The Relationship between Core Stability and a Hockey Specific Sport Performance in Elite vs. Non-Elite Hockey Athletes

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Dedication

This thesis is dedicated to my wife, Amanda, and my daughter, Adalyn. Without their support, I would not have been able to do this for them, and for myself.

Abstract

The relationship between core stability and sport performance is unclear. Proponents of core exercise theorize that improved core stability will lead to improvements in sport performance. Detractors argue that current measures of core stability have shown little relationship to sport performance. Current measures of core stability focus on core endurance and core strength, characteristics of subsystems of the greater construct of core stability. Sport performance can generally be characterized as being high in complexity. During these performances it can be reasoned that the demands placed on the core stability system will be similarly complex. However, the current measures of Core Stability are low in complexity, calling into question their validity, by virtue of the principle of dynamic correspondence. **PURPOSE:** To assess the validity of two common core stability tests (The Sahrmann Core Stability Test (SCST and The Sport Specific Endurance Plank Test (SSEPT)) within the context of level of sport performer (Elite vs. Non-elite). As well as to compare the neuromuscular activity of core muscles between Elite and Non-Elite athletes during a specific sport performance, an ice hockey slapshot. **METHODS:** Athletes were recruited into two groups, Elite (n=9, Age= 23.11 ± 1.69yrs, Weight= 190.3 ± 5.88lbs, Playing Experience= 18.33 ± 1.55yrs), and Non-Elite (n=8, Age= 28.25 ± 3.26yrs, Weight= 186.2 ± 2.91lbs, Playing Experience= 2.90 ± .83yrs). After being outfitted with an electromyogram device attached to 5 core muscles (Transversus abdominus, Rectus abdominus, Gluteus Medius, Gluteus Maximus, Multifidus), participants completed 10 slapshot trials, the SCST and the SSEPT. **RESULTS:** There were no significant between group differences for SCST (Elite 2.00 ±

0.47, Non-Elite 2.50 ± 0.38 p = .429) or SSEPT (Elite 228.89 ± 24.07, Non-Elite 215.38 ± 29.65 p = .726). There were significant between group differences in slapshot accuracy (Elite 5.00 ± 0.76, Non-Elite 0.75 ± .53, p = <.001). There were also significant between group differences in EMG Duration, Relative Energy and Relative Power. The Elite group had shorter EMG Duration in TVA (555.70 ± 21.97ms, 1111.29 ± 59.67ms), RA (367.33 ± 25.85ms, 803.63 ± 65.03ms), GMed (584.05 ± 35.69ms, 1486.89 ± 134.35ms), GMax (786.21 ± 54.94ms, 1522.92 ± 81.28ms) and Multi (961.11 ± 46.81ms, 1973.34 ± 115.7ms) , lower Relative Energy in TVA (56.94 ± 2.81mV•ms, 209.76 ± 29.16mV•ms), RA (27.65 ± 3.06mV•ms, 94.77 ± 10.09mV•ms), GMax (62.04 ± 4.72mV•ms, 128.30 ± 5.64mV•ms) and Multi (93.57 ± 3.67mV•ms, 218.18 ± 16.03mV•ms), as well as lower Relative Power in TVA (.1053 ± .0050, .1589 ± .0117mV) and RA (.0746 ± .0054, .1119 ± .0071 mV) and higher Relative Power in GMed (.0592 ± .0026, .0447 ± .0028 mV).

CONCLUSION: The SCST and the SSEPT are not valid measures of core stability within the context of level of sport performance. Neither measure was able to distinguish between Elite and Non-Elite groups. It is important to stress the difference in playing experience between the two groups (Playing Experience, Elite= 18.33 ± 1.55yrs, Non-Elite= 2.90 ± .83yrs). The Elite group was comprised of professional and D-I NCAA hockey players, whereas the Non-Elite group was comprised of bottom level recreational players described as working on skills such as learning to skate with the puck. The differences in sport specific skill level were further reinforced by the significant between group differences observed in the slapshot accuracy test. The inability of the two studied measures to differentiate between such different levels of athlete bring into question their validity within the broader context of sport performance in general. Further research is necessary to justify such extrapolations of findings. The neuromuscular activity of the core musculature of Elite and Non-Elite hockey athletes during a slapshot differs in terms of muscle activation duration, relative energy and relative power. These differences imply that neuromuscular coordination may play a role in the core stability of an athlete during a specific sport performance. Based on these results, a valid measure of Core Stability should be similar in complexity to the targeted sport performance and related to meaningful outcomes specific to the nature of that sport, in accordance with the principle of dynamic correspondence. An approach in which exercises are chosen based on their similarity to desired sport performance in terms of neuromuscular coordination, as opposed to training general athletic qualities such as, in this case, core endurance or core strength.

Key words: Core, Core Stability, Core Strength, Core Endurance, The Sahrmann Core Stability Test, The Sport Specific Endurance Plank Test, Sport Performance, Neuromuscular Coordination, Electromyography, EMG

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Chapter 1. Introduction

For the purposes of this thesis, sport performance refers to sport specific movements that are intrinsic to a specific sport. Examples include a slapshot to ice hockey, a golf swing to golf, and a handball throw to team handball. Indirect measures of sport performance refer to measures of general athletic movements that are not necessarily specific to any one sport. Examples include vertical jump tests, sprint speed tests, weightlifting strength tests and measures of balance. The inclusion of indirect measures of sport performance into the scope of this thesis is necessary, in order to fully understand the current understanding of the relationship between core stability and sport performance, as many researchers have used these indirect measures as surrogates for sport performance.

Currently, research related to the relationship between core stability and sport performance is limited and inconclusive (Reed, Ford, Myer, & Hewett, 2012).

Some researchers have found no, or weak, relationships between core stability and sport performance, or indirect measures of sport performance; and have suggested that core training should not be the focus of a sport performance training program (Cressey, West, Tiberio, Kraemer, & Maresh, 2007; Mills, Taunton, & Mills, 2005; Nesser, Huxel, Tincher, & Okada, 2008; Nesser & Lee, 2009; Okada, Huxel, & Nesser, 2011; Parkhouse & Ball, 2010; Reed et al., 2012; Stanton, Reaburn, & Humphries, 2004; Tse, McManus, & Masters, 2005). While others have found significant and positive relationships between core stability and sport performance (Kibele & Behm, 2009; Pedersen, Magnussen, Kuffel, & Seiler, 2006; Saeterbakken, Van Den Tilaar, & Seiler, 2011; Sato & Mokha, 2009; Seiler, Skaanes, & Kirkesola, 2006). However, in practice, training to improve core stability with the intention of improving sport performance is promoted by the preeminent strength and conditioning authority in the United States, the National Strength and Conditioning Association (Baechle & Earle, 2000). The discrepancy between substantiated research and common practice has created interest in the question, "is there a relationship between core stability and sport performance?" The aims of the current study are as follows: 1) Assess the validity of the Sahrmann Core Stability Test within the context of level of sport performance 2) Assess the validity of the Sport Specific Endurance Plank Test within the context of level of sport performance; and 3) Compare the electromyographic activity of core muscles during a sport performance between elite and non-elite athletes.

Our current understanding of the relationship between core stability and sport performance has largely been shaped by measures of core stability that were originally developed for use in the study of lower back pain within the general population. Though these measurement tools and practices for core stability have been found to be reliable, they have not yet been validated for use within competitive athletic populations. It is the purpose of this research project to determine the validity of two such measurement tools, The Sahrmann Core Stability Test and the Sport Specific Endurance Plank Test. A secondary aim of this research project, is to investigate the role of neuromuscular control as it relates to core stability within the context of a sport performance, by comparing the EMG activity of core muscles during a slapshot accuracy test between elite and non-elite athletes.

Chapter 2 summarizes and reviews the current literature related to the core, core stability and their relationship to sport performance. Specific emphasis is placed on definitions of the core and core stability, our current understanding of the relationship between core stability and sport performance, as well as methodological concerns from published works.

Chapter 3 addresses the methodology of the current study, including participant descriptions and demographic information, test procedures as well as data collection measures and protocols.

Chapter 4 presents the reader with the results of the study from the tests of core stability, sports performance and the EMG analysis.

Chapter 5 discusses the importance of the findings and inherent limitations of this study in the context of the literature.

Chapter 6 concludes the current study and discusses possible future directives for research.

Chapter 2. Review of Literature

Section I: Core Definitions and Measurement Practices

The Core

There is not a singular accepted definition of the core (Akuthota, Ferreiro, Moore, & Fredericson, 2008; Borghuis, Hof, & Lemmink, 2008; Faries & Greenwood, 2007; Hibbs, Thompson, French, Wrigley, & Spears, 2008). Historically, the perspective of the researcher has framed the definition of the core. For instance, researchers focused on rehabilitation and prevention of lower back pain tend to be relatively limited in their definitions of the core, emphasizing the role of the core in maintaining a neutral spine and including only the musculature involved in this function (Bergmark, 1989). Whereas, researchers interested in sport performance tend to include both the role of the core in the maintenance of a neutral spine position, as well as in the transmission of energy from the lower to the upper body, or from proximal to distal segments; these definitions, logically, include more muscles. (Kibler, Press, & Sciascia, 2006).

For example, in a paper written from a rehabilitation perspective, the authors describe the core as "…a box with the abdominals in the front, paraspinals and gluteals in the back, the diaphragm as the roof, and the pelvic floor and hip girdle musculature as the bottom." (Akuthota & Nadler, 2004).

Whereas a definition from a sport performance researcher indicates that "the musculoskeletal core of the body includes the spine, hips and pelvis, proximal lower limb and abdominal structures. The core musculature includes the muscles of the trunk and pelvis that are responsible for the maintenance of stability of the spine and pelvis and help in the generation and transfer of energy from large to small body parts during many sports activities." (Kibler et al., 2006). For the purposes of the current study, this definition of the core will be used.

As core research has evolved from focusing on the assessment and treatment of lower back pain, to the role of the core in sport performance, so too must the definition of the core evolve. Rehabilitation researchers based their definition on a single function, stabilizing the spine, whereas sport performance researchers are interested in both the stability of the spine and the transmission of force throughout the kinetic chain. This difference in scope necessitates a broader definition of the core (Borghuis et al., 2008; Kibler et al., 2006; Young, Herring, Press, & Casazza, 1996). A new definition should encompass both the stabilizing and energy transmitting functions of the core, and include all of the musculature that is responsible for carrying these functions out.

