Trainability of Core Stiffness: Studies of Core Training Methods on Naive and Savvy Populations

by

Benjamin Lee

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2013

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Core exercise is a staple of many physical training regimens with goals ranging from improving athletic performance to rehabilitation of spine and knee injuries. Traditionally, dynamic movements such as flexion, lateral bending and twisting core exercise maneuvers are used in training programs; an approach consistent with training the distal limbs where muscular effort is mostly devoted to creating motion. However, knowledge of the functional anatomy of core musculature and spine injury mechanisms questions the use of these types of exercises. Alternative core exercises make use of isometric postures and static bracing to create muscular activation while minimizing spine loads and injury mechanisms linked with movement.

This study aims to quantify the effect of various core training programs on the change of passive and active stiffness properties of the torso. This study was driven by several curiosities:

1) Isometric core exercises are reported to help some people who have low back pain. Is there a short lasting 'enhanced stiffness' after performing these exercises?

2) Core training regimens use Isometric and Dynamic core exercises to enhance core bracing properties. Is one method superior to the other in terms of enhancing core stiffness?

3) If adaptations to core stiffness can be achieved with core exercise, do these adaptations differ between beginners and trained individuals?

Twenty four healthy male subjects (22.9 ± 2.7 years, 1.79 ± 0.06 m, 77.5 ± 10.8 kg) were recruited for short and long term core training. Of the overall population, twelve subjects (21.7 ± 1.89 years, 1.80 ± 0.076 m, 78.3 ± 12.3 kg) were University students with little to no experience in performing regular core exercise. The other twelve subjects (24.2 ± 2.89 years, 1.79 ± 0.047 m, 76.8 ± 9.71 kg) were athletically trained with at least one year of experience performing regular core exercise (minimum three times per week). This study was a repeated measures design examining short and long term core stiffness (active and passive) and range of motion before and after a single fifteen minute bout of isometric core exercise and a six week core training program. The long term training groups were divided evenly into isometric, dynamic and control groups. The Isometric group received a six week training program consisting of core bracing exercises ranging from basic static bodyweight exercises to weighted exercises with additional challenge of distal limb mobility while maintaining a braced core, while dynamic group exercises consisted of movement and speed based core exercises. The Control group received no further training during this period. All subjects were asked to refrain from any extra core demands not given by the researchers. After the training period was complete all subjects were retested for stiffness and range of motion.

Passive stiffness tests were performed using a frictionless bending apparatus for flexion, extension, left and right lateral bend and left and right axial twist directions. Active stiffness was assessed via a 'quick release' mechanism, preloaded with a 16 kg mass and randomly released to assess active extension. Participants were instrumented with unilateral electromyography

(EMG) of selected core musculature and electromagnetic signals for motion capture for lumbar kinematics. To determine if training had an effect on dependent variables a series of repeated measures ANOVAs were performed; short term training utilized a 2x2 Repeated Measures ANOVA using the pre/post condition and training experience (naïve vs. savvy) as factors. Long term training utilized a 3x2x2 Repeated Measures ANOVA using training group (Isometric vs. Dynamic vs. Control), training experience (naïve vs. savvy) and pre/post condition as factors.

In general, short term isometric core training increased core stiffness in all directions for naïve and savvy subjects. Comparisons between these two subject groups did not yield any significant differences. After long term training stiffness was increased the greatest in the Isometric training group with both naïve and savvy subjects. Dynamic training yielded significant increases in stiffness but for only one direction in each subject group (right lateral bend in naïve subjects and left axial twist in savvy subjects). The Control group did not show any significant changes in stiffness. Comparisons between training groups and training experience did not yield any significant differences. Isometric training lead to significant stiffness increases in all test except for passive and active extension in naïve subjects, and similar results were found for savvy subjects except for right lateral bend not showing any significant changes. Researchers believe reasons for insignificant changes are related to high variances which may be due to inadequate statistical power and a wide variety of responses within each subject group. Though some analyses showed inadequate statistical power due to small sample sizes it should be noted that this research is the first of its kind investigating the trainability of core stiffness in the short and long term, and thus difficult to establish sample sizes without any baseline values.

The findings of this study can be directly applied to core training for rehabilitation and athletic function. Enhancements in core stiffness are thought to subsequently enhance traits such as load bearing ability, pain management and athletic function. The results of short term training give insight into how a short training session performed prior to a load bearing task can make the task safer and easier to perform. The results of long term training show that Isometric training performed over a long duration may induce more permanent enhancements to stiffness and core function.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Stuart McGill, for the guidance, advice and expertise he has offered during my time working with him. I can confidently say that without Stu I would not be where I am today or even have considered this academic program. We share a common bond in performing good science and an appreciation for what the high performing human body is capable of. The blend of passions of science and athletics has heavily influenced my work and this project. My mindset about life and academics has completely changed compared to when I started over two years ago and I have Stu's influence to thank for that.

Dr. Ed Cambridge, Mr. Christian Balkovec, Ms. Natalie Sidorkewicz – my labmates who have helped guide me through the post grad world and offered me their experience and advice. Thank you for all your help. Mr. Jordan Cannon for assisting with all data collections, without Jordan I would still be collecting data right now.

Mr. Jeff Rice, thank you for your help with hardware and equipment. Without you this project would not have even gotten off the ground. Thank you for your technical support and ensuring this project went smoothly with minimal collection issues.

All my study participants – thank you for enduring the long data collections and training sessions. Thank you for your stringent execution of my training program and high attention to detail. I hope you have learned as much as I have and continue to spread the word of effective core training.

Last but not least, thank you to my parents Chee Vun Lee and Ei Mayi Wong. Thank you for your continual support throughout my life and during this phase of post graduate studies.

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1 Introduction

The role of the core musculature (muscles proximal to the ball and socket joints) has been thought to prevent motion and provide buttressing to the torso, rather than generate movement akin to the musculature of the distal limb segments (McGill, 2007). This is thought to be achieved by increasing torso stiffness. Though torso stiffness can positively affect many physical characteristics it should be noted that detrimental effects of stiffness are also possible. In cases where mobility is required higher stiffness can increase the odds of injury risk and discomfort. Increased spinal stiffness is linked to decreased spinal range of motion, which in turn has effects on passive tissue loading and increased risk of injury during high range of motion activities (Beach et. al., 2005). Stiffer muscles have been linked to symptoms of greater muscle damage (soreness, strength loss, increased creatine kinase activity) following eccentric contraction (McHugh et. al., 1999). However, inducing greater torso stiffness, namely through muscular activation, has been also linked to enhanced load bearing ability and spinal stability (McGill, 2007). By stopping unwanted motion, activation of the abdominal musculature can be viewed as a strategy to enhance stability through generating stiffness and prevent energy loss during whole body coordinated movement and enhancing dynamic characteristics of athletic movements.

The basis of this theory has lead to strategies involving torso bracing and eliminating spine motion as a method of reducing pain in populations experiencing low back injury and pain (Gardner-Morse and Stokes, 1998; 2001; van Dieen et. al., 2003; Panjabi, 2003). Application of spine buttressing through torso musculature activation has lead to the implementation of bracing type core exercises as a method of improving spine stability in these clinical populations (McGill, 2007). This knowledge has not only influenced the clinical world but also motivated many high performing athletes to incorporate core training regimens into their physical training. However, much debate among athletic trainers has existed with regards to the most effective method to train the core musculature. Historically, many athletes have performed dynamic exercises such as sit-up and crunch variations as a staple of abdominal training. It has been shown that repetitive spinal flexion/extension maneuvers, especially under compressive spine load, typical of sit-up and crunch variations lead to disc herniation injuries while tested in vitro (Callaghan and McGill, 2001), and these exercises have questionable validity as to their ability to rehabilitate or prevent low back injury/pain (Jackson et. al. 1998; Akuthota and Nadler, 2004). More recently, the athletic industry has begun to implement isometric abdominal exercises requiring the generation of stiffness via buttressing as an alternative method of training the torso musculature, motivated by proof of core musculature activity with reduced spine loads and potential of spinal injury mechanisms (McGill, 2010). In both clinical and athletic populations the importance of abdominal bracing and torso stability has been demonstrated in order to prevent injury and/or pain by reducing spine motion and increasing spinal stability, as well as improving athletic performance via proximal stiffness influencing distal limb mobility. These two issues motivated the work performed here.

1.2 Purpose

The purpose of this investigation was to observe and measure if passive and active torso stiffness is enhanced with exercise. Due to the lasting debate regarding the efficacy of the various types of abdominal training the nature of this study will attempt to quantify the results of dynamic and isometric core training over a six week period.

1.3 Hypotheses

The investigation examined the effects of different core training modalities on core stiffness, during periods of muscle activity and while passive. This study was driven by several curiosities:

1) Isometric core exercises are reported to help some people who have low back pain. Is there a short lasting 'enhanced stiffness' after performing these exercises?

2) Core training regimens use Isometric and Dynamic core exercises to enhance core bracing properties. Is one method superior to the other in terms of enhancing core stiffness?

3) If adaptations to core stiffness can be achieved with core exercise, do these adaptations differ between beginners and trained individuals?

Due to the multifaceted nature of this study multiple hypotheses were formed for each phase of the investigation. Hypotheses were generated for comparing pre and post training values of stiffness and strike characteristics within subjects and between subject groups and subject training experience. Note the dependent variables are underlined in the following hypotheses and independent variables in bold.

In terms of short term exercise enhancing stiffness characteristics:

1) Post training <u>Passive stiffness</u> is increased over pre training passive stiffness with **short**

term isometric core training.

2) Post training Active stiffness is increased over pre training active stiffness with **short term isometric core training**.

3) Post training Passive and Active stiffness is increased over pre training stiffness to a greater degree in **naive populations** than in **savvy populations.**

In terms of long term exercise enhancing stiffness characteristics:

4) Post training Passive stiffness is increased over pre training values to a greater degree after **Isometric** training, in both naïve and savvy populations, whereas no significant pre/post changes are predicted for **Dynamic** or **Control** groups.

5) Post training Active stiffness is increased over pre training values to a greater degree after **Isometric** training, in both naïve and savvy populations, whereas no significant pre/post changes are predicted for **Dynamic** or **Control** groups.

6) Post training Passive and Active stiffness are increased to a greater degree in the **Naive** population than in the **Savvy** population.

7) Post training Passive and Active stiffness are increased to a greater degree in the **Isometric** training group than in the **Dynamic** or **Control** groups.

1.4 Basic Approach

The study design approach followed a repeated measures test/re-test of stiffness following a single fifteen minute isometric core training session, and following a six week training protocol; involving a sample population of twenty four participants. Active and passive stiffness values were measured before and after the short term training session, and subjects were split evenly into one of three training groups for long term training: Isometric, Dynamic or Control. The Isometric group received a six-week protocol of isometric core bracing exercises. The Dynamic group received a six-week protocol of movement based core exercises. The Control group received no further training during this period. During this training period all subjects will be asked to refrain from any additional core training to reduce training adaptations not associated with the given exercises. Following the six week training protocol all subjects were retested with active and passive bending trials.

Chapter 2
Literature Review

A review of existing literature regarding torso muscle function, stiffness, training and application to athletic performance is performed in this chapter.

2.1 Torso Exercise

Whether an individual exercises for general health, injury rehabilitation or athletic performance enhancement, training the torso musculature has been a large contingent of many exercise programs. Abdominal and torso exercises have been performed in order to strengthen musculature (Norris, 1993; Willett et. al., 2001), improve muscular endurance (McGill, Childs and Liebenson, 1999), reduce low back pain and maintain spine health (Gardner-Morse and Stokes, 1998; 2001) and improve sport performance (Hedrick, 2003; Willardson, 2007; McGill, 2009). Given the functional anatomy of the torso there are many muscles which in certain planes of motion and activate through differing strategies. This notion was acknowledged in which it has been stated that there is no single exercise which adequately challenges all abdominal musculature (McGill, 2009). Thus in order to fully train the core a plethora of exercises must be selected which challenge various directions of loading and achieve activation of the entire core. This is not only important for achieving balance of developing the entire torso musculature, but has foundations in the rehabilitation of low back injury populations in order to return to pain free activities of daily living, and high performance athletes performing ballistic multiplanar movements (Nadler, 2002; Hodges, 2003; Akuthota and Nadler, 2004).

Building on the notion of using multiple exercises to develop the torso musculature, consideration of proper movement mechanics and load tolerance when selecting exercises is of utmost importance for safety and performance. Violation of movement principles or exceeding tolerable loads can lead to further injury or decrement in performance, as opposed to achieving injury rehabilitation or performance enhancement (Jones and go, 1999; Childs et. al., 2009; George et. al., 2007; Taanila et. al., 2009). These principles are covered in depth in Section 2.2. Types of core exercises are grouped into two categories: dynamic and isometric. Dynamic core exercises include exercises which challenge the core musculature using movement. This includes such exercises as sit-ups, crunches, and side bends – all recruit various core musculatures by introducing motion through the torso. Historically some of these exercises have been used as a standard of testing in sport, police and military settings (US Army, 1992) but questions arise with regards to detrimental effects on spine health. EMG activity of various core musculature during dynamic torso exercises have been measured (McGill, 1995; Beim et. al., 1997; Escamilla et. al., 2006). Exercises such as sit-ups and crunches have shown activity of up to 50% of maximum voluntary contraction (MVC) through the rectus abdominis and bent knee sit- ups and obliques crunches showed activity of 30- 40% MVC through the external oblique (Escamilla et. al., 2006). McGill found high levels of activation of the rectus abdominis, external oblique and internal oblique (30 - 40% MVC) for both bent knee and straight leg sit ups (McGill, 1995). Similar results were found in Beim's investigation in which torso flexion maneuvers generated the greatest rectus abdominis activation, though units of measurement were not consistent with Escamilla or McGill's (uV*s compared to %MVC) and thus comparisons of results could not be made directly. Commercial exercise equipment designed to mimic these bodyweight dynamic exercises have also shown high levels of activation through the targeted musculature when examined by Escamilla. When examining the role of core exercises to athletics, theories of sport specific training can be applied for mimicking athletic movements in training. Such was the case with Stodden's study in comparing the kinematics of various dynamic core exercises to throwing tasks. Trunk kinematics during exercises such as cross knee sit ups, twisting cable core exercises and rotational medicine ball throws were shown to mimic the kinematics of throwing exercises and was concluded to be suitable training exercises for throwing athletes (Stodden et. al., 2008).

In contrast to dynamic exercises, isometric core exercises challenge the torso musculature through activation via bracing while being held in static postures. These exercises activate the musculature via stabilizing and bracing of the trunk and the challenge lies in the maintenance of posture (in other words, to stop motion of the torso), while more advanced versions of these exercises challenge the participant to maintain a core brace while coordinating distal limb movement and athleticism. Quantification of the EMG signal of a variety of isometric core exercises revealed moderate to high activation levels of target core musculature while minimizing imposed spine loads (a concept explored in the next section) (McGill and Karpowicz, 2009). Variations of the braced curl-up (a curl-up exercise designed to challenge the anterior core musculature where the torso is 'locked' in place via a braced core imposing little to no motion about the lumbar spine) resulted in mean activations of the rectus abdominis 20- 35% MVC, external oblique 8-18% MVC and internal oblique 12- 26% MVC. Though these values are lower than those reported during dynamic core exercises this still places adequate demand to the abdominals. A plyometric variation of the curl up such as the ‘dead bug twitch’; high velocity twitch of the contralateral arm and leg; demonstrated higher activation of the abdominals (50% MVC of the rectus abdominis, 30% MVC of the external oblique and 40% MVC of the internal oblique). Similar results were measured for the bird dog; quadruped extension of the contralateral arm and leg; comparable levels of activation were observed in the upper spinal erectors, gluteus medius and gluteus maximus. The results from McGill and Karpowicz were supported by other groups studying EMG activation of commonly performed rehabilitation exercises, including the bird dog, plank and side bridge (Ekstrom et. al., 2007). The results of Ekstrom’s study revealed similar results in the activation of targeted musculature during certain isometric exercises, including the side bridge (74% MVC glute med, 69% external oblique), plank (or prone bridge as described by Ekstrom, 43% MVC of the rectus abdominis, 47% MVC of the external oblique) and bird dog (36% MVC erector spinae, 56% MVC gluteus maximus and 42% MVC gluteus medius). Thus, Ekstrom showed the how these isometric exercises adequately created activation of the intended musculature. The main difference between Ekstrom and McGill and Karpowicz was the lack of spinal compression values from Ekstrom. However, inferences from activation level and spine kinematics would allow us to hypothesize that spine compression values would be low. Further evidence from Kavcic et. al. supports McGill and Karpowicz, and Ekstrom findings; isometric exercises including the side bridge and bird dog were analyzed and ultimately quantified for tissue loads and spine stability (Kavcic et. al., 2004). EMG findings were reported by Kavcic and these results agree with the activation levels reported in other studies.

Based on the results for EMG studies of dynamic and isometric exercises a solid argument can be made for both types of exercises in terms of creating challenge in the core musculature. Both types of exercises showed moderate to high levels of core activation and proof has been established for application of sport specific training (Nesser et. al., 2008; Stodden et. al., 2008; McGill, 2009).

2.2 Injury Mechanisms Associated With Movements and Exercises

Kinematic and kinetic values should be considered when determining the efficacy and injury potential of exercises, and the inclusion of spine load calculations makes the studies listed much more valuable in quantifying injury potential. As with any form of muscular exercise the goal is to provide appropriate muscular challenge but also minimize risk of musculoskeletal injury and keep the body in a safe posture.

Injury of the lumbar spine occurs with applied mechanical load – if the amount of load or number of cycles of movement exceeds the tolerance of spinal tissues, injury will occur (McGill, 1997). Lumbar spine injury is not non-specific; most injuries can be traced to a specific type and direction of mechanical loading. However this is not to say that all loading on the spine is detrimental. An adequate amount of loading provides an adaptive mechanism for spinal tissues to strengthen and become resistant to applied load. Too much load exceeds the tolerance of the spine and injury occurs, but proof has been established that not only is mechanical overload responsible for spinal disc degeneration and injuries (as further explained in the following subsections), but immobilization and underuse also induces changes in mechanical properties of spinal tissues which further promote disc degeneration (Stokes and Iatridis, 2004).

Kinematic mechanisms of spine injuries are factors which must be considered when selecting exercises. As stated in Chapter 1 it is thought that the musculature of the torso is designed to prevent motion, not create it. This is unlike distal limb musculature where muscles act as actuators to generate movement. Injury mechanisms can occur in various planes of motion, which will be further explained in the following four subsections.

2.2.1 Flexion

Flexion, in this context, refers to kinematic flexion movement and not kinetic flexion moment. Flexion based spine injuries are commonly associated with repetitive forward bending of the spine. Within a historical context, research dating back to the late 1950’s has shown links between spinal flexion and potential spine injury (Brown et. al., 1957; Lindblom, 1957; Hardy, 1958). Cyclical flexion/extension over prolonged periods is thought to cause disc bulges and herniation injuries, in which the nucleus of the disc pushes out against the annulus ring causing an extrusion type effect. This effect is more pronounced when under compressive load (Callaghan and McGill, 2001), through increasing the number of cycles (Tampier et. al., 2007; Marshall and McGill, 2010) and bringing the spine towards end range of motion flexion (Adams and Hutton, 1982; 1986). Mechanisms of action for this injury are linked to hydrostatic pressure of the nucleus fluid within the spinal disc; uneven pressure distribution pushes the nucleus against the annular rings of the disc leading to eventual bulging of the disc or herniation (Wilder et. al., 1998). Similar mechanisms have been shown for lateral bending, where instead of causing posterior disc bulges with forward flexion, lateral flexion increases risk of lateral disc herniations opposite to the direction of lateral bend (Costi et. al., 2007; Natarajan et. al., 2008).

The literature provided above has mostly been reported in vitro but examples of such mechanisms can be commonly found in practical applications through core exercises. Repetitive flexion/extension under spinal compression occurs frequently while performing dynamic core exercises where the athlete repetitive bends at the lumbar spine while creating spinal compression via activation of the core musculature or external load during the exercise (McGill, 1995). This mechanism is also mimicked in daily workplace tasks, such as lifting an object off the floor repetitively (Dolan and Adams, 1994). It was stated that dynamic core exercise can generate high levels of activation of the core musculature, but consideration of spine load must be accounted for. Analyses of torso flexion mechanics have shown spine compression values approaching NIOSH Action Limit values (3433 N) in isometrically held situp postures and dynamic situps (McGill, 1995). Dynamic straight leg sit-ups have also been measured to impose a compressive load of 3300 N on the spine while in flexion (Axler and McGill, 1997). Additionally, individuals performing situp type movements as part of a physical training regimen or fitness endurance test are more likely to incorporate high velocity and acceleration during the dynamic situp – the inertial load due to increased acceleration may impose further increased compressive and shear loads to the spine. The spine loads reported clearly take away from the spine's capacity to tolerate load but it may be argued that in athletic populations athletes are accustomed to experiencing higher than accepted loads due to adaption from rigorous training and selective muscular activation (Cholewicki, McGill and Norman; 1991). However, referring to literature cited with regards to repetitive flexion/extension cycles, injury to the disc is usually not from a single acute loading but rather from a cumulative effect over a period of time.

2.2.2 Extension

Extension injuries are typically due to excessive kinetic load and kinematic hyperextension of the spine, typically to the posterior processes of the vertebra. Direct loading from contact between the posterior elements of the vertebra leads to the generation of shear forces between these elements. Over time the accumulation of these shear forces create spondylitic fractures of the posterior vertebral elements. Akin to flexion related disc herniation from repetitive flexion-extension cycles, cyclical full spine extension may to fatigue portions of the neural arch from repeated stress reversals. Evidence of spondylolisthesis and knowledge of stress concentrations creating fractures of has been reported as early as the year 1931 (Meyerding, 1931). In an extreme case, a condition due to high extension range of motion known as 'kissing spines' has been noted to occur, where the interspinous ligaments are crushed between two posterior elements of adjacent vertebra (Twomey and Taylor, 1987). In vitro testing has revealed the human spine is able to withstand kinetic loads of up to 2000 N of shear force before fracture of the facet and pars (Cripton et. al., 1995). While maximum tolerance of anterior shear before fracture of the posterior elements occurs around roughly 2000 to 2800 N, discomfort and back pain has been reported at 500 N of shear load in jobs requiring repetitive shear loads (Norman et. al., 1998). Building on the kinematics and kinetics of spondylitic fractures, the speed at which these flexion-extension cycles are performed also has bearing on the risk of fractures, as demonstrated in Cricket bowlers in which extreme ranges of motion are achieved through extension and flexion (Ranawat et. al., 2003). Not only has evidence been given for tolerable load but load rate as well; lower anterior shear load rates (100 N/s) have been shown to produce soft tissue injuries but higher load rates (7000 N/s) have been shown to produce fractures of the posterior elements of the vertebral body (Yingling and McGill, 1999).

The kinematic and kinetic loads associated with extension injuries are replicable in a number of core exercises. Exercises such as the prone 'superman' generates high shear loads of the lumbar spine – this exercise is generally repeated for a high number of repetitions as it is thought to develop muscular endurance of the back extensor muscles. Additionally, if the individual increases the velocity of the movement then inferences can be made as to the risk of injury based on the load rate values given by Yingling and McGill. Further, inertial loads from the velocity of movement may further contribute to increased load values. Compression values have been reported during this exercise but anterior shear values have not been calculated. However, given the kinematics of the exercise and the knowledge of injury mechanism of shear fractures one can draw conclusions with regards to the safety of this exercise.

2.2.3 Axial Twisting

Movement about the transverse plane involves twisting about a vertical axis. With this movement mechanism, injury comes about via repetitive axial twisting of the spine, similar to twisting a corkscrew. The damage from this injury occurs about the disc; Akin to how repetitive flexion tasks promote posterior disc bulges, axial twisting results in an injury mechanism representative of the kinetics and kinematics associated – delamination of the annulus fibres of the disc is set off through repetitive twisting torque applied. Eventually as the layers of the annulus of the disc delaminate it becomes much easier for the nucleus material to seep through. In vitro testing of porcine vertebral specimens has demonstrated this effect; repetitive cycles of applied twisting torque applied to the specimens lead to the annulus fibres stripping away leading to thinner annular walls and ultimately greater incidences of disc herniation (Marshall and McGill, 2010).

Axial twisting torque is mimicked frequently in core training techniques. Exercises involving deviation of the hips and shoulders imposes twisting kinematics on the spine, and with increased velocity of movement twisting load increases. Movement such as twisting sit-ups and improperly performed 'Russian twists' (the individual twists through the spine, as opposed to the hips while holding one of a barbell with the other end pin jointed to the ground) all impose a twisting torque on the spine with the added cost of higher compressive load. This added effect of increased compression may compound damage to the spine; though only performed in vitro it has been found that the addition of torsional stress to the spine does reduce its ability to handle compressive load (Aultman et. al., 2004).

2.2.4 Kinematic Injury Mechanisms and Exercise

The kinematic mechanisms of spine injury described above show how certain movement patterns can put the spine at greater risk of injury. It can be inferred that by avoiding these mechanisms one can preserve integrity of the spine. However, many commonly performed core exercises mimic these exact mechanisms.

EMG activity gives insight to the motor demand of an exercise the effect of these exercises but consideration of spine load and movement is arguably even more important due to injury risk. This was a limiting factor when reviewing the studies of Escamilla and Stodden; Escamilla reported EMG activation normalized to MVC values and ranked exercises based on greatest to least recruitment as a metric of determining the efficacy of the exercises. However, this does not consider kinetic and/or kinematic injury mechanisms when performing these exercises. If an individual becomes injured while performing an exercise and can no longer perform, is this exercise still considered to be effective? Stodden examined kinematics of core exercises and compared these movements to similar throwing tasks. This method can make inferences to specificity of training and how it carries to sport specific tasks but the study did not assess EMG, spine load or injury mechanism. A search of literature revealed that the only studies which reported imposed spine loads during various tasks were those performed by McGill et. al. (Axler and McGill, 1997; Callaghan, Gunning and McGill, 1998; Kavcic et. al., 2004; McGill and Karpowicz, 2009). A comparison of dynamic and isometric exercises accounting for spine load has been examined thoroughly through these studies. Comparison of dynamic and isometric core exercises showed challenge similar groups of core musculature. Comparing the bird dog to a 'superman' exercise (prone leg and arm extension) both exercises provide challenge to the posterior core and hip musculature but the superman exercise imposed a 6000 N compressive load on the spine while in a hyperextended spine posture, repeated over a number of cycles depending on the number of repetitions performed. The bird dog, on the other hand, imposes a much lower compressive load (2000 N) and more importantly fosters a neutral spine posture helping prevent kinematic injury mechanisms (Callaghan, Gunning and McGill; 1998).

Excessive spine load is linked to compressive spine injuries, damaging the end plates of the vertebra (van Dieen et. al., 1999). Further, excessive compressive forces on the spine when out of neutral posture exacerbates mechanisms associated with bending and twisting, and decreases load tolerance (Callaghan and McGill, 2001; Cripton et. al., 1995; Aultman et. al., 2004). This is not to say all spine load is considered hazardous; optimal spine loading is thought to be comparable to a U-shaped curve – too much or too little load can be detrimental to injury risk but just enough loading allows adaptations leading to greater tissue strength and higher load tolerance (citation needed). When loads exceed tissue tolerance from excessive singular loads or repetitive submaximal loads, this is when injury occurs (Panjabi et. al., 1985; McGill, 1997). Thus, kinematic and kinetic loads should be considered when determining the efficacy and injury potential of exercises, and the inclusion of spine load calculations makes the studies listed much more valuable in quantifying injury potential. As with any form of muscular exercise the goal is to provide appropriate muscular challenge but also minimize risk of musculoskeletal injury and keep the body in a safe posture.

Injury of the lumbar spine occurs with applied mechanical load – if the amount of load or number of cycles of movement exceeds the tolerance of spinal tissues, injury will occur (Panjabi et. al., 1985; McGill, 1997). Lumbar spine injury is not non-specific; most injuries can be traced to a specific type and direction of mechanical loading. However this is not to say that all loading on the spine is detrimental. An adequate amount of loading provides an adaptive mechanism for spinal tissues to strengthen and become resistant to applied load. Too much load exceeds the tolerance of the spine and injury occurs, but proof has been established that not only is mechanical overload responsible for spinal disc degeneration and injuries (as further explained in the following subsections), but immobilization and underuse also induces changes in mechanical properties of spinal tissues which further promote disc degeneration (Stokes and Iatridis, 2004).

2.3 Stability and Stiffness

2.3.1 Mechanical Definition of Stability and Stiffness

Concepts of stability and stiffness are benchmarks for core function. Without accounting for stability almost all human activities cannot be successfully performed. Three major tenets with regards to stiffness and stability exist for human function (McGill, 2009):

1) Sufficient stiffness allows for the body and flexible spine to bear load.

2) Stiffness and stability are related through muscular mechanisms, creating a guy wire system for the spine.

3) Proximal stiffness may allow for distal mobility.

These tenets are explored in the following subsections.

The concept of ‘sufficient stiffness’ allows for load bearing activities while preventing buckling. If sufficient stiffness is not present for a given task, no matter what load is applied instability due to buckling will occur making the task impossible to perform. To illustrate this point, consider a rigid column held in equilibrium by a mass on one end and a spring on the other. To check if a system in equilibrium is stable, a perturbation is applied. If this disrupts equilibrium and the system does not return to the initial state then the system is considered unstable. Underlying mechanisms for maintaining stability relate to the stiffness of the spring. In a stable case the stiffness of the spring is adequate to overcome the potential energy due to the perturbation and hanging mass; deformation of the spring may occur along with oscillation of the system but as long as the system returns to equilibrium state then it can be concluded sufficient stiffness exists to maintain stability. If insufficient stiffness exists in the spring the system will become unstable and fall over once perturbed. Thus a relationship is soon formed between stiffness and stability – the stiffness of the spring determines the stability of the system and the load that can be successfully supported. The preceding example was introduced by Bergmark as a point of relating stiffness to stability (Euler column stability) (Bergmark, 1987). Extrapolating this example to the human body the anatomy of the torso can be compared to a beam-spring system – the spine can be represented by a pin-jointed beam which is supported by the complex core musculature which acts like a series of springs. When external force is applied to the system (via external load or movement) the stability of the system is mitigated by the stiffness of the musculature. Insufficient stiffness via activation of the musculature may cause the system to buckle or not return to its initial equilibrium, which in terms of the spine may lead to unwanted movement and/or injury. If muscular activation is finely tuned and sufficient stiffness is present then no buckling would occur and stability would be preserved. The role of stiffness on potential energy in a linear spring can be described from Equation 1.

$$k = \frac{F}{\delta} \quad (1)$$

The value δ represents displacement of a theoretical spring and k represents stiffness value. Stretching a spring will then result in the storage of potential energy. If the stored potential energy is greater than the energy perturbing the system then stability is maintained. Referring to the ball example, the higher k value resulting in greater potential energy stored would relate to a steeper bowl the ball sits in. This can also be represented in Bergmark' s example where a higher k value of the spring maintaining the system is able to overcome greater perturbations to the system. Muscular stiffness can be divided into two components – passive and active. Both can be defined as a property which resists changes in length of a muscle.

2.3.2 Muscular Stiffness

Taking the relationship between stiffness and stability one step further to a biological example, generation of stiffness through the core musculature would then increase the theoretical value of k and protect the spine from larger energy perturbations. Replacing the spring model with muscle tissue, stability can be maintained if muscular stiffness exceeds the critical stiffness required to maintain a system in equilibrium when a perturbation is applied. Thus, core stiffness is expected to buttress the spine and prevent unwanted movement with external perturbations. When a muscle is active it generates both force and stiffness. Though force is not always stabilizing, muscular stiffness always adds to joint stability (Brown and McGill, 2005). Given that knowledge, the relationship between muscular activation and stiffness is not completely linear – maximum stiffness is not achieved at full activation of the muscle. However, with increasing muscular activation the force generated will continue to increase; this may have stabilizing or destabilizing effects. Taking prior knowledge regarding spine compression it is known that increased compressive loads may take away from the spine's work capacity and ultimately lead to injury and thus high levels of activation may prove harmful. Instead, to achieve optimal stability (maximizing stiffness with minimal force applied) the goal is to not activate the muscle as hard as possible but instead to finely tune the activation. But the question remains, what is the level of activation required to achieve optimal stability? It has been demonstrated that stiffness values asymptote at approximately 25% MVC of core musculature (Brown and McGill, 2005; 2008).

2.3.3 Application to Stiffness to Athletics

From the earlier two subsections it is now understood that the role of stiffness helps prevent unwanted movement when external load is applied to the body in order to prevent instability and buckling. Applying the concepts of core stiffness and stability to athletic performance, it is expected that an athlete must generate sufficient stiffness in order to prevent instability when handling an external load, whether it be from a loaded barbell during weight training or from an opposing athlete during sport. In sport performance external load can be applied to the athlete from any direction in any orthogonal plane, or in a combination of directions, as well as at varying rates of loading. As a result the athlete must be ready to quickly generate stiffness throughout all core muscle tissues. In an example in weight training an athlete performing a unilateral suitcase carry exercise (forward locomotion with a heavy load picked up and carried unilaterally in one hand) imposes an uneven frontal plane bending moment which may cause the athlete to laterally bend toward the loaded side if they cannot create enough stiffness through the lateral core and hip musculature. Without sufficient core stiffness the athlete will fail at an attempt to support this uneven loading scenario. If sufficient stiffness is developed through the lateral core and hip musculature then this will prevent buckling and unwanted lateral bending, allowing the athlete to successfully complete the exercise in a more efficient manner. Essentially the use of stiffness in the human body buttresses joints to prevent unwanted movement, thus helping eliminate energy loss through forced eccentric movement.

Stiffness can be further enhanced through the concept of ‘superstiffness’ - the synergistic effect of muscular co-contraction can further enhance stiffness properties of the core musculature much more than the summation of the individual musculature. This has been demonstrated in stimulation studies using rat abdominal musculature (Brown and McGill, 2009) where the stimulation of groups of muscles together created an enhanced stiffness effect than the summation of individual muscles. This concept can be applied to practical situations where taking advantage of the superstiffness properties can allow individuals to further enhance core stiffness and ultimately athletic performance. However, to properly utilize superstiffness proper training protocols must be in place to groove the appropriate motor patterns. A list of essential components of training was compiled to outline the qualities associated with training for superstiffness (McGill, 2009):

1) Use rapid contraction, then relaxation of muscle. Speed results from relaxation for speed but also stiffness in some body regions (e.g., core) to buttress the limb joints to initiate motion or

enhance impact (of a golf club, hockey stick, fist, and the like).

2) Tune the muscles. Storage and recovery of elastic energy in the muscles require optimal stiffness, which is tuned by the activation level. In the core, this is about 25% of maximum voluntary contraction for many activities.

3) Enhance muscular binding and weaving. When several muscles contract together, they form a composite structure where the total stiffness is higher than the sum of the individual contributing muscles. This is particularly important in the abdominal wall formed by the internal and external obliques and transverse abdominis, highlighting the need to contract them together in a bracing pattern.

4) Direct neuronal overflow. Strength is enhanced at one joint by contractions at other joints — martial artists call this ‘‘eliminating the soft spots.’’ Professional strongmen use this to buttress weaker joints using core strength. Neuroscience data suggests that this technique inhibits signals which in turn inhibit the ability to create strength – essentially it is ‘inhibiting the inhibitors.’

5) Eliminate energy leaks. Leaks are caused when weaker joints are forced into eccentric contraction by stronger joints. For example, when jumping or changing running direction, the spine bending when the hip musculature rapidly contracts forms a loss of propulsion. The analogy ‘‘you can push a stone but you cannot push a rope’’ exemplifies this principle.

6) Get through the sticking points. The technique of ‘‘spreading the bar’’ during the sticking point in the bench press is an example of stiffening weaker joints.

7) Optimize the passive tissue connective system. Stop inappropriate passive stretching. Turn your athletes into Kangaroos. For example, reconsider if a runner should be stretched outside of their running range of motion. Many of the great runners use elasticity to spare their muscles or to potentiate them to pulse with each stride. However, do consider stretching to correct left/ right asymmetries shown to be predictive of future injury.

8) Create shock waves. Make the impossible lifts possible by initiating a shock wave with the hips that is transmitted through a stiff core to enhance lifts, throws, strikes, and the like.

9) Use proximal stiffness to enhance distal power, speed and strength.

The ability to create muscular stiffness has been hypothesized to reduce energy losses during dynamic movements. During ballistic movements there is a thought that to facilitate more efficient movement through the distal limbs a ‘punctum fixum’ (fixed point) must be created for the limbs to move about. This was thought be to created about proximal body segments which are required to stay stable. An example of firing a cannon out of a canoe on a body of water versus on a concrete sur face illustrates the previous point – to effectively fire a cannon (generate speed and power, comparatively the distal movement) there must be a stable surface in which to support the cannon on (proximal body segments). If the surface is labile and free to move (insufficient stability of the proximal body segments) then the cannon is inaccurate, optimal power is not achieved and canoe may tip due to instability. However, if the cannon is fired from a concrete surface then accuracy and energy transfer are improved. Thus the effect of sufficient stiffness and stability to facilitate movement elsewhere is illustrated – this gives the example of proximal stiffness enhancing distal mobility.

Tying together the rationale put forth with regards to injury mechanism and stiffness, the example of the unilateral suitcase carry will be brought forth again. As stated, sufficient stiffness of the lateral core and hip musculature must exist to prevent instability during the exercise. To achieve sufficient stiffness the athlete must not just create high levels of activation through these muscle groups – the compressive load associated with high levels of muscular activation compounded by the potentially heavy external load from the exercise may impose extremely high co mpressive load to the spine. Consequently, if sufficient stiffness does not exist then lateral bending of the spine will occur due to instability of the torso. If the athlete attempts to 'fight' this posture by pulling themselves upright only to fall back into lateral bend a repetitive kinematic lateral bending is created through the spine. Combined with the increased spine compression from the external load a scenario is now created where compression combined with repetitive bending of the spine occurs – a recipe for a herniation type injury. Thus generating sufficient muscular stiffness is not only important for athletic performance but also maintaining health.

2.3.4 Possible Trainability of Stiffness

While inherent muscular stiffness has been previously measured, the potential for training to change muscular stiffness are somewhat unknown. Changes in the stiffness properties of quadriceps tendons have been measured after isometric and plyometric training protocols (Kubo et. al., 2001; Burgess, et. al. 2007). A six week training protocol of isometric and plyometric exercises yielded increases in measured tendon stiffness, though isometric training yielded greater increases (61.6% vs. 29.4%). Burgess did not give any thoughts as to the mechanism of stiffness increase but as noted by Kubo, there may have been an effect due to alterations of the alignment of collagen fibres adapting to the imposed load from isometric training (Kubo et. al., 2001). This thought was supported in animal studies where realignment of collagen fibres in tendons was found in rodents after physical training (Michna, 1984). Increases in rate of force development (RFD) were also found for both types of training, and more importantly a crossover effect was observed where isometric training improved concentric jump height and RFD, both of which could be considered plyometric properties (Burgess, 2007). It was theorized that greater RFD achieved through these experiments was caused by greater tendon stiffness and not improved neural efficiency (Burgess, 2007). Increasing RFD can be linked to increased tendon stiffness as force transmission would become more rapid and less slack through the tendon would facilitate this force transfer (Wilson et. al., 1994). Extrapolating these findings to the architecture of the torso is unknown but a comparison between isometric and dynamic core training protocols may provide insight.

Further investigation of isometric exercises in the lower limbs has shown an increase in tendon and muscle stiffness properties (Burgess et. al., 2007) with isometric training. Findings from Kubo and Burgess support the notion that inherent stiffness can be altered through training. However, whether or not these results can be extrapolated to other body segments, such as the torso, is yet unknown. Though isometric core exercises have been prescribed enhance stability of the spine it is unknown if the mechanism of action in these exercises actually change the physical characteristics of stiffness within the torso. Thus this forms the basis of the research question in mind and helps drive the intended experiment.

2.5 Analysis of Torso Training

From Section 2.1 arguments for the efficacy of both dynamic and isometric core exercises have been made. It is known that both dynamic and isometric core exercises activate the torso musculature, but can training in one method influence performance in the other? Law enforcement and military personnel have historically used a timed sit up test as a method of examining core endurance and fitness (US Army, 1992). In this test the participants must perform as many sit ups as possible within an allotted time limit. A novel study was performed in which participants in a timed sit up test were trained prior to the test using either dynamic or isometric core exercises (Childs et. al., 2009). Though the isometric core exercises involved a completely different movement pattern compared to the sit up, performance on the sit up test improved to a greater extent compared to the group performing sit ups as part of their training regimen. This may demonstrate a carryover effect in training, where improved muscular endurance of general core musculature allowed for a greater number of contractions to be performed during the sit up test, essentially improving the endurance of the core musculature. Rationale for muscular endurance enhancing performance in tasks requiring core activation states that an increase in muscular endurance would allow the musculature to maintain prolonged contractions and continue to provide support for the torso by either protecting against injury mechanism or maintain sport performance (Nesser, 2008). A statement from Nesser falls in line with the thought of the synergistic contribution of the core musculature to athleticism – "Because the core muscles work synergistically during movement, it is difficult to single out one specific aspect of core strength and deem it responsible for any given sporting success or failure. The core works together as a unit and, thus, should be analyzed as a unit."

From the comparison of spine loads of dynamic and isometric core exercises it is also understood that isometric exercise impose much lower spine loads. A major incentive to decreasing spine loads through training is the concept of training capacity and injury. If overall capacity of the body to handle external load is compared to a drinking glass, as load is imposed the glass is filled with liquid – the greater the load the greater volume of liquid added. For athletes where sport training demand imposes a very high load (such as football players receiving numerous tackles, weightlifters who must train extremely high external loads) not much room is available in their training capacity before imposed loads exceeds capacity and injury may occur (McGill, 2009). Thus, if an athlete is already at a high load demand but still requires core training, in order to not exceed training capacity exercises must be carefully selected where overall imposed load is low. Taking the knowledge gained regarding injury mechanism, spine load and stiffness/stability relationships exercises where spine motion is kept to a minimum, stability increased and activation low will impose the lowest spine demand from a training capacity standpoint. In cases where additional training capacity is available exercises of increased load may be used to enhance athleticism or to adapt the athlete to performing at higher intensities, but thought must still be given to injury mechanism and training load versus capacity.

2.6 Summary

The importance of torso musculature function has been established for a wide variety of tasks; everything from general health, pain avoidance, injury rehabilitation and athletic performance can be enhanced via training of the torso. However, the method of torso training has come under scrutiny and debate. Dynamic exercises, which create challenge to the core musculature by introducing movement through the trunk, have been shown to generate high levels of activation to the targeted musculature but at the cost of increased spine loads and potentially harmful spine postures. Isometric exercises, which challenge core musculature by bracing and isometric contraction during static postures, have also been shown to generate adequate levels of activation of targeted musculature while imposing much lower spine loads and conserving the spine in safe neutral postures.

Previous research on the lower limbs has shown an adaptation of tissues to increase stiffness properties with both dynamic and isometric training. Whether or not the same adaptation can be observed in the musculature of the torso is unknown and hence drives the primary research question of this experiment. A comparison of isometric and dynamic exercises on active and passive torso stiffness properties would give insight to the efficacy of these exercises. The importance of torso stiffness has been explored, in which the concept of sufficient stiffness creating spine stability has implications in preventing spine injuries, as well as rehabilitation and athletic performance.

