsa, P. A., & Fu, F. H. (1994). Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. *Journal of Shoulder and Elbow Surgery, 3,* 371-80.

Lindsay, D., & Horton, J. (2002). Comparison of spine motion in elite golfers with and without low back pain. *Journal of Sports Sciences, 20,* 599-605.

Logan, G. A., & McKinney, W. C. (1977). The serape effect. In G.A. Logan & W.C. McKinney (Eds.), *Anatomic Kinesiology (2nd ed.,* pp 197-208). Dubuque, IA: Wm. C. Brown Company Publishers.

Loudon, J. K., Wiesner, D., Goist-Foley, H. L., Asjes, C., & Loudon, K. L. (2002). Intrarater reliability of functional performance tests for subjects with patellofemoral pain syndrome. *Journal of Athletic Training, 37,* 256-261.

Lucas, D. B., & Bresler B. (1961). *Stability of the ligamentous spine: Report 40 from the Biomechanics Laboratory*.Unpublished manuscript, University of California-San Francisco, Berkley.

Luoto, S., Heliovaara, M., Hurri, H., & Alaranta, H. (1995). Static back endurance and the risk of low-back pain. *Clinical Biomechanics, 10*, 323-324.

Malik, M. (1998). Heart rate variability. *Common Opinion in Cardiology, 13,* 36-44.

McGill, S. M. (2001). Low back stability: from formal description to issues for performance and rehabilitation. *Exercise and Sports Sciences Reviews, 29,* 26-31.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Archives of Physical Medicine and Rehabilitation, 80,* 941-944.

McGill, S. M., Grenier, S., Kavcic, N., & Cholewicki, J. (2003). Coordination of muscle activity to assure stability of the lumbar spine. *Journal of Electromyography and Kinesiology, 13*, 353-359.

Menz, H. B., Lord, S. R., St. George, R., & Fitzpatrick, R. C. (2004). Walking stability and sensorimotor function in older people with diabetic peripheral neuropathy. *Archives of Physical Medicine and Rehabilitation, 85,* 245-252.

Merritt, J. L., McLean, T. J., Erickson, R. P., & Offord, K. P. (1986). Measurement of trunk flexibility in normal subjects: reproducibility of three clinical methods. *Mayo Clinic Proceedings, 61*, 192-197.

Mikesky, A. E., Edwards, J. E., Wigglesworth, J. K., & Kunkel, S. (1995). Eccentric and concentric strength of the shoulder and arm musculature in collegiate baseball pitchers. *American Orthopaedic Society for Sports Medicine, 23,* 638-642.

Moreau, C. E., Green, B. N., Johnson, C. D., & Moreau, S. R.(2001). Isometric back extension endurance tests: a review of the literature. *Journal of Manipulative & Physiological Therapeutics, 24,* 110-122.

Moreland, J., Finch, E., Stratford, P., Balsor, B., & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *Journal of Orthopaedic and Sports Physical Therapy, 26,* 200-208.

Morris, J. M., Lucas, D. B, & Bresler, B. (1961). Role of the trunk in stability of the spine. *The Journal of Bone and Joint Surgery (Amer. Volume), 43-A*, 327-351.

Moseley, G. L., Hodges, P. W., & Gandevia, S. C. (2003). External perturbation of the trunk in standing humans differentially activates components of the medial back muscles. *Journal of Physiology, 547*, 581-587.

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clinical Journal of Sports Medicine, 10,* 89-97.

Nesser, T. W., Huxel, K. C., Tincher, J. L., and Okada T. (2008). The relationship between core stability and performance in Division I football players. *Journal of Strength and Conditioning Research, 22,* 1750-1754.

O'Sullivan, P. B., Manip Phyty, G. D., Twomey, L. T., & Allison, G. T. (1997). Evaluation of specific stabilization exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine, 22*, 2959-2967.

Panjabi, M. M. (1992). The stabilizing system of the spine: Part 1. Function, dysfunction, adaptation, and enhancement. *Journal of Spinal Disorders, 5*, 383-389.

Parkhurst, T. M. & Burnett, C. N. (1994). Injury and proprioception in the low back. *Journal of Orthopaedic & Sports Physical Therapy, 19,* 282-295.