Core Stability

Early definitions of core stability are again rooted in the perspective of rehabilitation researchers. Typical of these definitions is a narrow focus on the role of the core in maintaining a neutral spine position and a reference to pain. For example, "Clinical instability [of the spine] has been defined as the loss of the ability of the spine under physiologic loads to maintain its pattern of displacement so that there is no initial or additional neurological deficit, no major deformity, and no incapacitating pain." (White & Panjabi, 1990). Similar to the history of the definition of the core, the definition of core stability has evolved over the years, along with the aims of researchers, creating confusion as to what the "true" definition is (Hibbs et al., 2008).

More recent definitions of core stability, related to sport performance, are broader in nature, choosing to examine whole body movements and the role the core plays in transfer of forces from limb to limb, including effects on sport performance variables. For example, Kibler et al. (2006), defines core stability, "as the ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities." For the purposes of the current study, this definition of core stability will be used. Importantly, definitions related to sport performance research typically do not include reference to any measures of pain.

Another source of confusion surrounding the definition of core stability stems from the inappropriate use of the terms "core stability", "core endurance" and "core strength"; oftentimes interchangeably. Core strength has been defined, simply, as the ability of a core muscle to exert force (Faries & Greenwood, 2007). Core endurance is defined as the ability of a core muscle to exert low intensity forces over long tension times (Willardson, 2007b). Core strength and core endurance can be considered subset characteristics of core stability (Borghuis et al., 2008; Liemohn, Baumgartner, & Gagnon, 2005; Mcgill, 1998; Pool-Goudzward, Vleeming, Stoeckart, Snijders, & Mens, 1998; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Evidence suggests that a lack of core strength and/or endurance will likely cause dysfunction and create the need for compensation in the core, however it is inappropriate to assume that a lack of core stability is inherently due to a lack of core strength and/or endurance as there are other factors, including neuromuscular coordination, and structural factors, that affect the overall core stability of an individual (Panjabi, 1992).

In an example of the misuse of these basic terms, Nesser et al. (2008) conducted a study in which core endurance was tested using the McGill Core Endurance Test. However, the authors repeatedly referred to the score of this test as an indicator of core strength. They ultimately conclude that increases in core strength are not related to measures of sport performance and that strength training aimed at the core will not improve sport performance. Of course, these conclusions are at the very least misleading, as core strength was never actually measured.

In an effort to put a stop to the misuse of these terms, multiple reviewers have discussed the confusion in detail and urged the research community to adhere to stricter terminology standards (Borghuis et al., 2008; Hibbs et al., 2008; Liemohn et al., 2005). In the case of core stability, core strength and core endurance there is a need for clear definitions that encompass the demands placed upon the core in a dynamic sport environment. Once these new definitions are established, great care should be taken to use all of the terminology related to the core and core stability, properly.

Classification of Musculature

Individual muscles of the core are commonly categorized in terms of local or global characteristics. Bergmark (1989) first made this distinction and characterized local muscles as having their origin or insertion at the vertebrae, with the exception of the psoas. Local muscles have the responsibility of controlling the curvature and stiffness of the spine. Global muscles, sometimes referred to as “active components”, are involved in transferring load directly between the pelvis and the rib cage.

Since Bergmark (1989) first divided the musculature of the core into local and global categories, other researchers have further defined them and created subcategories (Akuthota et al., 2008; Faries & Greenwood, 2007; Willardson, 2007b). Faries and Greenwood (2007) replaced the original terms “Stabilisor” and “Mobilisor” with “Local Muscles” and “Global Muscles”. The classification titles used by Faries and Greenwood (2007) are used more predominantly in recent literature and for the purpose of this thesis these are the terms that will be used.

More recent definitions of local core muscles include descriptions of the muscles as small, slow twitch muscles, suited for controlling intersegmental movement, responding to changes in posture and external load, and responsible for increases in intra-abdominal pressure and stability of the spine and the lumbo-pelvic region; with special attention paid to the transversus abdominus and the multifidus as being the primary stabilizers (Akuthota et al., 2008; Faries & Greenwood, 2007; Willardson, 2007a, 2007b). Similar updates to the definition of the global core muscles describe them as larger, fast twitch muscles, capable of producing large amounts of torque required for high speed, dynamic movements and the resistance of external loads (Akuthota et al., 2008; Borghuis et al., 2008; Faries & Greenwood, 2007).

Systems and Function

Panjabi (1992) developed “The Spine Stabilizing System”, the current standard model to describe core stability, in which there are three subsystems, 1) The Passive Musculoskeletal Subsystem; 2) The Active Musculoskeletal Subsystem; and 3) The Neural and Feedback Subsystem. These systems work in concert to provide stability to the spine, as well as to transfer forces, during static and dynamic movements.

The Passive Musculoskeletal Subsystem refers to ligaments, and skeletal structures which act as stabilizers and proprioceptors but do not produce force. Proprioceptors imbedded within passive structures provide information about the position of the spinal and pelvic segments. Processing of this information is the responsibility of the Neural and Feedback Subsystem. The Passive Musculoskeletal Subsystem provides little stability to the spine when in a neutral position, it is near the end ranges of motion that the passive system provides stability. Dysfunction of the Passive Musculoskeletal system is generally caused by traumatic injury or degeneration (Panjabi, 1992).

The Active Musculoskeletal Subsystem includes the muscles and tendons used to support the spine and their related proprioceptors. The Active Musculoskeletal Subsystem is capable of providing force that can be characterized in terms of strength and endurance. Proprioceptors embedded within the muscles and tendons provide information to the Neural and Feedback Subsystem about the length, tension and force of individual muscles. Dysfunction in the Active Musculoskeletal Subsystem can be caused by deficits in endurance, strength or flexibility, as well as by injury or disease (Panjabi, 1992).

The Neural and Feedback Subsystem consists of proprioceptors and nerves and is responsible for making adjustments in the force output of individual muscles in order to provide stability to the spine during changes in posture and loading conditions. This subsystem is responsible for postural adjustments and compensations that can be made necessary by external forces or deficits in any of the other subsystems. The complexities of this system are still not fully understood. Dysfunction in this subsystem can be caused by injury, disease or degeneration (Panjabi, 1992).

Dysfunction in any of these subsystems can lead to dysfunction of the Spine Stabilizing System as a whole. Dysfunction can lead to any combination of three outcomes, acute compensation, chronic compensation or injury (Panjabi, 1992).

For the purpose of this thesis the Spine Stabilizing System will serve as a functional representation of core stability.

Current Measurement Practices

Current measures of core stability are low intensity in nature, typically focused on endurance related characteristics and have low complexity of movement (Mills et al., 2005; Nesser et al., 2008; Nesser & Lee, 2009; Okada et al., 2011; Parkhouse & Ball, 2010; Pedersen et al., 2006; Stanton et al., 2004; Tong, Wu, & Nie, 2013; Tse et al., 2005). The most common tests used to measure core stability in the current literature are the Sahrmann Core Stability Test, The McGill Plank Test and variations of the McGill Plank Test including the newly developed Sport Specific Endurance Plank Test (Mills et al., 2005; Nesser et al., 2008; Tong et al., 2013). It can be argued that the Sahrmann Core

Stability Test is actually a measure of core strength. The test involves increasing torque placed on the lumbar spine until failure. The application of torque within each level is short in duration, less than three seconds in each case. Results are measured, essentially, in level of torque withstood. It can also be argued that The McGill Plank Test, the Sport Specific Endurance Plank Test and variations thereof are actually measures of core endurance. These tests involve low force output from core muscles over relatively long durations; long enough to induce failure due to muscular fatigue. Results are measured in terms of time to failure. Of course, core strength and core endurance are subset pieces of the complex system that is core stability. By measuring these variables individually, it is not possible to draw all-encompassing conclusions about core stability as a whole. These approaches to measuring core stability can be traced back to research aimed at examining the cause and treatment of lower back pain in the general population (S. M. McGill, 2002). It is important to note that these measurement techniques have never been validated for use with healthy, competitive, athletic populations.

The Feedforward Nature of the Core

Researchers have conducted studies in which EMG data has been recorded and analyzed on many of the major muscles of the core; including the transversus abdominus, obliquus internus, obliquus externus, rectus abdominus, erector spinae, multifidus, and the diaphragm. Typically, a combination of fine wire and surface EMG electrodes are used to detect the onset of specific muscle contractions. Using these methods, researchers have investigated the activation sequence of the core muscles during simple upper and lower extremity movements. The findings of these studies have provided insight into how the muscles of the core act to ensure stability during movement of the limbs (Allison, Morris, & Lay, 2008; Cresswell, Oddsson, & Thorstensson, 1994; Cresswell & Thorstensson, 1994; Paul W. Hodges & Richardson, 1997a, 1997b; P W Hodges, Butler, Mckenzie, & Gandevia, 1997; Hungerford, Gilleard, & Hodges, 2003; Moseley, Hodges, & Gandevia, 2002).

It has been repeatedly shown that the muscles of the core are activated before the onset of shoulder and hip muscle activation during simple movements of both the upper and lower limbs (Allison et al., 2008; Cresswell et al., 1994; Paul W. Hodges & Richardson, 1997a, 1997b; P W Hodges et al., 1997; Hungerford et al., 2003; Moseley et al., 2002). The pre-programmed activation of core muscles, prior to limb movement, have been termed anticipatory postural adjustments (Cordo & Nashner, 1982; Kibler et al., 2006; Zattara & Bouisset, 1988). Anticipatory postural adjustments are feedforward in nature, meaning that the activation of the muscles of the core is not in response to perturbation, but instead, it is in anticipation of perturbation (Cresswell et al., 1994; Paul W. Hodges & Richardson, 1997a; Moseley et al., 2002). The feedforward activation of the core musculature acts to increase intra-abdominal pressure and stabilize the core before anticipated movement.

It has been shown that subjects experiencing chronic low back pain utilize different anticipatory postural adjustment strategies compared to asymptomatic subjects. Furthermore, these altered strategies of core muscle recruitment are only apparent on the unilateral symptomatic side of those subjects with low back pain (Hungerford et al., 2003).

Intra-abdominal pressure has been shown to increase stability of the spine during lifting, lowering and jumping (Cholewicki, Juluru, & Mcgill, 1999). The transversus abdominus, and the diaphragm have been shown to activate in unison, before the activation of any other studied core muscle, during movements of both the upper and lower limbs (P W Hodges et al., 1997). The timing of the onset of activation and the magnitude of activation of the transversus abdominus has been found to correlate with both, the onset of increases in intra-abdominal pressure, and the magnitude of intra-abdominal pressure, respectively (Cresswell & Thorstensson, 1994), leading researchers to believe that the transversus abdominus and the diaphragm play a large role in stabilizing the spine through intra-abdominal pressure regulation.