Chapter 3
Methods

The short and long term effects of core training on torso stiffness were investigated using twenty four (N = 24) healthy University aged males. Data collections were conducted in the Spine Biomechanics Laboratory (BMH 1408) at the University of Waterloo. The test/retest design of this experiment required collections to be split into two data collections spaced six weeks apart with a core training intervention taking place during this period.

3.1 Participants

Twenty four (24) young healthy University aged males (stats) were selected for this study. Of the total sample population, twelve (12) subjects were selected from the student population with limited experience in physical training. Inclusion criteria for this subgroup consisted of individuals with little to no experience in performing core exercises. Reasoning for this inclusion criterion was that this would allow researchers to examine the effects of training on completely naïve subjects and it would be expected that any changes in the dependent variables measured would be completely due to the core training program assigned. Exclusion criteria for this subgroup consisted of any individuals who have experienced low back pain or injury currently or within the past year, individuals who have consistently performed direct core training for the past six months and individuals with allergies to rubbing alcohol, skin adhesives and/or conductive gel.

Another subgroup of twelve (12) subjects was selected from a population of athletes with experience in core training. Inclusion criteria for this subgroup consisted of individuals highly experienced in core training methods, having regularly performed direct core exercises for at least one year. For convenience, researchers selected this population from a group of competitive martial artists. This special population was selected due to their rigorous focus on core training and direct core exercise. Researchers were interested in this population to examine the effects of core training on a group of subjects already savvy to core training methods, and to compare the effects of training on naïve versus savvy populations. Exclusion criteria for this subgroup consisted of any individuals who have experienced low back pain or injury currently or within the past year, individuals whose current athletic training deviates in intensity or volume from their regular training and individuals with allergies to rubbing alcohol, skin adhesives and/or conductive gel.

The reasoning for selecting two subgroups based on training experience was to investigate the effect of training adaptations on individuals who are well trained and individuals with little to no training. It is accepted by the athletic training industry that individuals who are accustomed to physical training require higher demands to illicit muscular adaptations – researchers wished to test this thought through the recruitment of subjects with varying levels of core training experience.

All subject recruitment and data collection procedures were performed in accordance with University of Waterloo's Office of Research Ethics guidelines.

3.2 Experimental Design

A test/retest study design was selected to examine the effect of short and long term core training on torso stiffness, and the effects on highly trained versus untrained subjects. This study required a repeated measures design; pre and post training considerations of multiple independent and dependent variables will change based on the stage of the study. Three cascading issues with specific hypotheses were investigated with the experiment. Each hypothesis was examined in with a series of approaches designed to occur in three different phases. For illustrative purposes a flowchart has been provided of these phases.

Approach 1 (Initial baseline and short term training): Quantified initial passive and active torso stiffness, and assessed the effect of a short term bout of core training on stiffness. Passive stiffness was assessed via a 'frictionless' bending apparatus in three planes of motion (sagittal, frontal and transverse) (Brown and McGill; 2005, 2008) while active stiffness was measured via a 'quick release' mechanism (Vera-Garcia et. al., 2007). The use of these devices have been documented in past research examining passive stiffness (Parkinson et. al., 2004; Brown and McGill, 2005; 2008) and contributions of muscular activation to stiffness (Vera-Garcia et. al., 2007). Further detail in the construction, use and mechanism of action of each apparatus is given in Section 3.6.1. These active and passive stiffness tests served as initial measurements of stiffness measurements prior to the implementation of the training protocol in Approach 2. After taking the subjects through the active and passive stiffness trials, a fifteen minute training session of isometric core exercises was performed under the supervision of the researcher and passive and active stiffness were measured again with the same instrumentation. Changes in stiffness and range of motion were to be measured for this pre/post test condition.

Approach 2 (Training protocol): Following Approach 1, subjects were split into three exercise groups: Isometric Training, Dynamic Training and Control. During this period each group underwent a six week intervention; Isometric and Dynamic groups participated in a core training program under the supervision of the researcher, and the Control group did not receive any additional training. The purpose of this approach block was to induce possible adaptations of core stiffness and activation due to training. Lifestyle factors regarding physical activity of the subjects were accounted for; regulation of the subjects' physical activities and training outside of the prescribed training regimen was closely monitored and recorded. During the initial data collection subjects were asked for a typical weekly schedule of their personal physical training. Subjects were asked to refrain from any direct core training performed from their typical schedule not associated with the training program from this study. The control group received no direct core training during this period and was asked to refrain from any additional core training. If any subjects were already performing other physical training (weight lifting, sport training) they would be allowed to continue pending approval from the researcher. Confirmation of adherence to the training program occurred on a weekly basis in which the researcher contacted subjects for an update with regards to their progress in training and any questions or concerns. During training subjects were asked to self report comments regarding difficulty of training and qualitative feelings with regards to core function. Detailed accounts of the training protocols will be explained in later sections.

Approach 3 (Retest): Following Approach 2 all subjects were retested for active and passive stiffness with the protocol explained in Approach 1. The purpose of this approach was to observe measurable differences in core stiffness after a longer duration of training or rest.

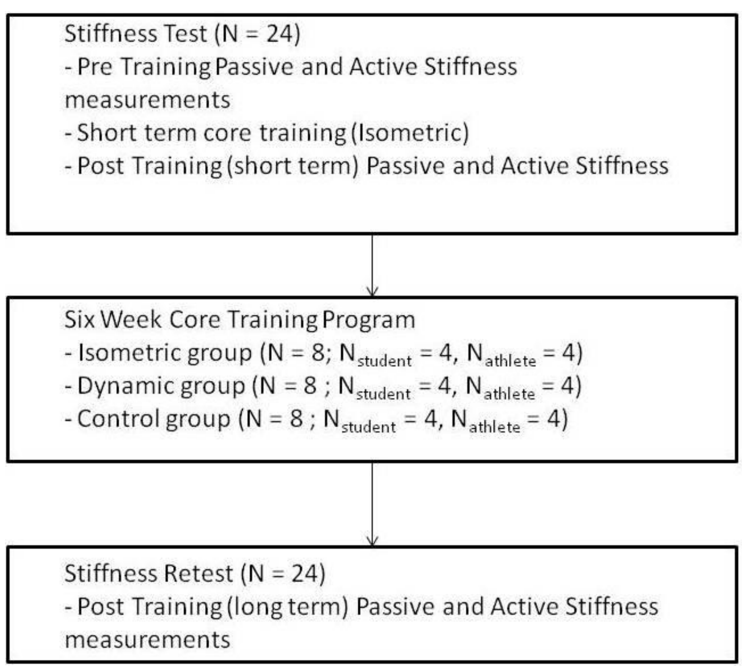

Figure 1: Overall experimental design of short and long term core training effects on core stiffness.

3.3 Initial Collection

The initial data collection established baseline values of core stiffness and served to measure changes in core stiffness after a short bout of core training. After arriving to the Spine Biomechanics Laboratory, subjects signed an Information Consent form and all applicable waivers, subjects were prepped for unilateral core EMG electrode placements and 3Space lumbar tracking monitor. Seven active and passive bending trials were performed with each trial repeated three times – these trials corresponded to passive bending about each anatomical plane in two directions, followed by an active bending trial. Researchers defined passive bending trials as trials where subjects were underwent trials without any voluntary muscular effort. Active bending trials were defined as bending trials where measured torso stiffness was a result of muscular activation from the subjects. The following flowchart outlines the steps taken during the initial data collection (Fig. 2).

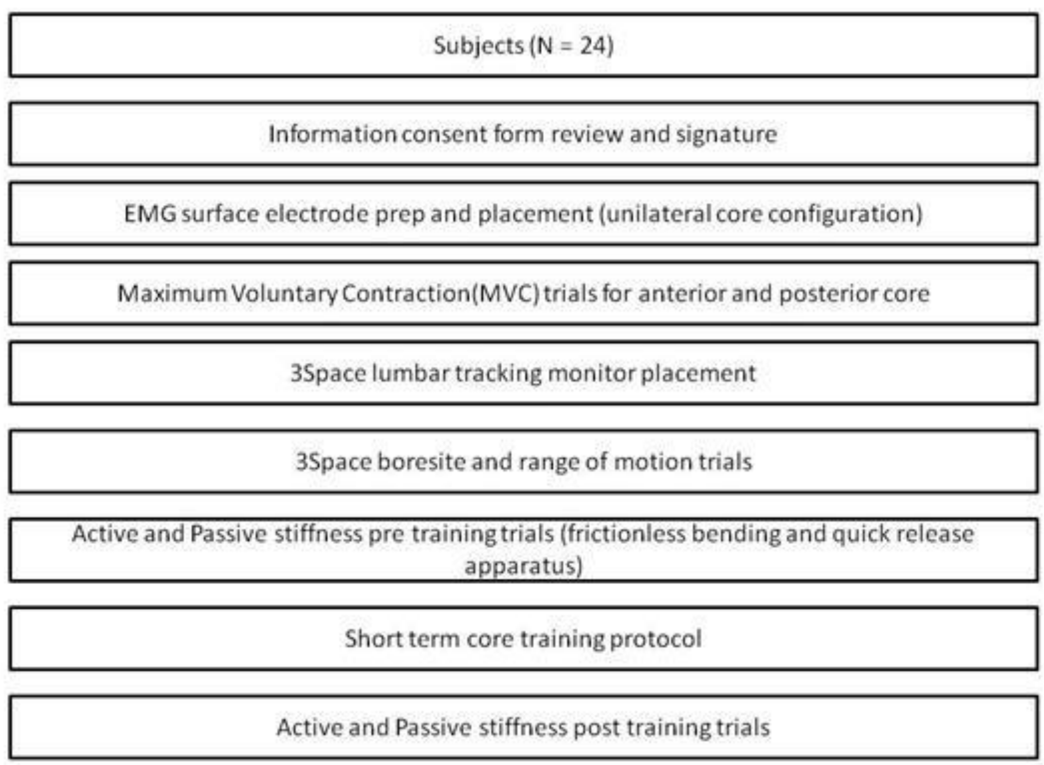

Figure 2: Flowchart of experimental procedures for pre training and short term training data collection.

3.3.1 Bending Trials

Seven active and passive bending trials were performed, with trials corresponding to a specific bending direction. The trials with descriptions are summarized below.

Table 1: List of passive and active bending trials with descriptions of how each trial was performed. Pictures of each trial are found in Appendix A.

Trial	Description
Flexion (passive)	Subject lays on their right side in the frictionless bending apparatus and is pulled from neutral to maximum forward spinal flexion position.
Extension (passive)	Subject lays on their right side in the frictionless bending apparatus and is pulled from neutral to maximum backward spine extension position.
Right bend (passive)	Subject lays on their back in the frictionless bending apparatus and is pulled from neutral to maximum right lateral bend position.
Left bend (passive)	Subject lays on their back in the frictionless bending apparatus and is pulled from neutral to maximum left lateral bend position.
Right twist (passive)	Subject stands on the frictionless twisting apparatus and is twisted counter clockwise (from top-down) to maximum twisted position.
Left twist (passive)	Subject stands on the frictionless twisting apparatus and is twisted clockwise (from top down) to maximum twisted position.
Extension (active)	Subject sits in the quick release mechanism preloaded with a 16 kg load which is randomly released via an electromagnet.

Each trial was repeated three times and trial order randomized for each subject. Prior to the start of each passive bending trial one or two practice trials were performed in order to establish the subject's maximum bending range of motion. This was verified by asking the subject to verbally cue when they had reached maximum range of motion while the researcher pulled them along the bending apparatus, in according with the University of Waterloo Standard Operating Procedure (UW SOP) 215. The subject was then asked if the limitation in range of motion was caused by external factors (belts and clips interfering with bending) or internal factors (soft tissues reaching end range of motion). If the subject responded with 'external' they would be adjusted in the bending apparatus and practice trial repeated. If the subject responded with 'internal' the researcher would physically mark the location of the maximum range of motion on the apparatus and recorded trials would begin. Prior to the start of each trial the subjects were verbally reminded to 'keep relaxed' in order to remind subjects to eliminate voluntary activity of core musculature during passive trials. Unilateral EMG of selected trunk musculature was recorded during each trial. The seven bending trials were repeated once during the initial data collection; before and after performing a short term bout of core exercises.

3.3.2 Short Term Core Stiffness

A fifteen minute core training protocol was performed, representative of a typical singular isometric core workout, after the initial baseline stiffness measurements were taken. Three exercises were performed; plank, side bridge and bird dog; each performed for 5 sets of 10 second holds. These exercises were selected due to their use in performance and spinal rehabilitation exercise regimens, and proof of challenging core activation while minimizing spine loads and injury risk. Coaching was provided by the researcher so that exercise technique and training cues were standardized among all subjects. Qualitative feedback as to the difficulty level and feeling of core activation was self reported by subjects during and after the training protocol.

Figure 3: Plank exercise used during short term core training.

Figure 4: Left side bridge exercise used during short term core training. Right side bridge is identical to this posture except mirrored on the subject's right side.

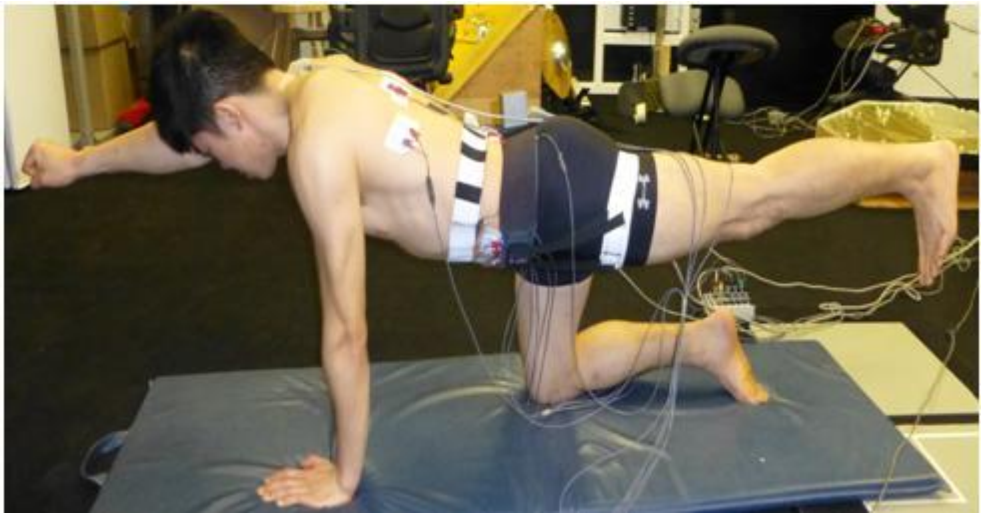

Figure 5: Bird dog exercise used during short term core training using right arm and left leg. The exercise was performed in this posture and with the subject's left arm and right leg.

3.4 Long Term Training Program

Following the initial data collection subjects were randomly placed into three training groups: Isometric, Dynamic and Control. Eight subjects were placed into each group, with four selected from the student population and four selected from the athlete population. During the six week training period subjects either performed their respective training programs or waited and refrained from performing any core training. During this period specific restrictions were made with regards to physical activity and training performed by the subjects extraneous to the study. Subjects were asked to refrain from any direct core exercise not specifically given in the training program, and to not embark on any new exercise regimen involving direct core exercise or static load bearing of the torso. If the subjects were already taking part in an existing exercise regimen they were allowed to continue but asked not to deviate from their normal training intensity or volume during this six week period. If the subjects were regularly performing direct core exercises they were asked to stop for this period as well. Subjects participating in training were asked to self report progress of training on a minimum of a weekly basis. Comments such as ease or difficulty of training, progression of training load and volume, qualitative observations of core function and general thoughts were made and recorded, and given back to researchers after the six week period.

The Isometric and Dynamic training programs were both periodized with three (3) two week (2 week) training blocks; each block progressed the intensity of the exercises via external load, increased moment arms and/or increased speed of movement while reducing weekly training volume as to not exceed training capacity. To ensure training equality between the two training programs an issue of workload equivalence was taken into consideration in order to create training load equality between both programs so that individuals in both training groups performed perform an equal amount of work. Factors such as number of sets performed, repetitions per set, training frequency, external load and moments, and muscular demand were accounted for when devising the training volume and intensity for each program. In each training block three or four exercises were used to challenge each anatomical direction – sagittal plane anterior, sagittal plane posterior, frontal plane lateral left bend, frontal plane lateral right bend, transverse plane left twist and transverse plane right twist.

3.4.1 Isometric Training Program

The Isometric training group performed exercises which challenged the core musculature via maintaining static muscular bracing and isometric postures. The six week training period was split into three (3) two week blocks (Appendix B). Each block progressed the level of challenge of the exercise; Block 1 (Weeks 1-2) consisted of exercises using bodyweight as the resistance level. Block 2 (Weeks 3-4) progressed the difficulty level by using external load and increased moment arms in various postures to challenge the core musculature. Block 3 (Weeks 5-6) increased difficulty further by creating challenge via distal limb motion while maintaining a statically braced torso, with or without external load. A brief description of each exercise and coaching cues (Table 2) is as follows, with pictures found in Appendix C. Phase 1 set/rep schemes followed a descending pyramid – multiple sets were performed with the number of repetitions per set decreasing by one as each set progressed. For example, if the plank was performed for 5 sets, the first set consisted of 5 holds each for 10 seconds long, the second set consisted for 4 holds each for 10 seconds long, and so forth. Subjects began performing 2 sets and slowly progressed to performing five. As Phase 2 and 3 required the use of external load and greater demand, training volume was decreased to match the output intensity.

Table 2: Summary of Isometric Exercises performed during the six week training period. Pictures of exercises are found in Appendix C.

Exercise	Training Week	Description	Extra coaching cues	Sets	Duration/ Repetitions
Plank	1-2	Performed on ground, subject lays prone, supporting themselves	- Create cocontraction by squeezing glutes,	Up to 5	10 seconds/1-5

		on toes and elbows, maintaining neutral spine posture resisting spinal hyperextension due to gravity and hip flexion.	contracting core harder, squeezing fists and pulling elbows toward bellybutton. - Increase external torque challenge by supporting self on hands and extending arms above head level ('High Plank').		
Side bridge	1-2	Performed on ground, subject lays on one side supporting self on feet and elbows, top foot in front, bottom foot behind, resisting lateral bending due to gravity and hip flexion. Posture held for required duration and then other side is performed. Repeated for left and right sides.	- Subject cued to 'push hips up and forward with a big chest' to maintain hip extension and resist hip sagging due to gravity. - Create cocontraction by squeezing glutes, contracting core harder, squeezing fists and pulling elbow toward waist.	Up to 5	10 seconds/1-5
Bird dog	1-2	Subject begins quadruped (hands and knees, hips flexed at 90 deg) and drives out contralateral arm and	- Create core brace prior to limb motion and squeeze fists/pull toes downward (lead	Up to 5	10 seconds/1-5 per side

		leg, resisting any axial rotation or spinal flexion/hyperextension. Posture held for required duration and then other side is performed. Repeated for right arm/left leg and left arm/right leg.	with heel of foot). - Cued to 'shoot limbs outward horizontally'; do not think of it as lifting the limbs upward but rather as shooting them outward.		
Torsional buttress	2	Subject begins quadruped (hands and knees, hips fully extended) and removes one hand from support resisting axial rotation of the torso. Repeated for left and right sides.	- Core brace, squeeze glutes, cross feet and create abduction torque, and grip into ground with hand while externally rotating hand. - If the subject cannot perform 10 second holds, they begin with a time that is comfortable and slowly increase hold time with each training session.	Up to 5	Up to 10 seconds/1-5 per side
Anterior Pallof Press	3-4	Using cable station, subject begins in tall kneeling stance and faces away from cable stack pressing cable	- Select weight that can be used comfortably for 5 sets of 10 seconds. - Maintain core	Up to 5	10 seconds per rep/3 reps per set

		overhead and resisting spinal hyperextension.	brace, glute contraction and cross foot abduction torque; crush cable handles in hands.		
Posterior Pallof Press	3-4	Using cable station, subject begins in tall kneeling stance and faces toward the cable stack pressing cable overhead and resisting spinal flexion.	- Select weight that can be used comfortably for 5 sets of 10 seconds. - Maintain core brace, glute contraction and cross foot abduction torque; crush cable handles in hands.	Up to 5	10 seconds per rep/3 reps per set
Anti-rotation Pallof Press	3-4	Using cable station, subject begins in tall kneeling stance and faces 90 deg to one side pressing cable in front of chest level and resisting axial twisting. Repeated for left and right sides.	- Select weight that can be used comfortably for 5 sets of 10 seconds. - Maintain core brace, glute contraction and cross foot abduction torque; crush cable handles in hands.	Up to 5	10 seconds per rep/3 reps per set
Suitcase Hold	3-4	Using cable station, subject begins in tall kneeling stance and faces 90 deg to one	- Select weight that can be used comfortably for 5 sets of 10 seconds.	Up to 5	10 seconds per rep/3 reps per set

		side, holding cable at side and resisting lateral bending. Repeated for left and right sides.	- Maintain core brace, glute contraction and cross foot abduction torque; crush cable handles in hands.		
‘Stir the pot’	5-6	Subject begins in plank position with elbows supported on an inflated swiss ball. Subject draws circles with their arms resisting any spinal hyperextension or axial twisting. Repeated for clockwise and counter-clockwise rotations.	- Maintain core brace, glute contraction, fist squeeze during 'stir.' - Subject begins drawing small circles and starting in quadruped position (similar to torsional buttress). As proficiency improves subject can progress to drawing larger circles, then moving onto toe support. - If the subject cannot perform 10 revolutions without technique breaking, train to just before the point of technical failure and slowly	5	10 seconds per direction

			add repetitions with each training session.		
Half kneeling woodchop	5-6	Using cable station, subject begins in half kneeling stance facing 90 deg to one side (leg closest to cable rack bent at 90 deg supported on foot). Grasping a long bar connected to the cable, subject pulls bar 45 deg downward across body resisting axial twisting.	- Maintain core brace and tight grip on bar. - If 10 repetitions cannot be performed without technique breaking, train to just before the point of technical failure and slowly add repetitions with each training session.	Up to 5 per side	Up to 10
TRX Inverted Row	5-6	Using a TRX system, subject lays supine and pulls themselves upward, resisting spine/hip flexion during each repetition.	- Squeeze grip on TRX handles and maintain core brace and glute contraction. - If subject cannot perform maximum number of repetitions, perform as many repetitions as possible and maintain static contraction for rest of duration of exercise.	Up to 5	Up to 10

Suitcase Walk	5-6	Subject begins holding a kettlebell in one hand and walks for a set distance. Subject is reminded to resist against torso lateral bending.	- Squeeze kettlebell in one hand and make a tight fist with the free hand. Maintain core brace during exercise. - Increase challenge by adding a high and long step, prolonging time under load in single leg support.	Up to 3 per side	30 m length

3.4.2 Dynamic Training Program

The Dynamic training group performed exercises which challenged the core musculature based on torso movement. The six week training period was split into three (3) two week blocks (Appendix D). Each block progressed the level of challenge of the exercise via external load and increased speed of movement; Block 1 (Weeks 1-2) consisted of exercises using bodyweight as the only means of resistance. Block 2 (Weeks 3-4) progressed the difficulty level by using external load and increased moment arms in various postures to challenge the core musculature. Block 3 (Weeks 5-6) increased difficulty further by creating challenge via increasing movement velocity with external load. A brief description of each exercise and coaching cues (Table 3) is as follows, with pictures found in Appendix E. Set/rep schemes followed a more traditional style of keeping repetitions consistent in each set. A maximum of 10 repetitions were used for Phase 1 exercises; subjects performed as many repetitions as possible while maintaining proper coaching and technique cues. If this fell below ten then subjects would maintain training volume before progressing as repetitions became easier to perform.

Table 3: Summary of Dynamic Exercises performed during six week training period. Pictures of exercises are found in Appendix E.

Exercise	Training Week	Description	Extra coaching cues	Sets	Repetitions
Curl up	1-2	Subject lays supine with both hands under lower back, one leg bent (foot flat on ground), other leg extended. Subject is cued to treat torso and head as a single rigid mass and to pick their head up off the ground like unweighting a scale their head is resting on.	- Imagine the torso and head as one rigid block, like the spine is a steel rod. Imagine the head is resting on a bathroom scale and the subject is just unweighting the scale during the exercise. Be careful to not use too much range of motion.	5	Up to 10
'Superman'	1-2	Subject lays prone with arms extended overhead. Subject lifts arms and legs 1-2" off the ground.	- Arms and legs are lifted only slightly off the ground; avoid spinal hyperextension by lifting limbs too high. - Squeeze fists and glutes during extension phase of exercise.	5	Up to 10
Modified curl up (lateral)	1-2	Subject lays similar to curl up posture but with one leg bent knee facing up, other leg bent knee facing to one side, resting side of hip on ground.	- Push hip into ground during curl up. - Use free hand to landmark lateral core musculature to feel contraction	5	Up to 10 per side

		Subject performs curl up maneuver. Performed for left and right sides.			
Modified curl up (twisting)	3-4	Subject lays similar to curl up posture but with a towel under the lower back and hands at sides or behind head. Subject performs shortened curl up maneuver followed by a twist toward upright. Performed for left and right sides.	- Push PSIS into ground during twisting portion of exercise. - Limit ROM of twist to reduce axial twisting injury mechanism of spine. - Use free hand to landmark lateral core musculature to feel contraction	5	Up to 10 per side
Curl up w/ extended arm and leg	3-4	Similar to curl up but with one arm extended overhead (contralateral limb to extended leg). Extended arm moves with torso and extended leg lifts 1-2" off the ground as curl up is performed.	- Same cues as curl up - If challenge diminishes add small external load (2.5 lb) in extended arm and leg.	5	Up to 10 per side
Back extension	3-4	Performed in a back extension apparatus, subject fixes feet in foot pad with edge of apparatus at the ASIS. Subject flexes through	- Keep an eye for lumbar rounding during exercise; use mirror at side to check technique. - Squeeze glutes during extension (concentric)	5	Up to 10 per side

		the hips and extends back up (similar to Biering-Sorensen).	portion of exercise.		
Russian Barbell Twist	3-4	Subject grasps one end of an olympic barbell with the other end set in the corner of the room. With arms extended supporting the barbell the subject twists through the hips allowing one foot to pivot. Performed for left and right sides.	- Keep core braced while bearing load. - Hips drive the exercise, not the arms. Initiate all movement from the hips and the arms are in place just to hold the barbell. - Pivot off foot during twisting portion. Ensure hips and shoulders are in line at all times. Cue pivot like 'putting out a cigarette.' - Start with an unloaded Olympic barbell. If 10 repetitions cannot be performed then train to the point before technical failure and slowly add repetitions each training session. If 10 repetitions per side over 5 sets can be easily performed slowly add external load to the barbell.	5	Up to 10 per side
Curl up 'twitch'	5-6	Similar to Curl up w/ extended arm and leg. Same movement patterns but now	- Same cues as curl up. - Keep relaxed during rest portions of exercise. Pulse activation like a	5	Up to 10

		performed with a quick rate of activation and relaxation - twitching the curl up and leg.	twitch and immediately relax as quickly as possible once at maximum range of motion. - If pulsing challenge diminishes add small external load (2.5 lb) in extended arm and leg.		
Superman 'twitch'	5-6	Similar to Superman exercise but arm and leg lifts are twitched to achieve quick rates of activation and relaxation.	- Same cues as Superman. - Keep relaxed during rest portions of exercise. Pulse activation like a twitch and immediately relax as quickly as possible once at maximum range of motion. - If pulsing challenge diminishes add small external load (2.5 lb) in arms and legs.	5	Up to 10
Lateral medicine ball throw	5-6	Performed holding a medicine ball, subject stands beside wall, facing 90 deg to the wall. Holding the ball close to the body and in a partial lunge (leg closest to the wall in front, knees slightly	- Pulse activation during release of ball. - Minimal involvement from arms; all movement should originate from torso. - Aim to achieve maximum ball release	5	Up to 10 per side

		bent), subject twitches a left lateral bend and throws the ball toward the wall. Performed for left and right sides.	velocity.		
Rotational medicine ball throw	5-6	Performed holding a medicine ball, subject stands approximately 5 feet away from the wall facing 90 deg to the wall in a square stance (both feet in line, facing side wall). Subject holds medicine ball close to body and twists through the hips, pivoting off the back foot, and throws ball to front wall. Performed for left and right sides.	- Back foot should be facing forward at end of exercise. - Ensure shoulders stay over the hips at all times. - Pulse core activation upon point of release of the medicine ball. - Minimal involvement from arms; all movement should originate from torso. - Aim to achieve maximum ball release velocity.	5	Up to 10 per side

3.5 Post Training Collection

Following the six week training/waiting period subjects were called back to the Spine Biomechanics Laboratory to re-collect active and passive bending trials. The procedures for this data collection are identical to those described in the initial collection (Section 3.3) without the short term core training session and re-test of bending trials (Fig. 6). The purpose of this data collection was to measure torso stiffness after a longer period of core training for comparison to pre training values and observe changes due to training.

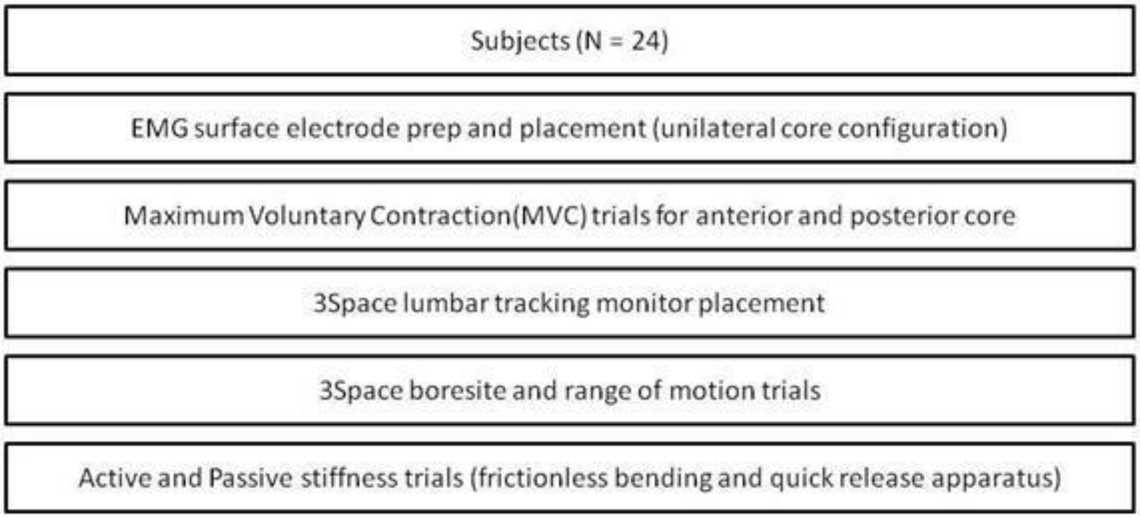

Figure 6: Post training collection experimental procedures.

3.6 Instrumentation

Approaches 1 and 3 involved in vivo data collection in the Spine Biomechanics Laboratory whereas Approach 2 consisted of a core training program performed in a gym setting. As Approach 2 did not require any data collections no special instrumentation was used aside from the required exercise equipment. Approaches 1 and 3 required the use of 6 channel unilateral core EMG, an electromagnetic kinematic motion tracking system (3Space lumbar tracking monitor), uniaxial force transducer and various apparatus used for passive and active bending trials. All instrumentation was turned on and warmed up for at least 60 minutes prior to collection to eliminate sources of error due to drift and thermal expansion.

3.6.1 Electromyography

EMG signals were collected on unilateral core musculature (rectus abdominis, external oblique, internal oblique, latissimus dorsi, upper erector spinae, lower erector spinae) during all stiffness trials. The purpose of EMG collection during bending trials was to verify the activation state of the subject during the trials to ensure passive trials were truly passive without voluntary muscular activity from the subjects; though processing of EMG data was performed this data was not used for any type of statistical or biological analysis but instead purely as a method of determining if passive trials were truly passive.

To measure the EMG signal of these selected muscles with the least electrode-skin interface impedance (Winter, 2009), the skin over the muscles where surface electrodes were placed were shaved with a new disposable razor, rubbed with an abrasive skin gel (Nuprep®, Weaver and Company, Cambridge, ON, CAN), and cleaned using rubbing alcohol. Pre-gelled, disposable, monopolar Ag-Cl disc shaped surface electrodes (30mm diameter, Medi- traceTM 100 Series Foam Electrodes, Covidien, MA, USA) were then placed on the skin over each muscle of interest. Two electrodes (30mm interelectrode distance) were placed at each muscle site, so that the difference in potential between the electrodes can be recorded (bipolar configuration) (Winter, 2009). Non-woven, adhesive fabric (HypafixTM, Smith & Nephew, Mississauga, Canada) and adhesive tape (3M, St. Paul, USA) were used for the fixation of the electrodes and EMG wires to the skin, respectively. This fixation ensured that the electrodes are properly secured to the skin, movement is not hindered, and cables were not pulling the electrodes. Electrode placements and orientations on the skin over the selected muscles of the torso were consistent with recommendations from the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) project and well-established surface EMG electrode placements for the abdominal wall (McGill et al., 1996) – these electrode arrangements have been shown to best represent the differential muscle activity patterns and minimize signal cross-talk between electrode pairs during bending and twisting tasks (Lafortune et al.,1988 cited in McGill, 1992). Specific surface EMG electrode placement locations and orientations for this research project are outlined in Table 4. Reference electrodes were placed on the left acromion of each participant as a grounding electrode.

Signal Channel Name	**Musculature**	**Surface Electrode Placement**
RA	Rectus abdominis	3cm lateral to the umbilicus in the vertical direction (McGill et al. 1996)
EO	External oblique	Approximately 15cm lateral to the umbilicus and at the transverse level of the umbilicus (McGill et al. 1996)
IO	Internal oblique	Approximately 50 percent on the line between the ASIS and the midline, just superior to the inguinal ligament (Axler & McGill 1997)
LD	Latissimus dorsi	Lateral to the ninth thoracic vertebra spinous process

		over the muscle belly (McGill 1992)
UES	Upper erector spinae (Longissimus thoracis and iliocostalis lumborum pars thoracis)	5cm lateral to the ninth thoracic vertebra spinous process in the vertical direction (McGill 1992)
LES	Lower erector spinae (longissimus thoracis and iliocostalis lumborum pars lumborum)	3cm lateral to the t hird lumbar vertebra spinous process in the vertical direction (McGill et al.1996)

Figure 7: Summary of electrode placement sites for core musculature.

3.3.1.1 Maximum Voluntary Contraction trials

In order to normalize EMG signals to known maximum value MVC trials were performed. Two quiet lying trials (participant lies prone and supine) were taken prior to data collection in order to collect EMG signal of low level activity. Raw EMG signal amplitude from these trials were used to remove zero bias from each EMG signal channel in data collection during post processing. Three MVC trials will be performed against manual isometric resistance (consistent with SENIAM ([updated 1999]) recommendations). The MVC trials were performed with the intention of producing the largest amplitudes of myoelectric activity from the selected trunk, hip, and leg muscles of each participant to provide a basis for normalization of these EMG signals. MVC trials were repeated three times with a minimum rest period of two minutes between the contractions (De Luca, 1997).

The spine extensors (UES, LES) were normalized to the maximal EMG activity recorded while the subjects lay prone on a table with their torso (ASIS and above) cantilevered over the edge of the table (Biering-Sorensen position). The feet were secured with a tight fitting Velcro strap and reinforced with manual resistance provided by a research assistant. While in this position, subjects started with a slightly flexed lumbar region and then slowly extend the lumbar spine against a resistance applied on the upper back by the researcher (McGill et al. 1996).

Maximal abdominal muscle (RA, EO, IO) activation were obtained with the subjects starting in a seated bent-knee ‘sit-up’ posture with the trunk reclined to approximately 30 degrees with the horizontal and the feet restrained by a strap. Each hand was placed on the opposite shoulder while an assistant provided matched resistance to the shoulders. The instructions for the exertion were to perform a sequence of maximal isometric efforts in trunk flexion, right and left lateral bend, and right and left axial twisting. On occasion, some maximal activation EMG signals obtained during other maximal exertions were slightly larger – the largest amplitude for each muscle were used regardless of the activity from which it is obtained.

A specific latissimus dorsi (LD) was normalized to the maximal EMG activity recorded while the subjects grasp a solid bar from overhead position with hands spaced approximately 50 cm apart. Subjects were instructed to pull themselves upward while manual resistance is applied to maintain an isometric latissimus dorsi contraction. Extra cues of gripping the solid bar 'as tight as possible' while attempting to 'bend the bar' were used.

3.6.1 Bending Apparatus

Three different apparatus setups were used to measure passive and active stiffness. Passive flexion, extension, right lateral bend and left lateral bend were measured on a ground based frictionless bending apparatus (Fig. 7). Passive left and right twist trials were performed standing on a frictionless rotating apparatus (Fig. 8). Active bending trials were performed using modified chair and harness to act as a quick release mechanism (Fig. 9).

3.6.1.1 Passive Bending

Passive stiffness was measured via bending the subject about the three anatomical planes in two 'frictionless' bending apparatus. The bending apparatus used for flexion, extension and lateral bend trials was a flat lying frictionless jig which was composed of three components:

a) Nylon ball bearings (diameter of 1.2 cm) (Specialty Ball Co., Rocky Hill, CT, USA) that are evenly distributed over a Plexiglas surface.

b) Thoracic wooden cradle lined with Plexiglas on the inferior surface, which glides over the ball bearings and a lower body support that restricts motion at the hip and is vertically adjustable.

c) A force transducer (Transducer Techniques Inc., Temecula, CA, USA) mounted to the top of the thoracic cradle placed in series with a cable to pull participants into flexion and extension, a metal rod fixed to the point of application of the applied force, and a parallel cable to ensure that applied forces are perpendicular to the thoracic harness.

Subjects lay in the apparatus with restraining straps fixing their lower extremities and pelvis (hips, knees and ankles) to the lower body support while their torso (top of head to approximately L5/S1) supported and fixed via straps on the floating thoracic cradle. Subjects lay on their right side during flexion and extension trials and on their back during passive lateral bending trials. By fixing lower extremities and allowing the upper body to 'float' in the apparatus any movement is constrained to purely bending about the lumbar spine. This apparatus minimized measurable friction and allowed trunk movement about either the flexion–extension or lateral bend axis, depending upon how the participant is secured. The orientation of the apparatus ensured that participants adopted and maintained a non-deviated (neutral) spine posture in their spinal elastic equilibrium state throughout the testing. To ensure the trials were completely passive EMG signal of the core musculature was monitored and the subject was notified if excessive activity is observed during trials. A trial was confirmed passive if muscle activity (as recorded with surface electrodes) of the anterior and posterior core musculature remained less than 5% MVC (UW SOP 215). This was assessed by looking at a graph of the muscle activation levels throughout the trial on a computer screen. Post processing of EMG recordings confirmed this. A concern of dirt and dust contaminating the Plexiglas surface would introduce resistive forces during trials, no longer making the apparatus frictionless. Thus, Plexiglas surfaces were cleaned using a soft cloth to remove dust and debris while avoiding scratching the Plexiglass surface, before each new subject to ensure a proper frictionless contact. Bending moments were applied to the torso-cradle with a cable whose line of action formed a normal tangent with the top of the cradle, which was aligned tangential with the spine bending arc. Slopes of the angular deflection/time curve were calculated during post processing to ensure trials subjects were pulled with a consistent velocity between trial directions and between pre and post training trials. Applied moments were calculated based on the measured pull force from the load cell and used with the perpendicular distance of the cable attachment on the cradle to the lateral iliac crest (approximately the level of L5).

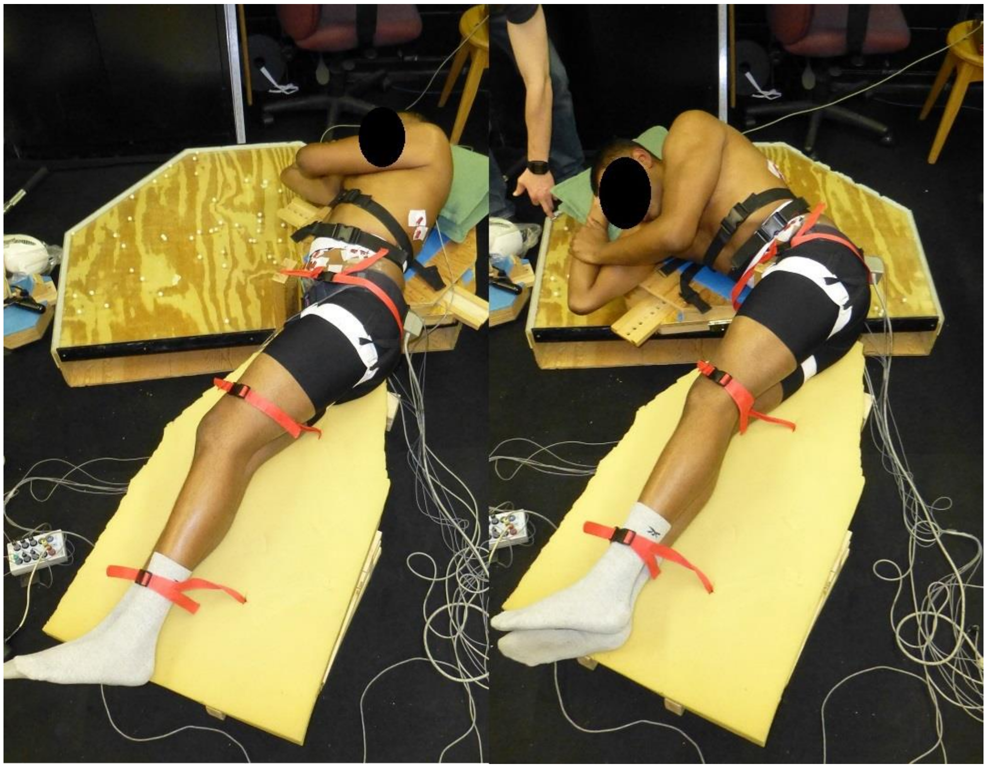

Figure 8: Forward flexion using the frictionless bending apparatus.