Parnianpour, M., Li, F., Nordin, M., & Kahanovitz, N. (1989). A database of isoinertial trunk strength tests against three resistance levels in sagittal, frontal, and transverse planes in normal male subjects. *Spine, 14,* 409-411.

Peate, W. F., Bates, G., Lunda, K., Frances, S., & Bellamy, K. (2007). Core strength: a new model for injury prediction and prevention. *Journal of Occupational Medicine and Toxicology, 2*, 3.

Reeves, N. P., Narendra, K. S., & Cholwicki, J. (2007). Spine stability: the six blind men and the elephant. *Clinical Biomechanics (Bristol, Avon), 22*, 266-274.

Reid, D. C., Burnham, R. S., Saboe, L. A., & Kushner, S. F. (1987). Lower extremity flexibility patterns in classical ballet dancers and their correlation to lateral hip and knee injuries. *The American Journal of Sports Medicine, 15,* 347-352.

Richardson, C. (1999). Traditional views of the function of the muscles of the local stabilizing system of the spine. In C. Richardson, Jull, G., Hodges, P.W., and Hides, J. (Ed.), *Therapeutic Exercise for Spinal Segmental Stabilization in Low Back Pain* (pp. 21-40). Edinburgh, UK: Churchill Livingstone.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part 1: The physiologic basis of functional joint stability. *Journal of Athletic Training, 37,* 71-79.

Roberts, D., Ageburg, E., Andersson, G., & Friden, T. (2007). Clinical measurements of proprioception, muscle strength, and laxity in relation to function in the ACL-injured knee. *Knee Surgery, Sports Traumatology, Arthroscopy, 15,* 9-16.

Saal, J. A. (1992). The new back school prescription: Stabilization training part II. *Occupational Medicine, 7*, 33-42.

Santana, J. C. (2003). The serape effect: a kinesiological model of core training. *Strength and Conditioning Journal, 25,* 73-74.

Sato, K., & Mokha, M. (2009). Does core strength training influence running kinetics, lower-extremity stability, and 5000-m performance in runners? *Journal of Strength and Conditioning Research, 23,* 133-140.

Schellenberg, K. L, Lang, J. M., & Burnham, R. S.(2007). A clinical tool for office assessment of lumbar spine stabilization endurance: prone and supine bridge maneuvers. *American Journal of Physical Medicine & Rehabilitation, 86,* 380-386.

Stanton, R., Reaburn, P. R., & Humphries, B. (2004). The effect of short-term Swiss ball training on core stability and running economy. *Journal of Strength and Conditioning Research, 18,* 522-528.

Stein, P. K, Rich, M. W., Rottman, J. N., & Kleiger, R. E. (1995). Stability of index of heart rate variability in patients with congestive heart failure. *American Heart Journal, 129,* 975-981.

Stephenson, J. Swank, A. M. (2004). Core training: designing a program of anyone. *Strength and Conditioning Journal, 26,* 34-37.

Szpalski, M., Michel, F., & Hayez, P. (1996). Determination of trunk motion patterns associated with permanent or transient stenosis of the lumbar spine. *Spine, 5,* 332-337.

Tesh, K. M., Dunn, T. S., & Evans, J. H. (1987). The abdominal muscles and vertebral stability. *Spine, 12*, 501-508.

Thompson, C., Blackwell, J., Kepesidis, I., & Myers-Cobb, K. (2004). Effect of core stability training on fitness, swing speed, and weight transfer in older male golfers. *Medicine & Science in Sports & Exercise, 36,* S204.

Tsai, Y. S., Sell, T. C., Myers, J. B., McCrory, J. L., Laudner, K. G., Pasquale, M. R. et al. (2004). The relationship between hip muscle strength and golf performance. *Medicine & Science in Sports & Exercise, 36*, S9.

Tse, M. A., McManus, A. M., & Masters, R. S. W. (2005). Development and validation of a core endurance intervention program: implications for performance in college-age rowers. *Journal of Strength and Conditioning Research, 19,* 547-552.