Due to its early activation and relationship to increases in intra-abdominal pressure the transversus abdominus has been hypothesized as being integral to the maintenance of core stability (Richardson et al., 2002). This hypothesis, combined with the discrepancy in anticipatory activation patterns between low back pain symptomatic and asymptomatic subjects, has led to the advent of training protocols that specifically target the muscles of the local core, including, of course, the transversus abdominus. For example, the hollowing technique, which has been shown to activate the transversus abdominus through ultrasound scan (Critchley D., 2002), is used by researchers and clinicians alike, in the study and treatment of lower back pain. The hollowing technique and other methods of training intended to target muscles of the local core, will be referred to as local core exercises for the purpose of this thesis. Interventions utilizing local core exercises have been found to change the anticipatory postural adjustment strategies of symptomatic populations, improving symptoms of low back pain (O'Sullivan, Twomey, & Allison, 1998; Tsao & Hodges, 2008).

The current body of research related to the feedforward nature of muscular activity in the core muscles highlights the complex nature of core stability. Bringing into question the simple measures of core strength and endurance used to quantify such a system. A valid measure of core stability must somehow capture core strength, core endurance, passive musculoskeletal integrity, as well as neurological feedback, coordination, and control of all involved components. Such a measurement system, in the context of sport performance must also be related to the specific movements required of the athlete by the sport.

It is important to point out, that to date, there has not been a study in which EMG activity of core musculature has been collected during a dynamic sporting movement, or compared between expert and non-expert athletes. It is reasonable to assume that the demands placed on the core musculature of expert athletes performing dynamic sport movements will be considerably different, compared to the demands placed on the core musculature of the general population, carrying out simple movements of the limbs. Furthermore, it is possible that local core exercises, developed to treat and prevent lower back pain symptoms, are not useful for asymptomatic populations of athletes. But this admission does not rule out the possible benefit of more complex training methods, aimed at both local and global core musculature. By investigating the EMG activity of the core muscles during sport performance in both elite and non-elite athletes it may be possible to better understand the role of the neural and feedback subsystem within the context of core stability.

Section II: Methodological Concerns

Validity of Measures

The primary methods used to measure core stability, the McGill Core Endurance Test and the Sahrmann Core Stability test, have never been validated for use as measures of core stability within healthy, athletic populations. Both of these tests are low in complexity of movement and display a lack of dynamic correspondence to sport performance. Dynamic correspondence refers to the relationship between an exercise or measure and a sport specific performance in terms of the amplitude and direction of the movement, the accentuated region of force production, the dynamics of effort, the rate and time of maximum force production, and the regime of muscular work (Siff & Verkhoshansky, 2009). This lack of dynamic correspondence to sport performance challenges the concept of the validity of these tests for use within populations in which meaningful outcomes are, in fact, related to sport performance; as opposed to reduction in pain.

The McGill Core Endurance Test was originally created by, Dr. Stuart McGill, a noted rehabilitation researcher, as a screen for susceptibility to lower back pain (S. M. McGill, 2002). It has been shown to be reliable and valid for use in measuring core endurance as it relates to outcomes in lower back pain research (S. McGill, Childs, & Liebenson, 1999). The test consists of three plank variations. The first is a measure of the muscular endurance of the trunk flexors. Subjects sit against a jig angled 60° from the ground, knees and hips are at 90° angles, while arms are held across the chest. The jig is pulled back 10 cm from the subject who is asked to maintain the initial 60° angle for as long as possible. When any part of the subject's body touches the jig, the trial is over. The second plank variation is a measure of the muscular endurance of the trunk extensors. The upper body is cantilevered out over the end of a bench or table. The pelvis, knees and hips are secured to the bench or table, and the arms are placed across the chest. The subject starts with the upper body horizontal to the ground. Failure to maintain this position ends the test. The third plank variation is a measure of the muscular endurance of the lateral musculature of the trunk. A standard, elbow based, side plank position is assumed by the subject and held until any deviations arise. For all tests a score is recorded in terms of seconds.

It is clear that the McGill Core Endurance test is a measure of core endurance, not core strength or core stability. However, researchers refer to the test as a measure of both (Nesser et al., 2008; Nesser & Lee, 2009; Okada et al., 2011). In an effort to justify the validity of the McGill Core Endurance Test as a measure of core stability Nesser et al. (2008) state that, "Because the core strength/stability tests used in the study had reported reliability coefficients of ≥0.98, we believe that McGill's assessment of core strength is accurate." In another paper authored by Nesser et al. (2009) the authors argue that, "Since the core strength tests used in the study had reported reliability coefficients of ≥ .97, we believe that McGill's assessment of core strength is accurate." In both of these papers the authors argue that reliability is an indicator of validity, which is inappropriate; and that an endurance test is an accurate measure of strength, also inappropriate.

A variation the McGill Plank Test, created to address concerns of valididty related to use with healthy athletes, The Sport Specific Endurance Plank Test. This test was developed by Mackenzie (2005) as a measurement tool for core performance and was later shown to be reliable and valid by Tong et al. (2013). The procedure for the test, described by Tong et al. (2013) is as follows:

"Participants were required to maintain the prone bridge in a good form throughout the following stages with no rest in between:

1.) Hold the basic plank position for 60 s
2.) Lift the right arm off the ground and hold for 15 s
3.) Return the right arm to the ground and lift the left arm for 15 s
4.) Return the left arm to the ground and lift the right leg for 15 s
5.) Return the right leg to the ground and lift the left leg for 15 s
6.) Lift both the left leg and right arm from the ground and hold for 15 s
7.) Return the left leg and right arm to the ground, and lift both the right leg and left arm off the ground for 15 s
8.) Return to the basic plank position for 30 s
9.) Repeat the steps from (1) to (9) until the maintenance of the prone bridge failed."

Tong et al. (2013) conducted surface EMG analysis of selected core muscles in order to assess the validity of the Sport Specific Endurance Plank Test. The authors found that over the course of the test, surface EMG activity increased as a percent of maximal volitional isometric contraction indicating that fatigue was occurring in the measured muscles. Moreover, the researchers in this study compared the results of the Sport Specific Endurance Plank Test between a group that had undergone a core fatigue training session prior to testing and a group that had not. With this, Tong et al. (2013) found that the fatigued group scored significantly lower compared to their own non-fatigued scores, whereas the non-fatigued group did not. Additionally this research demonstrated that the test was also reliable with an ICC of 0.97 (95% confidence interval: 0.94-0.99) across three trials.

From this research it is clear that the Sport Specific Endurance Plank Test is reliable and that it is valid in the assessment of core muscle endurance. However, the validity of this test in terms of measuring the larger construct of core stability related to meaningful outcomes within a healthy, athletic population have not been addressed.

The Sahrmann Core Stability Test consists of five stages described below. A Pressure Biofeedback Unit (Chatanooga, Australia) is placed under the lower back of the participant and inflated to a pressure equivalent of 40 mmHg. The inability of the participant to maintain pressure between 30-50 mmHg results in a failure of the level and the end of the test.

1.) In a crook lying position an abdominal hollowing maneuver preset the abdominal muscles and the participant slowly raised one leg to a position of 100 degrees of hip flexion with 90 degrees knee flexion. The other leg was then slowly raised to a similar position. This position was the start position for the following four levels.

2.) From the start position, the participant slowly lowered one leg and, with the heel down on the plinth, slid the leg out to straighten the knee, then slid it back up into the start position.

3.) From the start position, the participant slowly lowered one leg and, with the heel maintained approximately 12 cm off the plinth, fully extended the leg and then moved it back to the start position.

4.) From the start position, the participant lowered both legs together and, with the heels down on the plinth, slid the legs out to straighten the knees and then slid them back and raised them to the start position.

5.) From the start position, the participant simultaneously extended both legs keeping the heels approximately 12 cm off the plinth and then flexed the legs back to the start position. (Mills et al., 2005)

The Sahrmann Core Stability test, like the McGill Core Endurance Test, was designed for use in the clinical assessment and treatment of lower back pain. The use of this test in the context of a healthy, athletic population has also, never been validated. In fact, Mills (2005) concluded that the use of this test was not appropriate for identifying meaningful improvements in core stability for a population of female college varsity athletes.

For the purposes of the current study the Sport Specific Endurance Plank Test will be studied instead of the McGill Core Endurance Test as it was created to address the limitations of The McGill Core Endurance Test in the context of sport performance.

Volume or Training Effect

Many longitudinal trials studying the relationship between core performance and sport performance involve a control group that is given no intervention (Mills et al., 2005; Pedersen et al., 2006; Saeterbakken et al., 2011; Sato & Mokha, 2009; Stanton et al., 2004; Tse et al., 2005). This is of concern as the observed changes in performance may be due simply to the effect of training. Without a control training intervention matched for volume it is impossible to rule out this training effect.

Pre-Intervention Between Group Differences

Sato and Mokha (2009) found that six weeks of core training improved 5000 meter run times compared to a control group. There were however, significant pre-test differences between the groups in terms of bodyweight and pre-intervention 5000 meter run time. The core training group was significantly slower during the pre-test 5000 meter run and heavier in terms of bodyweight. This difference implies differing levels of training status. The difference in training status could be responsible for the significant differences in 5000 meter run time improvement, as it is well understood that lower level athletes make larger adaptations to exercise compared to higher level athletes over the same time period (Zatsiorsky & Kraemer, 2006).

In a study of Elite Norwegian soccer players, Pederson et al. (2006) found significant increases in kicking velocity and balance in a group exposed to sling exercise training compared to a control group that had no training intervention. The authors also disclosed that four of the 12 participants in the training group suffered from lower back pain whereas none of the control group did. Furthermore all four cases of lower back pain were reduced over the course of the trial, consistent with previous research that has shown that similar training interventions have positive effects on treating lower back pain symptoms (O'Sullivan et al., 1998; Tsao & Hodges, 2008). It is not possible to determine whether the improvements in kicking velocity and balance were attributable to improvements in core performance or a reduction in lower back pain symptoms.

Inappropriate Conclusions

In a cross sectional study involving Division I football players, Nesser et al. (2008) concluded that, "The results of this study suggest that core stability [endurance] is moderately related to strength and performance. Thus, increases in core strength [endurance] are not going to contribute significantly to strength and power and should not be the focus of strength and conditioning." Of course, given the cross sectional nature of this study design it is inappropriate to suggest a causal relationship between the variables in question. It should also be pointed out that the word significantly does not appear to be used in a scientific context, as many significant correlations were indeed found, between measures of core endurance (The McGill Plank Test), referred to as measures of stability and strength by the authors, and indirect measures of sport performance, including strength and sprint speed variables.