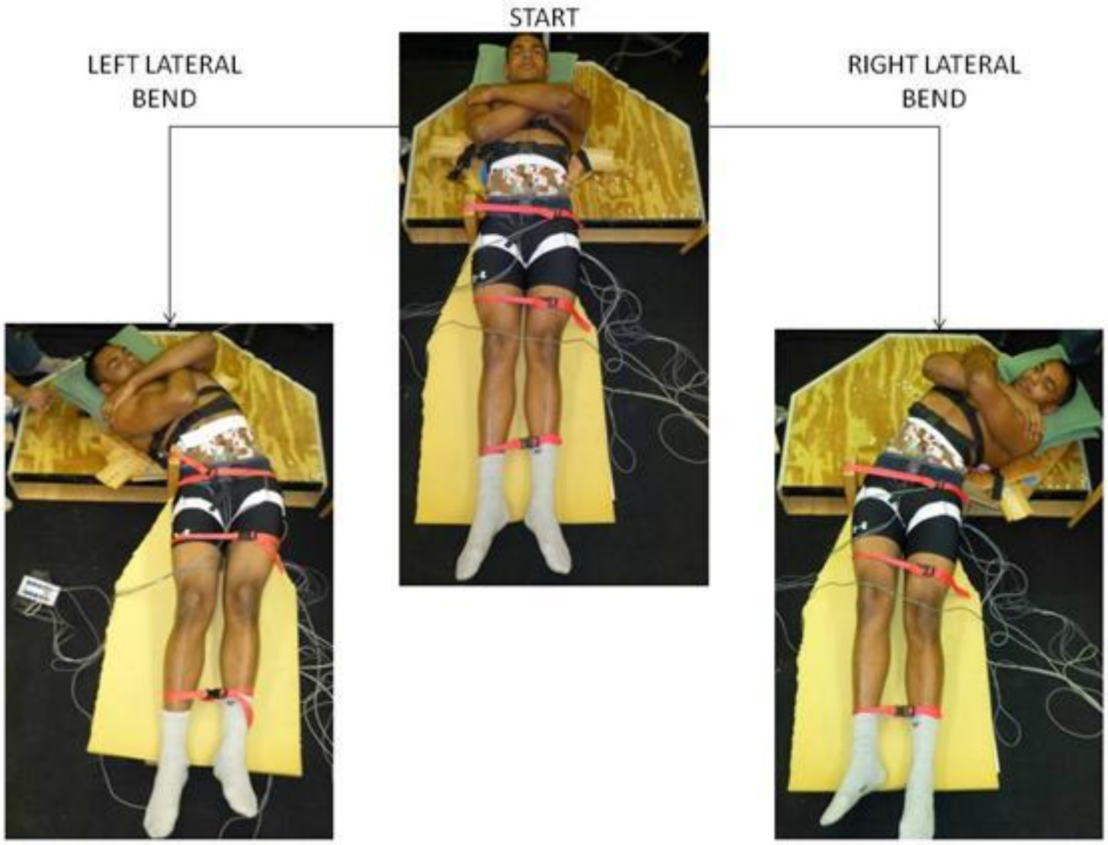

Figure 9: Left and right lateral bend using the frictionless bending apparatus.

Axial twisting trials (clockwise and counter-clockwise) were performed in a separate apparatus designed for rotation about the transverse plane in a frictionless environment. This apparatus consisted of rotating wheel platform mounted to a fixed base via ball bearings with a frictionless contact. The subject stood on upright on the wheel maintaining neutral spine and hip posture with their upper body fixed via a harness strap to a vertical post (strap approximately at the level of T9). This ensured the torso was fixed during twisting trials and all twisting range motion occurred through the lumbar spine. A force transducer was fixed to the outer edge of the wheel and used to pull the subject, pulling tangent to the wheel with trials for both directions of twisting. Stiffness values were obtained from the slope of the moment/angular displacement curves obtained. Moment values were obtained by taking the product of the measured force from the load cell and the perpendicular distance from the load cell to the centre of the wheel (26 cm). The same methods used to facilitate relaxation of the subject's core musculature from the flexion, extension and lateral bend trials were used.

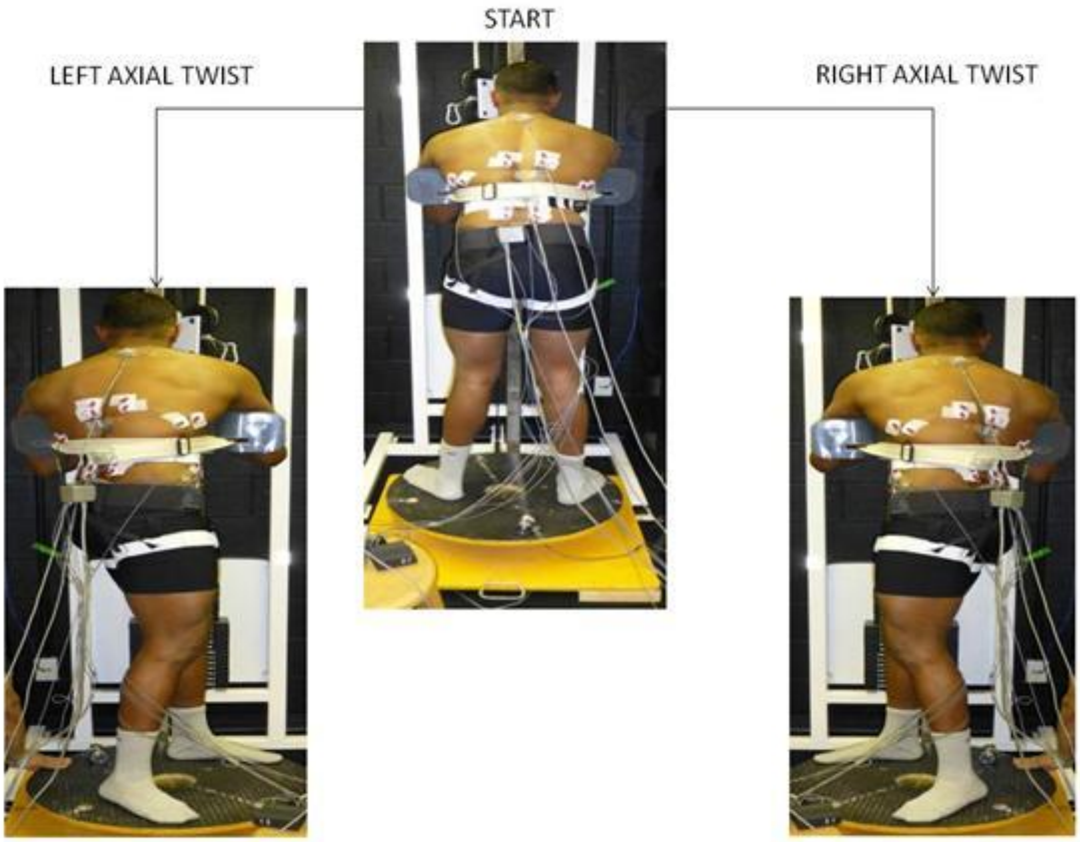

Figure 10: Left and right axial twist trials performed on the 'frictionless' rotating wheel apparatus.

3.6.1.2 Active Bending

A quick release mechanism allowed researchers to measure torso stiffness of the subject during periods of core musculature activity. Subjects were placed in a semi-seated position in an ergonomically designed chair which restricted hip motion while leaving the trunk free to move in all directions (Global Upholstery Co. Inc., Toronto, Canada). This has been shown to foster a neutral spine posture and elastic equilibrium for the hips and spine (Sutarno and McGill, 1995). Then, the subject was be instructed to create an abdominal brace and pre-loaded with a 16 kg (35) lb mass via a steel cable attached to a harness, applied at a zero degree angle (parallel to the ground) (Fig. 10). With the load applied, the subject was 'quick released' with an electromagnet (Job Master Magnets, Oakville, Canada) without prior knowledge; this created a sudden drop to the subject under load and the subject was required to create trunk muscle co-contraction in order to stop motion from the quick release. Muscle activity was measured via EMG, with cable tension measured via a load cell instrumented in series with the harness, electromagnet and cable. Lumbar spine angles were measured via the 3Space lumbar tracking monitor.

In order to preserve an upright seated posture quick co-activation of trunk musculature is required to stiffen the spine and enhance spine stability. Upon application of load an initial velocity of the trunk has been observed in previous experiments (Sutarno and McGill, 1995; Vera-Garcia et.al., 2007). Stiffness values are acquired via a function of the applied load and trunk displacement measurements. Displacement of the subject due to the initial acceleration following release along with the measured applied load act as moment/angular displacement values which then are used to calculate active stiffness

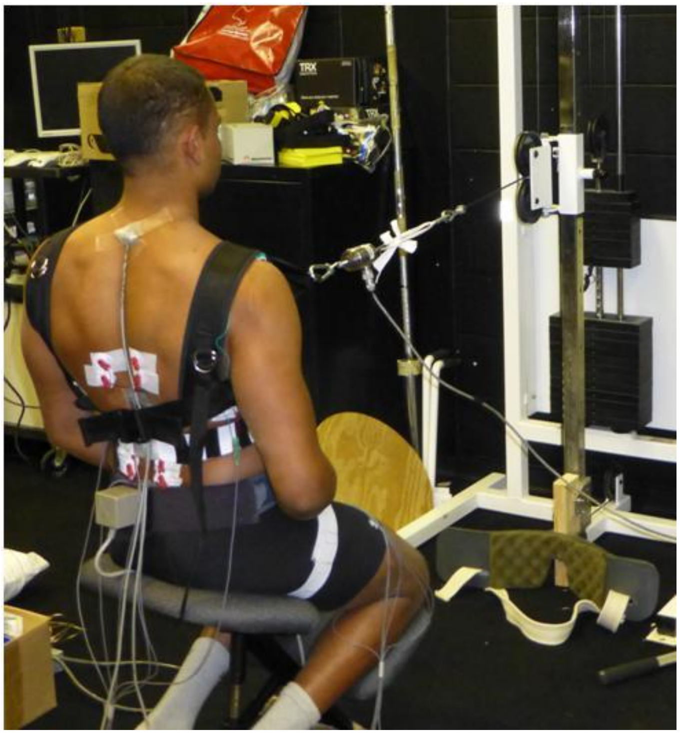

Figure 11: Active extension trial setup. The subject sits in a 'balans' chair used to foster a neutral spine and hip posture, loaded anteriorly with a 35 lb load. Applied moments were calculated based off the applied load and moment arm from the point of load application to the level of the L5.

3.6.1.3 Trial Descriptions

Each passive and active bending trial was standardized with specific instructions to the subject to ensure consistent procedure and minimize errors during trials.

Passive trials began with the subject fully secured in the appropriate apparatus (Fig. 8-10). Before the beginning of each trial researchers practiced a ‘dry run’ trial in which the subject would be pulled along the bending direction without any data collected. Subjects were instructed to relax as much as possible with cues of ‘imagining you are taking a nap’ to assist with relaxation. This dry run trial was used to establish maximum range of motion and the subject was asked to verbally confirm when they reached end range of motion while being passively bent. Subjects were then asked if this end range was due to internal factors such as resistance from passive tissues, or external factors such as any of the apparatus restricting movement. If the subject responded with 'external' researchers repositioned the equipment on the apparatus and another dry run was performed, repeating the process until external factors did not affect end range of motion. If the subject responded with 'internal' researchers physically marked the end range location and confirmed by viewing the output on the computer controlling the electromagnetic motion capture system. This established maximum range of motion for the specific bending trial and three trials were collected. If any trials were deemed unacceptable due to improper collection of kinematic and/or kinetic data, said trial was repeated and replaced. This procedure was repeated for each passive bending direction. Kinetic and kinematic data was recorded during this process to be used for analysis of torso stiffness in each bending direction.

Active bending trials began with the subject seated in the balans chair with harness applied but without the 16 kg preload. Trials were recorded for ten seconds but only relevant data (data collected during release) was extracted from this time period. Subjects were instructed of the procedures for this set of trials:

- The 16 kg mass would be anteriorly preloaded via the torso harness.
- Said mass would be randomly quick released via an electromagnet without prior knowledge.
- Quick release could occur at any point during the ten second trial. Though subjects were not told when the mass would release they were informed of when the trial began.
- Instructions were given to stop torso motion upon release without external help (ie. Limbs), relying on core bracing techniques to stop motion.
- If there was time remaining during the trial after release subjects were asked to sit still until the ten second period expired.

Kinetic and kinematic data was collected for the ten second trial duration. Trials were clipped during post processing to only include data following magnet release.

3.6.2 Electromagnetic Motion Capture

The purpose of using a lumbar tracking monitor was to measure spine angular kinematics during bending trials, to be used with the measured applied external torque to calculate stiffness through a range of motion. Angular kinematics of the spine was measured via a 3Space Isotrak electromagnetic system (Polhemus Navigation Systems, Colchester, VT, USA).

The electromagnetic motion capture system is a camera-less 3D human motion measurement system that uses a transmitter ('source'), which generates a varying electromagnetic field, and a receiver ('sensor'), which senses the electromagnetic field; the position and orientation of the receiver relative to the transmitter is recorded (McGill et al. 1997). Certain considerations must be taken into account to ensure accurate readings from the device; the restriction of conductive metallic objects in the electromagnetic field must be ensured due to interference with the electromagnetic field (McGill et al. 1997). As the bending apparatus is constructed from wood and plexiglass, with a layer of nylon balls this was not a concern. Subjects were also asked to remove any metallic jewelry or piercings to minimize the effects of electromagnetic interference. The unaxial load cell was mounted at the superior end of the floating frame and out of the field of the sensor. This was confirmed during pilot testing where no interference in the signal collected from the device was observed. Angular displacements were measured by the device about three axes; sagittal bending (flexion/extension), frontal plane bending (left and right lateral bend) and transverse plane twisting (left and right axial twist) were recorded by the device.

The electromagnetic source was fixed at the subject's sacrum via a custom built belt with Velcro hip and leg straps to secure the sensor. A layer of double sided adhesive tape was applied between the source and the subject's skin to assist with secure fixation. A sensor was applied to the subject's twelfth thoracic spinous process (T12) and secured with doubled sided adhesive tape and fabric Velcro fastener elastic straps. The second sensor was placed on the seventh cervical spinous process (C7) as a 'dummy' sensor, to ensure the 3Space system would operate correctly. After application of the source and sensors two calibration trials were performed. An initial trial ('Boresite') was performed to zero the source and sensor, and remove any bias offset, based on the subject's posture. The boresite trial was repeated each time the subject changed postures for each trial; separate boresite trials were performed for flexion/extension trials, lateral bend trials, axial twist trials and seated active bending trials. A second calibration trial ('ROM') was performed to determine the subject's maximum range of motion about the three bending axes.

3.6.3 Load Cell

The magnitude of the applied force and cable tension during active and passive bending trials were measured using a load-cell force transducer (Transducer Techniques Inc., Temecula, CA, USA). The uniaxial load cell was mounted to the distal end of the floating thoracic cradle for flexion, extension and lateral bend trials; on the outer edge of the rotating wheel for axial twist trials; and set up in series with the electromagnet and external load cable for active bending trials. Prior to the start of each trial the load cell was digitally zeroed to eliminate bias offset of the signal. Linear calibration of the load cell was performed to establish a voltage-newton relationship to allow for conversion of voltage values to newtons of force.

3.7 Data Processing

Collected signals for stiffness trials (EMG, spine kinematics, applied loads) were filtered and processed using MATLAB software (Version r2012a; The MathWorks Inc., Natick, Massachusetts, USA). The digitized EMG and load signals were collected on a personal computer (Vicon Antec® Intel® CoreTM 2 Duo PC) using Vicon Nexus 1.8 software, and spine kinematic signals collected on a different personal computer (specs) using custom written software, in the Spine Biomechanics Laboratory (BMH 1407).

3.7.1 EMG Processing

Raw EMG signals were collected at an oversampled rate of 2160 Hz; over the recommended sampling rate (2000 Hz) (i.e., four times the highest frequency of surface EMG signal [500Hz]) (Durkin and Callaghan, 2005; Winter and Patla, 1997). The EMG data was amplified with two eight-channel differential amplifiers (common mode rejection ratio of 115 dβ at 60 Hz; input impedance 10 GΩ; Model AMT-8, Bortec Biomedical, Calgary, AB, CAN) and set to the same amplification setting (gain = 1000). The differential amplifier specifications exceed recommendations (i.e., common - mode rejection ratio greater than 80 dβ; input impedance greater than 100MΩ) when measuring surface EMG (De Luca, 1997). The EMG signals were analog to digital (A/D) converted (Vicon MX 64 - channel A/D interface unit) using a 16- bit converter (Vicon MX 20 MX control box) with a ± 2.5 V range. Soft gains were individually set for each channel to fill this input range without clipping the signal based on signal outputs during MVC trials for each subject. The filtered EMG signals were then full wave rectified (FWR) to generate the absolute value of the EMG (Winter, 2009) and low pass filtered using a 2^{nd} order low pass Butterworth filter (single-passed to introduce a phase lag, which represents electromechanical delay between the onset of the motor unit action potential and the resultant muscle tension) with a cut- off frequency of 2.5 Hz to produce a linear envelope. The linear envelope closely resembles the muscle twitch tension curves of the trunk musculature (Winter, 2009) by selecting a 2.5 Hz cut-off frequency that matches the 2.5 Hz twitch response of the trunk musculature (Brereton &

McGill, 1998). The EMG signals will then be normalized to the maximum EMG signal amplitudes achieved at each muscle site during MVC trials and expressed as a percentage of these maximums. Finally, the normalized EMG signals were downsampled to 60 Hz to enable the synchronization with kinetic and kinematic signals.

3.7.2 Load Cell Processing

Raw voltage values from the uniaxial load cell were collected at an oversampled rate of 2160 Hz. Load cell signals were converted from analog to digital (A/D) (Vicon MX 64 - channel A/D interface unit) using a 16 bit converter (Vicon MX 20 MX control box) with a ± 2.5 V range. Raw signals were filtered in a custom coded program using a 2^{nd} order low pass Butterworth filter with cut-off frequency set at 3.6 Hz, with cut-off confirmed via a custom coded Fast Fourier Transform program, and downsampled to 60 Hz to match kinematic data.

3.7.3 Electromagnetic Kinematic Processing

Raw values of spinal angular kinematics were collected at an oversampled rate of 60 Hz. Human movement is classified to occur at a frequency of less than 10 Hz – slow movement trials have been shown to occur at below 5-6 Hz (Winter, 1974). A custom coded Fast Fourier Transform program determined from pilot data the majority of frequencies fell below 3.6 Hz. Processing of raw kinematic data was performed with a 2^{nd} order low pass Butterworth filter (dual passed to create a fourth order filter with zero phase shift) with an upper cutoff frequency of 3.6 Hz preserved as much signal and filtered out as much noise as possible.

3.7.4 Calculation of Dependent Variables

Processed kinetic and kinematic data collected were matched at an output frequency of 60 Hz. Three trials for each bending test were collected and kinematic and kinetic data was ensemble averaged to produce the mean response for a subject. A custom coded Matlab program determined the beginning and end of each trial via change in the slope and maximum (passive trials) or minimum (active trials) values of the kinetic data, respectively. Trials were clipped within this range for both kinetic and kinematic data; this process was repeated for all three trials for each test and averaged together. Kinetic and kinematic data was then plotted against each other (kinetic data on the Y axis and kinematic data on the X axis) to give a relationship between applied moment and angular deflection. To account for unequal trial lengths the data was ensemble averaged to 100 frames of data.

3.7.4.1 Passive Stiffness

Passive stiffness values were calculated using the following method. Angular displacement values were normalized as a percentage of maximum displacement obtained during range of motion trials for the electromagnetic motion capture system. Moment and displacement values were then combined for each unique combination of participant training type, experience and bending direction, and fit using an exponential curve fitting function. (Equation 2).

$$M = \lambda e^{\phi\vartheta} \quad (2)$$

Where M is the applied moment (N-m), λ and ϕ are curve fitting constants and ϑ is the angular displacement of the torso. This equation was differentiated once with respect to ϕ to obtain a measure of torso angular stiffness, k (Equation 3).

$$k = \lambda\phi e^{\phi\vartheta} \quad (3)$$

A custom coded Matlab program calculated stiffness about the entire trial and peak stiffness for each trial and condition were selected.

Researchers selected this method of obtaining stiffness rather than calculating slopes of raw data as this method of curve fitting data to obtain stiffness values has been used in similar experiments measuring trunk stiffness via the frictionless bending apparatus (Parkinson et. al., 2004; Brown and McGill, 2008). Raw moment and angular displacement data points could be plotted and stiffness obtained via directly calculating the slope of these points but researchers determined that this method of curve fitting data points allowed for an expression of overall stiffness throughout the trial.

3.7.4.2 Active Stiffness

Active stiffness values were calculated using an alternative method due to the difference in biological signals between active and passive trials. As shown by Equation 1, stiffness is defined as the slope of force with respect to displacement. Values of force and displacement can be replaced with angular values (moment, M, and angular displacement, ϑ, respectively) to give the following equation:

$$k = \frac{M}{\vartheta} \quad (4)$$

A gross measure of lumbar stiffness was obtained from Equation 4. Moment and angular displacement values were recorded for the first 250 milliseconds following release of the preloaded mass of the active bending trials to be analyzed for stiffness measurements. Within the first 250 ms voluntary reaction the mechanism of active stiffness is mainly due to tendon and muscle tissue recoiling after preload. Beyond this time frame voluntary control from the subject dominates the reaction and thus the first 250 ms was deemed most important by the researchers. This method of active stiffness calculation has been used in similar research involving the quick release mechanism and stiffness measurements for gross lumbar stiffness (Brown et. al., 2006).

3.7.5 Data Analysis

3.7.5.1 Passive Stiffness

To assess stiffness pre and post training applied moments were normalized as a percentage of the maximum pre training moment value. Assessment of range of motion at corresponding moment percentages (50, 65, 80, 90, 95 and 100% of pre training moment) were used as an inference of stiffness; as stiffness is directly proportional to moment and inversely proportional to displacement (Equation 4) for the same applied moment a stiffer torso would experience lesser displacement. Statistical tools were then used to compare pre and post training conditions, as explained in Section 3.8.

3.7.5.2 Active Stiffness

Assessment of active stiffness did not require the curve fit methods described for passive stiffness tests. As trials were clipped to the first 250 ms upon release of the quick release mechanism, the instantaneous slope (Equation 4) was taken at each data point and peak slope value was used in the statistical analysis.

3.8 Statistics

Multiple statistical analysis tools were used given the variety of data and hypotheses to be examined. All statistical analysis was performed using IBM® SPSS ® Statistical software (Version 19, IBM Corporation, Somers, New York, USA).

3.8.1 Descriptive Statistics

The means and standard deviations were calculated for all outcome variables (range of motion at corresponding percentages of applied moment). These values were split based on the training group and training level of the subjects. Individual analysis included means and standard deviations of stiffness and absolute range of motion for pre and post short term isometric training as a whole group and divided by experience level (students vs. athletes), and pre and post long term training as a whole group and divided by experience level (students vs. athletes) and training type (Isometric vs. Dynamic vs. Control).

3.8.2 Inferential Statistics

Inferential statistical analyses were performed for each hypothesis formed for short term and long term training. Examination of short term training on pre/post values of stiffness and range of motion were performed using a paired T-test and one way ANOVA. Examination of long term training on pre/post values of stiffness and range of motion were performed using one way ANOVAs. For one way ANOVA tests a new variable (net stiffness/ROM) was created by subtracting the pre training value from the post training value. Overall statistical analysis approaches are summarized in the table below.

Table 4: Summary of statistical tests and variables for short and long term training.

Hypothesis	Interaction	Dependent Variable(s)	Independent Variable(s)	Test Used
1	Pre/Post short term core training	Passive range of motion (deg)	Time (pre/post, within subjects factor)	2x2 Repeated Measures ANOVA
2	Pre/Post short term core training	Active range of motion (deg)	Time (pre/post, within subjects factor)	2x2 Repeated Measures ANOVA
3	Pre/Post short term core training	Range of motion (deg)	Training experience (naive/savvy, between subjects factor)	2x2 Repeated Measures ANOVA
4	Pre/Post long term core training	Passive range of motion (deg)	Time (pre/post, within subjects factor)	3x2x2 Repeated Measures ANOVA
5	Pre/Post long term core training	Active range of motion (deg)	Time (pre/post, within subjects factor)	3x2x2 Repeated Measures

				ANOVA
6	Pre/Post long term core training	Range of motion (deg)	Training experience (naïve/savvy, between subjects factor)	3x2x2 Repeated Measures ANOVA
7	Pre/Post long term core training	Range of motion (deg)	Training group (Isometric/Dynamic/Control, between subjects factor).	3x2x2 Repeated Measures ANOVA

Chapter 4
Results

Stiffness values were acquired from an exponential curve fit of collected and processed moment and deflection values. Plots of the raw moment/deflection data showed an initial peak which researchers determined to be of non-biological significance. This is believed to be due to 'stiction' where the subjects' initial inertia required greater force application to overcome before transitioning out of their neutral zone. This stiction peak was removed from all trials and an exponential curve fitted to the data, producing a relationship for applied moment as a function of range of motion (Equation 2). The first derivative of Equation 2 produced a relationship for stiffness as a function of range of motion (Equation 3).

The average of three trials per bending test was taken and the result plotted as seen above. Moment and deflection data points were plotted to give a general representation of the stiffness response for a given trial. Moment values are reported in Newton-metres and deflection values are reported in degrees. Figure 12 shows sample raw moment/deflection data with and without the stiction peak, and curve fit.

Comparison of Original vs. Modified Passive Moment/Deflection Curves

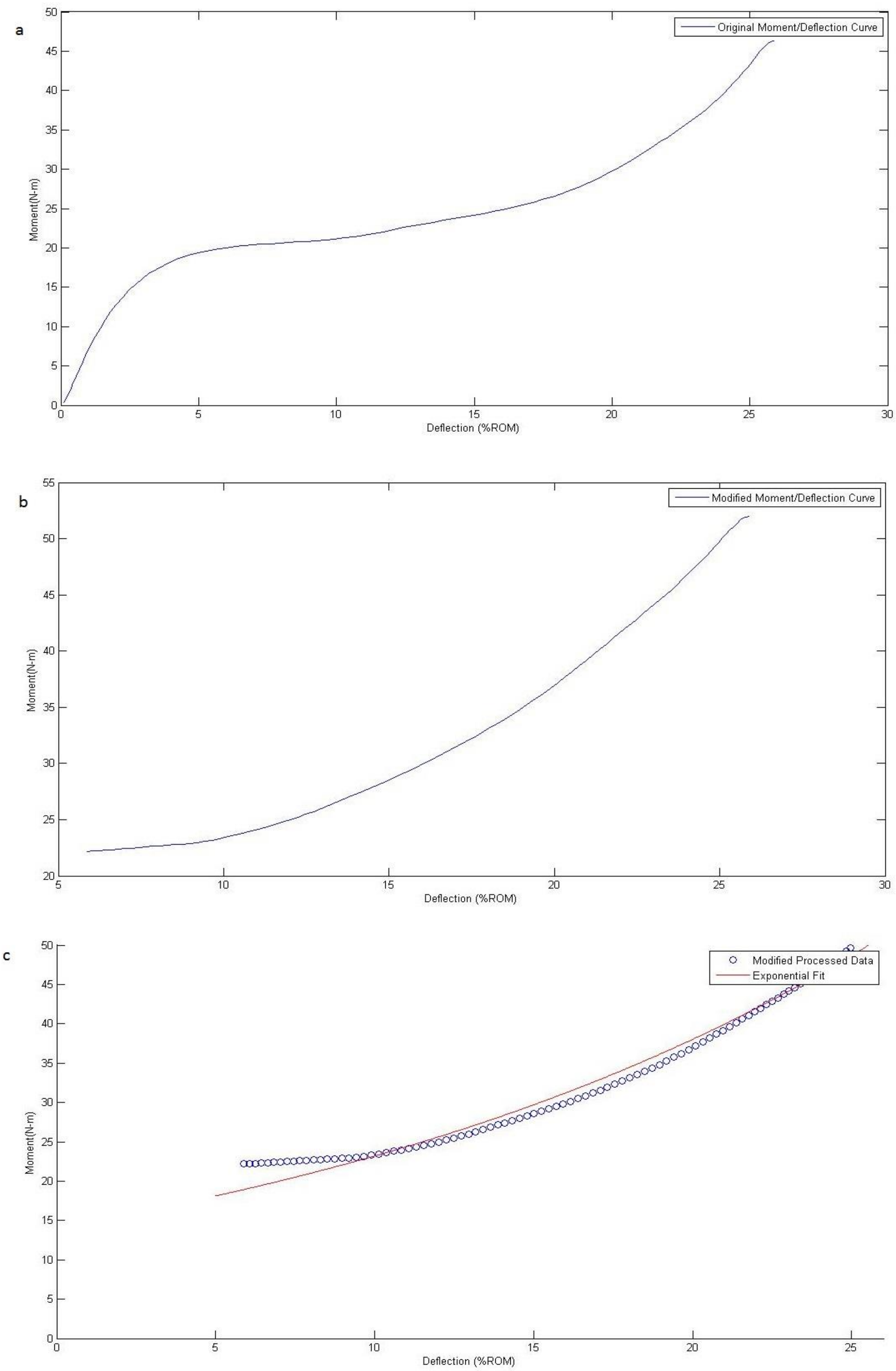

Figure 12: a – Sample processed moment/deflection curve. Note the initial rise and peak for the first 3 degrees of the trial. b – sample processed moment/deflection curve with the initial stiction peak removed. c – exponential curve fit overlaid on the curve shown in b.

Moment data was normalized to 100% of the peak pre training moment value for pre and post training conditions. As an inference of stiffness at specific instances the corresponding range of motion was calculated for moments at 50, 65, 80, 90, 95 and 100% of pre training peak moment for pre and post training conditions. A sample of this method is shown in Figure 13.

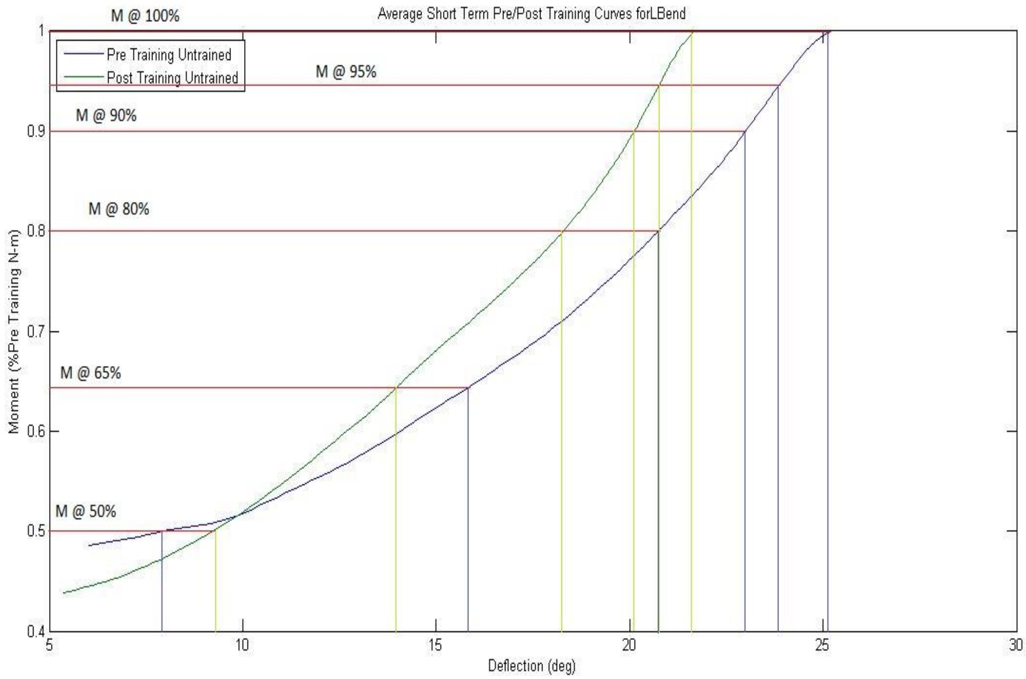

Figure 13: Curve fit moment/deflection data of pre and post training. Red horizontal lines show where data was taken at 50, 65, 80, 90, 95 and 100% of peak pre training moment. Blue vertical lines show the corresponding range of motion (ROM) values of the pre training plot. Green vertical lines show the corresponding ROM values of the post training plot. Matched pre and post training ROM values at each moment percentage were compared to determine any significant changes pre and post training.

4.1 Short Term Training

Comparison plots were made between pre and post short term isometric training for all subjects, between subject training experience (naïve vs. savvy populations). A two factor repeated measures ANOVA was performed on pre/post range of motion values at specific instances of applied moments, to determine if significant differences ($p <= 0.05$) were found in pre/post conditions within savvy and naïve subject groups, and if changes between subject groups were significant. Recorded values and associated p values are summarized in Table 5 for pre/post conditions within subject groups. Many significant differences were observed after short term training for both naïve and savvy subjects over multiple bending tests at multiple levels of applied moment; these interactions are highlighted in Table 5 with red denoting $p < 0.05$, yellow denoting $p < 0.01$ and green denoting $p < 0.001$. P values associated with the comparison of of response between subject groups are summarized in Table 6. Statistical analysis revealed no significant differences ($p < 0.05$) between the naïve or savvy groups for any of the bending tests. Plots of the mean pre/post training moment/deflection curves are shown in Figures 15-20.

Table 5: Summary of pre/post training ROM values (rows) at various instances of pre training applied moment (columns) for the short term data collection. Stiffness was inferred from ROM at certain applied moment values. Shorter ROM at the same applied moment infers greater stiffness at that instantaneous point. Results are summarized for each bending test at 50, 65, 80, 90, 95 and 100% of applied pre training moment and the subsequent range of motion experienced pre and post training. Comparisons were made to determine significant changes in ROM values following short term training at each level (applied moment, subject group).

		Ext			Flex			Lbend			Ltwist			Rbend			Rtwist			Active		
Training Exp		Mean (deg)	Std. Deviation	p	Mean (deg)	Std. Deviation	p	Mean (deg)	Std. Deviation	p	Mean (deg)	Std. Deviation	p	Mean (deg)	Std. Deviation	p	Mean (deg)	Std. Deviation	p	Mean (N-m/deg)	Std. Deviation	p
Naïve	ROMPre50	12.37	8.23	0.115	19.67	8.12	0.005	10.67	7.15	0.098	6.46	2.40	0.051	13.92	4.83	0.003	5.17	2.97	0.005	3.30	1.18	0.04
	ROMPost50	4.50	0.77		10.49	8.17		8.39	6.78		4.77	2.04		9.58	3.48		2.42	1.50				
	ROMPre65	16.00	9.82	0.087	22.12	10.39	0.000	13.59	6.40	0.004	8.07	3.40	0.001	17.03	4.33	0.000	7.38	3.23	0.001			
	ROMPost65	8.95	2.15		13.32	8.29		11.11	6.11		5.47	2.96		12.16	4.45		4.32	1.84				
	ROMPre80	19.98	11.42	0.020	25.87	12.69	0.002	17.33	8.93	0.005	10.75	4.51	0.000	18.75	7.67	0.001	9.06	4.25	0.000			
	ROMPost80	13.72	5.98		18.33	8.94		13.80	7.58		7.67	3.96		14.77	6.37		5.71	3.20				
	ROMPre90	21.01	11.77	0.027	31.76	11.39	0.000	21.63	9.43	0.005	12.28	5.27	0.000	22.09	6.27	0.001	10.48	4.72	0.000	1.63	1.10	
	ROMPost90	16.01	8.67		21.72	9.30		16.79	8.15		8.92	4.68		17.40	6.73		6.97	3.62				
	ROMPre95	23.92	11.19	0.050	34.20	11.24	0.000	23.60	9.78	0.006	12.98	5.64	0.000	23.62	5.74	0.001	11.14	4.95	0.000			
	ROMPost95	19.18	9.40		23.84	9.35		18.16	8.46		9.49	5.03		18.67	6.79		7.55	3.82				
	ROMPre100	25.60	11.07	0.050	35.60	11.23	0.000	24.73	10.02	0.007	13.38	5.85	0.000	24.50	5.47	0.002	11.52	5.09	0.000			
	ROMPost100	20.96	10.12		24.94	9.34		18.95	8.67		9.81	5.23		19.39	6.85		7.87	3.93				
Saavy	ROMPre50	15.88	7.07	0.390	19.51	7.96	0.007	13.64	7.15	0.968	6.91	2.34	0.334	14.13	10.98	0.246	7.47	3.51	0.008	3.21	1.75	0.03
	ROMPost50	18.65	11.86		10.53	2.64		13.55	8.24		5.86	1.92		11.12	5.73		3.46	1.63				
	ROMPre65	19.63	8.42	0.316	23.25	8.46	0.003	15.65	6.88	0.929	9.44	2.87	0.009	13.90	10.26	0.022	8.99	4.04	0.001			
	ROMPost65	22.22	12.01		13.56	3.48		15.82	7.27		7.27	2.37		9.92	7.59		5.11	2.25				
	ROMPre80	18.59	9.13	0.359	27.65	9.71	0.003	16.91	8.05	0.530	13.52	3.28	0.000	17.63	10.49	0.007	12.29	4.28	0.000			
	ROMPost80	16.70	12.05		18.52	4.14		15.75	8.40		10.05	2.93		12.79	8.22		7.88	2.85				
	ROMPre90	25.52	7.69	0.051	28.37	11.72	0.011	19.55	8.24	0.440	15.84	3.80	0.000	20.45	10.53	0.007	14.15	4.57	0.000	1.9	1.56	
	ROMPost90	20.58	11.16		20.85	5.05		18.03	7.45		11.63	3.38		15.09	8.39		9.45	3.26				
	ROMPre95	28.71	7.96	0.042	30.13	11.09	0.004	21.58	8.14	0.306	16.91	4.09	0.000	21.75	10.59	0.007	15.01	4.73	0.000			
	ROMPost95	22.36	11.11		22.10	5.52		19.44	7.13		12.36	3.60		16.15	8.52		10.16	3.46				
	ROMPre100	30.54	8.37	0.042	31.15	10.91	0.002	22.75	8.29	0.255	17.52	4.26	0.000	22.51	10.62	0.007	15.51	4.83	0.000			
	ROMPost100	23.38	11.19		22.82	5.81		20.25	6.99		12.77	3.74		16.76	8.61		10.58	3.58				

Table 6: Summary of p values for pre/post short term training data collection. P values reported were acquired via a repeatd measures ANOVA comparison of pre/post short term training ROM values between subjet groups (naïve vs. savvy) for each bending direction test.

	p value (ROM@50%)	p value (ROM@60%)	p value (ROM@80%)	p value (ROM@90%)	p value (ROM@95%)	p value (ROM@100%)
Ext	0.08	0.12	0.85	0.24	0.29	0.33
Flex	0.98	0.83	0.80	0.56	0.43	0.38
Lbend	0.32	0.21	0.89	0.90	0.91	0.92
Ltwist	0.36	0.17	0.10	0.09	0.08	0.08
Rbend	0.78	0.38	0.64	0.54	0.49	0.47
Rtwist	0.08	0.31	0.08	0.07	0.07	0.07
Active	.91					

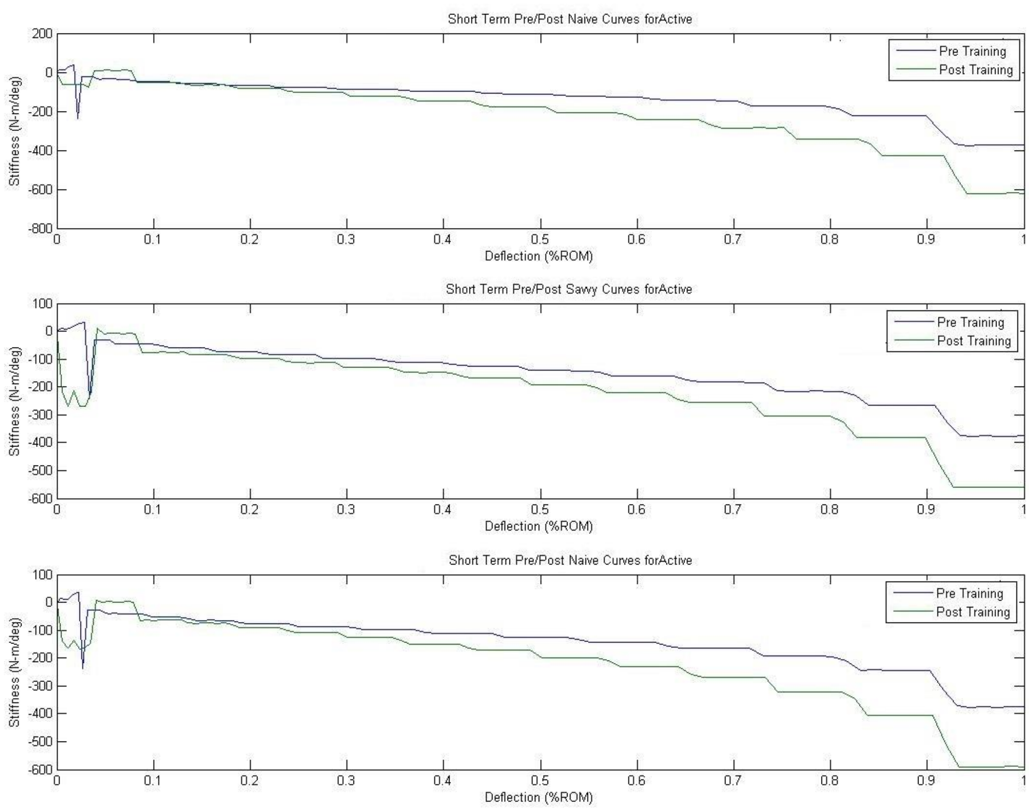

Figure 14: Summary of pre/post short term stiffness curves for active extension trials; stiffness values (N-m/deg) on the Y axis and range of motion (%ROM) on the X axis. These plots represent the moment/deflection response of the first 250 ms

following release of the applied load. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

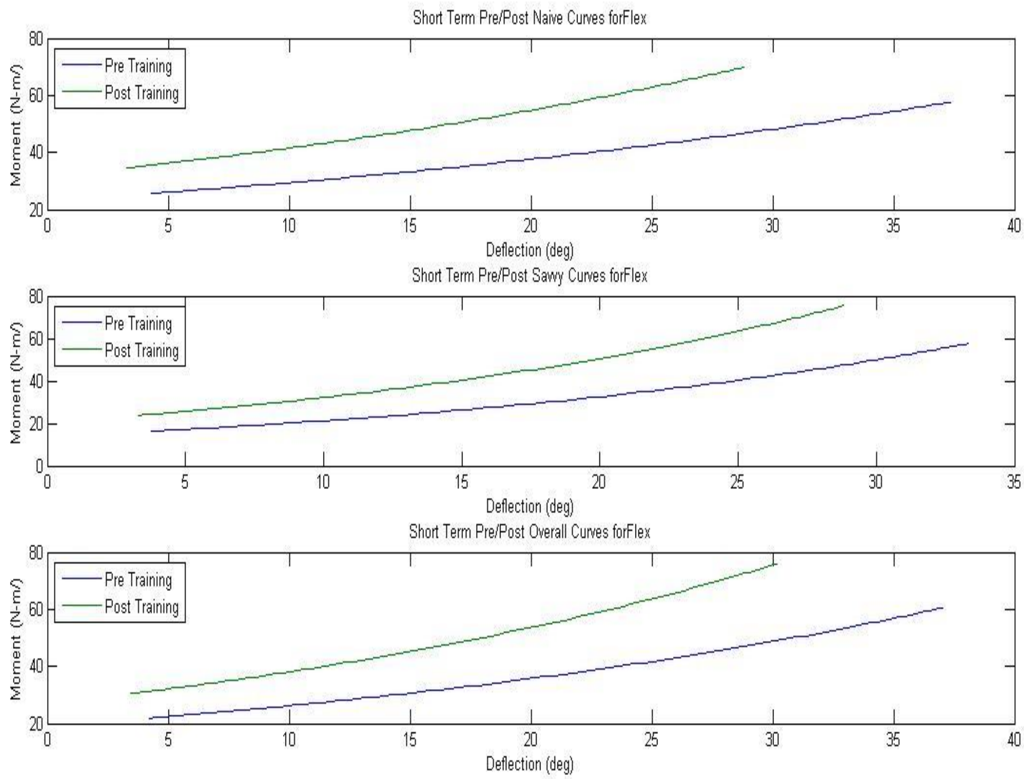

Figure 15: Summary of pre/post short term stiffness curves for passive flexion trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