Vleeming, A., Pool-Goudzwaard, A. L., Stoeckart, R., van Wingerden, J. P., & Snijder, C. J. (1995). The posterior layer of the thoracolumbar fascia: its function in load transfer from spine to legs. *Spine, 20,* 753-758.

Walsh, A. J. L., & Lotz, J. C. (2004). Biological response of the intervertebral disc to dynamic loading. *Journal of Biomechanics, 37,* 329-337.

White, A. A., & Panjabi, M. M. (1978). *Clinical biomechanics of the spine*. Philadelphia, Toronto: J.B. Lippincott.

Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., & Borsa, P. A. (2006). Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. *Sports Medicine, 36*, 393-410.

Willardson, J. M. (2007). Core stability training: applications to sports conditioning programs. *Journal of Strength and Conditioning Research, 21,* 979-985.

Willson, J. D., Dougherty, C. P., Ireland, M. L., & Davis, I. M. (2005). Core stability and its relationship to lower extremity function and injury. *Journal of the American Academy of Orthopaedic Surgeons, 13*, 316-325.

Willson, J. D., Ireland, M. L., & Davis, I. M. (2006). Core strength and lower extremity alignment during single leg squats. *Medicine & Science in Sports & Exercise, 38,* 945-952.

Wooden, M. J., Greenfield. B., Johanson, M., Litzelman, L., Mundrane, M., & Donatelli, R. A. (1992). Effects of strength training on throwing velocity and shoulder muscle performance in teenage baseball players. *Journal of Orthopaedic & Sports Physical Therapy, 15,* 223-228.

APPENDIX B: INFORMED CONSENT

1. Study Title: Testing the Reliability and Validity of a New Clinical Assessment of Core Stability

2. Performance Site: Biomechanics Lab, Room B2 Gym Armory, Louisiana State University-Baton Rouge

3. Investigators: The investigators listed below are available to answer questions about the research, M-F, 8:00 a.m. - 5:00 p.m.

Dr. Li Li	Andy Waldhelm
225-578-2036	225-328-3890
lli3@lsu.edu	awaldh1@lsu.edu

4. Purpose of the Study: The purpose of this study is to test a new core stability test.

5. Subject Inclusion: Males and Females, ages 18-30, who have not suffered from low back pain or an injury to their arms and legs in the past year.

6. Number of Subjects: 40

7. Study Procedures: Each person will perform a core stability test, which is made up of several individual tests that measure strength, flexibility, endurance, joint position, and overall function and balance. Each participant will perform the core stability test twice on two separate days with a week in between the tests. Each person will be given a written description of each test. Also, each test will be explained in detail and demonstrated. For safety, a spotter will be used on the more difficult tests.

8. Benefits: Each participant will be given extra credit in their kinesiology course, and the individual with the highest score on the core stability test will win one hundred dollars.

9. Risks/Discomforts: There may be slight discomfort during the test as well as the possibility of muscle soreness and fatigue a couple days following the test. To minimize this risk there will be a warm-up and cool-down period. Also, a licensed physical therapist will be conducting the test and will explain how to limit the amount of muscle soreness.

10. Right to Refuse: Participant may choose not to participate or to withdraw from the study at any time without penalty.

11. Privacy: The LSU Institutional Review Board (which oversees university research with human subjects) and SPONSOR NAME (if applicable) may inspect and/or copy the study records.

Results of the study may be published, but no names or identifying information will be included in the publication. Participant identity will remain confidential unless disclosure is legally compelled.

13. Financial Information: There is no cost to the participant, nor is there any compensation for participating in the study.

14. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Robert C. Mathews, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of the consent form.

Subject Signature:_______________________________ Date:___________________

VITA

Andy Waldhelm grew up with a love of sports, playing several different sports including baseball, football, basketball, soccer, and golf. It was his participation in sports that led him to a career in sports medicine after fracturing his right ankle playing high school football. He has been a practicing physical therapist for nine years specializing in orthopedic and sports rehabilitation. Furthermore, Andy is a Certified Strength and Conditioning Specialist through National Strength and Conditioning Association. Prior to Louisiana State University, Andy received his bachelor's degree in education/health science from Baylor University in Waco, Texas and master's degree in physical therapy from Nova Southeastern University in Fort Lauderdale, Florida.