In a study in which no correlations were found between measures of core performance (The McGill Plank Test) and multiple indirect measures sport performance, Nesser et al.

(2009) concluded that, “Based on the results of the current and previous research, it is believed core training is necessary for optimal sport performance and should not be dismissed. However, it should not be the emphasis of any resistance training program. The core is one part of the body thus it is should not be the focus of any training program taking time away from other body parts which may lead to a muscle imbalance and possible injury.” Not only does this conclusion contradict the study results, the first two lines contradict one another.

The literature compiled by researchers thus far detailing the relationship between core stability and sport performance is riddled with methodological concerns. Of which, the primary concern is the validity of the currently accepted standard measures of core stability. Aside from this primary concern, basic methodological oversights abound, including inadequate control over the training effect, unwanted between group differences and inappropriate inferences rooted in the misuse of basic terms including validity, core strength, core endurance and core stability. These concerns should be kept in front of mind when examining the current evidence related to the relationship between core stability and sport performance.

Section III: The Relationship Between Core Stability and Sport Performance

Longitudinal Findings

There are multiple studies that have experimentally investigated the effect of improvements in core stability on measures of sport performance. These studies have utilized pre- and post-test batteries consisting of a measure of core stability and multiple measures of performance, with interventions lasting between six and 10 weeks and involving two to four training exposures per week (Cressey et al., 2007; Kibele & Behm, 2009; Mills et al., 2005; Parkhouse & Ball, 2010; Pedersen et al., 2006; Saeterbakken et al., 2011; Sato & Mokha, 2009; Seiler et al., 2006; Shinkle, Nesser, Demchak, & McMannus, 2012; Stanton et al., 2004; Tse et al., 2005). Typically, these studies include a treatment and a control group. The treatment group is exposed to training that primarily involves local core exercises; including instability training, sling exercise training, swiss ball training and varieties of hollowing exercises. While the control group is exposed to either, no training, or a matched volume of “other” training, including, core training targeting global musculature, and what is referred to as typical strength training. Subjects used in these trials range from recreationally active, to NCAA Division I level college athletes. Sport performances that have been studied directly include distance running, rowing, soccer (kicking velocity), handball (throwing velocity) and golf (club head speed) (Hibbs et al., 2008; Pedersen et al., 2006; Saeterbakken et al., 2011; Sato & Mokha, 2009; Seiler et al., 2006; Stanton et al., 2004). Many indirect measures of sport performance have also been studied including measures of maximal strength and power outputs as well as jumping and running abilities (Cressey et al., 2007; Kibele & Behm, 2009; Mills et al., 2005; Parkhouse & Ball, 2010; Shinkle et al., 2012; Tse et al., 2005). These experimental studies have yielded mixed results with authors drawing conclusions that both support and oppose the benefit of core training to sport performance training regimens (Cressey et al., 2007; Kibele & Behm, 2009; Parkhouse & Ball, 2010; Shinkle et al., 2012; Stanton et al., 2004; Tse et al., 2005).

Seiler et al. (2006) compared maximal club head velocity in two groups of junior golfers exposed to either core and rotational stability training, or traditional strength training. There were no measures of core performance. It was found that after nine weeks of training, the core training group improved measures of maximal club head speed significantly more than the control group. This is one of few studies that showed an improvement in performance after core training. Interestingly, it is also one of few studies that did not include any measures of core stability.

In a study of 24 female, high school handball athletes Saeterbaekken et al. (2011) found that a training group exposed to sling exercise training, a form of global core training, significantly improved their throwing velocity compared to pre-test, whereas a control group, exposed to no training, did not. There was, however, no mention of between group comparisons.

In a similar study, Pedersen et al. (2006) conducted a study in which elite soccer players were exposed to eight weeks of Sling Exercise Training. They found that, compared to controls, the intervention group improved in measures of balance and kicking velocity.

However, pre-intervention between group differences in lower back pain may have played a confounding role in these results.

Mills et al. (2005) conducted a randomized controlled intervention in which 3 groups received either local, global or no core training. Core stability was measured using the Sahrmann Core Stability Test and indirect measures of sport performance including a T-test, a non-countermovement vertical jump and the Bass Stick Balance Test. Both training groups saw significant improvements in Sahrmann scores whereas the control group did not. The local training group saw significant improvements in all three measures of sport performance whereas the global training and control groups only saw significant improvement in the balance test. However, the score for the Sahrmann test did not significantly correlate with the scores on any of the performance tests. For this reason the authors argue that a confounding variable must have been responsible for the improvements in sport performance seen by the local training group. They also suggested that improvements in score on the Sahrmann Core Stability Test may not relate to meaningful outcomes for the healthy, athletic population studied.

Cressey et al. (2007) reported that training on unstable surfaces does not improve measures of sport performance compared to traditional resistance training without unstable surface training. The authors concluded that training on unstable surfaces should not be used to aid in sport performance training. Interestingly, Kibele & Behm (2009) also found that training on unstable surfaces led to no significant improvement compared to traditional strength training and argued that unstable methods should be used because they are no less effective than traditional methods.

Parkhouse & Ball (2010) compared a static and dynamic core training intervention, focused on local core musculature, and found that neither intervention significantly improved a battery of indirect measures of sport performance, however, improvements were made in measures of local core strength and core endurance. These core measures included a prone plank test and a double leg lowering test; tests that resemble very closely the Mcgill Plank Test and the Sahrmann Core Stability Test, respectively.

After six weeks of swiss ball training Stanton et al. (2004) found significant improvements in measures of core stability, according to the Sahrmann Core Stability Test. However, these researchers did not find improvements in any direct or indirect measure of sport performance, including VO2 max, running economy, and running posture.

Similarly, Tse et al. (2005) found that a core endurance training intervention improved measures of core endurance, as measured by the McGill Plank Test, but did not observe any improvement in any direct or indirect measures of sport performance in competitive rowers.

Shinkle et al (2012) found that there were moderate, positive, relationships between various medicine ball throws, a proposed method of measuring global core performance, and common sport performance measures including one rep max squat and bench, 40 yard dash and the pro agility test. Though the proposed method of measuring core performance has not been validated it appears to fulfill many of the requirements for testing core stability outlined earlier in this review.

Cross Sectional Findings

Studies with cross-sectional designs have also been used to investigate the relationship between core stability and sport performance. These studies include a measure of core stability along with multiple measures related to sport performance. Subjects range from recreationally active, to NCAA Division I level college athletes. These studies include indirect measures of sport performance similar to those used in the intervention based trials described above (Nesser et al., 2008; Nesser & Lee, 2009; Okada et al., 2011).

In a study of Division I football players, Nesser et al. (2008) compared core endurance, as measured by the McGill Core Endurance Test, to strength and performance measures including one rep maximum bench, squat and clean, counter movement jump, 20 and 40 yard dash, and a 10 yard shuttle drill. The authors found moderate and significant correlations between core endurance score (which they referred to as core strength) and a majority of the indirect measures of sport performance. The authors then came to the surprising conclusion that core strength should not be considered beneficial to sport performance training.

In a similar study Nesser & Lee (2009) investigated a Division I college female soccer team. Participants performed the McGill Core Endurance test, as well as indirect measures of sport performance; including one rep maximum bench and squat, countermovement jump, 40 yard sprint and 10 yard shuttle. In this study the authors found no significant relationship between measures of core endurance (which they referred to as core strength) and any of the strength or sport performance variables.

In a study of 28 healthy individuals, Okada et al. (2011) compared the results of the Mcgill Core Endurance Test, the Functional Movement Screen and 3 measures of performance; a backwards medicine ball throw, a T-Run and a single leg squat. The authors found no correlation between the McGill Core Endurance Test and the Functional Movement Screen. They found weak and moderate, significant correlations between the McGill Core Endurance Test and the measures related to sport performance and concluded that core training and functional movement training should not be the emphasis of any training program.

All of these cross sectional studies used the McGill Core Endurance test as a measure of either “core stability” or “core strength”. Of course, the use of an endurance test to characterize core stability or core strength warrants skepticism.

After examining the longitudinal and cross-sectional data available there appear to be a number of key takeaways 1.) Core training does not appear to have a consistent relationship with measures related to sport performance 2.) Improvements in measures of core endurance and core strength do not always result in improvements in measures related to sport performance, 3.) Measures of core endurance and core strength do not have high correlations with direct or indirect measures of sport performance.

Summary of Current Literature and Study Purpose

The definitions of the core and core stability are not well established, creating confusion in this area of research. The misuse of related terms including core strength and core endurance have added to this confusion. These terminology-related issues, combined with a lack of valid measurement techniques and a body of work riddled with methodological concerns warrant a skeptical review of the current conclusions related to the relationship between core stability and sport performance. It is the purpose of the present study to accomplish the following aims: 1) Assess the validity of the Sahrmann Core Stability Test within the context of level of sport performance 2) Assess the validity of the Sport Specific Endurance Plank Test within the context of level of sport performance; and 3) Compare the electromyographic activity of core muscles during a sport performance between elite and non-elite athletes.

Chapter 3. Methodology

Study Population

Based on hockey playing level and experience, 17 participants were recruited into two groups. Testing took place in the summer and fall off-season for all participants.

The Elite Group was comprised of nine participants (n=9, Age= 23.11 ± 1.69yrs, Weight= 190.3 ± 5.88lbs, Playing Experience= 18.33 ± 1.55yrs). Inclusion criteria required a minimum playing level of Junior hockey with a current Division I hockey commitment. This criteria was used to determine Elite status based on data from the NCAA website, that demonstrates that less than 4% of high school hockey players are selected to play Division I hockey ("College Hockey & Scholarship Opportunities," 2016). It can be reasoned that even a lower percentage of athletes continue their careers into the professional ranks. Two of the Elite participants were headed into their last year of Junior hockey with Division I commitments, four were headed back to Division I hockey programs, three were headed back to professional hockey leagues in Europe and one was headed back to the National Hockey League.

The Non-Elite group was comprised of eight participants (n=8, Age= 28.25 ± 3.26yrs, Weight= 186.2 ± 2.91lbs, Playing Experience= 2.90 ± .83yrs). Inclusion criteria required the participants to be ranked as playing in the bottom half of the Adult Hockey League (AHL), levels 1 and 2. This level of hockey player is described by the AHL as not having played much organized hockey growing up and as working on basic skills such as skating forwards, backwards and crossing over, stickhandling while skating, making and receiving passes while skating, and shooting during gameplay.

Exclusion criteria for both groups included any injury within the last six months that prevented them from either training for or participating in a game or practice, or any muscular or neurological disease or disorder.