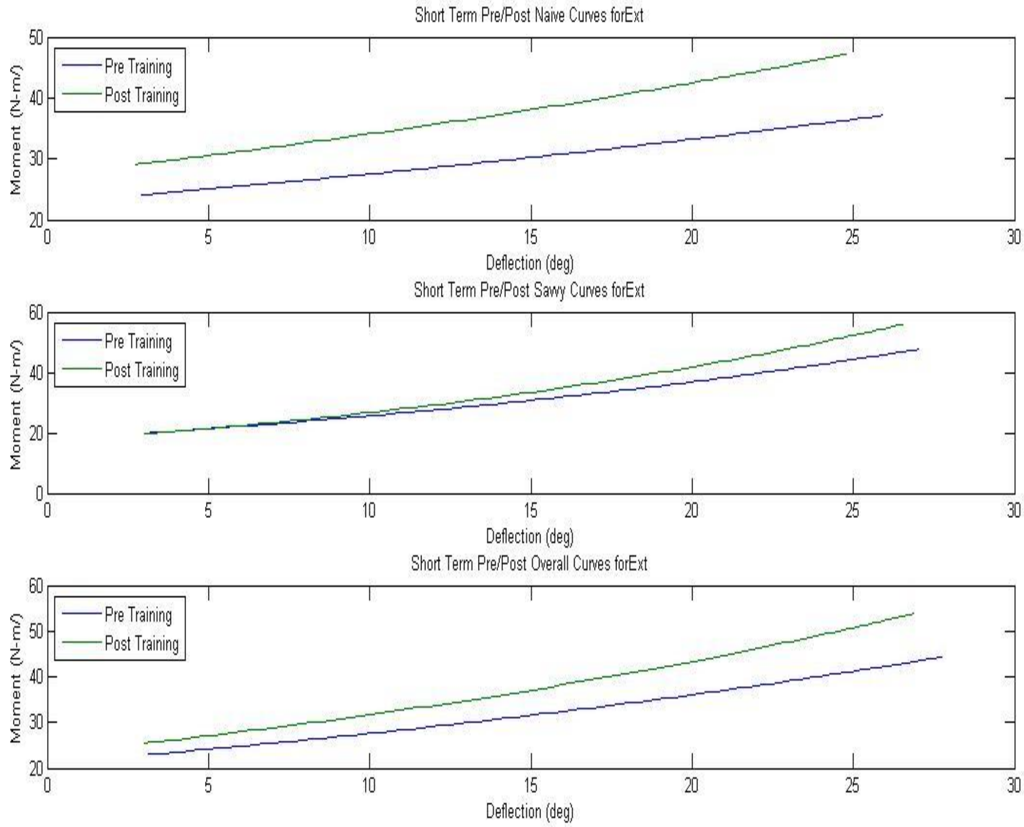

Figure 16: Summary of pre/post short term stiffness curves for passive extension trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

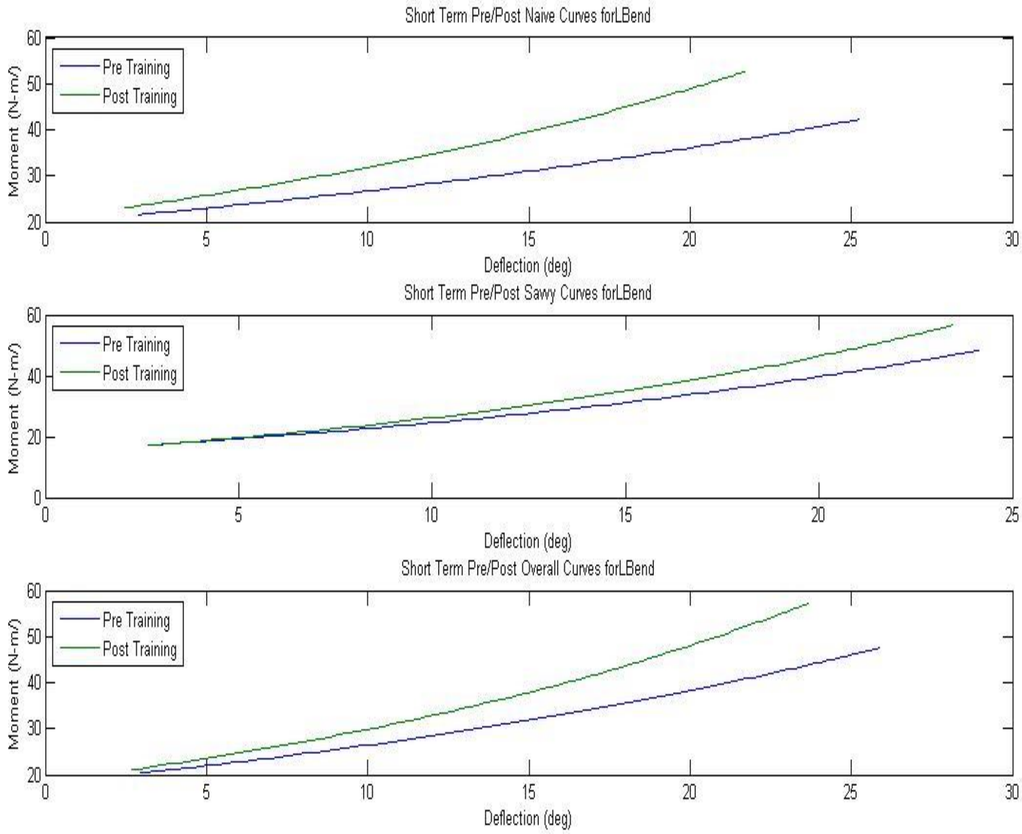

Figure 17: Summary of pre/post short term stiffness curves for passive left lateral bend trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

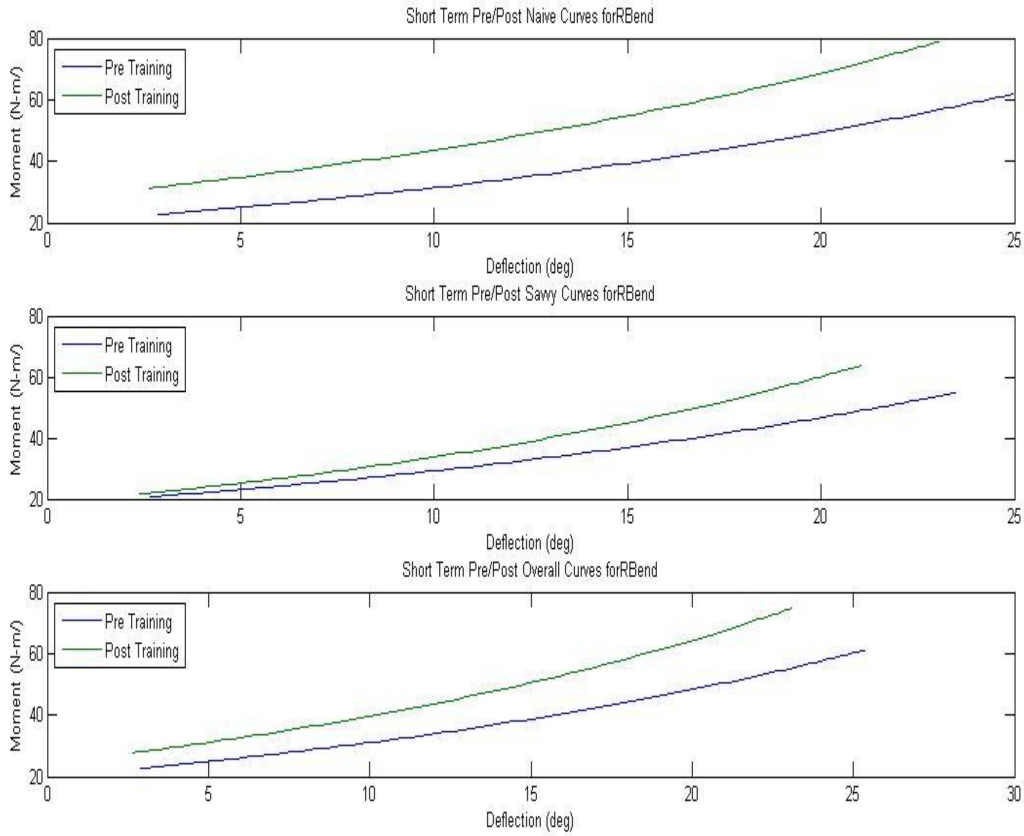

Figure 18: Summary of pre/post short term stiffness curves for passive right lateral bend trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

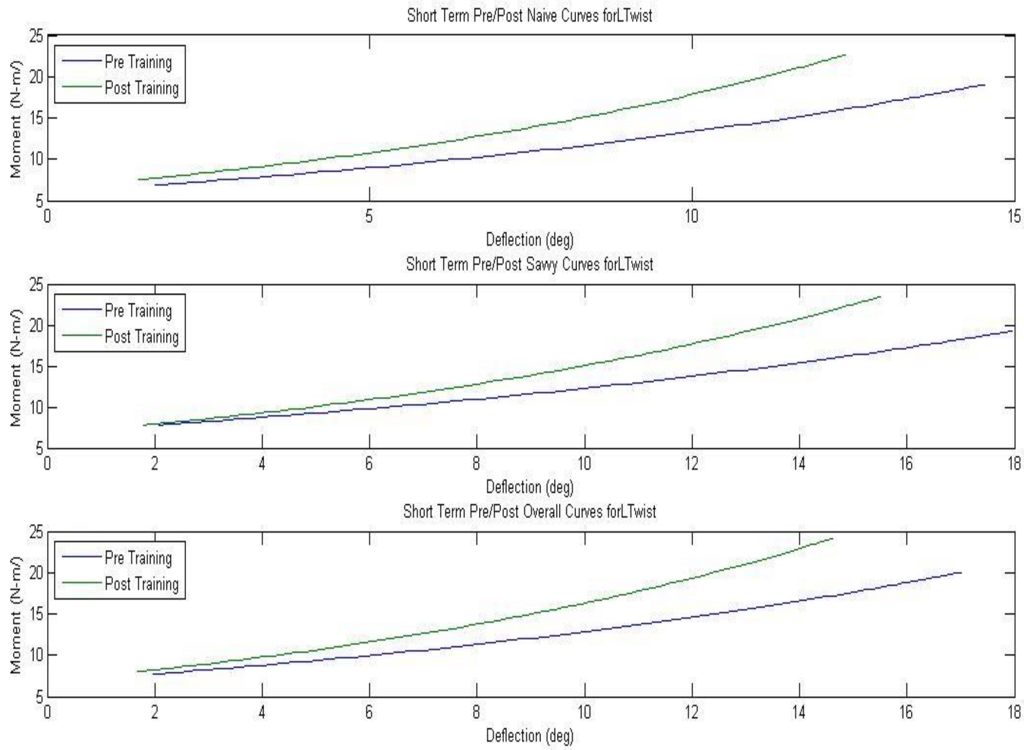

Figure 19: Summary of pre/post short term stiffness curves for passive left axial twist trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: student stiffness. Middle graph: athlete stiffness. Bottom graph: overall stiffness.

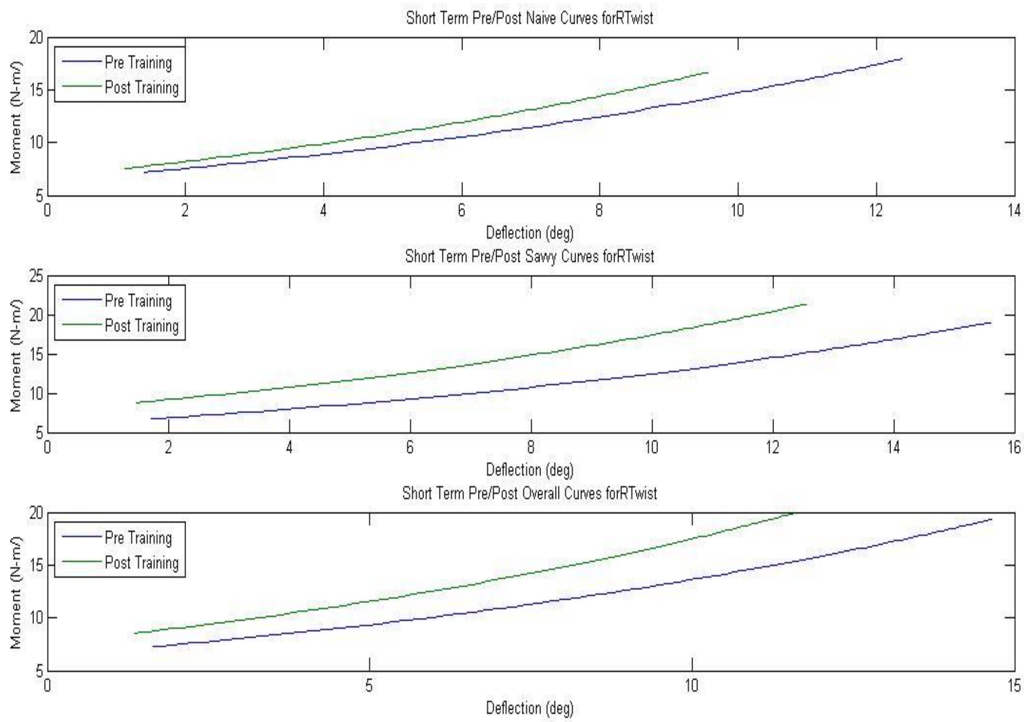

Figure 20: Summary of pre/post short term stiffness curves for passive right axial twist trials; applied moment (N-m) is denoted on the Y axis and deflection (deg) on the X axis. Top graph: naïve population response. Middle graph: savvy population response. Bottom graph: overall response.

4.2 Long Term Training

Similar analyses using corresponding range of motion at various percentages of applied moments was used to examine long term training response. A 3x2x2 repeated measures ANOVA (training group, subject group and time as the respective levels) was used to compare training response before and after training within each subject and training group, and between subject and training groups. Comparison plots of pre/post training response were made between training group (Isometric, Dynamic and Control) and subject groups (naïve and savvy).

As per the fourth and fifth hypotheses comparisons were made for pre/post long term training changes within each training and subject group to determine if each training style significantly changed torso stiffness for naïve and savvy subjects ($p < 0.05$). Significant changes were observed in both savvy and naïve populations following Isometric training for almost all bending tests and at multiple levels of applied moment, whereas only a single test at multiple levels of applied moment was found to be significantly different (RBend and LTwist for naïve and savvy populations respectively) following Dynamic training. Control groups had no significant changes in response after the six week period. A summary of the recorded range of motion values before and after long term training at 50, 65, 80, 90, 95 and 100% of pre training applied moment are shown in Table 9. Significant interactions are highlighted in Table 9; red denoting $p < 0.05$, yellow denoting $p < 0.01$ and green denoting $p < 0.001$.

Table 7: Summary table of ROM values at various instances of applied moment in response to pre/post long term core training for all bending tests. Values are organized by subject group and training group. ROM values were reported at 50, 65, 80, 90, 95 and 100% of applied pre training moment pre/post long term training. Comparisons were made to determine significant changes in ROM values at each level (applied moment, subject group, training group).

			Ext			Flex			Lbend			Ltwist			Rbend			Rtwist			Active		
Group	Exp		Mean	Std. Deviation	p	Mean	Std. Deviation	p	Mean	Std. Deviation	p	Mean	Std. Deviation	p	Mean	Std. Deviation	p	Mean	Std. Deviation	p	Mean (N-m/deg)	Std. Deviation	p
Isometric	Naive	ROMPre50	21.21			21.80	10.62	0.56	21.34			7.46	1.89	0.02	18.60	8.43	0.30	7.65	6.48	0.65	87.81	166.43	.21
		ROMPost50	6.81			18.54	4.56		9.49			1.25	1.00		4.20	1.82		5.54	1.62				
		ROMPre65	22.00	8.54	0.12	24.85	11.67	0.12	26.25		0.90	10.29	1.97	0.02	21.51	8.58	0.29	9.88	3.65	0.06			
		ROMPost65	6.51	4.43		16.18	10.10		11.12			2.65	1.87		5.53	2.60		3.70	3.43				
		ROMPre80	25.41	10.65	0.15	31.73	13.88	0.06	19.89	10.64	0.02	13.80	3.50	0.03	23.23	7.02	0.08	13.45	3.55	0.03			
		ROMPost80	12.69	1.64		19.29	9.72		7.05	4.78		4.40	2.99		6.10	3.14		5.04	3.34				
		ROMPre90	25.95	12.11	0.16	35.63	15.17	0.05	23.10	10.38	0.03	15.79	4.58	0.04	24.27	6.15	0.05	15.47	3.55	0.03	107.57	191.29	
		ROMPost90	15.74	4.11		21.06	9.51		11.04	5.37		5.38	3.62		8.67	4.90		5.80	3.29				
		ROMPre95	29.57	10.40	0.13	37.43	15.77	0.05	24.57	10.33	0.05	16.70	5.09	0.04	25.20	6.20	0.08	16.40	3.57	0.02			
		ROMPost95	18.12	4.31		21.87	9.41		12.87	6.19		5.84	3.91		10.50	6.47		6.15	3.27				
		ROMPre100	31.65	9.70	0.13	38.46	16.12	0.05	25.42	10.31	0.06	17.23	5.39	0.04	25.73	6.24	0.11	16.93	3.58	0.02			
		ROMPost100	19.46	4.54		22.32	9.33		13.91	6.76		6.09	4.09		11.55	7.50		6.34	3.27				
	Saavy	ROMPre50	9.58	6.41	0.29	23.24	3.89	0.23	20.28			6.78	2.00	0.16	11.58	11.02	0.39	10.28	3.38	0.08	92.91	163.18	.07
		ROMPost50	14.08	3.25		15.78	8.85		15.33			4.54	3.79		6.09	4.53		3.07	3.37				
		ROMPre65	12.09	4.95	0.74	28.35	4.01	0.12	13.12	10.45	0.90	11.08	0.32	0.12	15.38	10.76	0.31	10.72	4.94	0.04			
		ROMPost65	11.50	7.66		19.53	8.50		12.61	5.30		6.00	3.63		9.14	2.85		3.55	2.94				
		ROMPre80	15.17	7.20	0.45	34.70	4.93	0.03	17.31	10.97	0.49	14.38	4.33	0.04	20.10	10.71	0.22	14.26	4.23	0.01			
		ROMPost80	13.06	6.04		24.19	8.07		14.73	5.26		6.32	4.19		12.93	1.92		4.67	3.05				
		ROMPre90	19.48	7.38	0.19	30.96	15.40	0.03	23.79	9.54	0.04	17.20	5.10	0.04	22.77	10.82	0.18	16.26	3.84	0.01	149.61	170.19	
		ROMPost90	14.37	5.84		21.59	12.30		16.47	5.78		7.35	4.23		15.08	2.57		5.30	3.12				
		ROMPre95	21.45	7.92	0.16	34.33	12.29	0.00	26.77	9.64	0.02	18.50	5.48	0.04	24.00	10.90	0.17	17.18	3.67	0.01			
		ROMPost95	14.97	5.76		22.67	12.48		17.28	6.05		7.82	4.25		16.07	3.04		5.59	3.16				
		ROMPre100	22.59	8.34	0.16	36.27	10.60	0.00	28.48	9.91	0.02	19.25	5.71	0.04	24.71	10.96	0.16	17.71	3.57	0.00			
		ROMPost100	15.32	5.71		23.29	12.59		17.74	6.22		8.09	4.27		16.64	3.33		5.76	3.18				

Dynamic	Naïve	ROMPre50	7.66	4.34	0.46	14.33	3.27	0.12	6.961800^{0}	0.00		4.02	3.57	0.88	14.72	0.24	0.03	5.29	2.70	0.51	3.47	4.33	.25
		ROMPost50	6.47	6.61		17.75	0.98		9.308300^{0}	0.00		3.74	3.85		7.85	2.44		3.04	0.61				
		ROMPre65	11.22	5.29	0.17	19.21	4.72	0.38	12.54	0.41	0.53	5.76	4.49	0.48	18.41	0.70	0.02	6.91	2.53	0.09			
		ROMPost65	8.37	7.67		22.68	0.70		11.82	1.27		4.69	4.21		10.09	2.62		5.83	2.32				
		ROMPre80	12.34	8.47	0.89	21.58	9.12	0.46	17.89	10.07	0.46	7.92	5.90	0.18	18.09	9.84	0.24	6.31	3.30	0.45			
		ROMPost80	13.24	8.89		24.77	8.38		14.11	1.67		5.85	4.67		12.07	2.83		5.12	5.92				
		ROMPre90	16.48	6.74	0.73	26.67	7.40	0.86	23.70	10.92	0.19	9.15	6.77	0.13	22.09	7.11	0.04	7.26	3.48	0.73	30.21	38.06	
		ROMPost90	14.80	9.64		27.66	9.78		15.56	1.96		6.52	4.92		13.49	3.10		6.50	7.18				
		ROMPre95	18.38	6.37	0.52	29.01	7.03	1.00	26.36	11.43	0.13	9.71	7.18	0.12	23.93	5.88	0.01	7.69	3.56	0.83			
		ROMPost95	15.51	9.98		28.99	10.43		16.23	2.09		6.82	5.04		14.14	3.23		7.14	7.77				
		ROMPre100	19.47	6.31	0.39	30.35	6.97	0.94	27.89	11.76	0.11	10.03	7.41	0.12	24.99	5.18	0.01	7.95	3.61	0.87			
		ROMPost100	15.92	10.18		29.75	10.81		16.61	2.17		7.00	5.11		14.52	3.31		7.50	8.11				
	Saavy	ROMPre50	18.30			16.16	7.88	0.27	10.29	3.80	0.44	7.94	3.13	0.27	5.05	1.15	0.16	4.19	1.46	0.78	4.41	5.09	.35
		ROMPost50	15.40			20.39	7.98		14.98	6.68		4.17	2.46		12.29	5.75		3.77	1.41				
		ROMPre65	21.65			18.88	8.81	0.23	12.41	3.63	0.46	10.19	2.41	0.15	8.15	1.15	0.29	5.77	2.66	0.56			
		ROMPost65	17.54			23.99	8.01		17.38	7.28		5.83	2.15		14.55	6.60		4.45	1.41				
		ROMPre80	16.85	7.23	0.23	24.01	8.85	0.90	15.05	3.49	0.48	12.98	1.58	0.06	10.83	3.42	0.48	7.73	4.22	0.45			
		ROMPost80	14.42	6.82		22.97	12.80		20.36	8.06		7.90	1.78		14.49	8.49		5.29	1.41				
		ROMPre90	25.47	3.14	0.05	26.07	9.45	0.95	14.33	5.26	0.56	14.56	1.22	0.03	13.57	3.68	0.67	8.84	5.11	0.41	107.73	190.21	
		ROMPost90	17.48	6.42		26.51	11.14		17.68	11.17		9.07	1.57		16.15	8.78		5.77	1.40				
		ROMPre95	29.42	3.05	0.07	27.02	9.73	0.87	16.26	3.43	0.71	15.29	1.10	0.02	14.78	4.14	0.74	9.35	5.52	0.40			
		ROMPost95	18.89	6.56		28.14	10.41		18.63	11.00		9.61	1.48		16.91	8.92		5.99	1.40				
		ROMPre100	31.70	3.78	0.07	27.56	9.89	0.82	17.37	2.88	0.79	15.71	1.06	0.02	15.44	4.51	0.78	9.65	5.75	0.40			
		ROMPost100	19.70	6.73		29.08	10.01		19.18	10.91		9.91	1.43		17.34	9.00		6.12	1.40				

Control	Naïve	ROMPre50	4.37			23.71	4.35	0.26	5.48	3.16	0.26	6.26	2.65	0.36	8.71	2.93	0.63	3.26	0.22	0.53	24.95	16.56	.44
		ROMPost50	11.49			21.78	3.17		12.57	7.52		8.24	1.48		9.49	1.90		4.43	3.43				
		ROMPre65	13.49	12.61	0.99	22.24	13.45	1.00	9.71	4.31	0.05	8.17	2.17	0.38	13.58	1.92	0.17	5.11	0.69	0.17			
		ROMPost65	13.27	7.91		22.27	5.21		16.32	5.18		9.97	1.74		12.46	2.68		7.62	2.76				
		ROMPre80	21.29	13.79	0.78	26.05	14.38	0.44	14.26	7.54	0.00	10.54	2.08	0.41	16.02	7.44	0.33	7.42	1.81	0.05			
		ROMPost80	17.70	6.52		22.43	8.02		17.27	7.76		12.11	2.21		13.93	5.38		11.59	2.50				
		ROMPre90	20.59	16.00	0.95	32.97	11.57	0.11	18.12	8.65	0.25	11.89	2.31	0.43	20.01	6.59	0.09	8.72	2.45	0.04	17.49	14.16	
		ROMPost90	19.87	4.75		24.54	7.98		19.28	8.47		13.33	2.52		15.54	6.44		13.83	2.72				
		ROMPre95	23.82	15.07	0.78	36.15	10.49	0.07	19.89	9.18	0.80	12.51	2.47	0.45	21.84	6.27	0.07	9.33	2.74	0.04			
		ROMPost95	21.06	4.47		25.50	7.99		20.20	8.82		13.89	2.67		16.26	6.98		14.87	2.90				
		ROMPre100	25.67	14.71	0.69	37.98	9.94	0.06	20.91	9.48	0.90	12.87	2.58	0.46	22.89	6.11	0.07	9.67	2.90	0.04			
		ROMPost100	21.71	4.37		26.04	8.00		20.72	9.04		14.20	2.77		16.66	7.30		15.44	3.04				
	Saavy	ROMPre50	21.30	0.13	0.90	19.35	10.68	0.85	14.77	9.91	0.99	7.80	2.39	0.86	17.26	12.79	0.31	6.79	0.58	0.73	22.39	31.58	.58
		ROMPost50	19.86	13.11		18.72	9.91		14.82	5.10		8.27	1.75		14.23	12.76		5.29	4.15				
		ROMPre65	26.67	1.93	0.78	22.32	11.35	0.94	17.16	9.82	0.93	8.85	3.50	0.90	16.92	13.50	0.21	7.88	2.53	0.39			
		ROMPost65	23.62	14.11		22.04	10.69		17.47	5.02		8.66	3.17		14.22	12.89		6.26	3.26				
		ROMPre80	23.74	12.10	0.29	26.00	12.21	0.97	17.92	9.08	0.91	12.21	3.08	0.50	22.20	13.16	0.20	11.75	2.75	0.61			
		ROMPost80	18.28	14.65		26.16	11.74		17.64	7.43		11.04	3.10		18.61	13.31		10.81	2.65				
		ROMPre90	31.63	7.34	0.08	28.09	12.70	0.94	20.53	8.29	0.72	14.12	2.84	0.36	25.20	13.06	0.23	13.95	3.17	0.81	10.53	8.06	
		ROMPost90	20.46	15.31		28.50	12.37		19.40	7.58		12.40	3.16		21.11	13.57		13.39	2.78				
		ROMPre95	35.25	5.65	0.07	29.05	12.93	0.92	21.73	8.05	0.67	14.99	2.73	0.32	26.57	13.03	0.24	14.96	3.41	0.88			
		ROMPost95	21.47	15.61		29.58	12.66		20.21	7.66		13.02	3.22		22.25	13.69		14.58	2.96				
		ROMPre100	37.34	5.02	0.07	29.60	13.06	0.91	22.42	7.94	0.64	15.50	2.67	0.30	27.36	13.02	0.25	15.54	3.55	0.92			
		ROMPost100	22.05	15.79		30.19	12.83		20.68	7.70		13.38	3.25		22.91	13.77		15.26	3.08				

As per the sixth and seventh hypotheses, comparisons were made between training groups (within each subject group) and between subject groups (within each training group) to determine if the changes experienced through changing were statistically different between these groups ($p < 0.05$). These comparisons were assessed using a 3x2x2 repeated measures ANOVA with training group, subject group and time as the various factors. A summary of p values for comparison between subject groups (naïve vs. savvy) is found in Table 8 and a summary of p values for comparison between training groups (Isometric vs. Dynamic vs. Control) is found in Table 9. No significant interactions were found when comparing between both of these groups.

Mean response of pre/post training moment/deflection plots are found in Figures 28-34. The plots are separated by training group and subject groups with each figure separated by the bending test. Nine plots are found in each figure and correspond to (starting top left and moving to the right) naïve isometric, naïve dynamic, naïve, control, savvy isometric, savvy dynamic, savvy control, overall isometric, overall dynamic and overall control.

Table 8: Summary table of p values for comparison of stiffness between subject groups (naïve vs. savvy groups within each training group) for each bending test.

Test	Training Group	Subject Group	p (50%)	p (65%)	p (80%)	p (90%)	p (95%)	p (100%)
Ext	Iso	Naïve						
		Savvy	0.78	0.70	0.34	0.43	0.24	0.14
	Dyn	Naïve						
		Savvy	0.26	0.32	0.57	0.21	0.13	0.10
	Con	Naïve						
		Savvy	0.36	0.09	0.85	0.41	0.38	0.36
Flex	Iso	Naïve						
		Savvy	0.91	0.63	0.82	0.83	0.90	0.95
	Dyn	Naïve						
		Savvy	0.65	0.92	0.96	0.87	0.79	0.74
	Con	Naïve						
		Savvy	0.65	0.99	0.82	0.95	0.84	0.78
Lbend	Iso	Naïve						
		Savvy	na	0.58	0.66	0.59	0.57	0.56
	Dyn	Naïve	0.17	0.22	0.66	0.94	0.77	0.69

		Savvy						
	Con	Naïve						
		Savvy	0.42	0.44	0.73	0.83	0.88	0.90
Ltwist	Iso	Naïve						
		Savvy	0.40	0.85	0.58	0.51	0.49	0.48
	Dyn	Naïve						
		Savvy	0.25	0.23	0.22	0.22	0.22	0.22
	Con	Naïve						
		Savvy	0.34	0.12	0.85	0.69	0.63	0.60
Rbend	Iso	Naïve						
		Savvy	0.63	0.80	0.46	0.51	0.57	0.61
	Dyn	Naïve						
		Savvy	0.24	0.19	0.54	0.38	0.30	0.25
	Con	Naïve						
		Savvy	0.42	0.76	0.48	0.49	0.49	0.49
Rtwist	Iso	Naïve						
		Savvy	0.98	0.88	0.92	0.95	0.96	0.96
	Dyn	Naïve						
		Savvy	0.72	0.34	0.75	0.88	0.93	0.96
	Con	Naïve						
		Savvy	0.23	0.64	0.24	0.16	0.15	0.14
Active	Iso	Naïve						
		Savvy	0.85					
	Dyn	Naïve						
		Savvy	0.46					
	Con	Naïve						
		Savvy	0.62					

Table 9: Summary table of p values for comparison of stiffness between training groups (isometric vs. dynamic vs. control groups within each subject group) for each bending test.

Test	Subject Group	Training Group	p (50%)	p (65%)	p (80%)	p (90%)	p (95%)	p (100%)
Ext	Naïve	Iso						
		Dyn						
		Con	0.62	0.62	0.28	0.54	0.33	0.24
	Savvy	Iso						
		Dyn						
		Con	0.46	0.25	0.55	0.30	0.20	0.15

Flex	Naïve	Iso						
		Dyn						
		Con	0.38	0.96	0.95	0.97	0.96	0.95
	Savvy	Iso						
		Dyn						
		Con	0.98	0.94	0.93	0.96	0.97	0.97
Lbend	Naïve	Iso						
		Dyn						
		Con	0.43	0.32	0.86	0.89	0.90	0.90
	Savvy	Iso						
		Dyn						
		Con	0.74	0.71	0.93	0.99	0.93	0.87
Ltwist	Naïve	Iso						
		Dyn						
		Con	0.09	0.14	0.23	0.27	0.29	0.30
	Savvy	Iso						
		Dyn						
		Con	0.23	0.88	0.75	0.74	0.72	0.71
Rbend	Naïve	Iso						
		Dyn						
		Con	0.44	0.80	0.93	0.91	0.92	0.93
	Savvy	Iso						
		Dyn						
		Con	0.49	0.80	0.48	0.44	0.42	0.40
Rtwist	Naïve	Iso						
		Dyn						
		Con	0.44	0.96	0.23	0.23	0.23	0.23
	Savvy	Iso						
		Dyn						
		Con	0.21	0.45	0.06	0.06	0.06	0.06
Active	Naïve	Iso						
		Dyn						
		Con	0.49					
	Savvy	Iso						
		Dyn						
		Con	0.44					

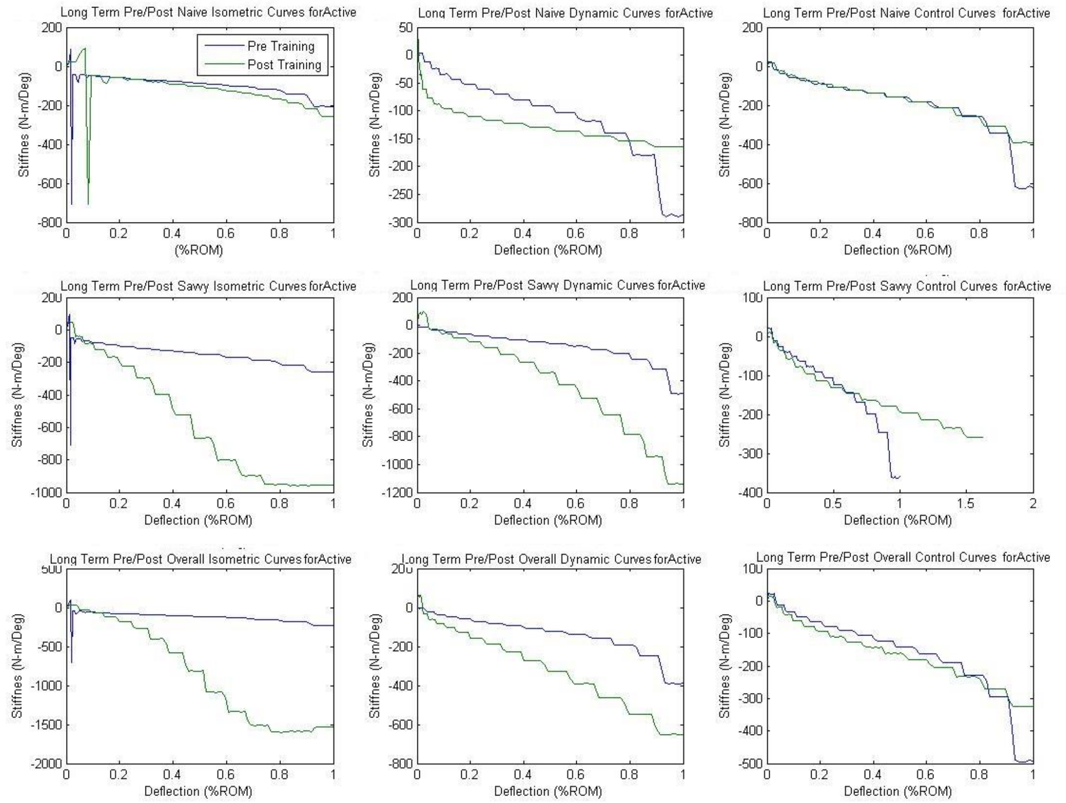

Figure 21: Summary stiffness curves for active extension trials with stiffness (N-m/deg) plotted on the Y axis and range of deflection(%ROM) on the X axis. Plots were created from the data obtained during the first 250 ms following release of the applied load. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

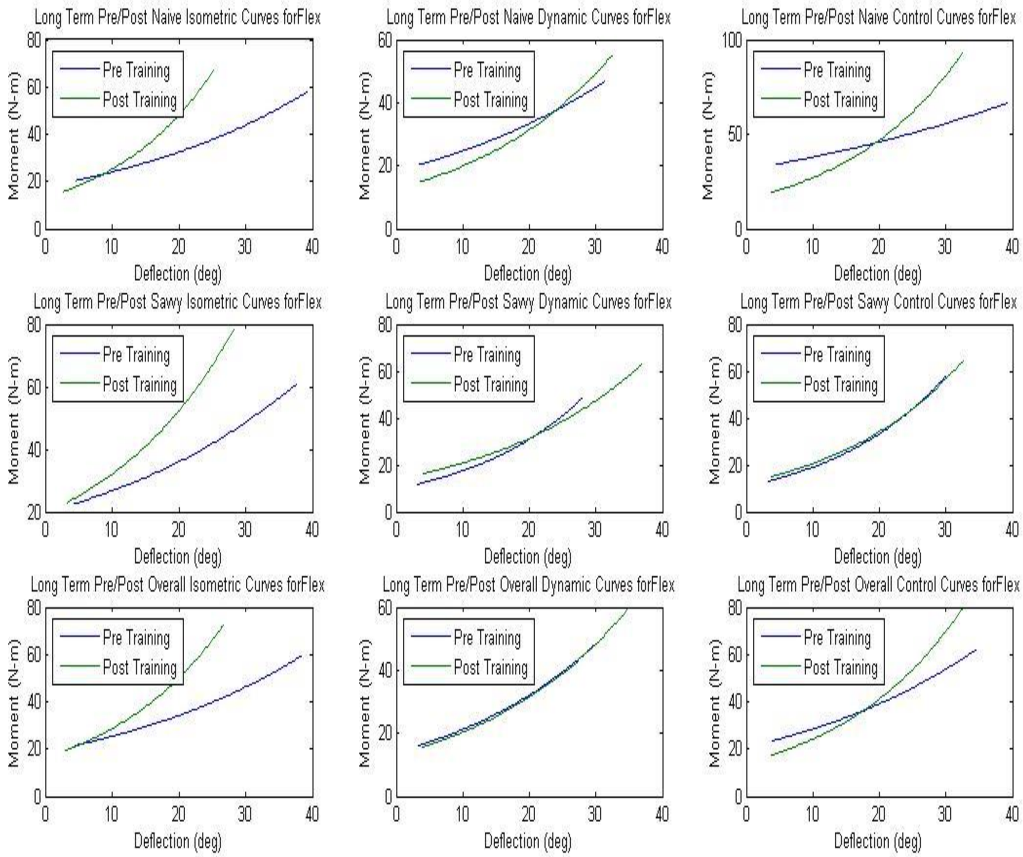

Figure 22: Summary stiffness curves for passive flexion trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

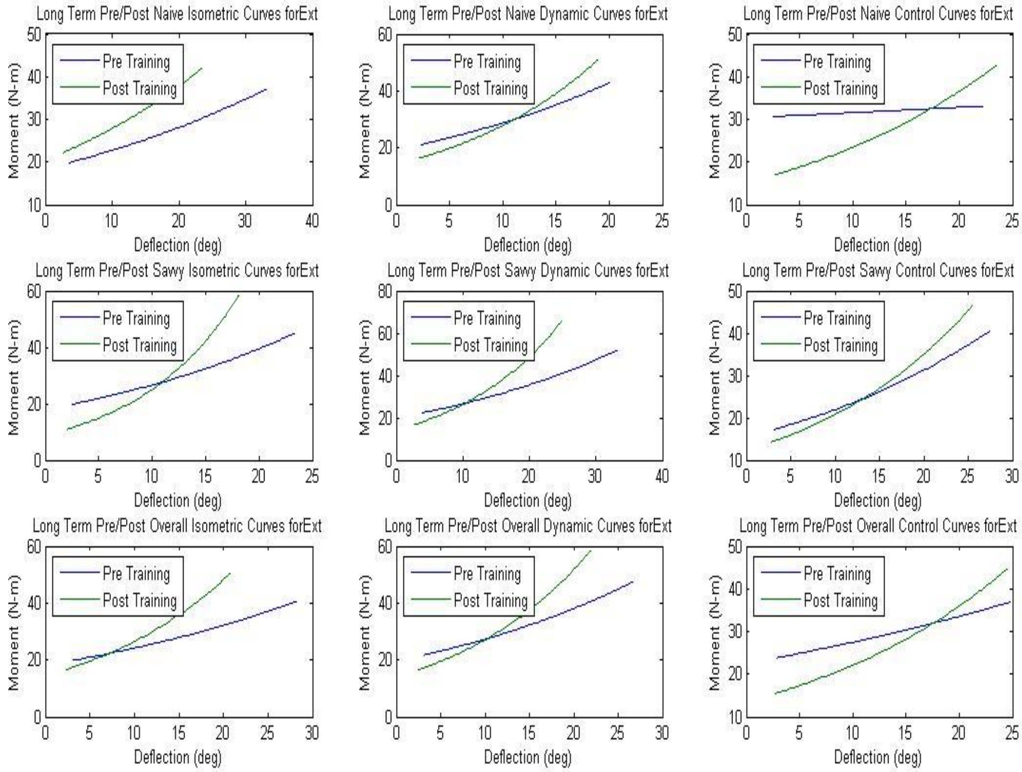

Figure 23: Summary stiffness curves for passive extension trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

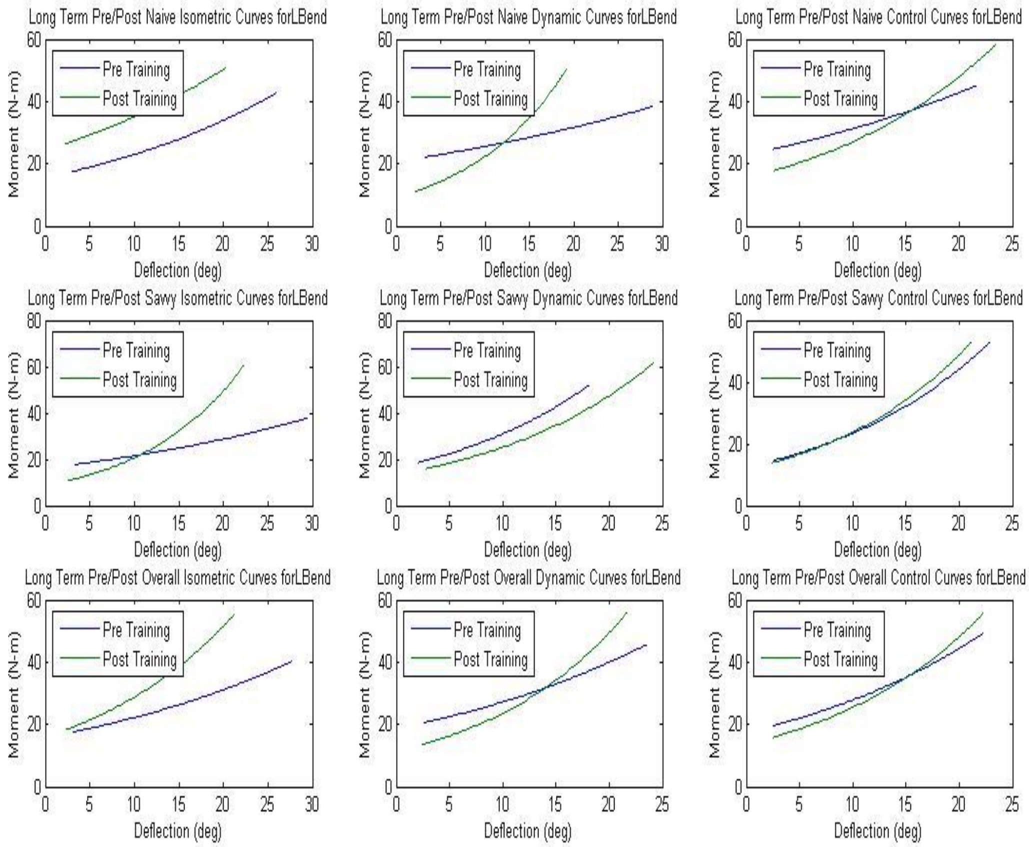

Figure 24: Summary stiffness curves for passive left lateral bend trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

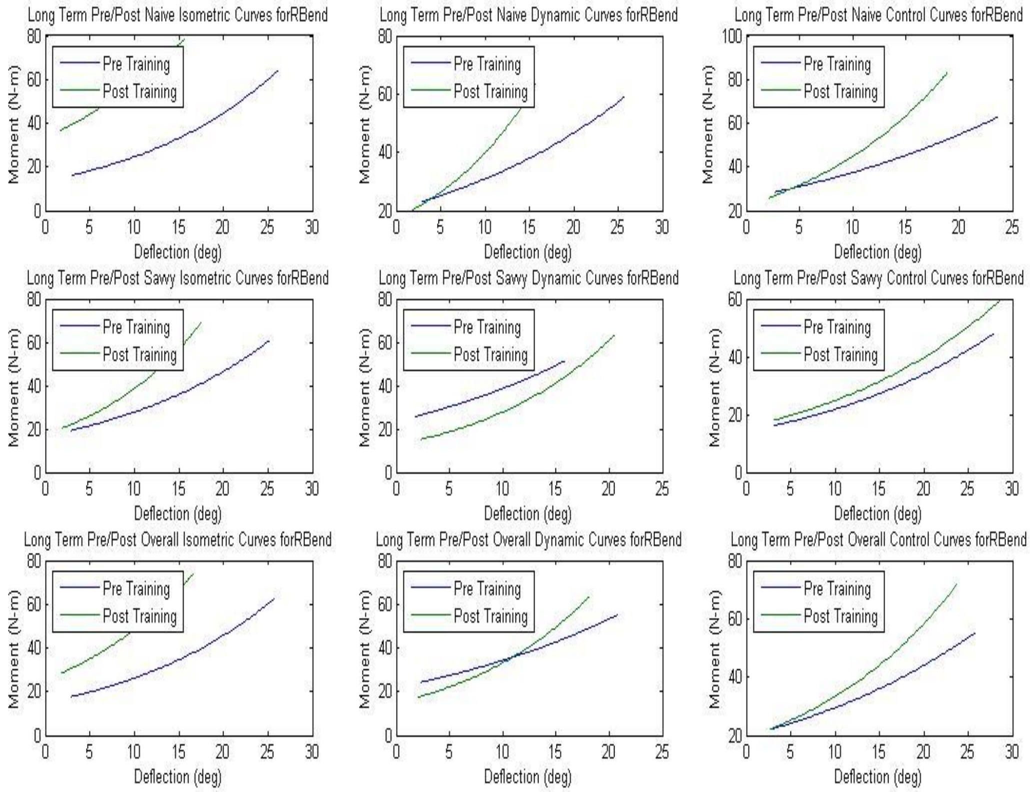

Figure 25: Summary stiffness curves for passive right lateral bend trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

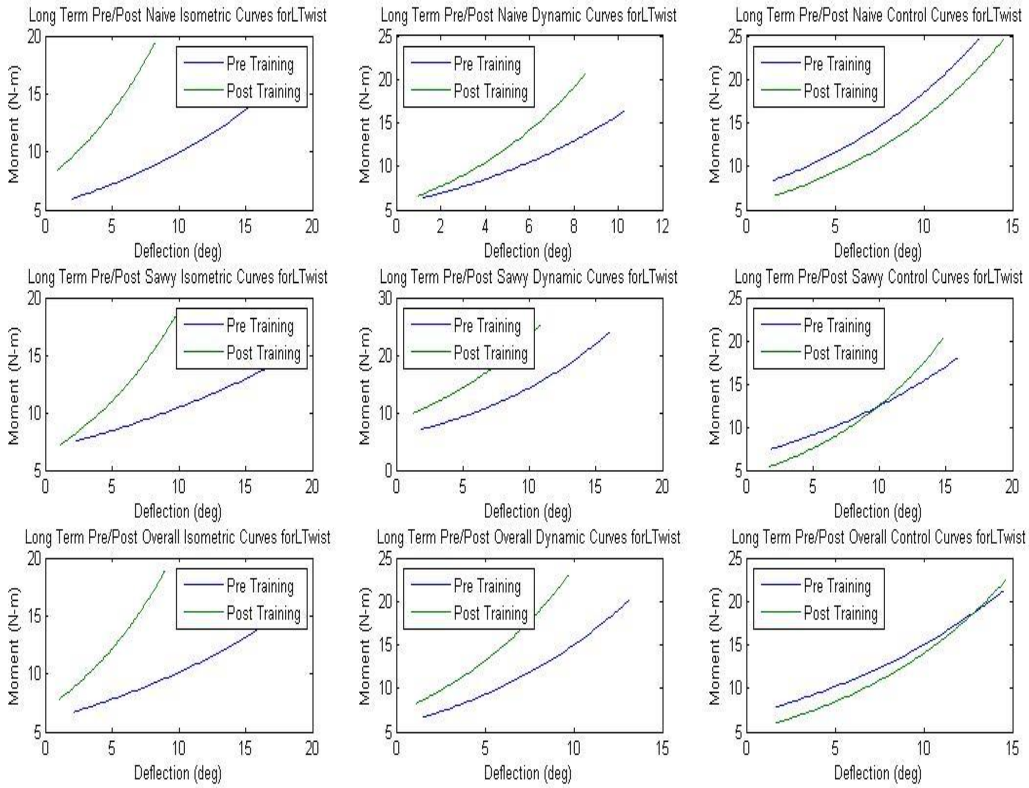

Figure 26: Summary stiffness curves for passive left axial twist trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

.

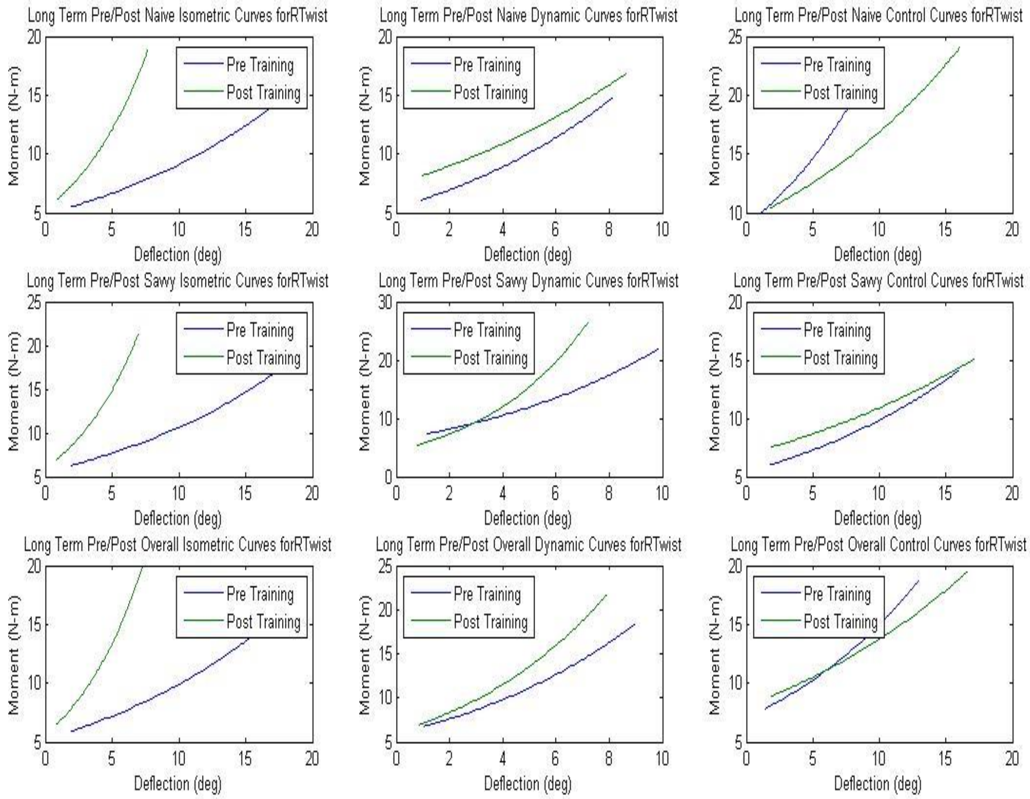

Figure 27: Summary stiffness curves for passive right axial twist trials with applied moment (N-m) plotted on the Y axis and deflection (deg) on the X axis. Top left: naive isometric group. Middle left: savvy isometric group. Bottom left: Overall isometric. Top middle: naive dynamic group. Centre: savvy dynamic group. Bottom middle: Overall dynamic. Top right: naive control group. Middle right: savvy control group. Bottom right: Overall control.

Chapter 5

Discussion

The goal of this experiment was to investigate potential adaptations to core stiffness during short duration and long term bouts of differing core training types.. Distinct hypotheses were made with regards to the effects of short and long term training on torso stiffness. Each hypotheses was tested via statistical analysis of the results of short and long term training on torso stiffness and summarized below.

Table 10: Summary of hypotheses and results based off statistical analysis.

Hypothesis	Accept/Reject?	Comments
1) Post training Short Term Passive stiffness is increased over pre training passive stiffness with **short term isometric core training**.	Accept	Post training range of motion significantly less than pre training value. This held true beyond 80% of applied moment for all directional tests and beyond 50% of applied moment in some cases ($p < 0.05$)
2) Post training Active stiffness is increased over pre training active stiffness with **short term isometric core training**.	Accept	Post training stiffness values significantly higher than pre training values ($p < 0.05$)
3) Post training Short Term Passive and Active stiffness is increased over pre training stiffness to a greater degree in **naive populations** than in **savvy populations.**	Reject	2x2 Repeated Measures ANOVA between subject groups showed no significant changes ($p < 0.05$) for all directional tests.
4) Post training Long Term Passive stiffness is increased over pre training values to a greater degree after **Isometric** training, in both naïve and savvy populations, whereas no significant pre/post changes are predicted for **Dynamic** or **Control** groups.	Accept	Significant decreases ($p < 0.05$) in range of motion found for almost all directional tests.

5) Post training Long Term <u>Active stiffness</u> is increased over pre training values to a greater degree after **Isometric** training, in both naïve and savvy populations, whereas no significant pre/post changes are predicted for **Dynamic** or **Control** groups.	Reject	No significant changes detected ($p < 0.05$)
6) Post training Long Term <u>Passive</u> and <u>Active stiffness</u> are increased to a greater degree in the **Naive** population than in the **Savvy** population.	Reject	3x2x2 Repeated Measures ANOVA revealed no significant changes between subject groups for all directional tests ($p < 0.05$)
7) Post training Long Term <u>Passive</u> and <u>Active stiffness</u> are increased to a greater degree in the **Isometric** training group than in the **Dynamic** or **Control** groups.	Reject	3x2x2 Repeated Measures ANOVA revealed no significant changes between training groups for all directional tests ($p < 0.05$)

Given the multitude of tests and relationships formed it is difficult to generalize an overall effect but the following statements can be made:

- Short term Isometric core training increased passive stiffness in both naïve and savvy populations.
- Short term Isometric core training increased active stiffness in both naïve and savvy populations.
- Naïve and savvy populations did not significantly ($p < 0.05$) differ in response to short term Isometric core training.
- Long term Isometric core training increased passive stiffness in both naïve and savvy populations, whereas long term Dynamic and Control groups did not experience such increases.
- Long term Isometric, Dynamic or Control training did not significantly ($p < 0.05$) increase active stiffness.
- Naïve and savvy populations did not significantly ($p < 0.05$) differ in response to any long term core training.
- Isometric, Dynamic and Control groups did not experience any significant differences in

response to training.

Mechanisms and factors addressing the results of each hypothesis will be made in the following subsections. Researchers believe there to be many underlying biological issues which affected statistical significance, and that statistically insignificant data does not mean it is not biologically significant. Explanations of such issues, as well as potential mechanisms for adadptations to core training will be discussed.

Statistical analysis was performed on range of motion data for corresponding percentages of applied moment. As stiffness is directly proportional to applied moment and inversely proportional to range of motion, shorter range of motion values at the same applied moment would infer greater stiffness at that instantaneous point.

Observations of the original filtered moment/deflection curves yielded three distinct phases – an initial high stiffness zone, a transition zone and end high stiffness zone. The initial high stiffness zone was thought to be a result of stiction due to the subject's mass, requiring a higher applied torque to overcome the initial inertia. As this was of non-biological significance the initial high stiffness zone was removed before curve fits were applied (Figure 12). The transition and end high stiffness zones agree with curves generated from previous passive stiffness research (Beach et. al., 2005). The transition zone is characterized by a low stiffness region occurring for most of the trial. This can be described as the period in which initial inertia of the subject has been overcome and the subject has been pulled out of their neutral zone, but not yet approaching end range of motion. The end high stiffness zone occurred as the subject approached end range of motion. In this high stiffness zone tendons, ligaments, discs and other passive tissues contribute greatly to passive stiffness, akin to what has been described in the Force-Length relationship of Hill's Muscle Model, and helps explain how peak stiffness is achieved at end range of motion.

5.1 Short Term Training

Subjects completed a fifteen minute bout of isometric core exercises between passive and active stiffness measurements. Investigation into the muscle activity and spine load of the plank, side bridge and bird dog have revealed their ability to create high levels of core musculature activation while minimizing compressive and shear loads to the spine (McGill and Karpowicz, 2009). For some subjects these exercises were brand new and have never been performed, but for other subjects these exercises were typical of a training regimen regularly performed. The most popular comment (22 out of 24 subjects made the same qualitative statement), when asked by researchers to describe how they felt after training, was an increased feeling of ‘warmth’ and ‘pump’ throughout the anterior, posterior and lateral core. Whether this feeling was due to increased blood flow to the musculature (Eklund et.al, 1974; Brundin, 1976) or enhanced neural activation of core musculature (Carolan and Cafarelli, 1992) is unknown but speculation can be made to the mechanism of increased stiffness.

5.1.1 Passive Stiffness

Passive stiffness generally increased with short term training for both naïve and savvy subjects. The first hypothesis proposed was proven to be true – both naïve and savvy groups increased stiffness across all passive and active tests – all subjects saw significant reductions in range of motion ($p < 0.05$) for all passive tests at 80% of applied moment and above. At 65% of applied moment naïve subjects still showed significant reductions in range of motion in all tests except for extension direction whereas savvy subjects showed significant changes in all tests except for extension and left lateral bend directions. Naïve subjects still showed significant changes at 50% of applied moment in all tests except for extension and lateral bend directions but savvy subjects did now show such a response to training at this level of applied moment with only flexion and right axial twist showing significant changes. A general trend appeared with this analysis – as applied moment increased larger differences in range of motion (and thus stiffness) were detected – this held true generally above 80% of applied moment for all subjects across all tests. As passive stiffness becomes a greater function of passive stiffness near end range of motion, this explains the reasoning of researchers to use a more sensitive scale to detect changes beyond 80% of applied moment. Interestingly, naïve subjects showed more changes than savvy subjects at lower applied moments. Greater changes in the transition zone indicate possible greater adaptations to short term training. However, when comparing changes between subject groups no statistically significant differences were detected in all tests and across all percentages of applied moment. Some comparisons showed close significance ($p \sim= 0.07 – 0.08$), namely left and right axial twist trials. Though naïve subjects showed greater changes in the transition zone than savvy subjects, lack of statistical significance caused researchers to deem Hypothesis 3 as invalid. Researchers felt that insignificance between groups may have been due to inadequate power and/or high variances. Though statistically insignificant, researchers believe this does not mean the data is biologically insignificant. High variances suggest a wide response to training.

Though these variances contribute to statistical insignificance, biologically this would mean that subjects responded to training in a variety of ways – some gaining great amounts of passive stiffness while others not responding to training. Many possible reasons as to why this occurred are discussed later in this section. Issues of non-responders vs ‘super responders’ and physical adaptations to imposed demands were proposed as biological factors affecting variances.

Researchers proposed the mechanisms of action affecting stiffness changes by investigating physiological and neural adaptations following isometric and resistance exercise. Evidence suggests that stiffness increases measured in the transition zone may have been due to hyperemia experienced by skeletal muscle following isometric contraction. As passive tissue stiffness were thought to contribute to the changes experienced above 80% of applied moment, changes within skeletal muscle are thought to contribute to stiffness increases in the transition zone. Brief sustained contractions have been shown to increase blood flow when applied to various body parts; forearm (Corcondilas et. al., 1964), arm and back (Bonde-Petersen et. al., 1975) and arm and lower limb (Laughlin et. al., 1996). During isometric contraction blood flow to the muscle decreases but upon release an overshoot effect occurs followed by a period of sustained hyperemia (Laughlin, et. al., 1996). It would not be surprising that this effect occurred following the short bout of isometric core exercise and hyperemia of the core musculature explains the feeling of ‘pump’ described by the subjects. How hyperemia affects muscular stiffness may be linked to intramuscular pressure; some researchers believe muscular stiffness results from the accumulation of extracellular muscle fluid (Schaefer, 1986), which in the case of the experiment would be due to the hyperemic state following sustained isometric contraction. Intramuscular pressure has been proposed as a mechanism of increasing passive stiffness in skeletal muscle (Iinuma et. al., 1996; Miyamoto et. al., 1998). The increased extracellular fluid retention from increased muscular blood flow may increase intramuscular pressure and thus explain mechanisms of action for enhance passive stiffness following isometric core training.

Comparing changes between subject groups yielded no significant changes despite observations that naïve subjects changed stiffness in the transition zone whereas savvy subjects did not. Though these differences were not statistically significant a biologically significant effect can be construed from this data. While some subjects experienced little to no changes in stiffness and range of motion others experienced drastic increases in stiffness and reduction in passive range of motion. As a result mean effects resulted in little to no overall change or contributed to large values of variance. Statistically this overall effect was considered insignificant but an underlying issue of biological individuality and significance is raised. Variation between subjects suggests a training effect has occurred but other factors may influence training response. Multiple explanations for this variability are proposed here. First, there may have been a time-dependent effect on this where temporary increases in stiffness wore off due to the length of time each trial required. As the training session took only 10-15 minutes there is a great possibility that the temporary stiffness enhancements wore off due to dissipation of blood flow or decline in neural drive. Though participants reported a 'pump' like effect after isometric training, a qualitative description which agrees with observations of enhanced vasolidation following sustained isometric contractions (Laughlin et. al., 1996). However, vascular dynamics following isometric contractions are dependent on the intensity and duration of contractions (Bellemare et. al., 1983). Enhanced blood flow can last up to 60-120 minutes after repeated contractions of large muscle groups but these findings were made for dynamic contractions where rhythmic contraction of skeletal muscle expels blood during contractile periods and increases the arterio-venous pressure gradient for blood flow (Korthuis, 2011). It is a possibility that the magnitude and type of contractions (sustained short isometric compared to intense dynamic) performed by the subjects were not intense or long enough to incur the magnitude vascular response described by Korthuis. Though enhanced blood flow may occur as explained by Laughlin the residual effect may have ended by the time subjects were measured during post training tests. A second possible explanation for variance between subjects involves the issue of responders vs. non responders to physical stimulus. As a subject performs a greater deal of physical activity, neurological, physiological and biomechanical adaptations occur to suit this imposed demands (Kraemer et. al., 1988; Hakkinen et. al., 1988; Fahey, 1998; Folland and Williams, 2007). Intensity and volume demands were held constant during the short term training bout and it can be assumed that subjects with greater training experience did not incur adaptations seen in lesser trained subjects and perceived training to be easier (decreased %MVC and feeling of intensity/demand). It was expected that subjects from the athletic population would not respond to the short term training program as much as the student population. To standardize the dependent variables, exercise cues were held constant for athletic and student populations. While these exercises may have been considered challenging to the student population, the athletic population was familiar with regular resistance and core exercise. As the body adapts to specific demands applied to it, it would make sense that the athletic population would not respond as drastically as the student population.

Specific cases of 'super responders' (individuals who saw the highest net changes in stiffness after training) and ‘non responders’ (individuals who did not see much or any net changes) were observed; these two opposite ends of the response spectrum may explain why few overall net changes were observed for some directions of passive bending. Two examples of this are shown below; Figure 40 compares an example of an athletically trained ‘non-responder’ and student ‘super-responder.’ Despite undergoing the same core training program as all other subjects the non-responder showed little change in pre/post stiffness values. Not surprisingly, this subject was self described as performing bodyweight core exercises almost daily and regularly performing barbell exercises involving load bearing of the torso up to four times per week. The evidence cited with regards to adaptations to resistance training supports the hypothesis that subjects with experience in core training would not respond to low level core exercises as well as untrained subjects. In contrast, the comparison plot exemplifies a good responder belonging to the student population. Note the distinct decrease in end range of motion for the same moment applied, indicating greater overall stiffness. Unlike the non-responder, this subject was self described as being an ‘on and off’ recreational weight lifter but had not been active for four months prior to the start of the study. Again, this supports the thought that individuals not accustomed to core training would achieve much more drastic results than those experienced in training.

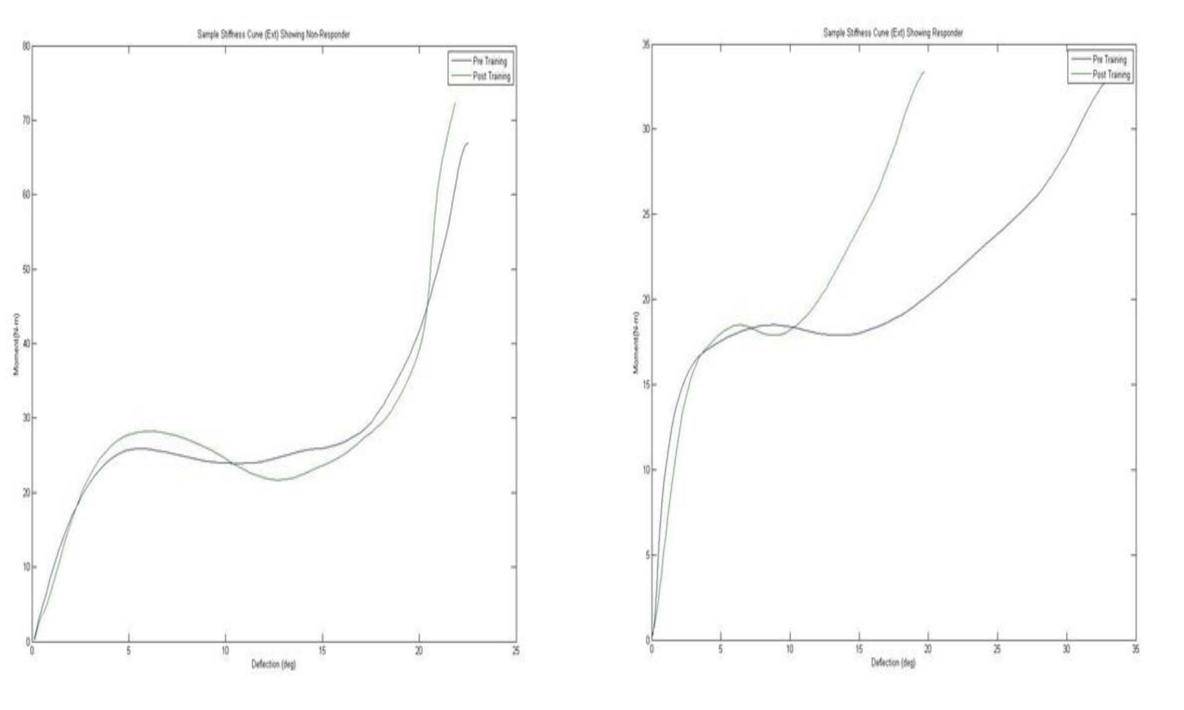

Figure 28: Example raw stiffness curves of a 'non-responder' (left) and ‘super-responder (right). After short term core

training, stiffness among the various phases and end range of motion did not change significantly from the pre training condition. This non-responder subject belonged to the athletically trained subgroup and self described as regularly performing bodyweight core exercises almost daily and barbell exercises involving heavy external load and load bearing through the torso four times per week. The super-responder was self described as an on and off recreational weight lifter but had not been performing any exercise regularly for four months prior to the start of the study. Note the 15 degree decrease in range of motion after short term core training. Applied moments were similar but significant decrease in end range of motion is observed in this figure.

The reduction in passive end range of motion is thought to be a direct result of increased stiffness. By its mathematical definition, as stiffness increases the amount of deflection experienced will decrease given the same kinetic input. Taking this finding into practical application there are many instances where decreasing spinal end range of motion will prevent spine injury and help decrease pain response. Taking the spine to extreme ranges of motion is an accepted mechanism of injury to ligamentous, disc and facet structures (McGill, 1998; Liebenson, 2008) and avoidance of this kinematic motion acts as a prevention mechanism. From an athletic perspective, there are many instances where spinal motion is an unwanted byproduct of poor movement mechanics and/or core activation. Many athletes involved in 'powerlifitng' type movements (heavy load bearing exercises such as the barbell squat and deadlift) incur injuries about the spine due to a combination of high compressive loads with intersegmental spine motion (Brown and Albani, 1985). Similar exercises involving high compressive loads without spine motion (such as Olympic Weightlifting movements) do not incur as many spinal injuries, and further evidence showing the elimination of spine movement during the traditional powerlifts reduced the incidence of spine injuries (Farfan, 1975; Farfan, 1983; Fortin and Falco, 1997). Though compressive loads during Olympic Weightlifting remain extremely high, beyond that of what is predicted to cause compressive injuries (Granhed, 1987), enhanced muscular activation and stiffness allows the spine the bear greater loads (Cholewicki et. al., 1991) and reduce spine range of motion, improving safety and performance during these high load exercises. As a result, it is evident that the short duration isometric core exercise protocol improves the ability to prevent injury and improve performance in load bearing tasks. The results showed passive and active stiffness both improved after isometric core training, however in real world applications where active contributions of muscular activation are seen in almost all tasks involving the trunk, the effects from active bending trials have the greatest applicability.

The application of a training regimen consisting of short duration isometric exercises may serve well as part of an athlete's warm up routine prior to any physical activity which requires heightened levels of core stiffness, such as heavy load bearing. Temporary enhancements to passive stiffness may give insight as to how short duration isometric core training may assist individuals in activities where passive spine motion is unwanted – this may range from basic activities of daily living, such as picking a basket off the ground, to higher demand and more complex tasks such as running or other multi-directional high speed/load tasks. The issue with unwanted passive spine motion is that kinetic or kinematic loads at the joints may influence spine motion especially if loads are placed off axis from the centre of the spine and introduce external moments about the spine. In a task such as running or walking, uniaxial loads about distal limb segments create external moments about the spine – if stiffness throughout the torso is insufficient these external moments will lead to cyclical kinematic motion of the spine. Analysis of walking and running patterns on spinal kinematics back this statement up as three dimensional kinematic analysis of the lumbar spine during running revealed a ten degree cyclical axial twisting and lateral bending motion (Schache et. al., 2002). Even lower level tasks such as walking have been shown to repetitive spinal flexion-extension cycles (Levine et. al., 2007).

5.1.2 Active Stiffness

Significant increases in active stiffness were recorded for both naïve and savvy subjects. Though these changes were significant within subject groups, between subjects analysis revealed no significant differences suggesting both naïve and savvy subjects both increased stiffness similarly. Researchers felt hyperemia was not a mechanism affecting active stiffness changes a time delay effect involving activation state of the core musculature may be. As core stiffness and spinal stability are closely related to muscular activation level researchers believed an enhanced motor activation state was responsible for increases in active stiffness. Taking this theme of unwanted spine motion explored in the previous section, a strategy which can be readily adopted to prevent this motion is reactive control and activation of the core musculature. While reductions in passive spine motion were shown to be achieved through short term core training, the strategy of reactive core activation seems to make more sense in a practical setting for real world tasks. Increased core stability through core musculature activation has been stated to enhance a multitude of physical features – load bearing ability, pain management and distal limb movement are all examples (McGill, 2009). Preservation of neutral spine postures is a function of core musculature activation (Cholewicki et. al., 1997). Not surprisingly core activation has been shown to increase with applied loads to the trunk, demonstrating the reactive control of the neuromuscular system to preserve spinal stability and resist buckling (Bergmark, 1987). Results from this experiment agree with this rationale as active bending trials required not only sufficient core activation, but reactive activation against sudden perturbations. Short term core training enhanced active stiffness to a greater degree than passive stiffness. These results were not surprising to researchers – the short duration exercise is thought to enhance neural drive to the core musculature temporarily, allowing greater activation and thus stiffness and stability of the torso. This thought is akin to the post activation potential phenomenon – after periods of sustained MVC (Vandervoort et. al., 1983; Gossen and Sale, 2000) or repeated submaximal stimulus (Macintosh et. al., 2000) an overflow of calcium ions (Ca^{2+}) potentiates affected musculature enhancing contraction strength, rate of force development and twitch potentiation (Gullich and Schmidtbleicher, 1996; Gossen and Sale, 2000; French et. al., 2003). The research cited used short term near maximal isometric contraction as a method of inducing post activation potential prior to a strength task, similar to the isometric exercises given to participants in this study. Two main differences between the isometric exercises in the cited literature and this study exist: isometric contractions performed by subjects in this study were not maximal contractions, and the cited studies examined the effects only on limb musculature (lower and upper limbs for bench press, squat and jump performance). Though the isometric core exercises were submaximal subjects were given cues (bracing core, squeezing glutes, tightening fists) to potentiate neural activation of the entire body (McGill, 2009). These isometric exercises, without bracing cues, create activation levels between 20-70% MVC (Ekstrom et. al, 2007; McGill and Karpowicz, 2009), which would further be enhanced by co-contraction cues. To the researcher's knowledge, threshold activation levels to induce post activation potential has not been explored, but enhancements in activation during isometric exercises are thought to illicit this effect on subjects.

It was concluded that more research is needed to give greater insight into the effects of short term training on active stiffness. Though mean values showed increases in active stiffness, high variances between subjects resulted in insignificant changes and thus hypotheses set regarding increases in stiffness within and between subject groups for active stiffness were considered invalid. Statistically significant changes in stiffness could not be reported but cases of biologically significant changes via qualitative reporting from subjects showed that a training effect was taking place. From the comments of the subjects, an increased warmth or pump like feeling was reported, along feelings of greater motor control of the core musculature (common reports 'of it was easier to contract my core muscles'). Based on the available research into mechanisms affecting changes in activation level of muscle following isometric contraction and reports from subjects, a proposed application of this training protocol may be implemented as a 'neural warmup' for athletes in order to improve performance while decreasing injury risk, and may also be used by clinical rehabilitation patients or less athletically inclined populations as a method of making activities of daily living safer. Well trained athletes who did not respond as well to these basic exercises would require more intense core exercises or cues to experience the enhanced stiffness traits exhibited by their student counterparts.

5.2 Long Term Training

The results of long term training revealed significant reductions in passive range of motion within naïve and savvy groups, and most of these changes were found within the Isometric training group. Thus, Hypothesis 4 was deemed as true. Mean active stiffness was increased in both isometric and dynamic core training but without statistical significance and thus invalidates Hypothesis 5. Passive stiffness was mostly increased with Isometric training for naïve and savvy subjects, showing statistically significant changes. Some statistically significant changes were experienced following Dynamic training (right lateral bend for naïve subjects, a single case during forward flexion and left axial twist for savvy subjects). No significant differences were measured for the Control group in either naïve or savvy subjects. When comparing changes between training group (Isometric vs. Dynamic vs. Control) and subject group (naïve vs. savvy subjects within the same training group), no significant changes were measured, and thus Hypotheses 6 and 7 were considered invalid. Again, the issue of statistical and biological significance was brought up here and will be discussed later in this section.

The dynamic core training program consisted of exercises where core activation was the product of torso movement. One challenge in designing such a program was to ensure adequate activation of the core musculature while not reproducing movement patterns associated with mechanisms of spine injury. Strategies such as limiting spinal motion as to not reach end range especially under compressive load and using smart movement patterns by facilitating motion through the hips helped reduce the possibility of back injury during the six week period. Unlike other training studies where the same exercises are repeated over the course of multiple weeks, considerations of adaptations to training were made, especially for the athletic population (Kraemer et. al., 2002; Fleck, 2004; Kraemer and Ratamess, 2004). A periodized program was developed for the Isometric and Dynamic programs following concepts of a linear periodization and balancing training volume with training intensity; training intensity and difficulty started low for the first two weeks, beginning with basic bodyweight exercises to introduce subjects to the associated muscle activation patterns and grooving motor patterns for the targeted core musculature. Exercise intensity was increased following two weeks of basic bodyweight exercises by the addition of external load and increased moment arms. The final phase of training added greater athletic demand by either introducing distal limb movement with proximal stiffness

(Isometric program) or greater speed demands of movement (Dynamic program). As exercise intensity increased over the training blocks, training volume and frequency subsequently decreased as to not exceed training capacity of the subjects.

5.2.1 Passive Stiffness

Enhancements in passive stiffness were both recorded in dynamic and isometric training groups, but the greatest changes occurred in the isometric training group for both naïve and savvy subjects. Naïve and savvy subjects experienced significant changes in stiffness for all passive tests except for extension and left lateral bend directions. The effect of stiffening the transition zone in naïve subjects was not found in long term testing, with both subject groups experiencing these changes at 80% and above of applied moment, though some exceptions were noted (naïve subjects experienced changes starting at 50% of applied moment for left axial twist). These findings generally agree with work done to measure changes in tendon stiffness of the quadriceps (Kubo et. al., 2001; Burgess, et. al. 2007). Unlike the short term results, intramuscular pressure and hyperemia cannot be used to explain possible mechanisms for these changes; these effects after isometric training are short lived over the span of minutes to hours (Laughlin et. al., 1996) and would not be present at the time of post long term training measurements. As subjects trained with external loads over the six week period one explanation for these changes may be physical adaptations of hypertrophy and strength gain. Relationships between muscular strength and muscle size have been explored since 1897 (Morpurgo, 1897). All subjects increased muscular strength over the six week period, evidenced by the use of increasingly heavier loads and the decrease in exercise difficulty when loads were held constant. Hypertrophy of core musculature was not measured after the training period but evidence exists of hypertrophy and strength adaptations in resistance training after a similar duration (Garfinkel and Cafarelli, 1992).

An interesting observation made was the sharp increase in passive stiffness near the end range of motion for isometrically trained subjects. At the end range of motion during passive bending it can be assumed passive tissues contribute greatly to increases in stiffness. Since ligament length and stiffness were assumed to not have been affected during the training period it is hypothesized that adaptations to tendon properties may have occurred with Isometric training. This hypothesis is supported by research investigating remodeling of collagen structures in rat tendons after overload, suggesting the tendons underwent a remodeling phase with mechanisms similar to that of muscular hypertrophy (Michna, 1984; Zamora and Marini, 1988; Kubo et. al., 2001). Isometric training of human quadriceps muscle also showed enhancements in tendon stiffness;

mechanisms of action were not explored but researchers made similar hypotheses pointing out collagen bundle remodeling as a potential mechanism of action (Kubo et. al., 2001; Burgess et. al., 2007). After six weeks of loaded isometric exercise there is a distinct possibility of tendon remodeling resulting in greater passive stiffness at end ranges of motion.

Similar to the results of short term training, comparisons of changes between training and subject groups did not yield any statistically significant results. Again, researchers found that post training variances increased greatly compared to pre training variances which indicate a wide range of responses to training. Though not statistically significant, subjects felt they experienced biological adaptations as evidenced in journals recorded during the training period. In weekly self reports of training the student population described the beginning of each training phase to be manageable yet challenging, with challenge level increasing with each phase. The athletic population, however, reported the first phase to be of little challenge but difficulty levels increased starting Week 3. The bodyweight exercises, similar to those performed during the short term training session, proved to be unchallenging to athletic subjects but all subjects found adequate challenge once external load was applied. These comments lead researchers to believe that though athletic subjects were accustomed to bodyweight core training, the application of external load pushed all subjects beyond what their bodies were conditioned to handle. No subjects in either group reported training phases 2 and 3 to be of little to no challenge, and the progression in difficulty lead researchers to believe this is why similar adaptations were observed after long term training, between similar training groups. An issue of exercise technique adherence may have also played a role in the range of variance. Researchers made all efforts possible to supervise training, coaching subjects in a one-on-one setting at least once per week to teach all required technical cues (Tables 2 and 3). Participants were also reminded of technique cues during weekly meetings with the researchers. However, due to time constraints it was not possible for researchers to supervise all training sessions, and there is a distinct possibility some technical cues were missed by subjects resulting in improper muscle activation or exercise performance. Variances in muscular activation magnitudes and patterns in coached vs. uncoached scenarios have been observed in past training studies (McGill and Karpowicz, 2009). Different subjects may also interpret technical cues differently based on past training experience or inexperience in training; interpretation of these cues may have been ‘lost in translation’ between the researcher and subject. This ‘translation’ effect is a function of the type of language use, verbal cues and subject understanding, among other factors (Turman, 2003); despite the researcher’s best efforts to remind subjects of the standard technical cues variations in understanding the cues may have led to discrepancies in exercise technique. Lastly, lifestyle and environmental factors played a role in post training passive stiffness results. Many subjects in both subject groups are University students, a lifestyle which requires many hours of seated work. Other subjects not at the University were required to drive to meet with researchers for data collection. Sustained periods of sitting have been shown to immediately reduce passive stiffness of the spine (Parkinson et. al., 2004). Despite training for six weeks, overall torso stiffness may have increased but acute periods of prolonged sitting prior to post training data collections may account for decreases and variances in stiffness measurements.

5.2.2 Active Stiffness

Active stiffness values were not statistically different from each other but researchers account for this due to high variances compared to mean values. Analysis of means and variances revealed increases in mean stiffness but accompanied by comparatively high variances, two to three times greater than the mean value. Researchers interpreted these results similarly to the passive results which showed high variances – cases of super responders and non-responders could be made. Though statistically significant data could not be provided, 'biologically significant' effects were recorded through qualitative statements of the subjects' feelings after training (Appendix X). Comments made by subjects in their training logs, feelings of greater motor control and activation of core and hip musculature were common in both Isometric and Dynamic trained subjects. These comments lead researchers to believe that physical adaptations were occurring but the variety in response masked significance during statistical analysis.

The subjects' comments regarding feelings of greater control of core musculature has ties to changes in muscular activation levels following prolonged resistance exercise. Garfinkel and Cafarelli's experiment showed significant increases in MVC after eight weeks of isometric limb training; not only did muscular cross sectional area increase but increased EMG amplitude during MVC trials was also observed. Other groups have reported similar findings where long (multi-week) periods of resistance training, whether isometric or dynamic training, lead to increases in EMG amplitude during maximal exertions (Komi et. al., 1977; Hakkinen et. al., 1985; Jones et. al., 1989). Though the literature cited focused on lower limb musculature we can hypothesize that similar adaptations may occur for core musculature. Enhancements in neural adaptations are supported with EMG recordings during active bending trials and agree with results from Garfinkel and Cafarelli; as subjects learn to activate musculature and repeatedly perform high intensity contractions it would make sense that ease of activation would improve among subjects. Active stiffness was enhanced by both Isometric and Dynamic training methods, further supporting the proof of enhanced motor control. This may not be the only mechanism of action present; enhancements in general muscular strength have also been consistently achieved with long term resistance training programs. Thus, performance on active bending trials may have been enhanced simply due to the fact subjects' core musculature were stronger and able to resist greater loads. Relationships between enhanced muscular strength and EMG output are established through Henneman's Size Principle; as load or speed demand increases, higher threshold motor units are recruited to suit these needs; contractions above 35% MVC are thought to recruit mainly Type IIa fast twitch oxidative glycolytic muscle fibres while contractions beyond 65% recruit Type IIb higher threshold fast twitch glycolytic fibres (Kukulka and Clamann 1981; Deluca, et al 1982). Differences in motor unit recruitment between untrained and highly trained subjects have been observed (Sale, 1988) as subjects with little experience in resistance training produce smaller EMG amplitudes than their higher trained counterparts, suggesting they are unable to fully recruit higher threshold motor units. Further, increases in strength in long term training studies are often credited to enhanced neural adaptations such as improved motor learning and coordination (Rutherford, 1986), and activation level of the trained muscle (Hakkinen and Komi, 1983; Moritani and DeVries, 1979). In fact, Moritani and DeVries showed that strength gains with resistance training are initially the product of enhanced activation state, with muscular hypertrophy contributions not occurring until up to 8 weeks into a resistance training program.

Reports of strength increases by subjects were further investigated through the theory of muscle contraction at the cellular level. During rapid length changes, muscular stiffness is proportional to the number of actin-myosin crossbridges formed during contraction (Joyce and Rack, 1969; Ford et al., 1981; Ettema and Huijing, 1994). Initial velocity from the quick-release mechanism cause crossbridge bonds to break (of the muscular responsible for eccentric contraction), akin to pulling apart a strip of Velcro (Rack and Westbury, 1984; Mutungi and Ranatunga, 1996). During active extension trials, the release of the preloaded mass causes crossbridges formed to release, then reattach in a shortened state. With adaptations from the long term training program enhancements to crossbridge strength can occur. This has been demonstrated where Ca^{2+} accumulation and rate of accumulation in the sarcoplasmic reticulum increased after strength and plyometric type training (Viru, 1994). Long term resistance training (8 week) has also been shown to induce increases in Ca^{2+} uptake and Ca^{2+}-ATPase activity, though this data was taken from elderly women (Hunter et. al., 1998). It is inferred that the long term training programs enhanced calcium ion activity leading to greater strength of crossbridge formation. This hypothesis was tested by examining initial velocity during active trials – slopes of the displacement/time curves gives insight into the initial velocity upon quick release; if crossbridge formation strength were increased one would expect a decrease in initial velocity via lengthening of the displacement/time slope.

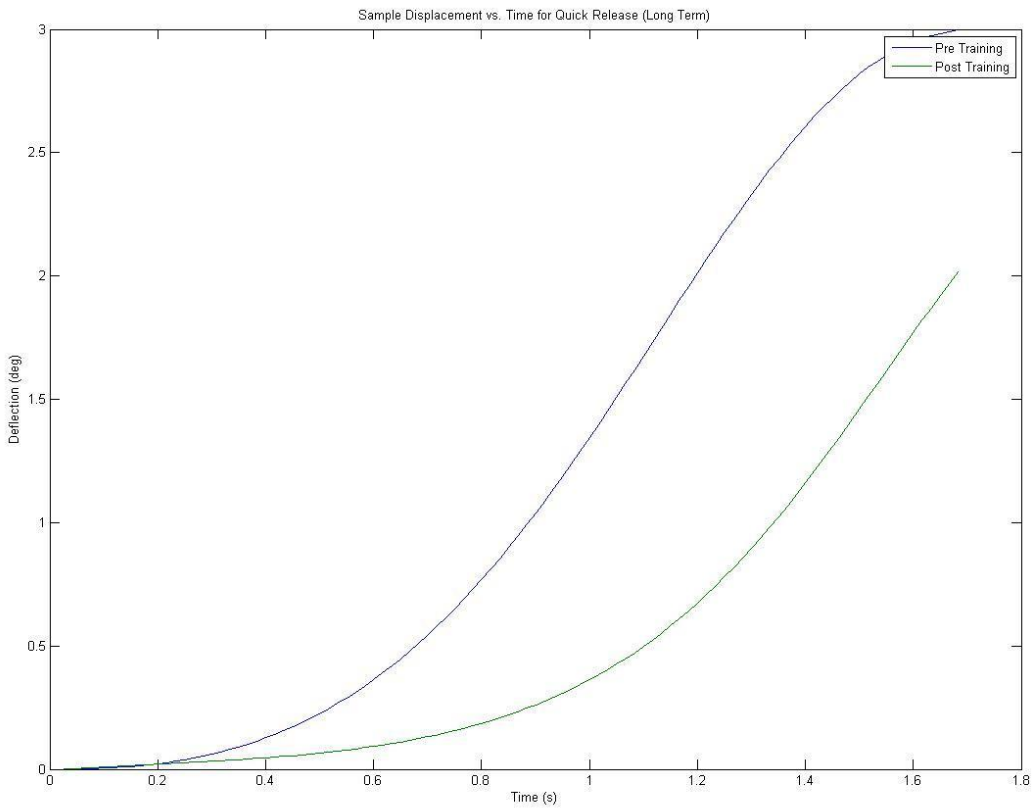

Figure 29: Sample displacement/time curve for active stiffness trials. Note the longer slope for the post training condition indicating a decrease in initial velocity upon quick release. The slower release velocity indicates greater muscular stiffness. During rapid length changes muscles display stiffness properties proportional to the number of crossbridges formed to produce contraction.