Word of mouth and emails to the AHL were used to recruit participants. The protocol was reviewed and approved by the University of Minnesota Institutional Review Board. All participants provided written informed consent prior to study, and all aspects of the study were performed according to the declaration of Helsinki.

Anthropometrics and Warm Up

Upon arrival participants were weighed and asked to provide information about age, hockey playing experience and current playing level. The participants were then lead through a standardized 10-minute warm-up that included range of motion exercises as well as light to moderate intensity cardiovascular exercise, intended to raise the temperature of peripheral muscle and increase cardiac output, in order to prepare the participants for the testing procedures.

Electromyogram Devices

EMG data was collected using an eight channel wireless EMG amplifier (Datalog MWX8, Biometrics, Newport, UK). Five channels were used to simultaneously monitor the Rectus Abdominus, Transversus Abdominus, Gluteus Medius, Gluteus Maximus and Multifidus muscles. A bandpass filter set at 20-1000 Hz and a sampling rate of 2000 Hz were used for data collection. Two Ag-Ag/Cl surface electrodes (Biopac systems INC, Goleta, CA), 1.5 cm in diameter were placed two cm apart on the muscle belly in parallel with the fibers of the muscle (Konrad, 2006). The skin surface was prepared by shaving, if necessary, followed by cleaning and agitation with a sterile alcohol pad (70% isopropyl alcohol). Recorded data was stored on a memory card and later transferred to a laptop for analysis using Datalog software (Biometrics, Newport, UK).

Electromyogram Data Processing

Rectified EMG signal was normalized by maximal voluntary isometric contraction (MVIC) and was then smoothed by applying a 50 ms window to calculate moving average. Onset of muscle activation was defined as the point at which the smoothed EMG signal passed above the threshold of three times the average of baseline activity. Offset of muscle activation was defined as the point at which the smoothed EMG signal passed back below the threshold of three times the average of baseline activity.

Outcome measures included duration of muscle activation (EMG Duration), Relative Energy Expenditure (Relative Energy) and Relative Power Expenditure (Relative Power). Energy was calculated as the area under the EMG curve during muscle activation by using the following equation:

$$E = \int_{Onset}^{Offset} X(t)dt$$

Where E is energy and X(t) is the EMG signal.

Power was calculated as the area under the curve during muscle activation divided by the duration of muscle activation by using the following equation:

$$P = \frac{E}{D}$$

Where E is energy and D is the activation duration.

Maximal Voluntary Isometric Contraction Testing

MVIC testing for each measured muscle, was conducted before data collection. Manual muscle testing procedures were consistent with Hislop, Avers and Brown (2014). For each MVIC trial, participants exerted maximal force for three rounds of three seconds, with a 10 second rest between rounds. Before each trial, participants were given instructions describing the test, as well as a practice trial, in order to demonstrate participant understanding. During each trial investigators urged participants to exert maximal force.

Slapshot Accuracy Test

The Slapshot Accuracy Test was developed in order to capture the EMG activity of selected core muscles of healthy, competitive athletes, executing a sport performance. Inline with the aims of this study, the primary objective of this test was not to observe shooting accuracy, but instead to observe neuromuscular coordination of selected core muscles, during the act of a maximal effort slapshot. The slapshot was selected over the wrist- and snapshot, arguably more common and meaningful shots within the context of a hockey competition, because of the familiarity of both levels to its execution. Many of the Non-Elite participants have not acquired the skill required for a snapshot whereas many of the Elite participants no longer use the more basic wrist shot. This test has not been demonstrated as valid or reliable, however similar tests have been used in the research interests of other sports, including a handball throwing test for team handball athletes, a soccer kicking test for soccer athletes and a golf swing test for golfers (Pedersen et al., 2006; Saeterbakken et al., 2011; Seiler et al., 2006).

The slapshot test was performed on synthetic ice. Participants used their personal ice hockey skates, gloves, helmets and hockey sticks. A puck was placed on a mark 25 feet from the middle most point along the goal crease of a standard hockey net. A circular, rubberized shooting target (diameter-17.5”) was hung in the corner of the net that corresponded with the handedness of the participant. The shooting target was hung in a way that it contacted both the vertical and horizontal bars of the hockey net. Before shooting, participants were instructed to prepare themselves in a shooting position comfortable to them that included: both hands on the stick, the stick blade touching the puck and the puck on the mark indicating 25 feet from the middle of the net. Once instructed, the participants, in one fluid motion completed a slapshot aimed at the shooting target. The participants were instructed to shoot as hard as possible while still trying to be accurate, just as if they were trying to score in a game. For data collection, participants each completed 10 trials. Attempts resulted in either a hit or miss. The total number of hits was used as the final score. Before data collection participants were allowed as many familiarization trials as desired.

Sahrmann Core Stability Test

The Sahrmann Core Stability test was conducted in accordance to the protocol from Mills (2005). A stabilizer Pressure Biofeedback Unit (Chatanooga, Australia) was used to determine success or failure of each level. The PBU was comprised of an inflatable rectangular cushion (23x14 cm) connected to a pressure gauge (measuring 0–300 mmHg). To begin the test, participants laid supine with the rectangular cushion placed under the lumbar spine and inflated to 40 mmHg. Failure to maintain pressure in the cushion within 10 mmHg (30-50 mmHg) at any point during the test resulted in failure of the level and cessation of the test. The final level successfully passed, was used as the final score. Before data collection, participants were allowed as many familiarization trials as desired. For a description of the levels see pages 19-20.

Sport Specific Endurance Plank Test

The Sport Specific Endurance Plank Test was administered in accordance with the protocol from Tong et al. (2013). Elbows were vertically below the shoulders with the forearms and fingers extending straight forward. The neck was kept neutral so that the body remained straight from the head to the heels. Participants were required to maintain the prone bridge in a good form throughout the following stages with no rest in between. Participants were given a familiarization trial in which they were asked to demonstrate the position required in each stage, in order, for less than five seconds. This familiarization protocol was used to ensure that the participants understood the test, but were not fatigued before data collection. Total time, from the beginning of the test, until failure to maintain the prone bridge, was used as the final score. For a description of the stages see page 18.

Statistical Analysis

Between groups differences of Group Characteristics and Test Scores were calculated using independent two tailed t-tests. Within, and between groups correlations were calculated using Pearson Correlations. A MANOVA was used to compare EMG Duration, Relative Energy and Relative Power of Group (Elite and Non-Elite) Slapshot Outcome (Hit and Miss). For all tests alpha $\leq .05$.

Chapter 4. Results

Group Characteristics

Independent sample, two tailed, t-tests revealed no between group differences in Age *t(15) = 1.45, p = .168* or Weight *t(15) = -.60, p = .554*. However, significant between group differences were found for Playing Experience *t(12.07) = -8.764, p = <.001*.

Testing Scores

Independent, two tailed, t-tests revealed no between group differences for Sahrmann Score *t(15) = .813, p = .429* or Sport Specific Endurance Plank Score *t(15) = .952, p = .726*. However, significant between group differences were found for Slapshot Score *t(15) = -4.467, p = <.001*.

Pearson correlations between Sahrmann Score, Sport Specific Endurance Plank Score and Slapshot Score revealed no overall significant correlations. However, within the Elite Group the Sahrmann Score and Sport Specific Endurance Plank Score were moderately to highly, and significantly, correlated *r(15) = .722, p = .028*. No other within group correlations were observed.

EMG Duration

For EMG Duration, the multivariate effects were significant for Group, *F(5, 1)= 19.16, p <.001* indicating a difference in EMG Duration between the Elite and Non-Elite groups. However there were no significant multivariate effects for EMG Duration according to Slapshot Result nor in the interaction of Group x Slapshot Result.

We found significant differences between the Elite and Non-Elite groups in the Transversus Abdominus $p = <.001$, the Rectus Abdominus $p = <.001$, the Gluteus Medius $p = <.001$, the Gluteus Maximus $p = <.001$ and the Multifidus $p = <.001$. These differences suggest that, for all muscles, the Elite group has shorter EMG Duration.

Relative Energy

For Relative Energy, the multivariate results were significant for Group $F(5, 1) = 12.72$, $p = <.001$ Slapshot Result, $F(5, 1)= 2.59$, $p =.029$ and a Group x Slapshot Result interaction $F(5, 1)= 2.435$, $p =.038$ indicating a difference in Relative Energy between, the Elite and Non-Elite groups, the Hit and Miss slapshot trials, as well as an interaction between Group and Slapshot Result.

We found significant differences in Relative Energy between the Elite and Non-Elite groups in the Transversus Abdominus $p = <.001$, the Rectus Abdominus $p = <.001$, the Gluteus Maximus $p = <.001$ and the Multifidus $p = <.001$. These differences suggest that the Elite group uses less Relative Energy during a slapshot.

We also found that a difference between the Hit and Miss Slapshot Result conditions in the Transversus Abdominus $p = .002$ and the Gluteus Medius $p = .041$. These results suggest that in trials that included a Hit target the Transversus Abdominus and the Gluteus Medius output less energy. This difference could be driven by the between group differences for Relative Energy and the fact that the majority of Hit targets (88.2% 44/51) came from the Elite group.

The interaction between Group and Slapshot Result was observed in the case of the Transversus Abdominus $p = .005$. In both the Elite and Non-Elite groups a hit was preceded by increased Relative Energy output from the Transversus Abdominus. However, the Non-Elite group increase in Relative Energy for a Hit was 2.35 times that of a Miss. Compared to an increase of .83 by the Elite group.

Relative Power

For Relative Power, the multivariate results were significant for Group $F(5, 1) = 12.601$, $p = <.001$ and Slapshot Result $F(5, 1)= 3.796$, $p =.003$ indicating a difference in Relative Power between the Elite and Non-Elite groups as well as between Hit and Miss Slapshot Results.

We found significant differences between the Elite and Non-Elite groups in the Transversus Abdominus $p = <.001$, the Rectus Abdominus $p = <.001$ and the Gluteus Medius $p = <.001$. These results show that the Elite group uses greater Relative Power in the Gluteus Medius and less Relative Power in the Transversus Abdominus and Rectus Abdominus.

We also found a significant difference in Relative Power between the Hit and Miss Slapshot Result conditions in the Transversus Abdominus $p = <.001$ and the Gluteus Medius $p = <.001$. In the Hit condition, the Transversus Abdominus exerted less Relative Power, whereas the Gluteus Medius exerted more. This difference could, again, be driven by the between Group differences for Relative Power and the fact that 88.2% of the hits came from the Elite group.