5.3 Limitations

As with any study, limitations and assumptions are inherent and impinge the interpretation and relevance of the results. The most salient limitations are as follows:

- With any training study, subject compliance and training technique are always a limiting factor. Researchers made their best efforts to standardize subject training by providing one-on-one coaching during training sessions. Researchers observed subjects as they progressed through one training session and established coaching cues to ensure subjects maintained the best exercise technique possible. Subjects were required to maintain a training journal documenting exercise progression, changes in difficulty level, comments regarding technique and overall comments with regards to the training program. Updates were made once per week at a minimum, up to updating the journal after each training session. The researchers also made an effort to contact the subjects on a weekly basis to receive verbal updates and comments. These written and verbal updates helped the researchers maintain compliance among subjects.

- The 3Space source and sensor, though secured to the subject, are prone to small shifts especially over seven bending tasks with three trials per task, especially when subjects lay on their back during passive lateral bending trials. These shifts may introduce bias due to misalignment the source and sensors. The source and sensors were secured on the subject's posterior side; it is possible to fix these to the anterior side but the bulky source pack may lead to encumbrance during forward flexion trials. In the future researchers may consider changing the source and sensor from anterior to posterior depending on the task, with recalibration of the boresite and range of motion trials. During post processing researchers noted that initial baseline values were similar among like trials. Thus, systematic elimination of biases was performed without the risk of attenuating useful information from the signal.
- Differences in EMG signal between pre and post data collections may have been from slight differences in the placement of electrodes as well as changes in skin condition and subcutaneous layer distribution. Though proper care was taken through visual landmarks, palpation and graphical response to activation by the subject small differences in placement may lead to inconsistencies in EMG output. Thus EMG signals collected during the post training collection should not be normalized to the pre training collection MVC trials. New MVC trials were recorded during the post training data collection and all signals during this collection were normalized to these new MVC trials. In the future researchers may consider physically marking EMG sites on the core musculature with permanent marker from the initial collection over the training period, at the subject's consent.
- Muscle activity was only measured unilaterally for all subjects. EMG was recorded during passive trials to ensure subjects remained truly passive, and not to analyze any type of activation pattern. Active trials were also measured unilaterally but the assumption for healthy participants performing symmetrical movements was that left side activity of the same sites would mirror those measured from the right side. Symmetrical muscle activation of healthy subjects has been shown in previous research (McGill, 1998). Mirrored muscle activity was

assumed for passive and active trials.

- End range of motion during passive bending trials was determined based on the subject's command to stop pulling. However, the subject's perception of end range is controlled by muscle spindle sensivitity; after three trials per direction and multiple stretches the sensitivity of the spindles may have been altered (Edin and Vallbo, 1988; Avela et. al., 1999). The methods used by researchers were in accordance with UW SOP 215 for the frictionless bending apparatus but tests of changes in muscle sensitivity can be performed in future trials where subjects report end range of motion after multiple trials of full range bending. To account for differences in range of motion between trials, each trial was repeated three times and the average of all three trials were taken to represent the mean range of motion for that bending direction.
- Stiffness curves were affected by speed of pull during passive bending trials. To standardize bending kinematics careful consideration was taken to ensure bending velocity was consistent between pre and post training. To verify this displacement/time plots were compared for pre/post short and long term collections (Fig. 45).

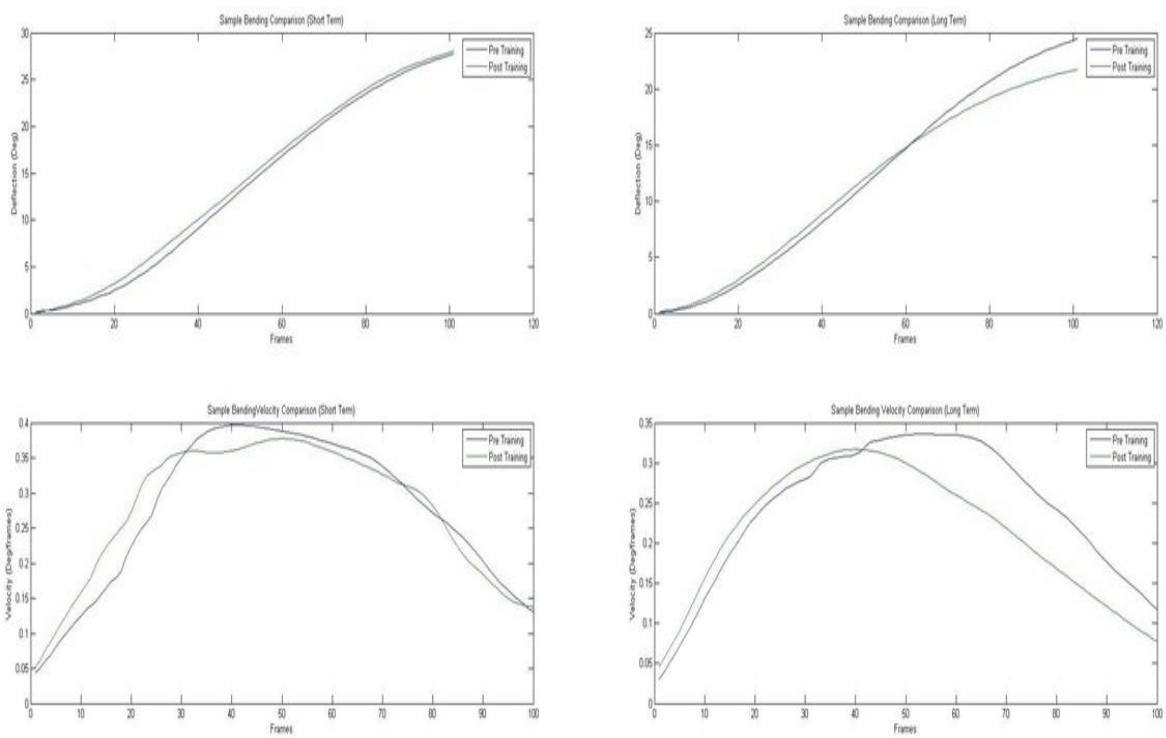

Figure 30: Sample comparison of bending displacement and velocity for pre and post training. Top left: Pre/post short term training displacement. Bottom left: Pre/post short term training velocity. Top right: Pre/post long term training displacement. Bottom right: Pre/post long term training velocity. Rate of displacement was attempted to be held constant to reduce inertial effects of pulling during passive trials.

- Passive stiffness measured was assumed to be due to contributions from many soft tissues and bony geometry of the torso, not just the musculature. Ligaments and intervertebral discs (Adams et. al., 1980), core musculature and bony geometry all contribute to stiffness to the trunk, especially as end ROM is approached, and each provides varying amount of stiffness.
- An issue of statistical power for the long term training analysis was a concern for researchers. When comparing between subject and training groups only four subjects were available for each specific group (Isometric naïve, Isometric savvy, Dynamic naïve, Dynamic savvy, Control naïve, Control savvy). Due to this split N values for specific groups became very small which affected statistical power. However, we should note that to the researcher's knowledge this research is completely new and novel and without previous information or values to go off it is difficult to establish a suitable sample population.

Chapter 6

Conclusions

This is the first study researchers are aware of which quantifies the effects of core training on stiffness. The exercises used in short and long term training are popular among athletic and rehabilitative training programs and the results of this study gives insight into the effectiveness of these exercises.

In general, Hypotheses 1 and 2 were proven mostly true as passive stiffness was increased with short term isometric core training for both naïve and savvy subjects but no statistically significant changes were revealed in active stiffness measurements. Not all tests showed significant changes (left lateral bend for savvy subjects being the exception) but generally all subjects saw increases in stiffness at 80% of applied moment and beyond, though some naïve subjects experienced changes starting at 50% of applied moment. Naïve subjects experienced stiffness changes earlier in the trials (in the transition zone) whereas savvy subjects experienced stiffness changes in the high stiffness zone. Active stiffness values did not show any significant changes but researchers believe this to be due to high variance values, two to three times greater than the mean value. Hypothesis 3 was proven invalid as no significant differences were found between naïve and savvy populations. Hypotheses 4 and 5 were proven mostly true as long term passive stiffness was enhanced to the greatest degree with the six week isometric training program but active stiffness did not show any significant changes following Isometric or Dynamic training. Again, insignificance in active trials was accounted for due to high variances between subjects. As differences between training and subject groups did not show any significant differences, Hypotheses 6 and 7 were considered invalid. This was thought to be due to a low number of subjects in each specific group, limiting statistical power. However, without any past information to base experiments off (investigation of core training on stiffness is the first of its kind that the researchers were aware of) it was difficult to establish sample sizes for adequate statistical power. Though statistical significance was not reached, biologically significant changes were recorded via the comments of the subjects during short term training and in journals recorded during long term training.

Rises in short term passive stiffness were attributed to increased intramuscular pressure from hyperemia following isometric training while enhanced long term passive stiffness was attributed to remodeling of tendon and skeletal muscle structures. These enhancements in stiffness were more pronounced for the student population than the athletic population. Researchers believe the differences post training stiffness between subject subgroups were due to differences in baseline fitness and training experience; adaptations to training are dependent on the current level of fitness and thus it would make sense that athletically trained subjects would not respond as greatly as student subjects unaccustomed to this method of physical training. Reduced absolute range of motion during passive bend trials was observed after short and long term isometric training, which is a direct result of increased stiffness.

These results offer new insight to the adaptations of stiffness following training, and has implications to training the core given the role of core stiffness for injury resilience and athletic performance enhancement. Core stiffness has been shown to play a role in physical traits such as load bearing and the ability to withstand force, pain management and control of spinal micro movements, and the ability to generate ballistic limb motion. Increases in core stiffness would then be believed to lead to the ability to bear greater load, reduce acute incidences of low back pain and enhance ballistic limb action. These traits are important to all individuals, from the clinical population experiencing low back pain, lay individuals performing activities of daily living while trying to minimize injury risk, and athletes attempting to enhance athleticism.

This experiment has laid the groundwork for future investigations into the mechanisms speculated in the discussion, whether they are vascular, neural or mechanical.

APPENDIX A

Active and Passive Bending Trials

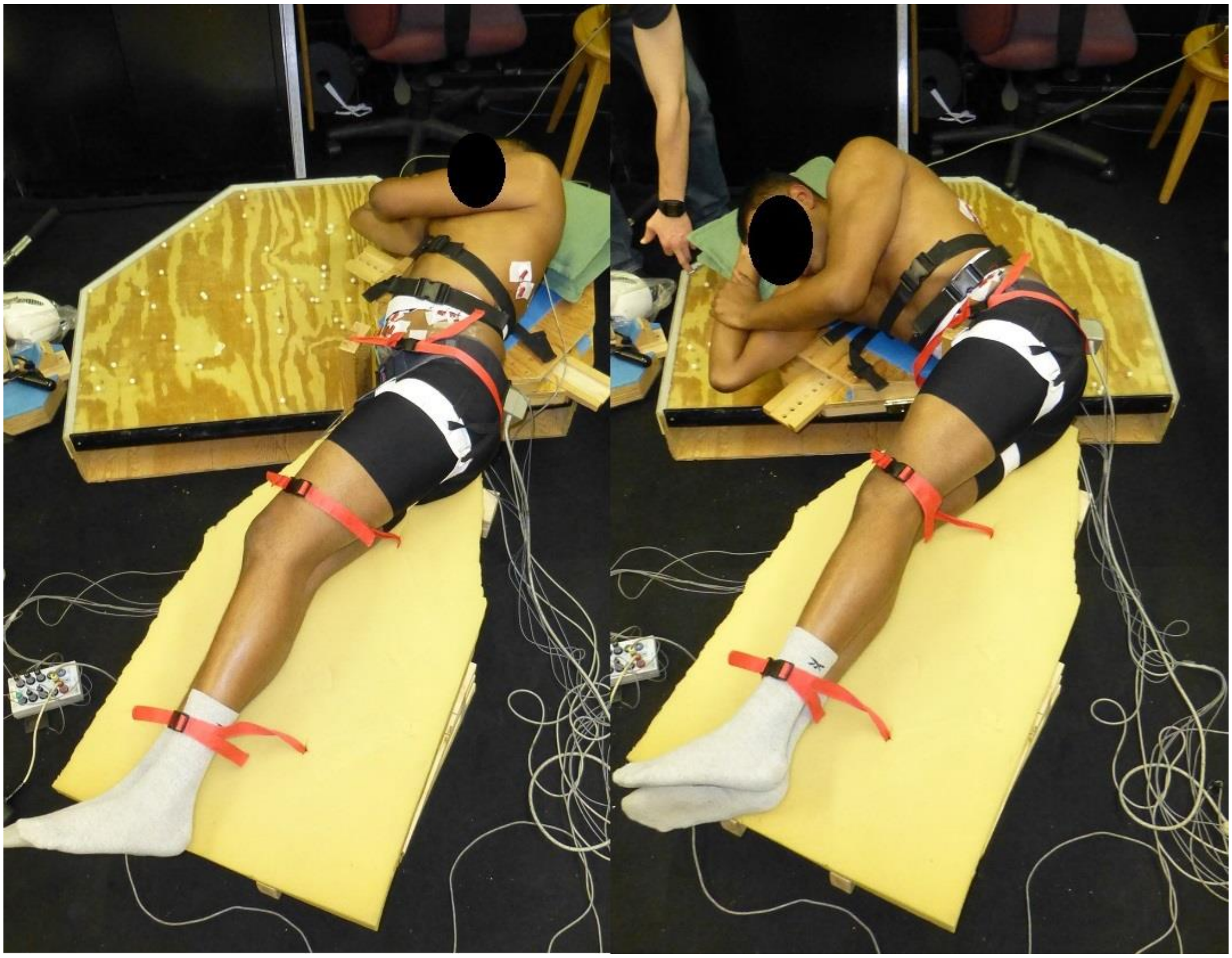

Figure 31: Example of passive flexion bending trial. Subject was pulled from neutral elastic equilibrium (set by allowing the subject to reach a neutral rest state in the frictionless bending apparatus) to full range flexion (set via an initial pull where the subject notified the researchers verbally that end range of motion was reached). Three trials were performed recording applied force and angular displacement.

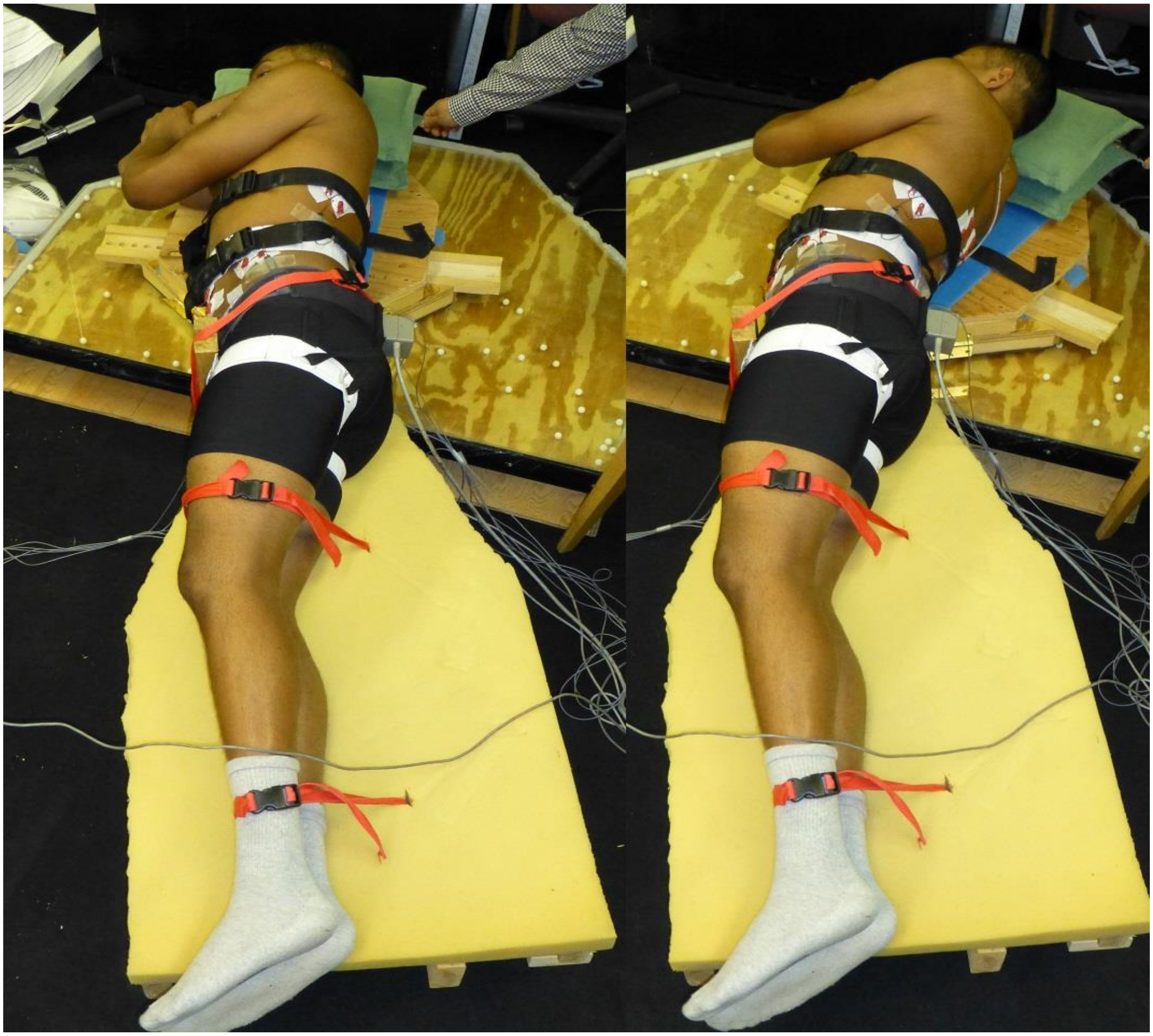

Figure 32: Example of passive extension bending trial. Subject was pulled from neutral elastic equilibrium (set by allowing the subject to reach a neutral rest state in the frictionless bending apparatus) to full range extension (set via an initial pull where the subject notified the researchers verbally that end range of motion was reached). Three trials were performed recording applied force and angular displacement.

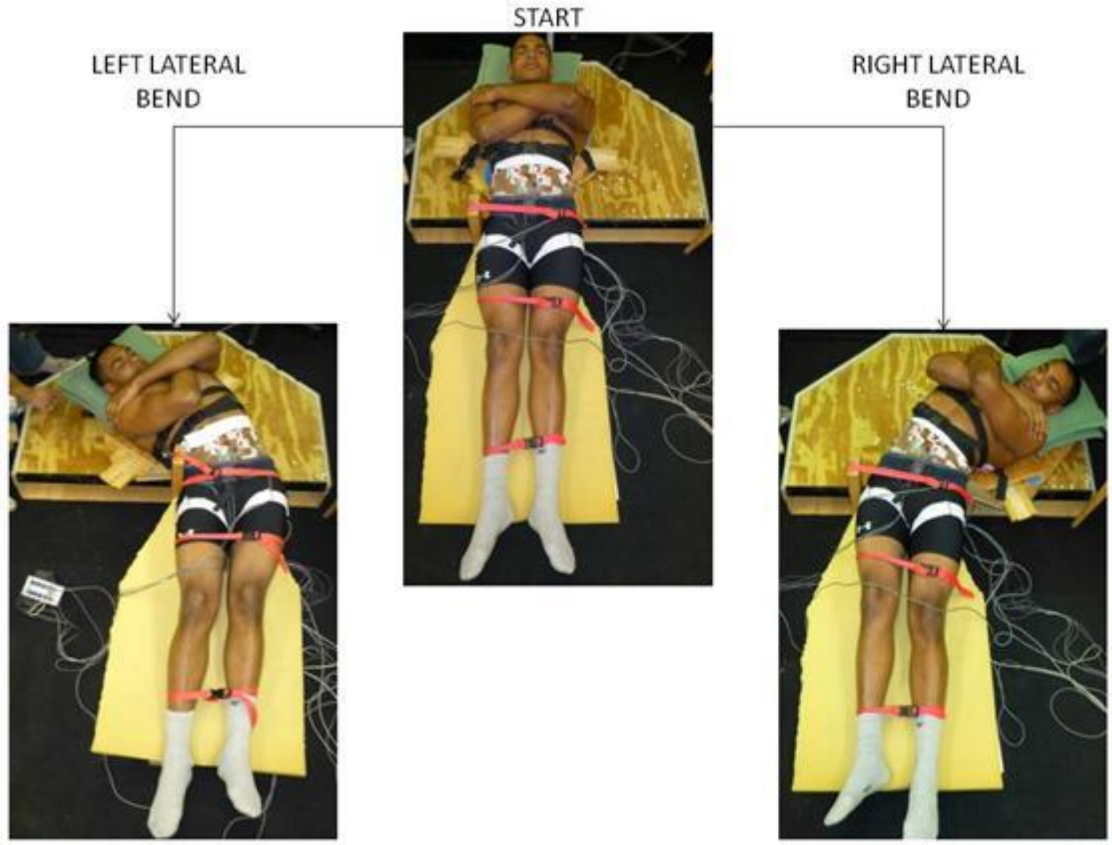

Figure 33: Example of left and right lateral bending trials. Subject was pulled from neutral elastic equilibrium (set by allowing the subject to reach a neutral rest state in the frictionless bending apparatus) to full range lateral bend (set via an initial pull where the subject notified the researchers verbally that end range of motion was reached). Three trials of each direction were performed recording applied force and angular displacement.

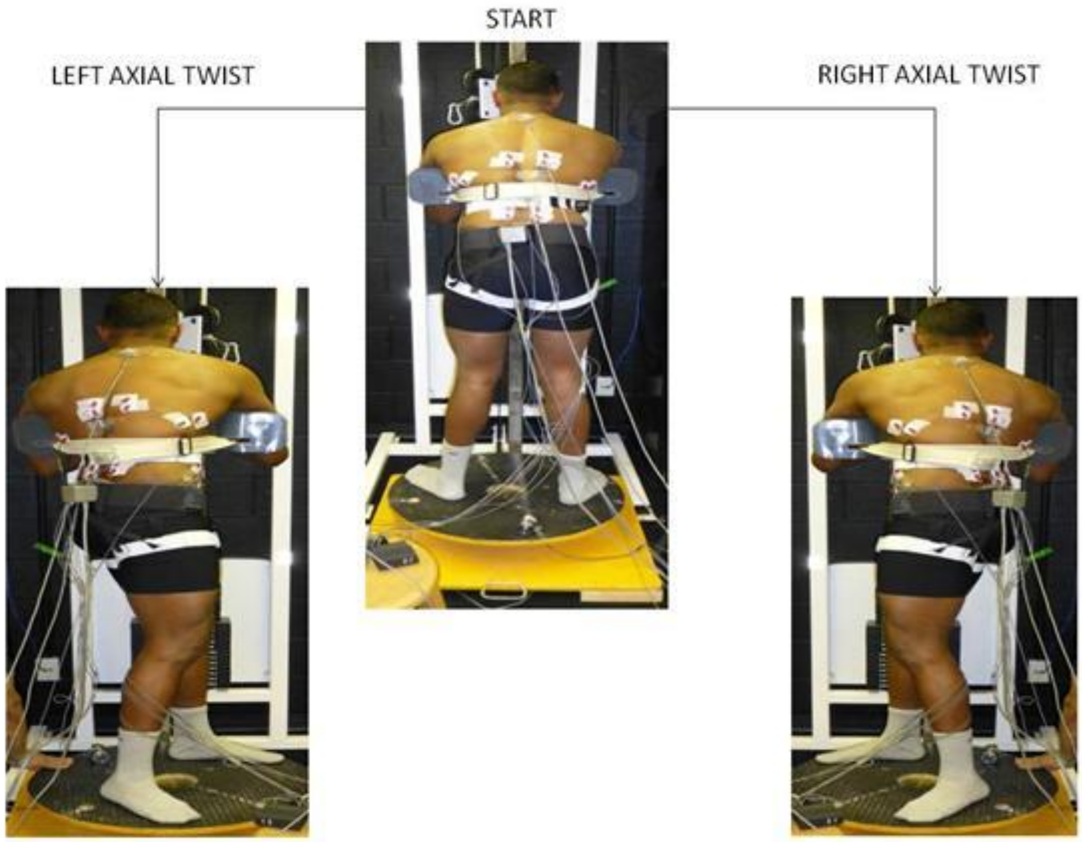

Figure 34: Example of passive right and left axial twist trial. Subject was pulled from neutral elastic equilibrium (set by allowing the subject to reach a neutral rest state in the frictionless bending apparatus) to full range twist (set via an initial pull where the subject notified the researchers verbally that end range of motion was reached). Three trials were performed for each direction recording applied force and angular displacement.

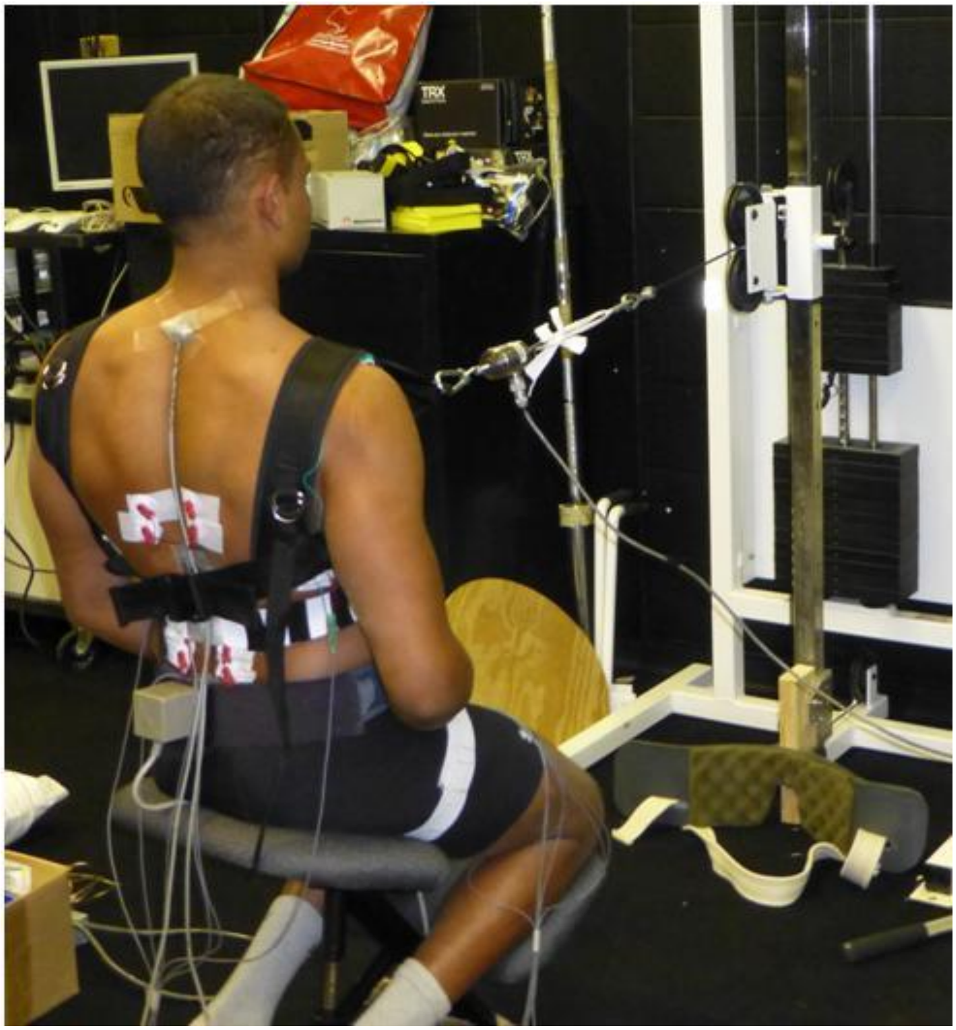

Figure 35: Example of quick release active extension trial. The subject sat in a neutral spine and hip posture preloaded anteriorly with 16 kg. Researchers randomly released an attached electromagnet 'quick releasing' the subject. Applied load from the weight stack and angular displacement were measured for three repeated trials.

APPENDIX B

Isometric Training Program

	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Comments
Exercise	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	
Plank	Up to 5x10 sec	4x per week	5x10 sec	6x per week									Focus on quality of core contraction and postural cues. Descending pyramid sets (Start at 5 reps, decreasing by 1 reps each set).
Bird Dog	Up to 5x10 sec	4x per week	5x10 sec per side	6x per week									
Side Bridge	Up to 5x10 sec	4x per week	5x10 sec per side	6x per week									
Torsional Buttress			Up to 5x10 sec per side	6x per week									Focus on quality of core contraction and postural cues. Train to time before shaking begins. Train at most to 5x10s per side, if possible.
Anterior Pallof Press					5x10 sec	4x per week	Same volume, increase load	4x per week					Focus on quality of core contraction and postural cues. 3 reps per set.
Posterior Pallof Press					5x10 sec	4x per week	Same volume, increase load	4x per week					
Suitcase hold					5x10 sec per side	4x per week	Same volume, increase load	4x per week					
Anti-rotation Pallof Press					5x10 sec per side	4x per week	Same volume, increase load	4x per week					
Stir the pot									5x10 sec per direction	4x per week	5x10 sec per direction	4x per week	Begin on knees, progress to toes. If 10 sec is not feasible, train below and progress through the phase.
Inverted Row									Up to 5x10	4x per week	5x10	4x per week	If 10 reps is not possible perform as many reps as possible and maintain static posture. Focus on keeping torso straight (avoid hip hiking/sagging)
Kettlebell Unilateral Rack Walk									3x 30 m walk per side	4x per week	Same volume, increase load	4x per week	Focus on core contraction and upright posture (avoid lateral lean)
Half Kneeling Woodchop (cable)									Up to 5x10 per side	4x per week	5x10 per side	4x per week	If 10 reps is not possible perform as many reps as possible and progress through the phase.

APPENDIX C
Isometric Exercises

Figure 36: Plank exercise. Cues for this exercise included preservation of neutral spine posture, active contraction of core musculature, gluteals and fists. During Week 2 an added cue of pulling the elbows toward the waist was given for additional external flexion torque.

Figure 37: Modified plank exercise for increased difficulty. Subject raised onto outstretched hands increasing the amount of external torque required to overcome. The same cues as the plank were used with extra cues of gripping the floor and externally rotating the hands were given for enhanced activation of the latissimus dorsi.

Figure 38: Remedial side bridge from knees. Note the hip posture from the side (left picture) and front (right picture) is neutral with no hip extension, flexion or lateral bend. This variation was used for subjects who at first could not support the full side bridge from the toes (Fig. 4). Technical cues included contraction of the core musculature, hips and fist. Subjects who used this exercise were graduated to the full side bridge, while subjects who found this exercise too easy started with the full side bridge (Fig. 4).

Figure 39: Bird Dog exercise start (top) and finish (bottom). The subject started in quadruped position under neutral spine posture and flexed hips, then cued to maintain a core brace while extending a contralateral leg and arm. Cues were given to maintain the core brace while pushing the leg out leading with the heel (pulling the toes downward) and squeezing a tight fist with the extended arm, as seen in the finish position.

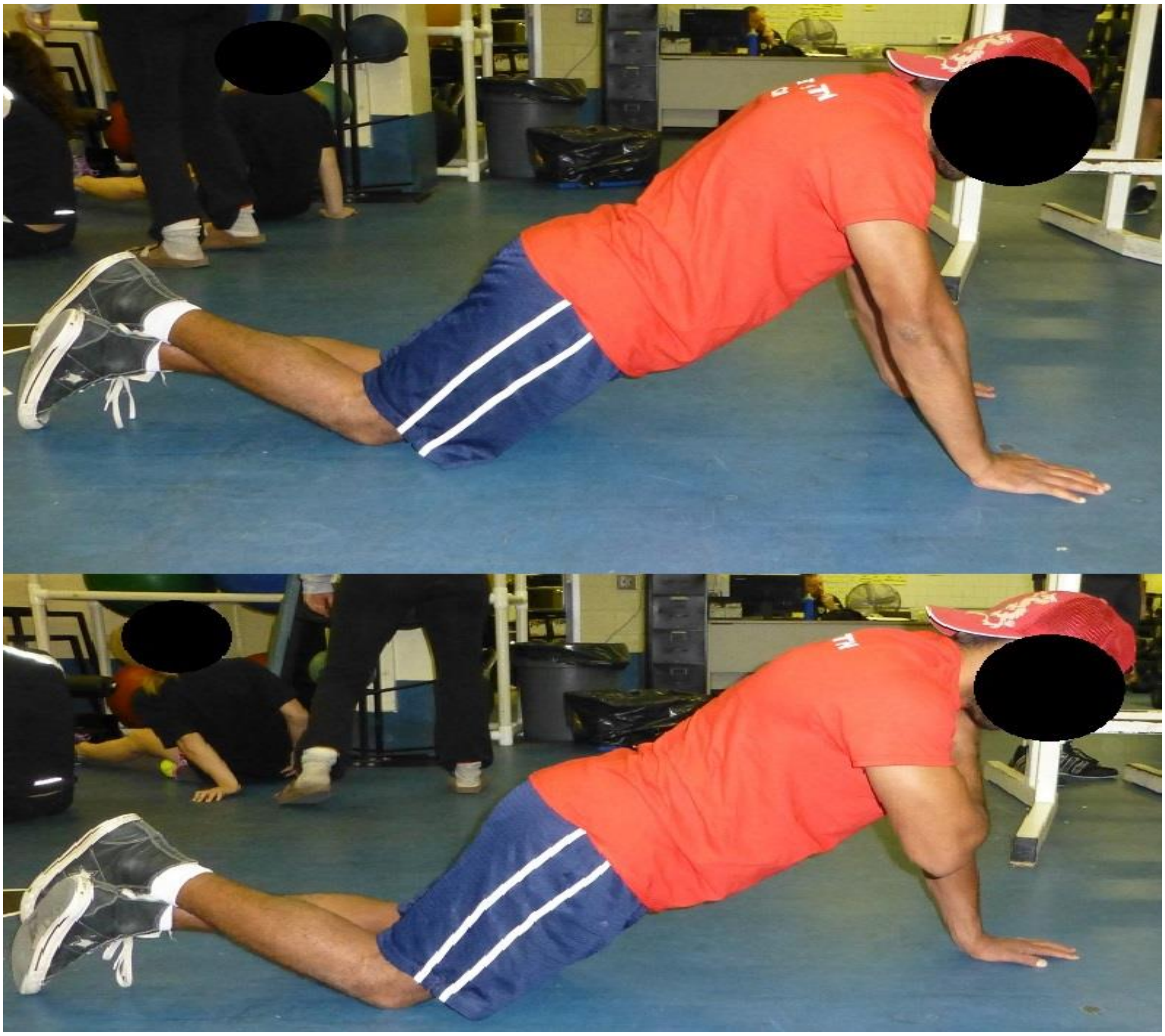

Figure 40: Torsional buttress start (top) and finish (bottom) positions. Subject begins quadruped position under neutral spine posture with extended hips. Cues to contract the core musculature and glutes were given prior to the removal of one support base of the hands. Maintenance of neutral spine and hip posture relative to the transverse plane were required to consider this exercise successfully performed.

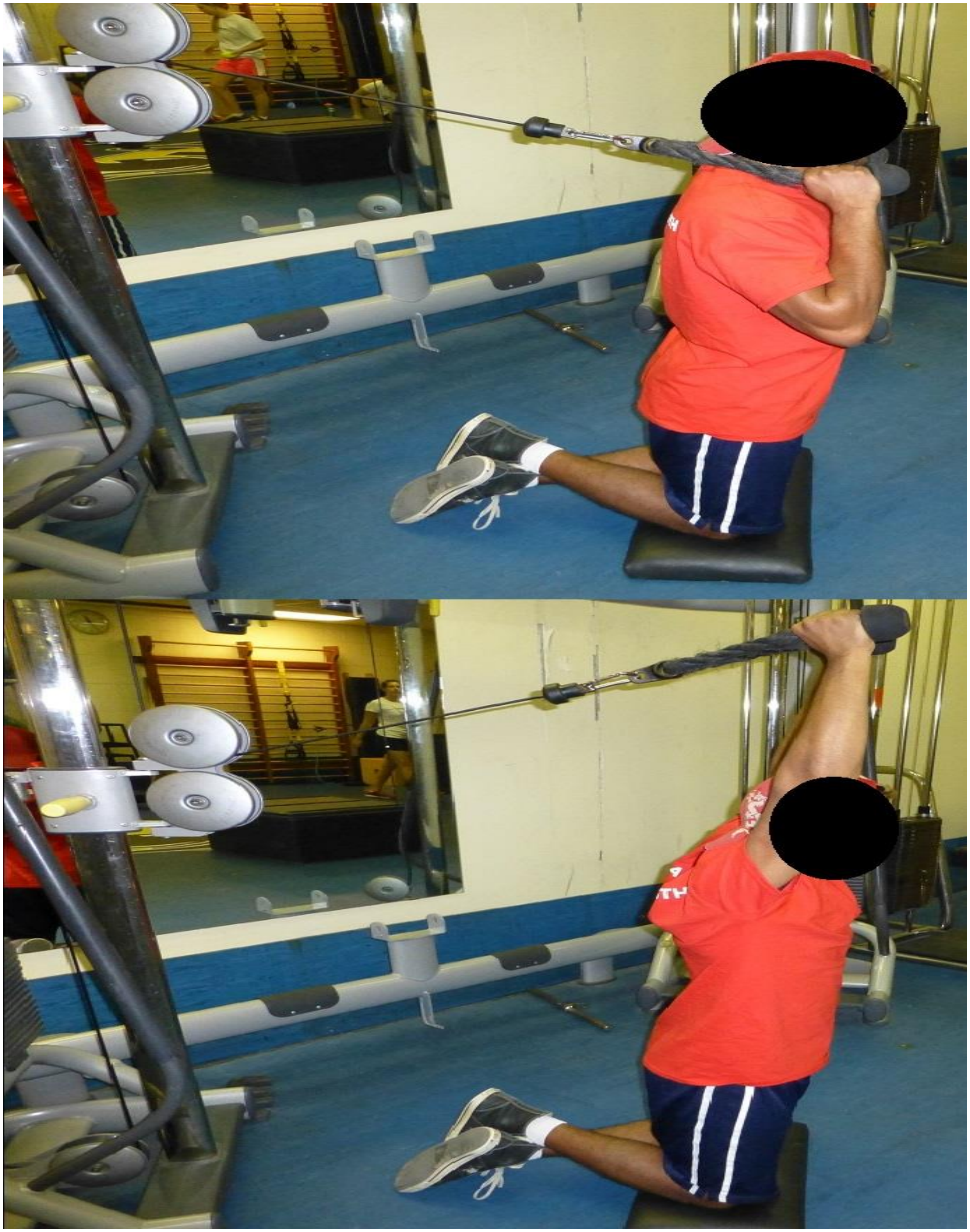

Figure 41: Anterior pallof press start (top) and finish (Bottom) positions. Subject begins on knees with extended hips, maintain contraction of the core and gluteal musculature. A rope attachment on a weighted cable stack is held at head level land pressed overhead, incurring external extension torque. The goal of the exercise is to maintain neutral posture while bracing against the external extension torque.

Figure 42: Posterior pallof press start (left) and finish (right) positions. Subject begins on knees with extended hips, maintain contraction of the core and gluteal musculature. A rope attachment on a weighted cable stack is held at head level land pressed overhead, incurring external extension torque. The goal of the exercise is to maintain neutral posture while bracing against the external flexor torque. A cue of actively pulling back on the rope attachment was given to maintain anti-flexion requirements of the posterior musculature.

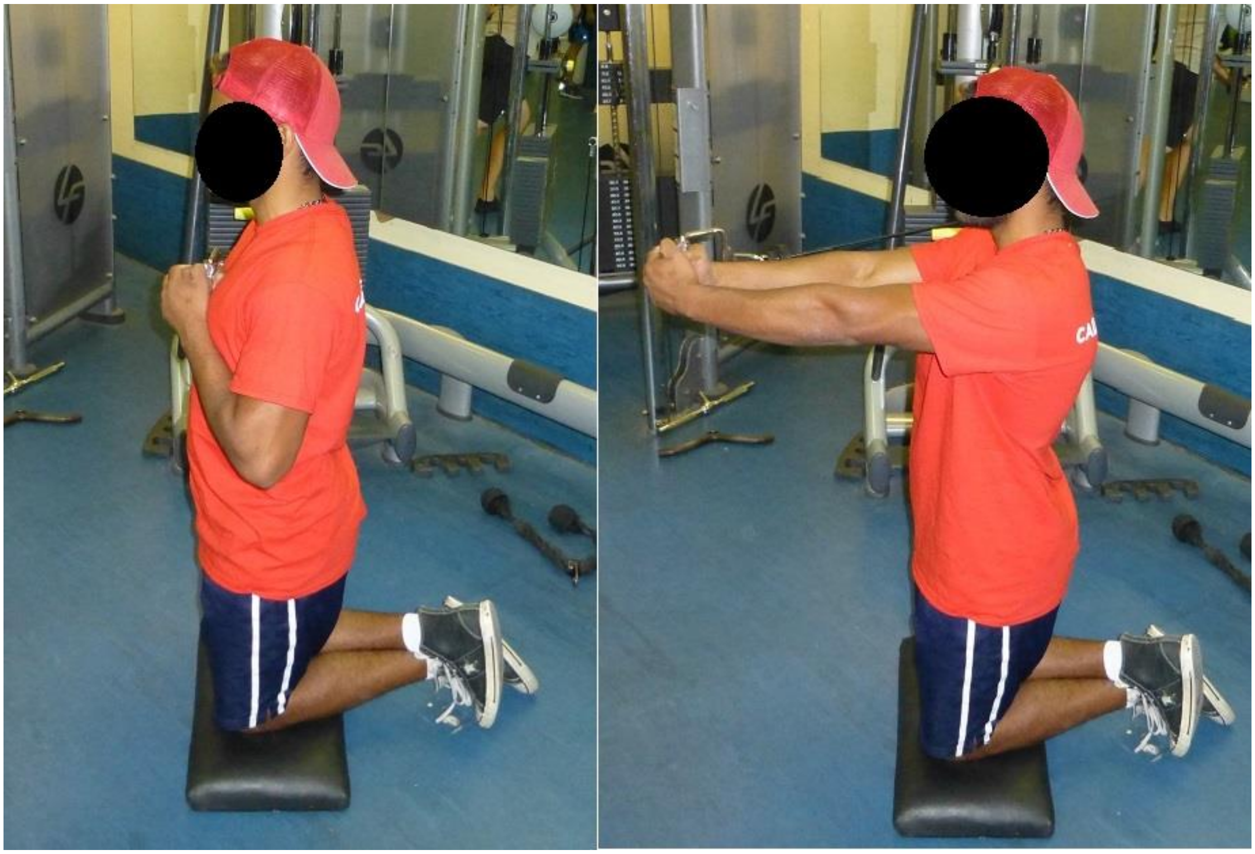

Figure 43: Anti-rotation pallof press start (left) and finish (right) postures. Subject maintains core and gluteal contractions holding the cable attachment at chest level. As the attachment is pressed in front of the subject external axial twisting torque is applied through the weight stack and moment arm created by the extended arms. The subject is required to maintain neutral hip and spine posture resisting the external rotation torque.