Chapter 5. Discussion

It is important to reiterate that though there were no statistical differences between the Elite and non-elite groups in terms of age, weight, Sahrmann Score or Sport Specific Endurance Plank Score, these were two very different groups in terms of sport-specific ability. The athletes from the Elite group averaged 18.33 ± 1.55 years of playing experience compared to 2.90 ± .83 years in the Non-Elite group. The Elite group was comprised of both professional and division I college athletes, whereas the Non-Elite group was comprised of athletes that play in the lowest division of adult recreational hockey in Minnesota and had limited experience playing hockey as youth. The Adult Hockey Association describes this level of player as working on basic skills, such as skating forwards, backwards and crossing over, stickhandling while skating, making and receiving passes while skating, and shooting during gameplay. These two groups were chosen purposefully in order to test the validity of the Sahrmann Core Stability Test and the Sport Specific Endurance Plank Test within the context of level of sport performance. If core stability is an important aspect of sport performance and the measures are valid, then it is reasonable to assume that the two groups should score significantly differently. This was not the case.

It can be argued that the Sahrmann Core Stability Test and the Sport Specific Endurance Plank Test are not, in fact, measures of core stability. Instead they are measures of core strength and core endurance, respectively. These variables are characteristics of the Active Musculoskeletal Subsystem, a subsystem of the larger System of Core Stability described by Panjabi (1992). To this point, measures of core strength and core endurance have effectively served as proxy measures of core stability. These measures have been efficacious for the purpose of the study, and treatment, of lower back pain in the general population. However, the contextual shift from the study of lower back pain in the general population to the study of sport performance in a healthy, athletic population warrants a revision of the use of simple proxy measures of core stability. Results of the current study imply, that the relationship between core strength and endurance, and sport performance could have a threshold. Meaning that a minimum level of core strength and endurance is necessary for participation in sport, however improvements in these areas above and beyond the minimum are not matched with concomitant improvements in sport performance. This statement refers to the findings that the two groups did not differ in terms of score on the Sahrmann Core Stability Test or the Sport Specific Endurance Plank Test. Of course, the cross-sectional nature of the current study limits the extrapolative power of such a cause and effect based statement.

Previous works exploring the relationship between core stability and sport performance may have been confounded by the lack of validity of the Sahrmann Core Stability Test and tests similar to the Sport Specific Endurance Plank Test. All of the longitudinal intervention based studies that have involved a measure of core stability have found core training to significantly improve measures of core stability, with no subsequent improvement in any measure of sport performance; direct or indirect (Mills et al., 2005; Parkhouse & Ball, 2010; Stanton et al., 2004; Tse et al., 2005). However, longitudinal intervention based studies that have not involved a measure of core stability have found a causal relationship between core training interventions and measures of sport performance (Pedersen et al., 2006; Saeterbakken et al., 2011; Seiler et al., 2006). Upon closer examination, the training protocols used in these studies, though uniformly considered core training, are clearly designed with differing goals. The training interventions used in studies that involve measures of core stability are clearly designed to improve those specific measures. Exercises are selected that dynamically correspond with the measures of core stability selected. However, the training interventions designed for studies in which only sport performance measures are collected involve training programs that dynamically correspond with the sport performance measures selected. In fact, if the studies that involve core stability measures are disregarded, there is little evidence to refute the theory that there is a positive relationship between core stability training interventions and sport performance.

In order to explore the theory that neurological coordination of the core plays an important role in differentiating between levels of sport performance, EMG activity of two groups of hockey athletes, with vastly differing levels of ability, was recorded during a mutually understood sport performance; the ice hockey slapshot. Participants were directed to shoot with maximal velocity and accuracy “as if in a game”. It was observed that the Elite group had significantly lower, by roughly 2.5 times, EMG Duration compared to the Non-Elite group in all muscle groups. It could be argued that the faster overall speed of movement of the Elite group was responsible for these differences. However, the key question to be answered is why the speed of movement is greater in the elite group. We contend that the cause, at least in part, of the increased speed in the Elite group is, in fact, due to their superior neurological coordination related to a highly practiced sport performance.

It was also observed that the Elite group exhibited Two to three and a half times less Relative Energy, compared to the Non-Elite group. These results were significant for all muscle groups studied with the exception of the Gluteus Medius, for which, the Elite group used two times less energy. Though it was not measured it reasonable to assume that the Elite group is inherently stronger than their counterparts, therefore a slapshot is relatively easier for them. However, both groups were instructed to shoot as hard as possible while still trying to be accurate, just as if they were trying to score in a game. These instructions were meant to elicit maximal effort, eliminating the issue of absolute task-specific strength.

Lastly, it was observed that the Elite group exhibited significantly less Relative Power in the Transversus Abdominus and Rectus Abdominus whereas they exhibited significantly greater Relative Power in the Gluteus Medius. These findings suggest that the strategies to transfer force through the core were different between the two groups. Furthermore, it was observed, but not measured, that the Elite group exhibited more movement of the lower body during the slapshot performance, whereas the Non-Elite group appeared to maintain a relatively static lower body while a majority of their movement came from above the waist. These findings suggest that the neurological patterns of recruitment to accomplish the slapshot task differ between the groups. Though this particular set of evidence is not substantial it is enough to warrant further investigation.

The combined differences in EMG activity between the two groups is not enough to justify a definitive argument as to the true nature of the relationship between core stability and sport performance. However, it does warrant further investigation and could serve as a starting point for a new approach to answering the question, “is there a relationship between core stability and sport performance?”

Application

Previous research has focused on the role of core strength and endurance for performance in sport. Measures of these variables were not related to differences in level of sport performer in our athletes. For this reason, conclusions related to the relationship between core stability and sport performance based on measures of these variables, specifically results of the Sahrmann Core Stability Test and the Sport Specific Endurance Plank Test, should be treated with extreme caution.

EMG evidence observed in the current study, coupled with existing research (Seiler et al., 2006), suggest the importance of the involvement of dynamic correspondence between a core training program and the sporting tasks intended to be enhanced. Specifically, velocity of movement, magnitude of force production, body posture, range of motion, amplitude and direction of the movement, the accentuated region of force production, the dynamics of effort, the rate and time of maximum force production, and the regime of muscular work during the sporting task, should all be considered when selecting core training exercises intended to improve sport performance (Siff & Verkhoshansky, 2009; Zatsiorsky & Kraemer, 2006).

Limitations

The current study was limited by small sample size as well as multiple instances of failure to collect potentially meaningful data. These include the lack of synchronized video data, indirect measures of sport performance and a measure of puck velocity.

Chapter 6. Conclusion

This study provided evidence to support the hypothesis that the Sahrmann Core Stability Test and the Sport Specific Endurance Plank Test are not valid measures of core stability within the context of sport performance. Conclusions drawn about the relationship between core stability and sport performance based on findings from these tests should be considered invalid as well.

This study has also provided evidence that warrants further research into the details of the role that neuromuscular coordination of core musculature plays in sport performance. Lastly, the results of this study combined with previous works suggest a high level of importance to be placed upon the concept of dynamic correspondence when creating a core training program with the intention of improving sport performance.

Future Directives

Future research is required to create a valid test for core stability within the context of sport performance. As well as to elucidate the best training techniques to improve performance.

Chapter 7. References

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Chapter 8. Appendix

Table 1. Muscle Characteristics

Local Muscles[1] (Stabilisors)[2]	**Global Muscles**[1] (Mobilisors)[2]
Deeply Placed[1,2]	Superficial[1,2]
Aponeurotic[1,2]	Fusiform[1,2]
Slow-Twitch[1,2]	Fast-Twitch[1,2]
Active in Endurance Activities[1,2]	Active in Power Actvities[1,2]
Selectively Weaken[1,2]	Preferential Recruitment[1,2]
Poor Recruitment- May become inhibited[1,2]	Shorten and Tighten[1,2]
Activated at Low Resistance Levels (30-40% MVC)	Activated at High Resistance Levels (>40% MVC) [1,2]
Lengthen[1,2]	

(Norris, 1999)[1] (Faries & Greenwood, 2007)[2]

Table 2. Core Musculature

Local Muscles	Global Muscles
Primary Stabilizers	Rectus Abdominus[1,2,3,4,5]
Transversus Abdominus[1,2,3,5]	**Lateral Fibers of External Oblique[1,5]
Multifidus[1,2,3,5]	**External Oblique[2,3,4]
	Psoas Major[1,2,4]
Secondary Stabilizers	Psoas Minor[1,2]
**Medial Fibers of External Oblique[1,5]	Erector Spinae[1,2,3,4,5]
Internal Oblique[1,2,3,5]	Iliocostalis (Thoracic Portion)[1]
Quadratus Lumborum[1,2,5]	Latissimus Dorsi[2,4]
Diaphragm[1]	Rectus Femoris[2]
Pelvic Floor Muscles[1,3]	Sartorius[2]
Iliocostalis (Lumbar Portion)[1]	Iliacus[2]
Longissimus (Lumbar Portion)[1]	Gluteus Maximus[2]
Rotatores[2]	Semimembranosus[2]
Interspinalis[2]	Semitendinosus[2]
Intertransversalis[2]	Long Head of the Biceps Femoris[2]
Internal Oblique Abdominus[2]	Adductor Magnus[2]
Deep Transversospinalis[3]	Adductor Brevis[2]
	Adductor Longus[2]
	Gracilis[2]
	Pectineus[2]
	Tensor Fascia Latae[2]
	Gluteus Medius[2]
	Gluteus Minimus[2]
	Quadratus Lumborum[3,4]
	Internal Oblique[4]

(Faries & Greenwood, 2007)[1] (Willardson, 2007b)[2] (Akuthota et al., 2008)[3] (Bergmark, 1989)4 (Norris, 1999)5
*Muscles in bold text have been categorized as both local and global by different researchers.
**Some researchers have placed specific fibers of the external oblique into both categories, others have categorized the external oblique as a single muscle in a single category.