Figure 44: Suitcase hold exercise. Subject stood upright with a unilateral load in one hand. Cues of core, gluteal and fist contractions were maintained while resisting kinematic lateral bending from the external load.

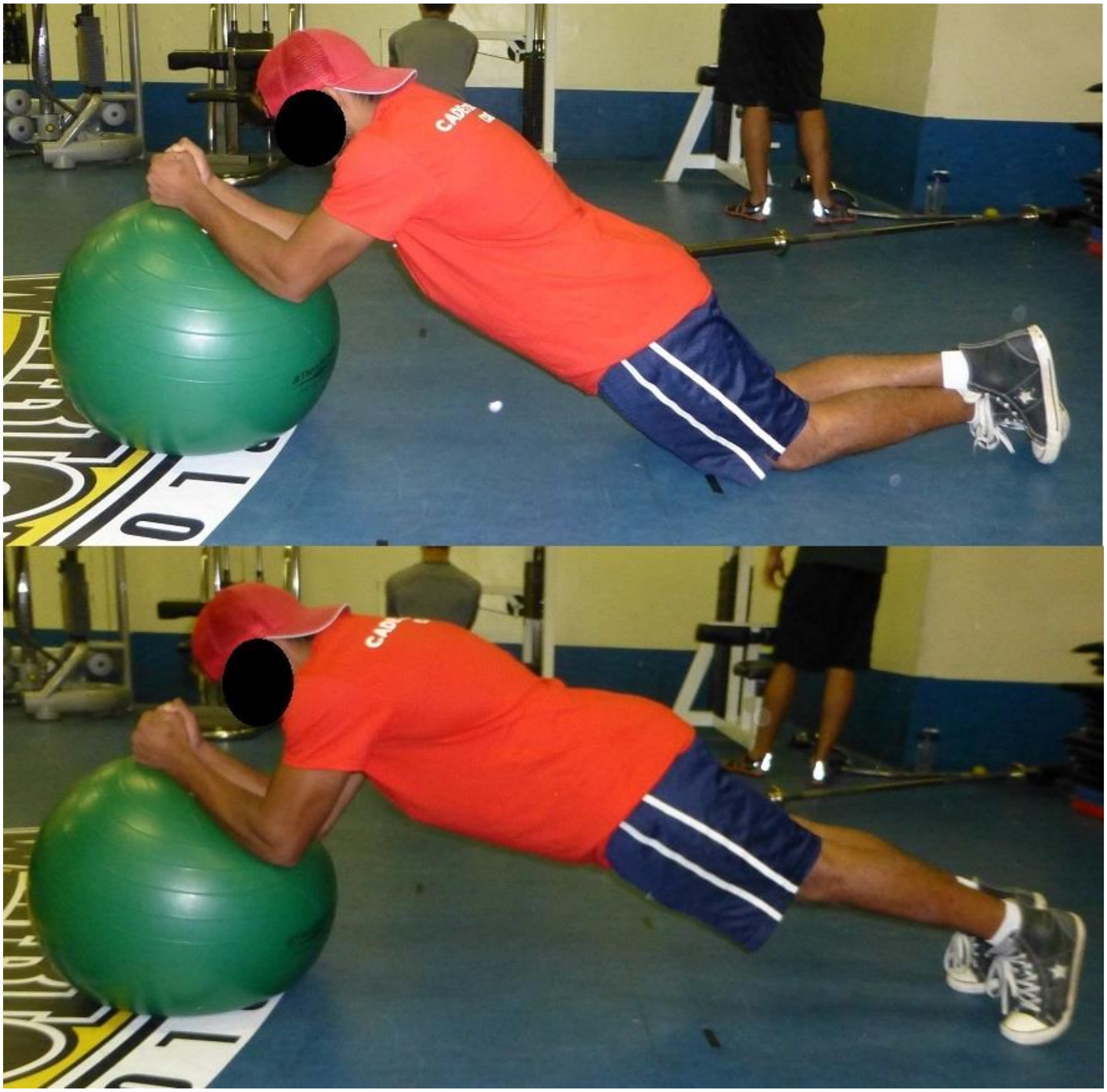

Figure 45: Two variations of the 'stir the pot' exercise. The top figure shows a remedial version starting from a quadruped hip extended posture whereas the bottom figure shows a more advanced version where support is placed on the toes. The subject maintains core, gluteal and fist contractions while rotating the arms in clockwise and counter clockwise directions. The goal of the exercise is to maintain neutral spine posture with minimal movement of the spine and hips during arm rotations.

Figure 46: Remedial TRX row exercise start (top) and finish (bottom) positions. Though involvement of upper limb musculature is required to maintain the pull the main goal of the exercise is to maintain neutral spine and hip posture during all repetitions, avoiding spine and hip flexion due to gravity. This exercise was made less challenging by starting the feet low, creating an angle with the ground to decrease the resistance from bodyweight due to gravity. Subjects who could not perform the full TRX row (Fig. 59) began with this exercise.

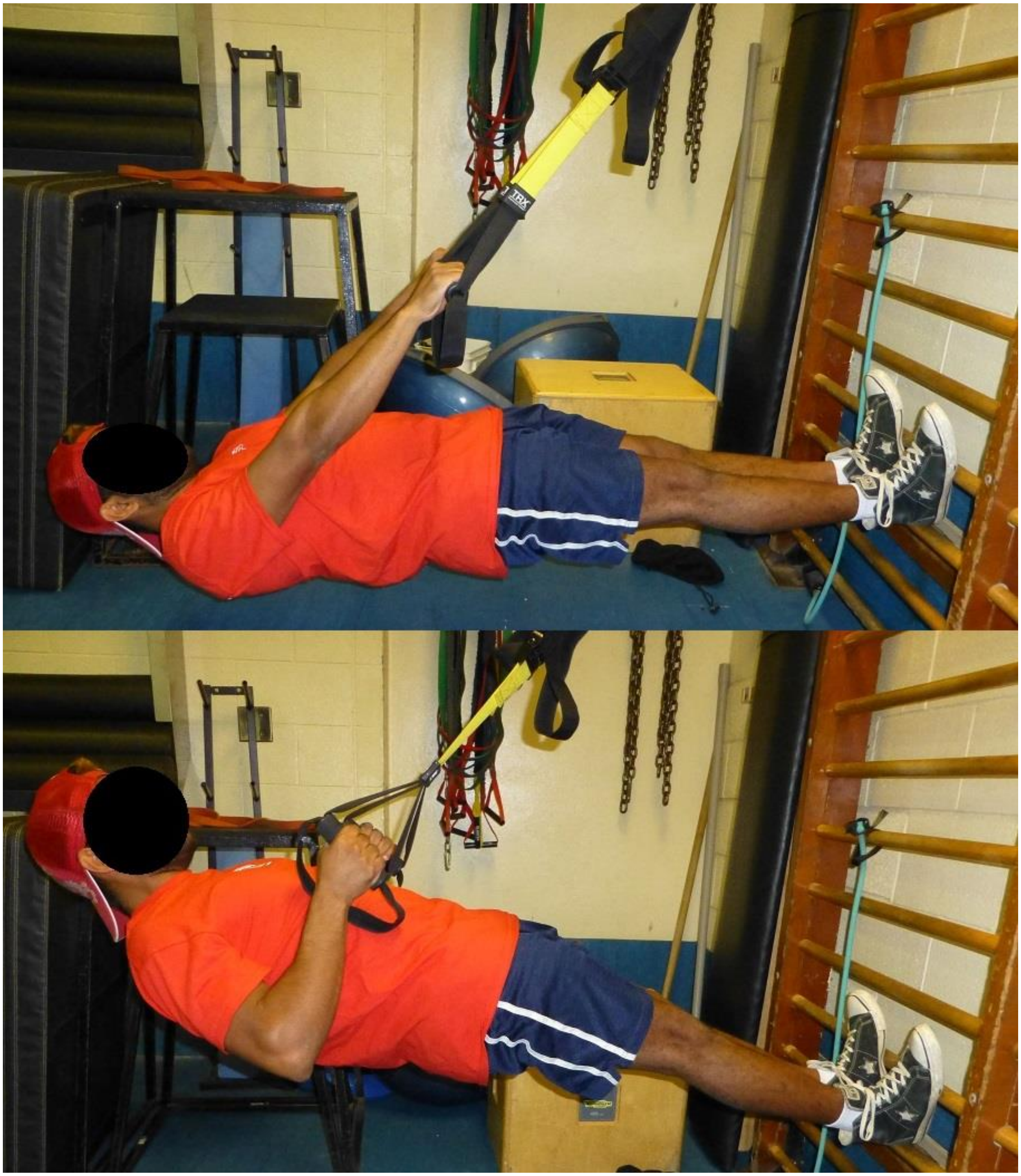

Figure 47: TRX row exercise start (top) and finish (bottom) positions. Though involvement of upper limb musculature is required to maintain the pull the main goal of the exercise is to maintain neutral spine and hip posture during all repetitions, avoiding spine and hip flexion due to gravity. This exercise was made more challenging by starting the feet higher, keeping the body near parallel to the ground and increasing the load challenge of bodyweight due to gravity. Subjects who found the remedial TRX row (Fig. 58) too easy graduated to this variation.

Figure 48: Half kneeling woodchop exercise start (left) and finish (right) positions. The goal of this exercise was to resist external dynamic twisting torque created by the subject pulling a weighted cable stack diagonally across the body. Maintenance of hip and shoulder positions were required via a core brace, avoiding deviation of shoulder and hip positions from twisting about the transverse plane.

Figure 49: Suitcase walk exercise from front (left) and side (right) views. Similar to the suitcase hold, the subject must maintain neutral posture avoiding any lateral bending of the torso while adding in the challenge of locomotion. As one foot leaves the ground an imbalance of structural support is created and contraction of the lateral core and contralateral hip musculature is required to maintain static equilibrium of the torso (McGill et. al., 2010). A more challenging version was given to subjects during the second week of this training phase (Fig. 62).

Figure 50: Variation of the suitcase walk using a 'high march' technique. Subjects were instructed to take a higher and slower step to increase the amount of time under single leg support. This forced the lateral core and contralateral hip musculature to maintain contraction for a longer period of time, increasing time under tension. Considerations of hip posterior pelvic tilt were made when instructing subjects to lift their leg to the desired height.

APPENDIX D

Dynamic Training Program

	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Comments
Exercise	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	Sets/Reps	Frequency	
Curl up	Up to 5x10	4x per week	5x10	6x per week									Focus on quality of core contraction.
Superman	Up to 5x10	4x per week	5x10	6x per week									
Side curl up	Up to 5x10 per side	4x per week	5x10 per side	6x per week									
Twisting curl up	Up to 5x10 per side	4x per week	5x10 per side	6x per week									
Advanced curl up (limbs extended)					Up to 5x10	4x per week	5x10	4x per week					
Back Extension					Up to 5x10	4x per week	5x10	4x per week					
Russian Barbell Twist					Up to 5x10 per side	4x per week	5x5-10 per side	4x per week					Begin with 5x5 and progress repetitions to 10. If 10 reps per side is too easy add weight.
Curl up twitch									Up to 5x10	4x per week	5x10	4x per week	Begin unweighted and focus on twitch speed and rate of activation/relaxation
Superman Twitch									Up to 5x10	4x per week	5x10	4x per week	
Lateral medball throw									Up to 5x10 per side	4x per week	Up to 5x10 per side	4x per week	Ball velocity comes from torso movement ,not arms.
Rotational med ball throw									Up to 5x10 per side	4x per week	Up to 5x10 per side	4x per week	Ball velocity comes from torso movement ,not arms.

APPENDIX E

Dynamic Exercises

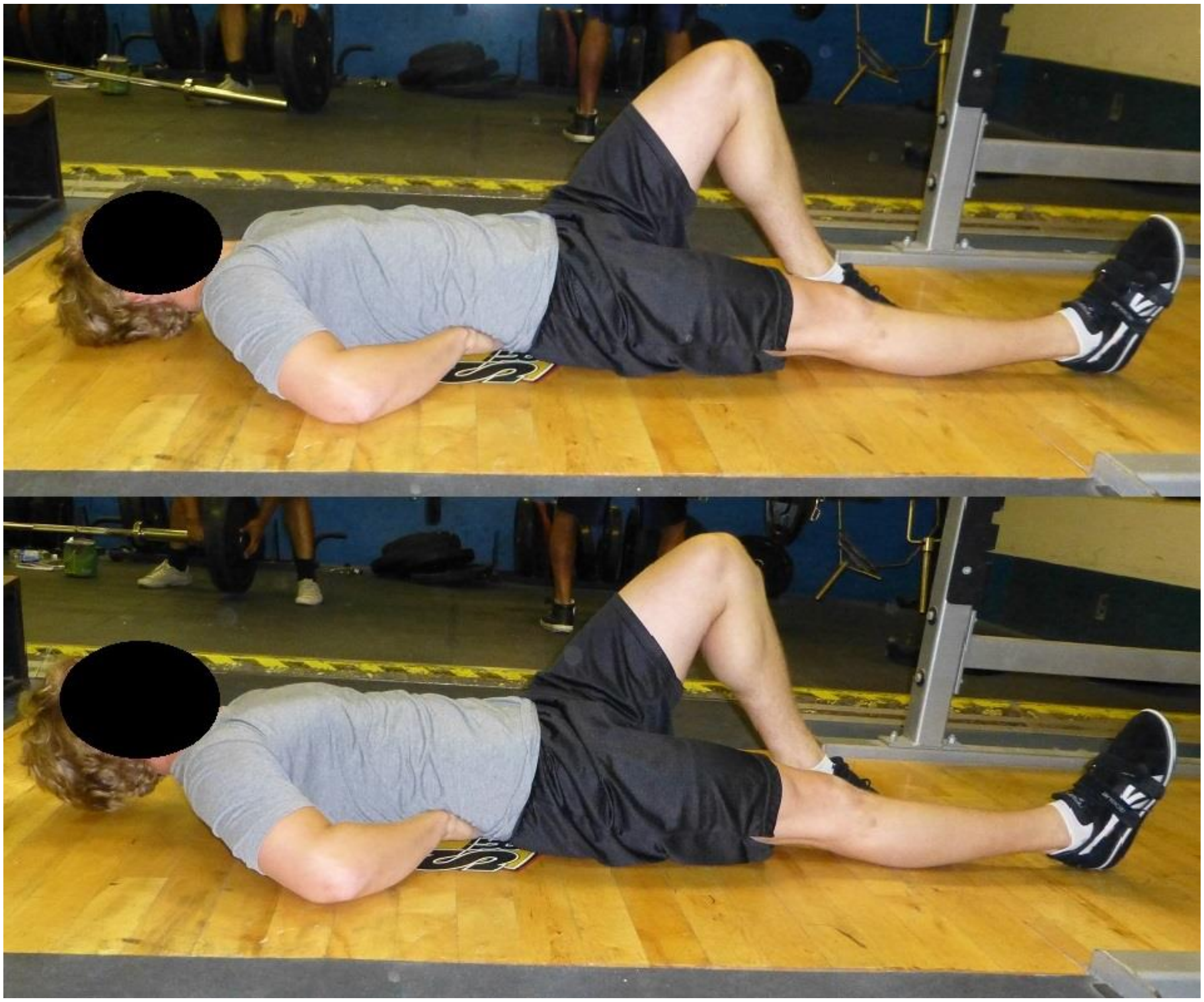

Figure 51: Start (top) and finish (bottom) positions of the curl up exercise. The subject performed this exercise for multiple repetitions, cued to brace the core to lock the torso and picking up the head off the floor by 1-2 cm. Considerations were made to ensure movement initiation was due to core activation and not cervical spine flexion.

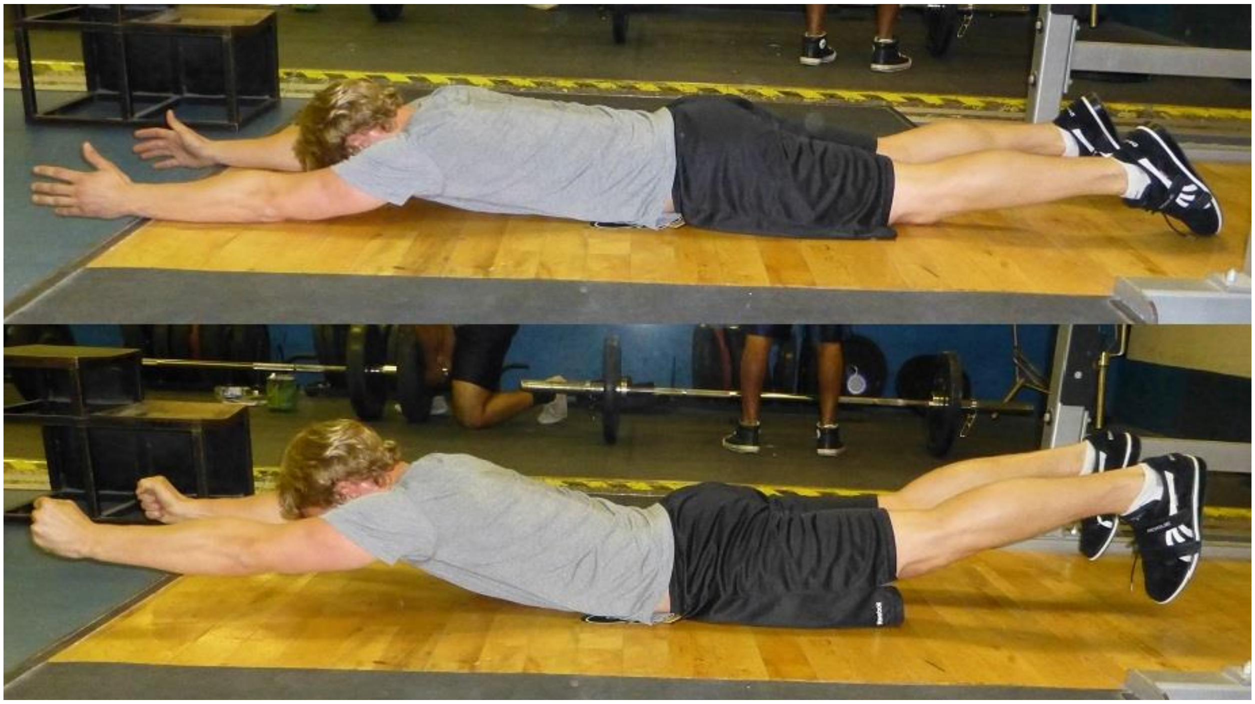

Figure 52: Superman exercise start (top) and finish (bottom) positions. This exercise was used during Phases 1 and 3, with an emphases on twitch speed and rate of activation/relaxation during Phase 3. Subject began laying prone and lifted both arms and legs. This exercise has been previously shown to incur high compressive load about the spine (Axler and McGill, 1997) and mimic kinematic extension injury mechanisms. Assumptions were made that subjects were young and robust enough to take compressive load without injury risk and kinematic range of motion of arm and leg movement were minimized. This helped reduce spine extension range of motion under compressive load while still creating challenge of posterior upper torso and hip musculature. During Phase 3, a 2.5 lb load was placed in each hand to increase twitch speed challenge under external load.

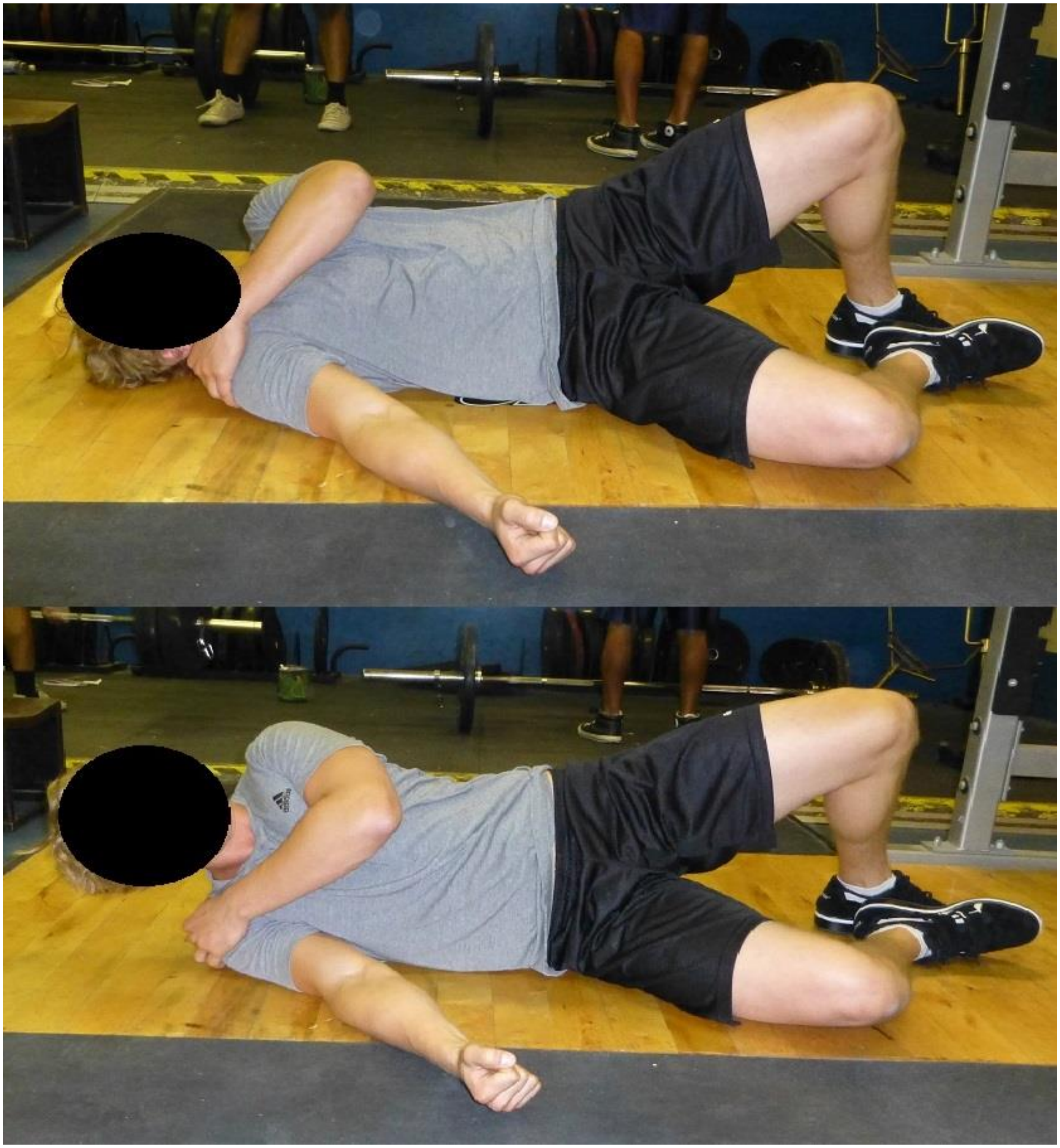

Figure 53: 'Side curl up' exercise start (top) and finish (bottom) positions. This exercise required kinematic lateral bending of the spine though total lateral bend range of motion was kept to a minimum. Subjects lay on one hip and performed a curl up with minimal spine range of motion, similar to the traditional curl up, creating activation of the lateral core musculature.

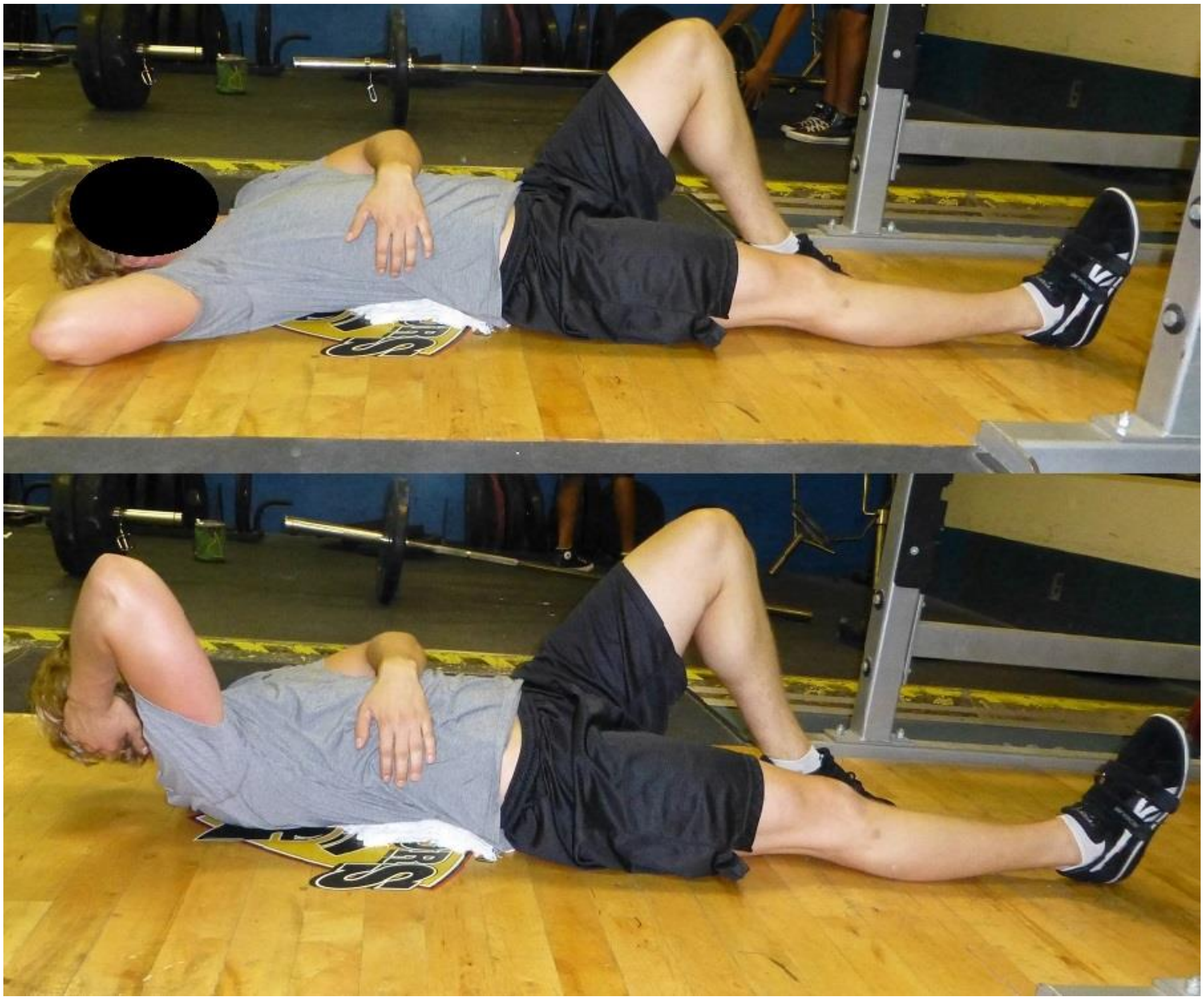

Figure 54: 'Twsting curl up' exercise start (top) and finish (bottom) positions. This exercise required kinematic axial twist of the spine though total range of motion was kept to a minimum. Subjects lay in a posture similar to the traditional curl up and performed a curl up with twist to the raised knee with minimal spine range of motion, , creating activation of the lateral core musculature.

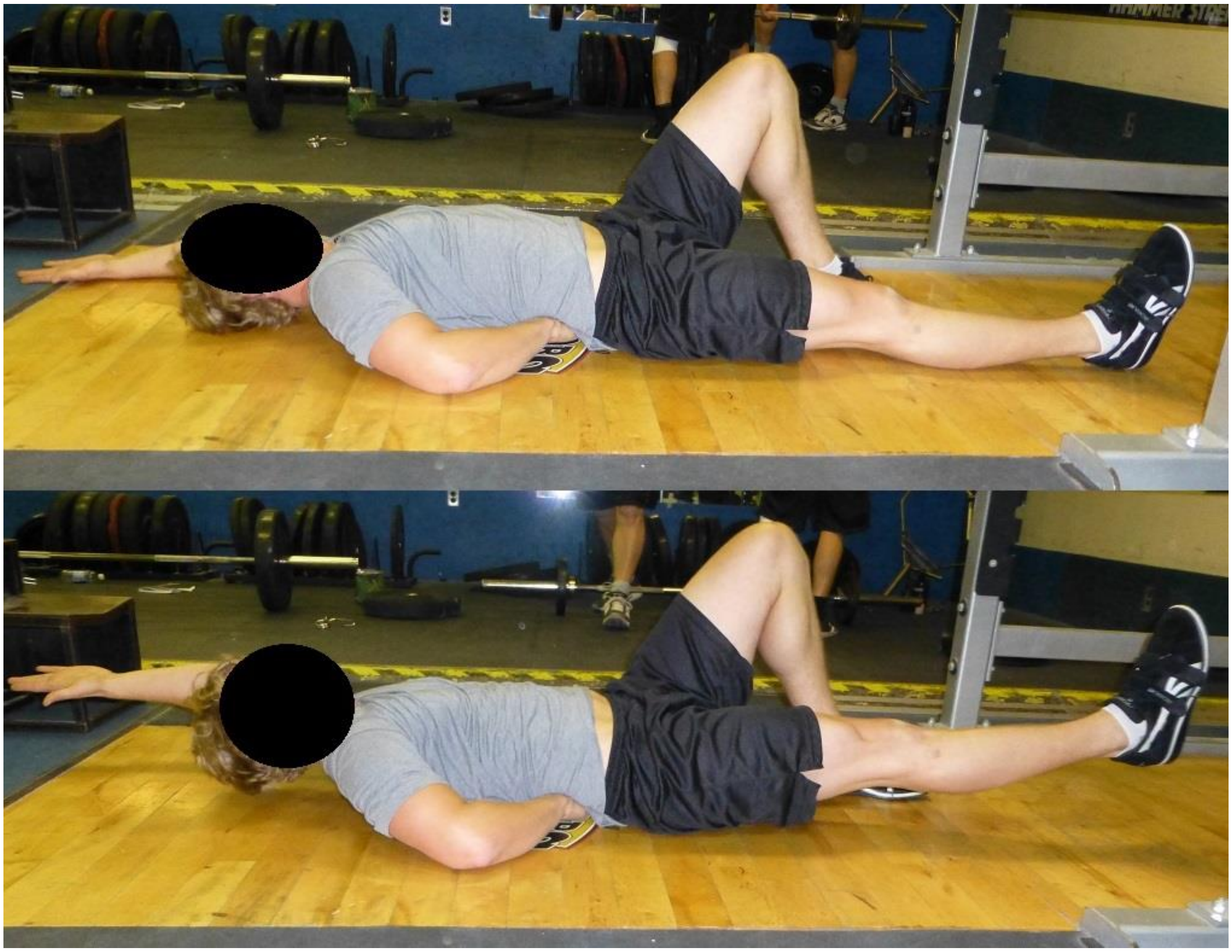

Figure 55: Advanced curl up exercise start (top) and finish (bottom) positions. This exercise was used in Phase 2 and 3 of the Dynamic training program but with an emphasis of twitch speed and rate of activation/relaxation during Phase 3. The subject began in a posture similar the traditional curl up (Fig. 63) with the contralateral arm extended overhead. The same curl up maneuver was performed but with the extended arm and leg raising with the torso (bottom figure). This increased the anterior core activation by including the mass of the arm and leg in challenging the anterior core. A 2.5 lb weight was placed on the subject's hand and secured to the extended leg if a greater challenge was needed. The same external load was used during Phase 3, requiring the subject to create twitch speed under greater load.

Figure 56: Back extension exercise start (top) and finish (bottom) positions. Subjects secured themselves in a roman chair/back extension device and flexed about the hips (top) and used posterior core and hip musculature to create torso extension (bottom). Subjects were cued to avoid spinal flexion in the start position and spinal hyperextension in the finish position. Though this exercise has been measured to impose high compressive spinal loads (Axler and McGill, 1997) researchers worked under the assumption that the subjects were robust enough to accept this level of load. Minimizing kinematic flexion and extension of the spine by using a hip dominant strategy also helped decrease injury potential.

Figure 57: Russian Barbell Twist exercise start (left) and finish (right) positions. An easier variation, depicted here, required subjects to hold one end of the barbell close to the body, reducing the moment arm contributing to external twist/lateral bend. The subject pivots from both feet, ideally turning the hips and shoulders together until the torso faces to one side (right figure). Avoidance of deviation of hip and shoulder posture about the transverse plane was cued. Once in the finish position the subjects rotated back to the start position and performed for the other side. All movement was cued to initiate from hip and core activation and not arm activation. A more advanced version requiring extended arms was used once subjects felt this variation was of too little demand (Fig. 70).

Figure 58: Star position of the advanced version of the Russian Barbell Twist. Subjects were cued to press the barbell away from the body to increase external twist/lateral bend torque via the moment arm created from the outstretched arm posture. Cues were given to maintain fully extended arms at all times and to initiate rotation via the hip and core musculature, and not the arms. A further advanced variation included the use of external load though no subjects progressed to this stage.

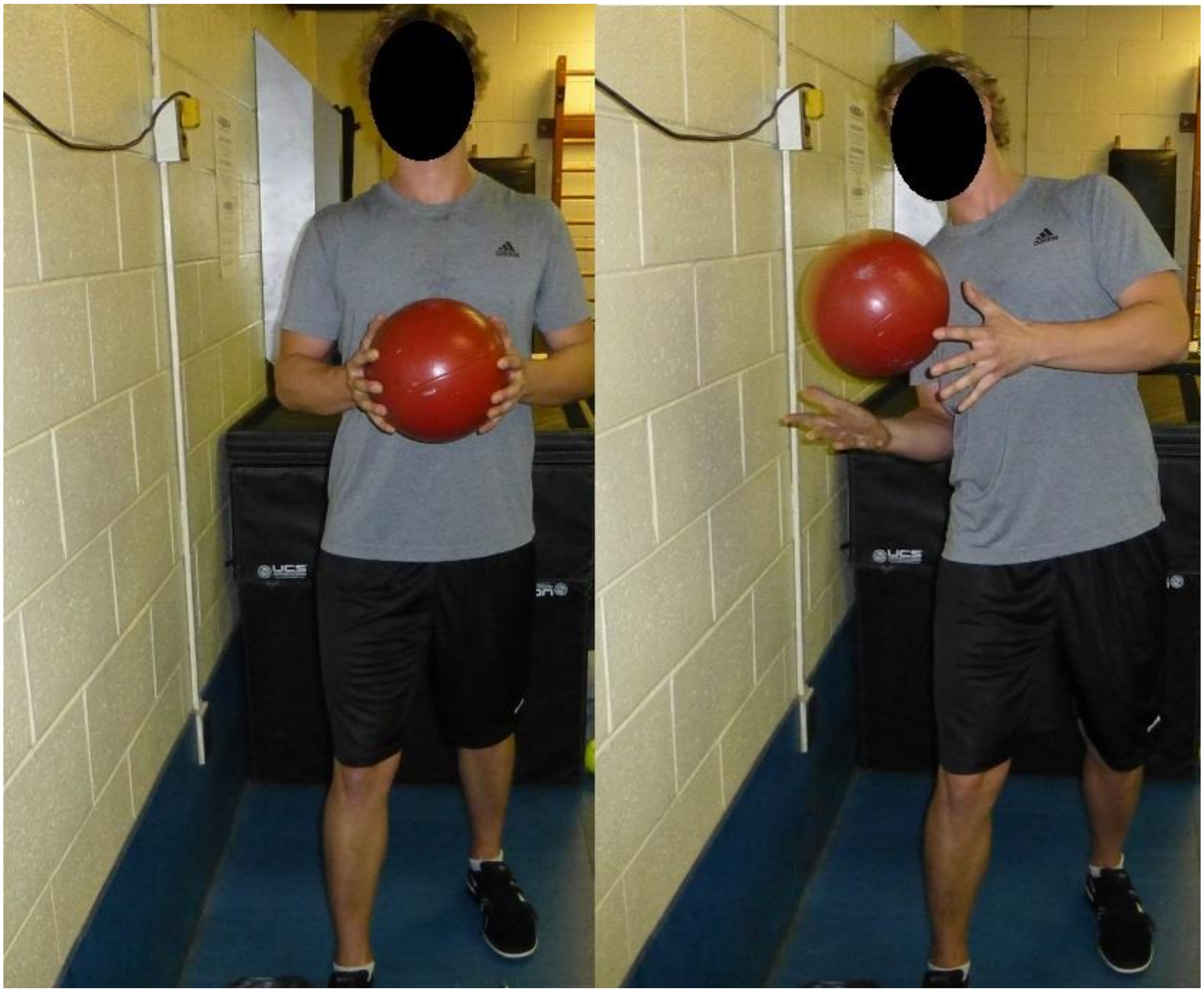

Figure 59: Lateral medicine ball throw exercise start (left) and finish (right) positions. Subjects began holding a medicine ball at chest level close to the body. The throw was initiated by a quick pulse of kinematic lateral bend via activation of lateral core musculature, though minimizing the total bending range of motion. Subjects were cued not to initiate the throw via the arms, and to maximize for medicine ball velocity and twitch speed.

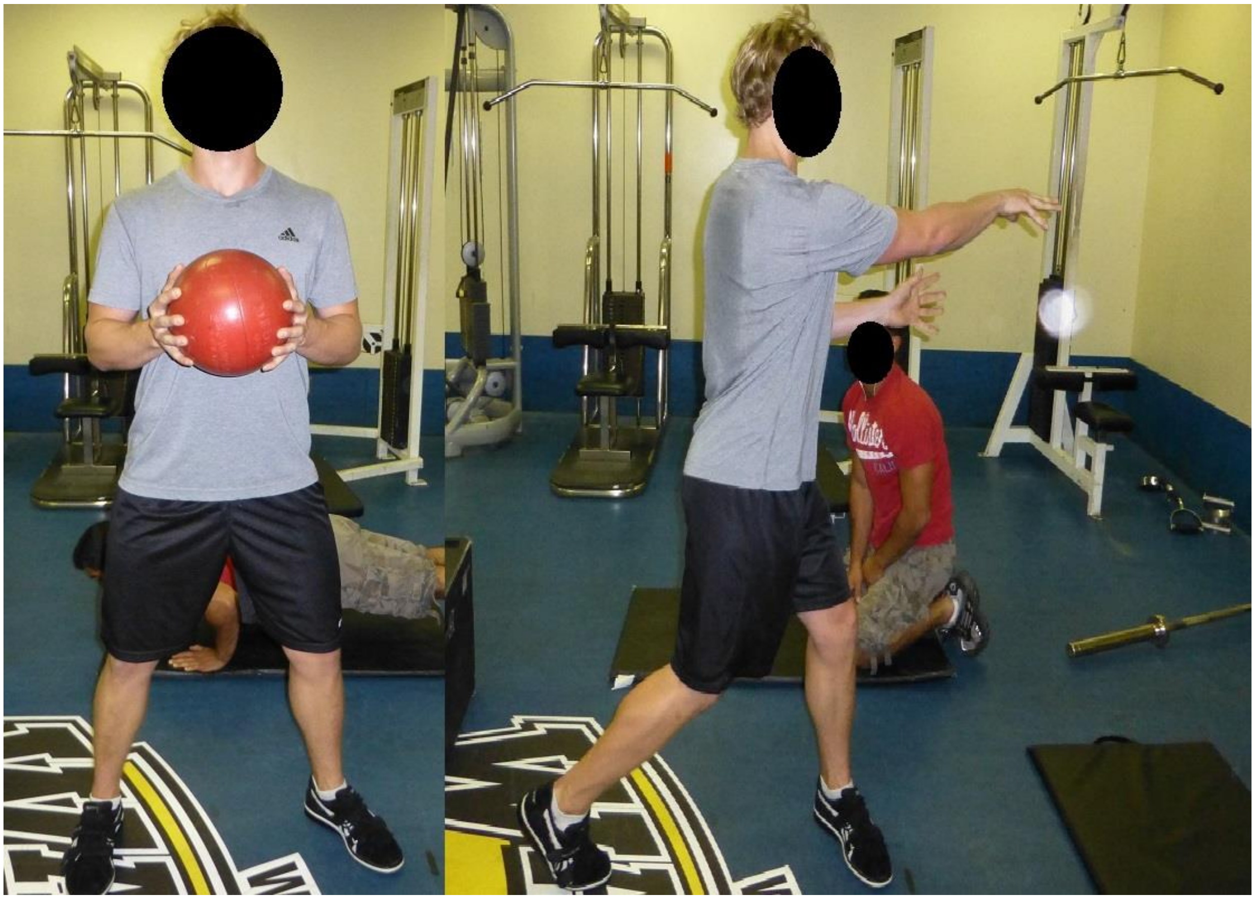

Figure 60: Rotational medicine ball throw exercise start (left) and finish (right) positions. Subject began standing approximately 5-10 feet away from a wall, facing to one side. Holding the ball close to the body at chest level, subjects initiated the throw via hip and torso rotation using hip and core musculature. By pivoting the back foot (seen on the right) the hips and torso are able to freely rotate, via the cue of 'putting out a cigarette.' Subjects were cued to avoid deviation of the hips and shoulders about the transverse plane and to drive ball velocity via the core and hip musculature, not the arms. This exercise was also cued for maximum ball velocity and rotational torso velocity.