Table 3. Group Characteristics

	Elite ± Std. Error n = 9	Non-Elite ± Std. Error n = 8	p-value
Age (Years)	23.11 ± 1.69	28.25 ± 3.26	0.168
Weight (Pounds)	190.3 ± 5.88	186.2 ± 2.91	0.554
Playing Experience (Years)	18.33 ± 1.55*	2.90 ± .83*	<0.001

** indicates significant difference*
p-values calculated using independent sample two tailed t-test

Table 4. Test Scores: Between Groups Comparison

	Elite ± Std. Error	Non-Elite ± Std. Error	p-value
Sahrmann Score (Level Attained)	2.00 ± 0.47	2.50 ± 0.38	0.429
Sport Specific Endurance Plank Score (S	228.89 ± 24.07	215.38 ± 29.65	0.726
Slapshot Score (Hits out of 10)	5.00 ± 0.76*	0.75 ± .53*	<0.001

** indicates significant difference*
p-values calculated using independent sample two tailed t-test

Table 5. Test Scores: Correlation Analysis

Overall	Sahrmann Score	Plank Score	Slapshot Score
Sahrmann Score	---	0.155 (0.553)	-0.155 (0.552)
Sport Specific Endurance Plank Score		---	-0.023 (0.929)
Within the Elite Group	Sahrmann Score	Plank Score	Slapshot Score
Sahrmann Score	---	0.722 (0.028)*	-0.193 (0.619)
Sport Specific Endurance Plank Score		---	-0.156 (0.688)
Within the Non-Elite Group	Sahrmann Score	Plank Score	Slapshot Score
Sahrmann Score	---	-0.520 (0.186)	0.449 (0.264)
Sport Specific Endurance Plank Score		---	-0.135 (0.749)

** indicates significant difference*
Results displayed as: Pearson Correlation Value (P-Value)

Table 6. MANOVA

	F	df	p-value
EMG Duration			
Group	19.115	5	< 0.001*
Slapshot Result	1.609	5	0.162
Group x Slapshot Result	1.29	5	0.272
Relative[1] Energy (area under curve)			
Group	12.716	5	< 0.001*
Slapshot Result	2.586	5	0.029*
Group x Slapshot Result	2.435	5	0.038*
Relative[1] Power (area under curve/milliseconds)			
Group	12.601	5	< 0.001*
Slapshot Result	3.796	5	0.003*
Group x Slapshot Result	2.223	5	0.056

** indicates significant difference*

[1] Energy and Power values are calculated relative to MVIC values

p-values calculated using two-way MANOVA

Table 7. Group x Slapshot Result Interaction

	Transversus Abdominus	Rectus Abdominus	Gluteus Medius	Gluteus Maximus	Multifidus
Duration (p-value)	*NS*	*NS*	*NS*	*NS*	*NS*
Energy (p-value)	0.005*	0.252	0.163	0.115	0.183
Power (p-value)	*NS*	*NS*	*NS*	*NS*	*NS*

** indicates significant difference*

Figure 1.

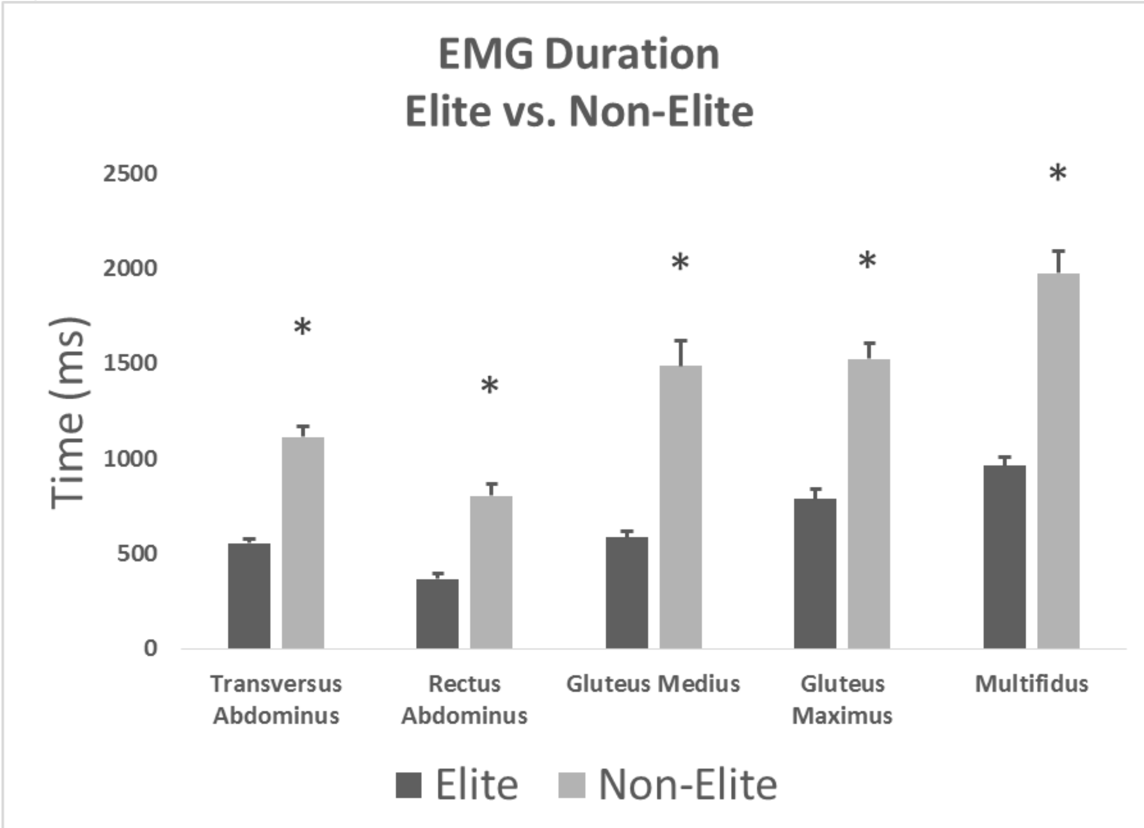

Figure 1 shows the difference in EMG Duration, for each studied muscle, between the Elite and Non-Elite groups.

* Denotes significance at p <.05

Figure 2.

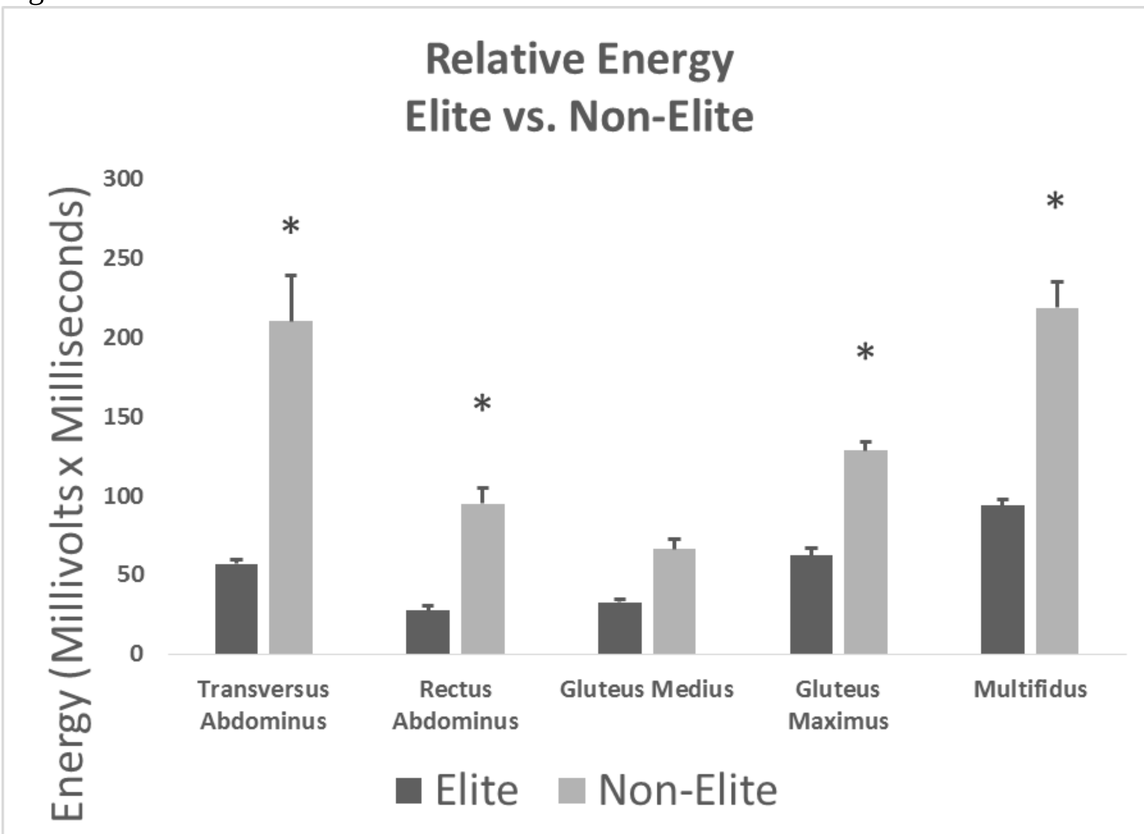

Figure 2 shows the difference in Relative Energy, for each studied muscle, between the Elite and Non-Elite groups.

* Denotes significance at $p < .05$

Figure 3.

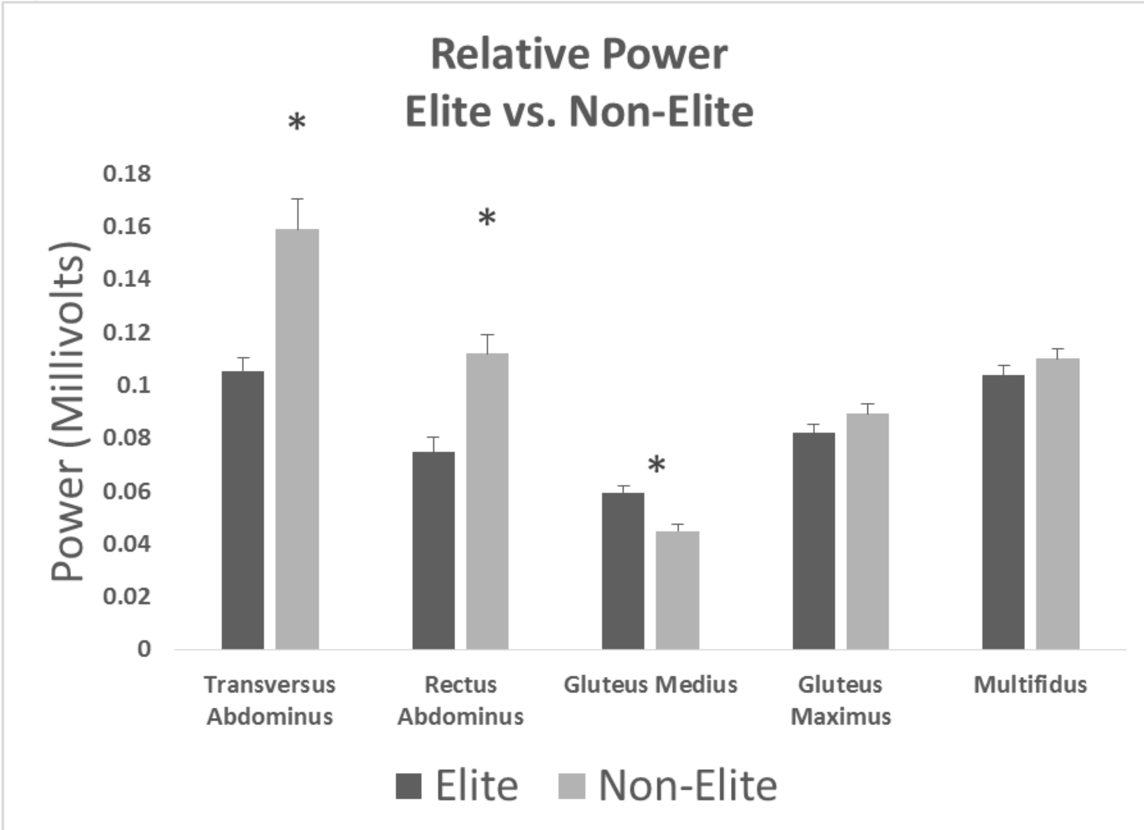

Figure 3 shows the difference in Relative Power, for each studied muscle, between the Elite and Non-Elite groups.
* Denotes significance at p <.05

Figure 4.

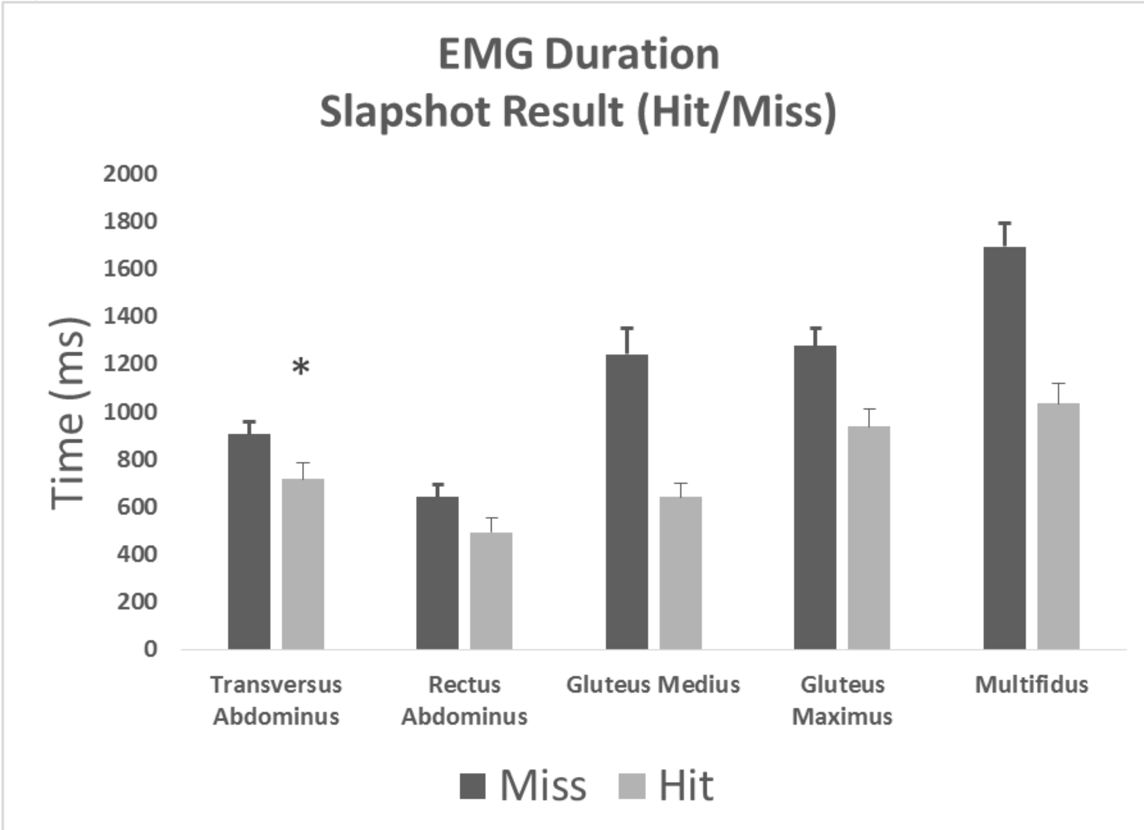

Figure 4 shows the difference in EMG Duration, for each studied muscle, between the Hit and Miss conditions.
* Denotes significance at p <.05

Figure 5.

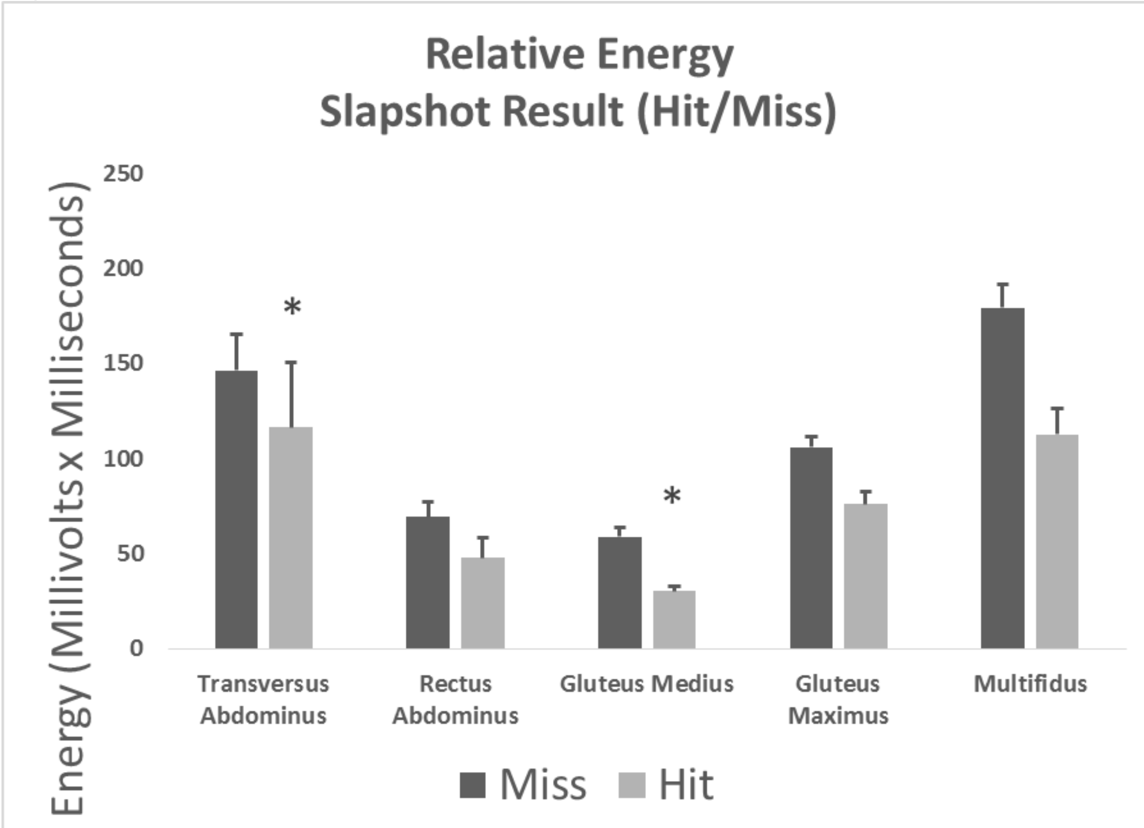

Figure 5 shows the difference in Relative Energy, for each studied muscle, between the Hit and Miss conditions.
* Denotes significance at $p < .05$

Figure 6.

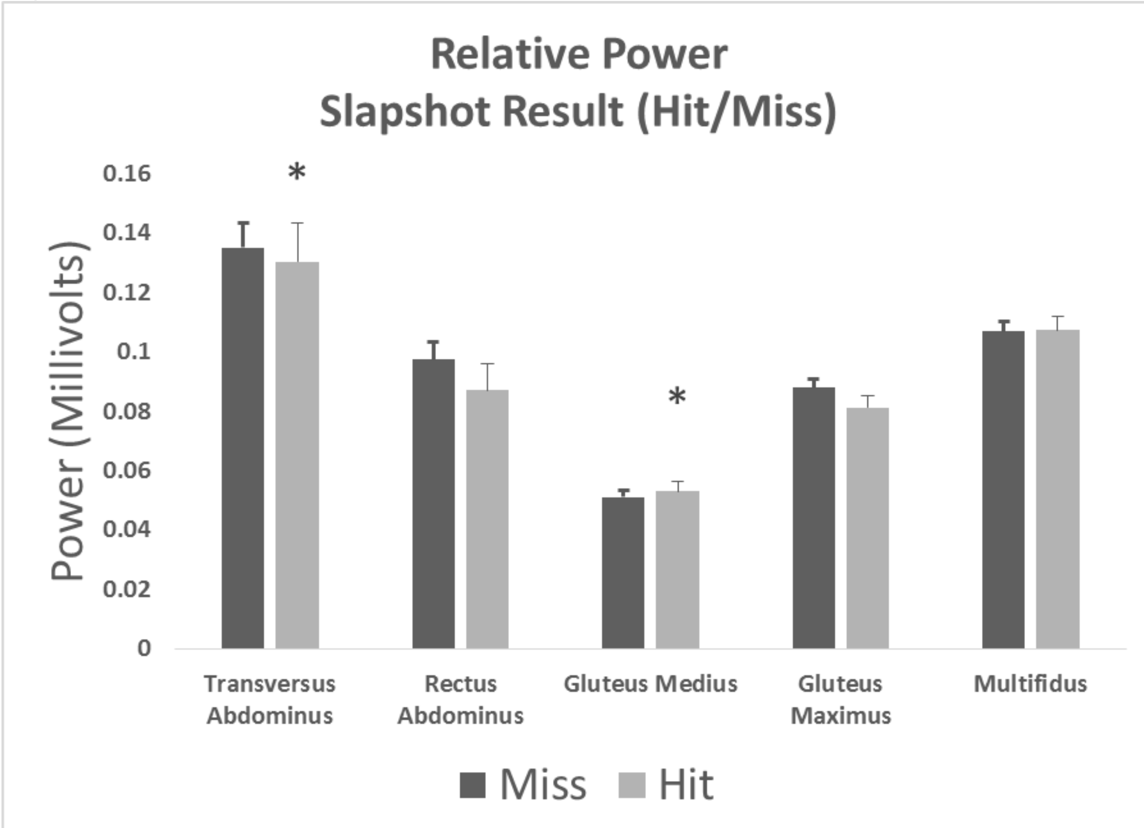

Figure 6 shows the difference in Relative Power, for each studied muscle, between the Hit and Miss conditions.
* Denotes significance at p <.05