APPENDIX F

Raw Processed Data

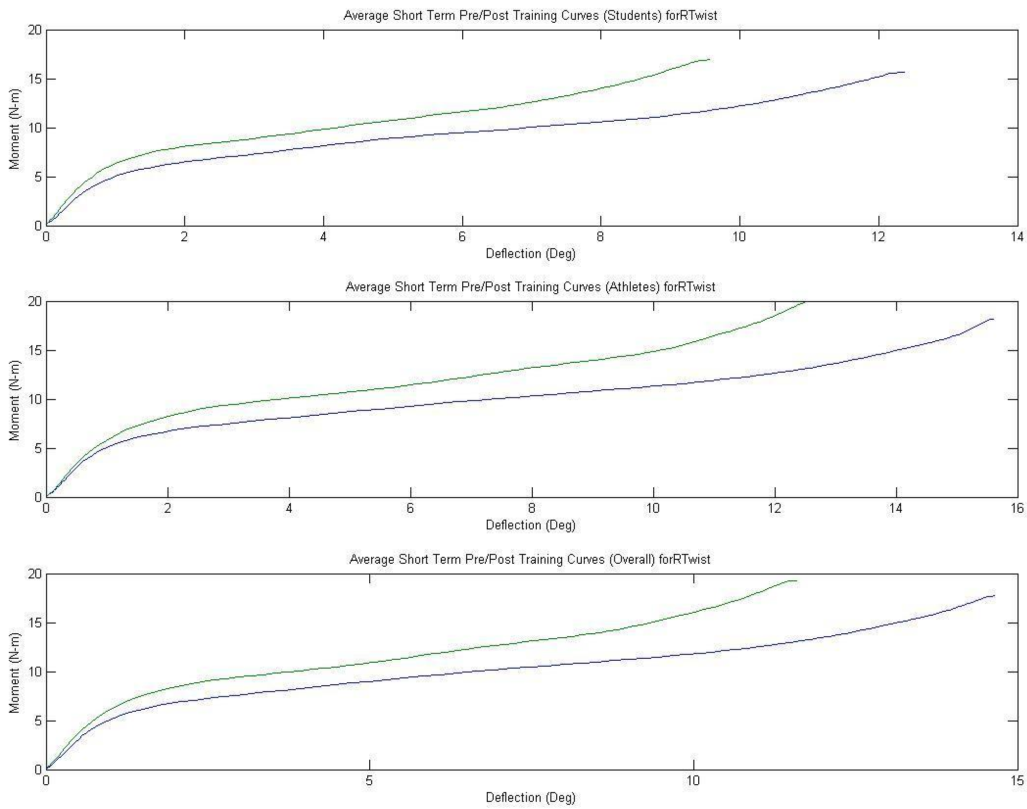

Figure 61: Plots of collected filtered and processed moment and angular displacement data for short term passive right axial twist trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

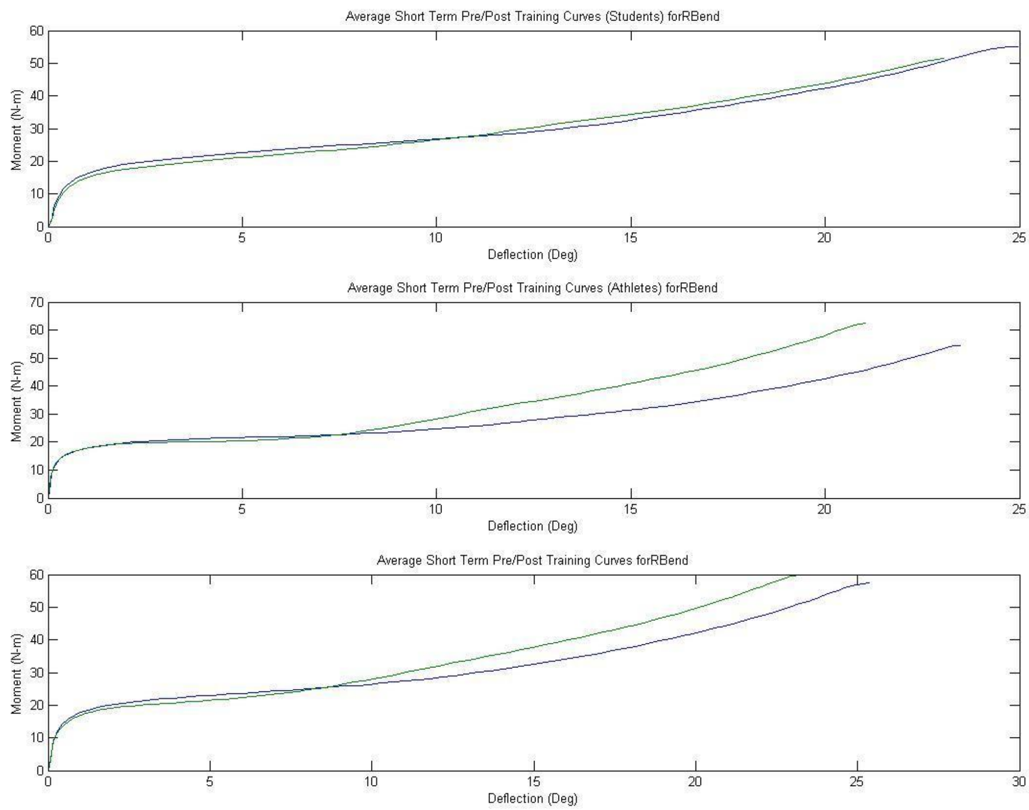

Figure 62: Plots of collected filtered and processed moment and angular displacement data for short term passive right lateral bend trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

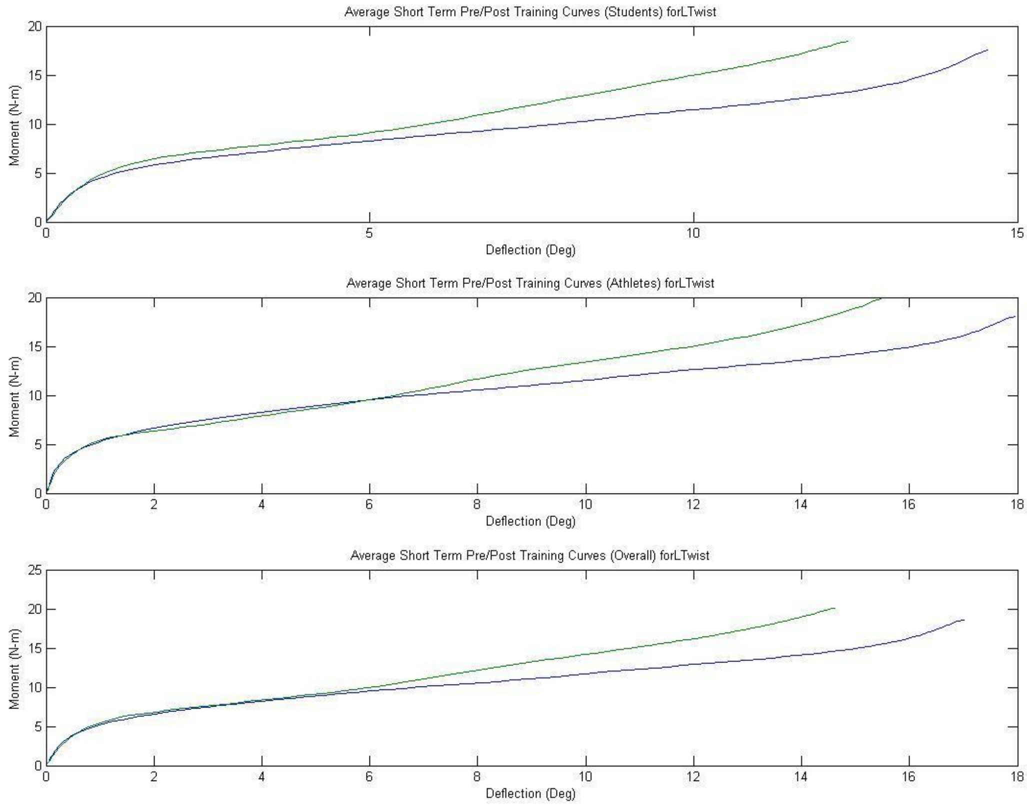

Figure 63: Plots of collected filtered and processed moment and angular displacement data for short term passive left axial twist trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

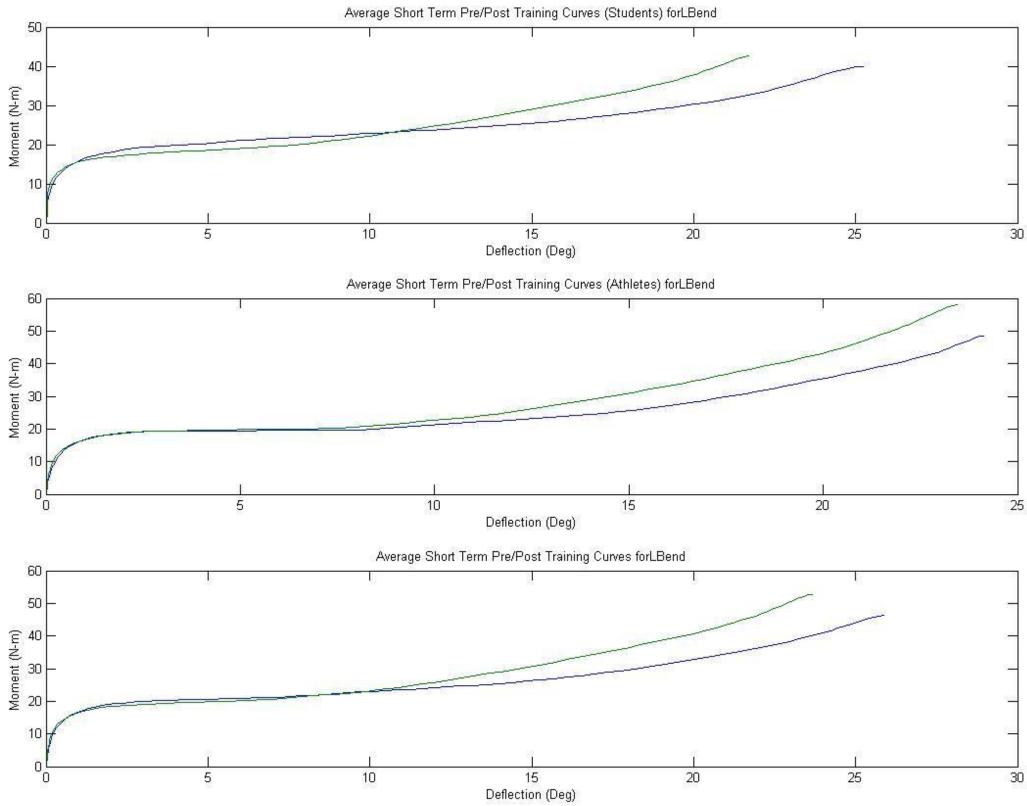

Figure 64: Plots of collected filtered and processed moment and angular displacement data for short term passive left lateral bend trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

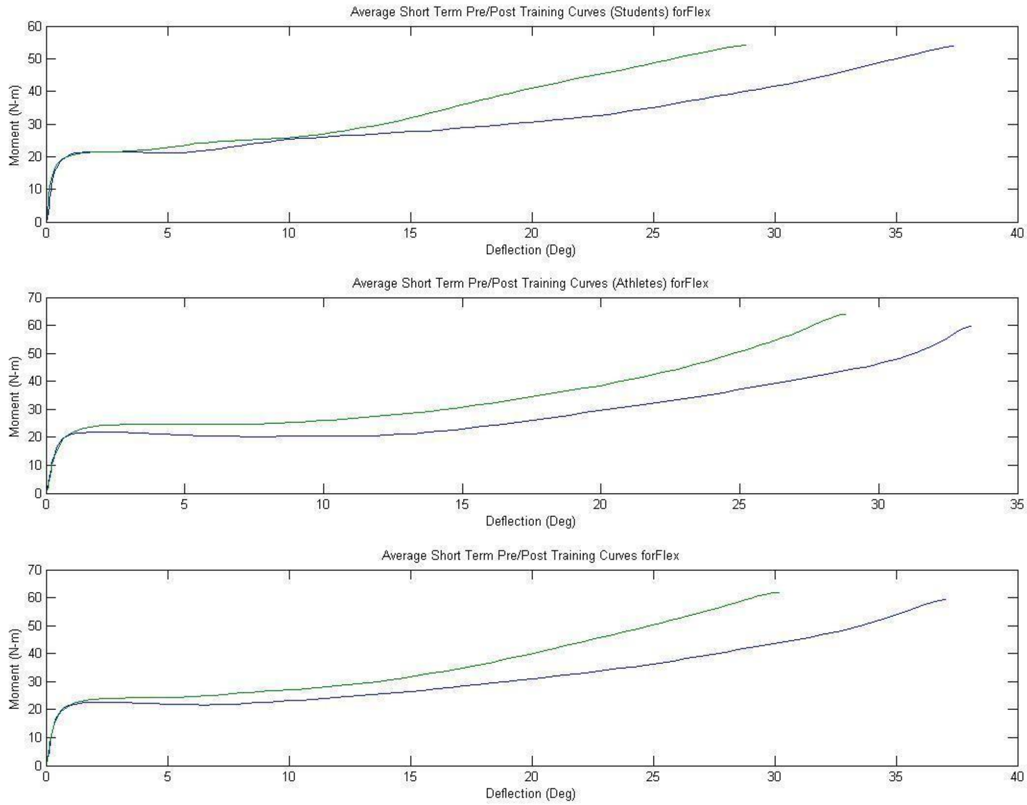

Figure 65: Plots of collected filtered and processed moment and angular displacement data for short term passive flexion trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

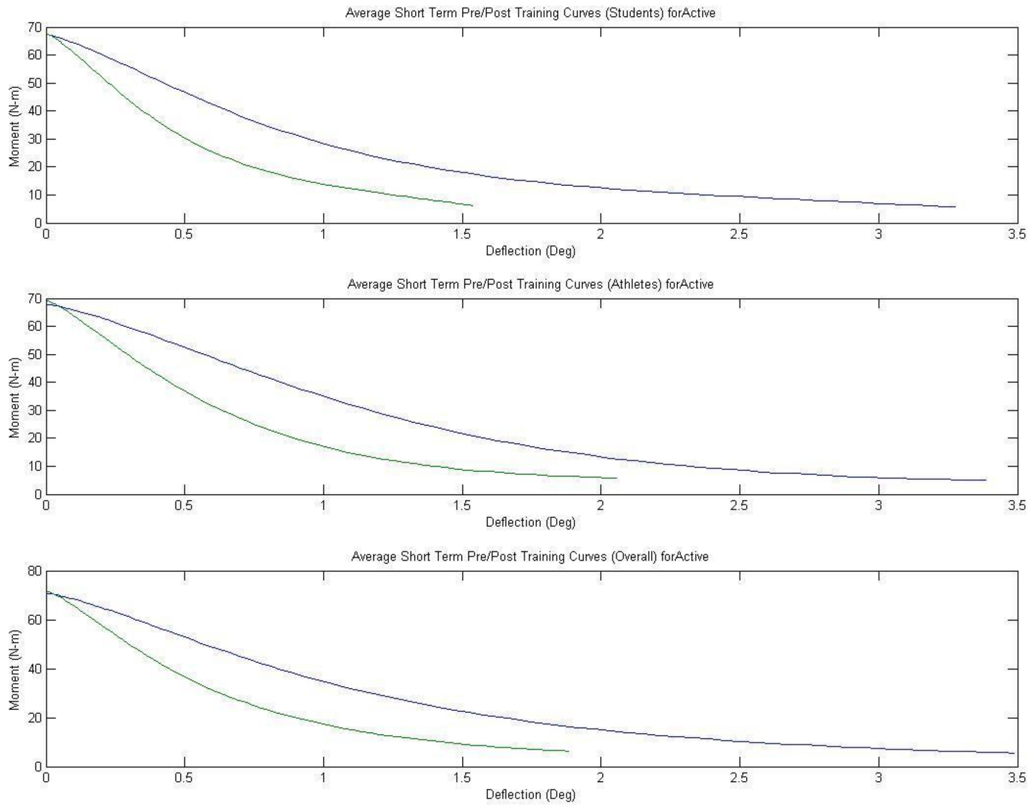

Figure 66: Plots of collected filtered and processed moment and angular displacement data for short term active extension trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

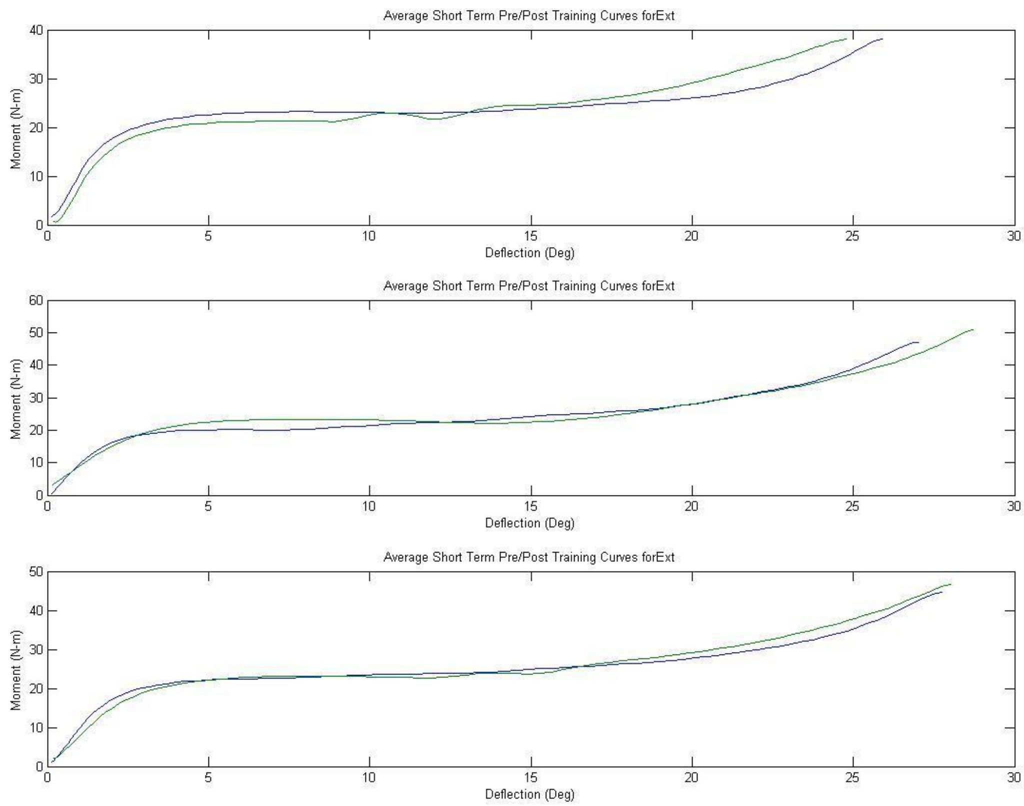

Figure 67: Plots of collected filtered and processed moment and angular displacement data for short term passive extension trials for students (top), athletes (middle) and overall (bottom). Exponential curve fit plots from the Results were created based off this data.

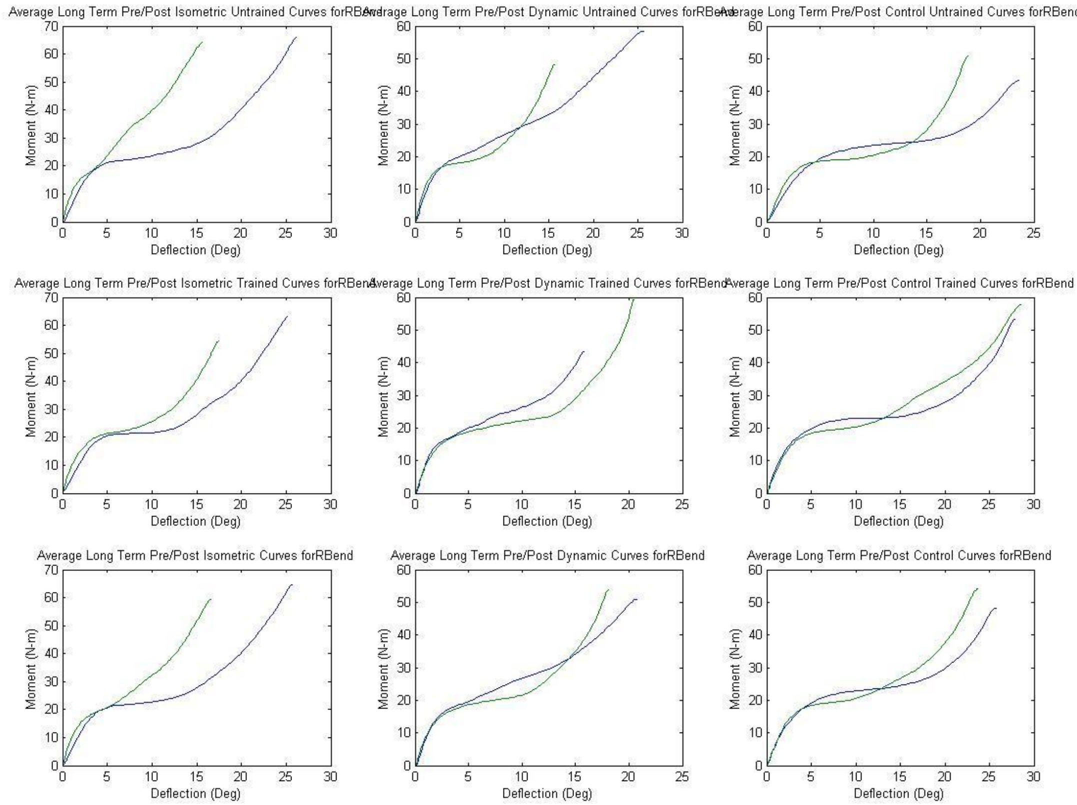

Figure 68: Plots of collected filtered and processed moment and angular displacement data for long term passive right lateral bend trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

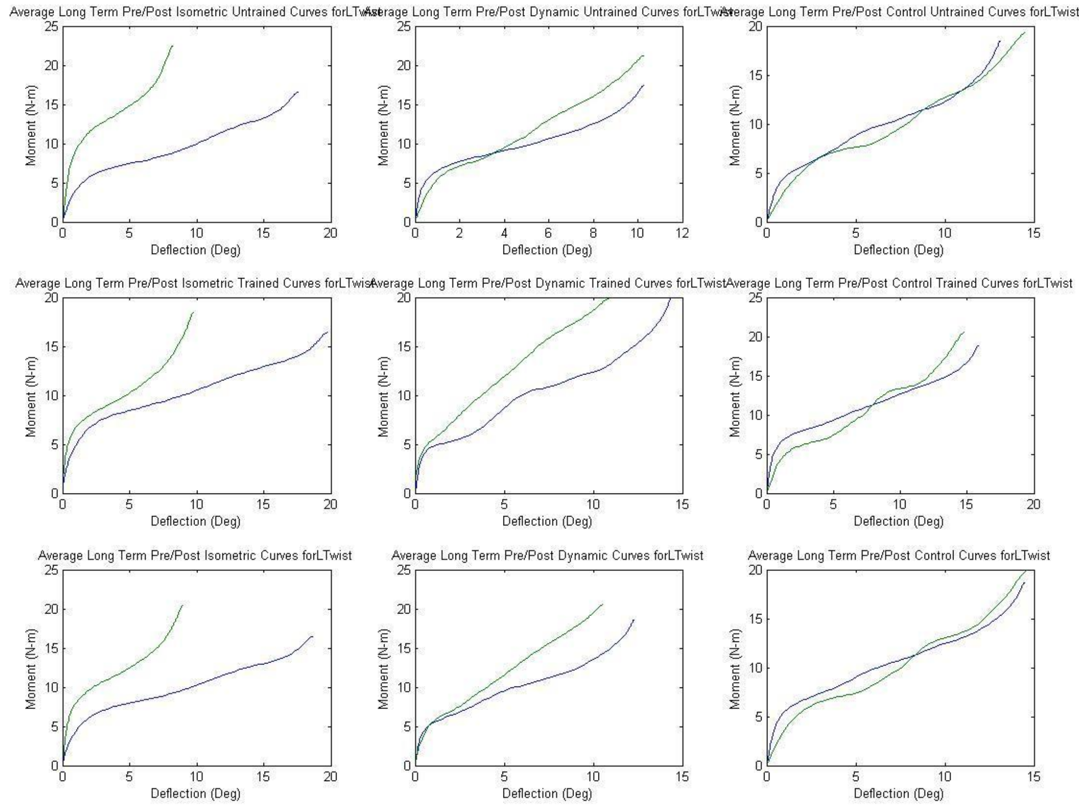

Figure 69: Plots of collected filtered and processed moment and angular displacement data for long term passive left axial twist trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

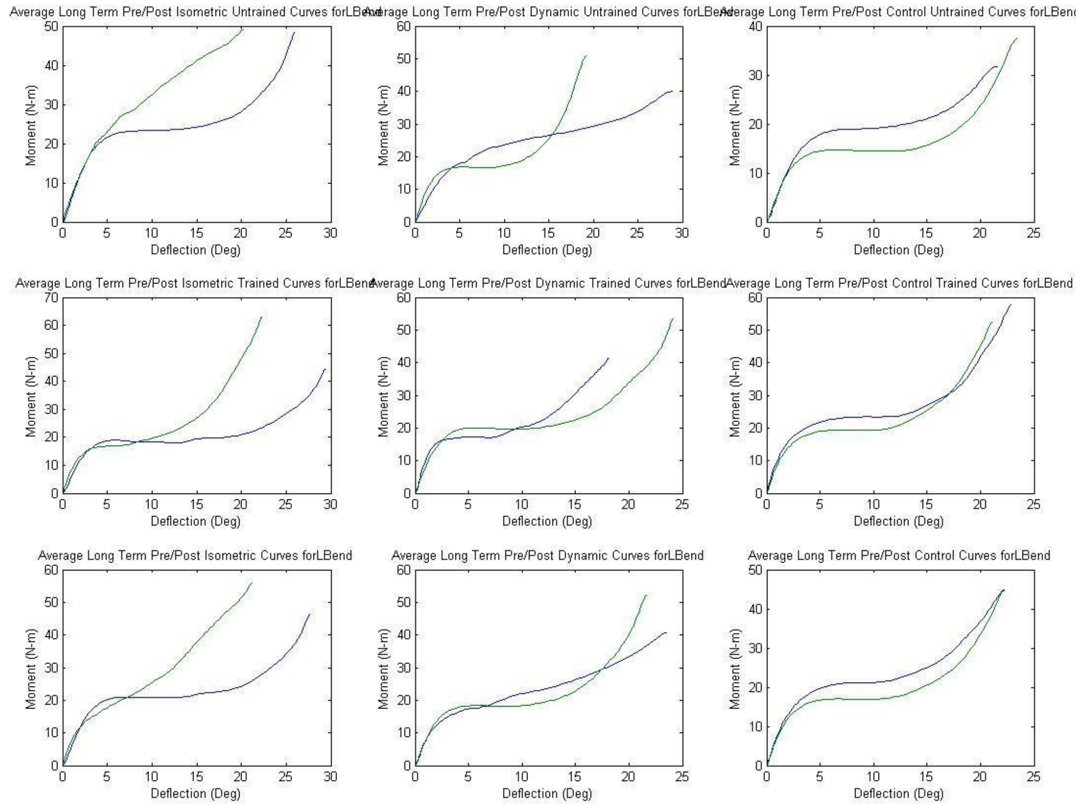

Figure 70: Plots of collected filtered and processed moment and angular displacement data for long term passive left lateral bend trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

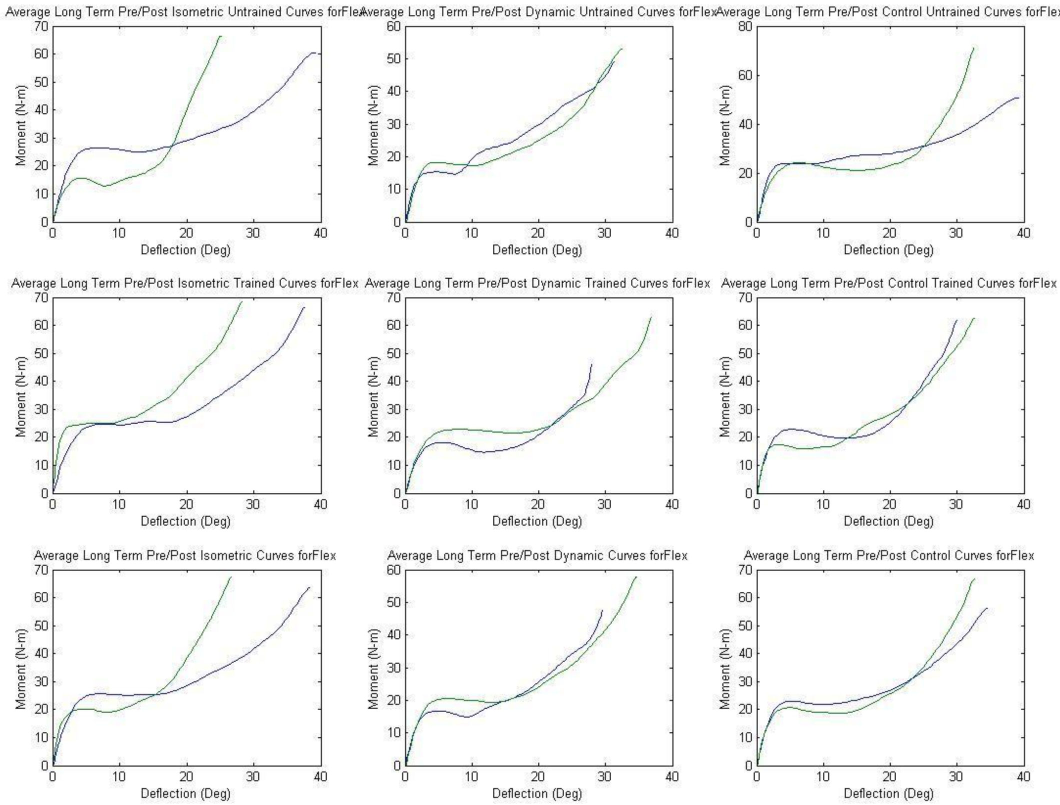

Figure 71: Plots of collected filtered and processed moment and angular displacement data for long term passive flexion trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

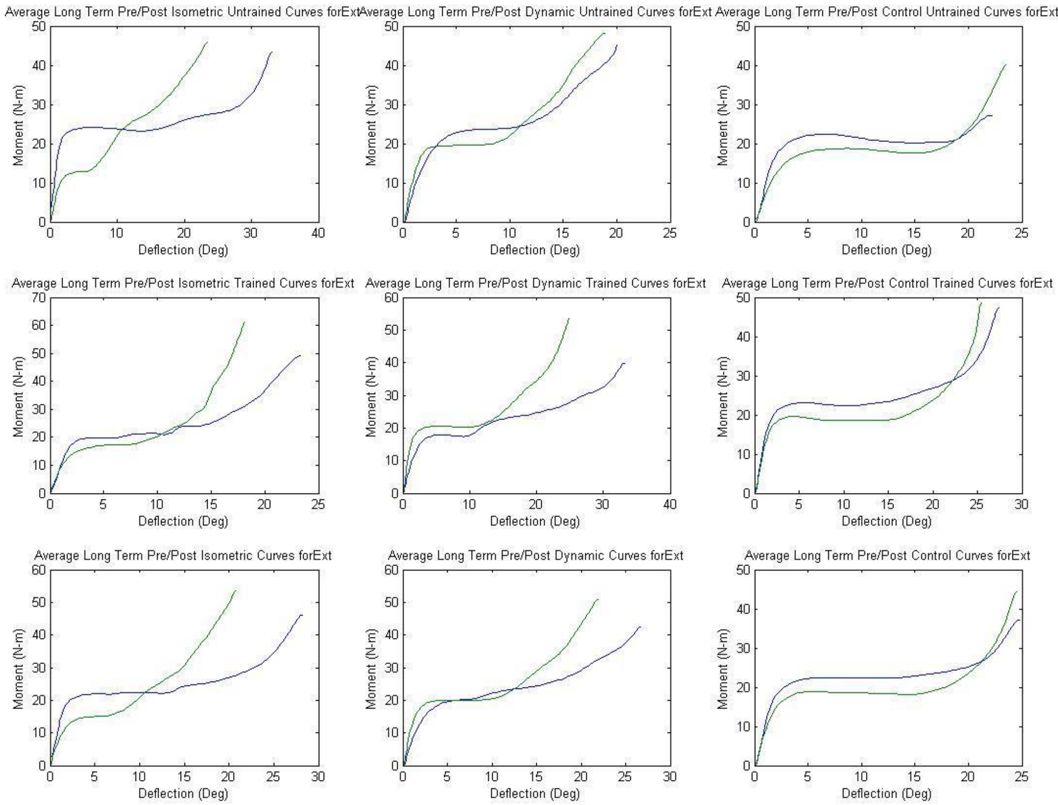

Figure 72: Plots of collected filtered and processed moment and angular displacement data for long term passive extension trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

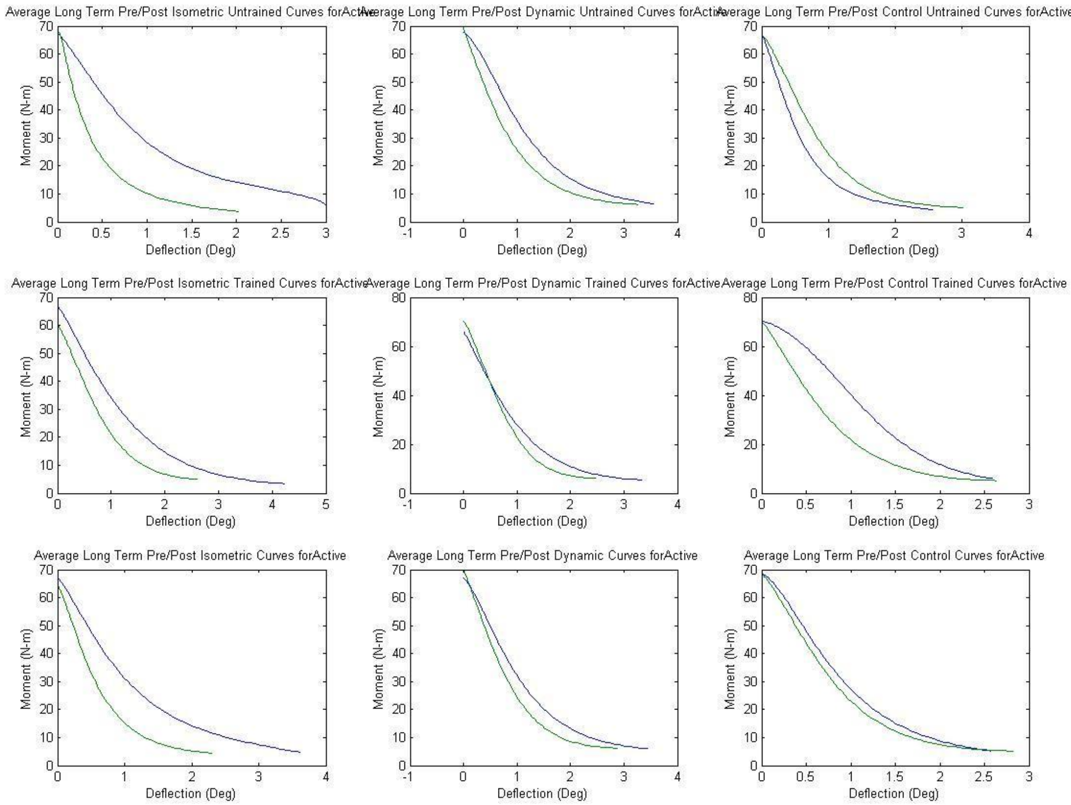

Figure 73: Plots of collected filtered and processed moment and angular displacement data for long term active extension trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

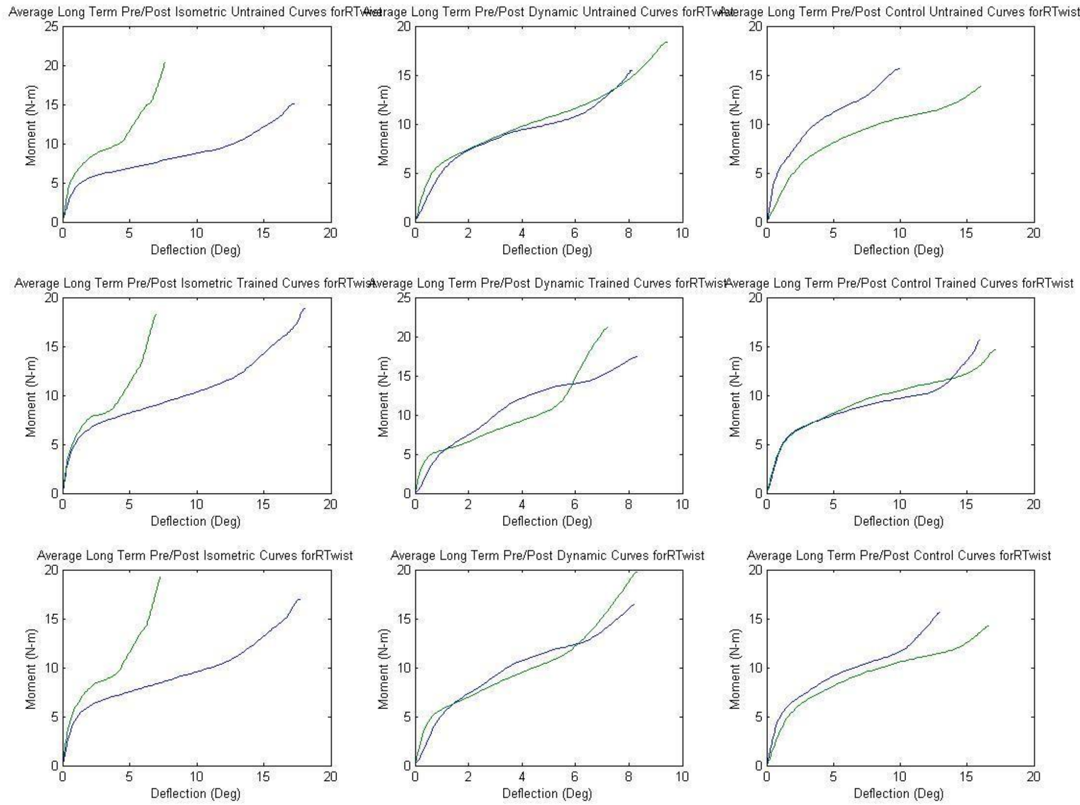

Figure 74: Plots of collected filtered and processed moment and angular displacement data for long term right axial twist trials. Exponential curve fit plots from the Results were created based off this data. Plots are organized by subject and training group; Top left: isometric student. Middle left: isometric athlete. Bottom left: isometric overall. Top middle: dynamic student. Centre: dynamic athlete. Bottom middle: dynamic overall. Top right: control student. Middle right: control athlete. Bottom right: control overall.

APPENDIX G

Training Journals

Subject	Group	Log Status
S01	Isometric naïve	Included
S02	Isometric naïve	Included
S03	Isometric savvy	Included
S04	Isometric savvy	Included
S05	Isometric naïve	Included
S06	Isometric naïve	Missing
S10	Dynamic naïve	Included
S11	Dynamic naïve	Included
S12	Isometric savvy	Included
S13	Dynamic savvy	Included
S15	Dynamic savvy	Missing
S18	Dynamic savvy	Included
S20	Dynamic savvy	Included
S21	Isometric savvy	Included
S23	Dynamic naïve	Missing
S24	Dynamic naïve	Missing

Subject ID: S01
Training Group: Isometric naive

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
Weight training at the gym (limited)

Past injuries (within last year):
Minor hip overworking injury.

Current physical training (physical activity performed during study aside from assigned training protocol):

Normal weight training, some focus on isolation exercises. Free weights and dumbells

Comments (weekly observations/changes in physical performance):
I flex my core subconsciously and stabilize myself if my body has a tendency to wiggle around. My abdominal muscles have slightly more definition. I can squeeze my abs A LOT harder than I used to before the training protocol

Subject ID: S02
Training Group: Isometric naive

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

Within the last year I played both softball and hockey through the Waterloo University intramural league. On average I played a game about once every two weeks.

Past injuries (within last year):

I did not suffer any major injuries within the last year. The only injury worth noting is some recurring soreness in my left shoulder.

Current physical training (physical activity performed during study aside from assigned training protocol):

Throughout the course of the study the only additional physical activity I performed was playing 4 intramural hockey games.

Comments (weekly observations/changes in physical performance):

I had a couple hockey games during the later portions of the study. During these games I noticed my balance and my ability to change directions while skating were both noticeably improved. My overall speed did not increase but every other aspect involved in skating seemed to be much easier and required much less effort compared to before I started this study.

Subject ID: S03
Training Group: Isometric savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

Muay thai, 1 amateur fight
Lift weight lifting

Past injuries (within last year):

None

Current physical training (physical activity performed during study aside from assigned training protocol):

Throughout the course of the study the only additional physical activity I performed was playing 4 intramural hockey games.

Comments (weekly observations/changes in physical performance):

Week 1 – Did plank, side bridge and bird dog. Not difficult since I am used to doing these exercises in muay thai training.

Week 2 – Increased difficulty by squeezing my fists on plank and side bridge. For bird dog I squeezed my fist and pushed my heel out harder. I can feel a bit more of my core working when I do this. Started to do the torsional buttress for 5 seconds at a time. Difficult at first but it got easier throughout the week and I increased to 8 seconds near the end.

Week 3 – Started new exercises with the cables. Definitely harder than the first 2 weeks and feel a bit sore after training.

Week 4 – Exercises are easier. I notice when I hit pads I can bring my hands back faster. Talked to Ben about this and we thought this might be from my ability to brace my core better and rotate my torso without my spine twisting.
Week 5 – New exercises with stir the pot, TRX row, kneeling cable and suitcase walk. Definitely is

a lot harder and I have to concentrate to keep my spine from moving while I move my arms and legs. I feel more sore after the first couple days but it’s getting easier near the end of the week

Week 6 – Exercises feel a lot easier now and I can control my core muscles much better than before I started. Compared to the basic core exercises we do in muay thai these exercises after Week 3 forced me to work harder but my core feels stronger than ever. My punching feels quicker and I can put more snap on them, and Andrew (my trainer) tells me I am bringing my hands back after I punch a lot quicker.

I also see my core muscles a lot better. I can feel my abs when I flex them and the v cut (Ben says these are my internal obliques) is more pronounced. I can squeeze my glutes better too which helps with the exercises and with kicking and knees.

Subject ID: S04
Training Group: Isometric savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

Amateur Muay Thai for the past 2 years, lifted weights on and off.

Past injuries (within last year):

None

Current physical training (physical activity performed during study aside from assigned training protocol):

Continued training at VMT@UW at the usually amount (3-5 times a week)
Training did increase for one month due to preparing for a Demo

Comments (weekly observations/changes in physical performance):

Week 1
Did the exercises mostly at the beginning of training sessions at VMT@UW. For the most part the difficulty was not too difficult I did not find myself shaking during them. Adding the tightening of the fist and pulling the elbow toward the hips made it more difficult. I felt slightly warmed up immediately after completing them mostly feeling the effect in the front part of my torso and in my lower back.

I don’t really feel much soreness in my core from these. On occasion when I lead the warm up I incorporate these exercises towards the end.

Week 2
One thing I noted from doing the exercises is that using the Ques that Ben gave me to perform these exercises I am more aware of what muscles perform the best and the least. I mainly noticed that when holding a plank my glutes become difficult to keep activated much faster than anything else and definitely before any trembling sets in.

Also, after all the sets of these exercises are completed I find myself more ‘warmed up than I would expect to be I feel like stretching and this amount of core work would be sufficient for me to warm up and throw a strike or begin hitting pads. Also I notice that when certain bits and pieces of the exercises were not done It would become more difficult to maintain balance, for example not using my feet to resist each other when holding the one handed plank. I feel like my ability to hold a plank and over all performance for core work would be better at this point though I haven't given that a test, i.e. I think id be able to hold an elevated plank much longer than I would have before.

Week 3
During this week I increased the amount of cardio I've been doing in preparation for the demo. I hit pads almost everyday. I noticed that my recovery time between rounds got shorter and overall fatigue after hitting pads became less. When I began hitting pads after a training session my entire core would feel like jello and I wanted nothing more than to slouch and recover. I would notice the variation of the plank (with the feet crossed over each other) is getting easier to maintain but I still notice that my glutes just seem to turn off first when I try to keep everything clenched. During these weeks as well my time in the weight room increased, Andrew had me doing split squats and deadlifts along with unilateral bench to get stronger for the demo. At the end of classes I would be put through the gauntlet usually with the last people being Richard or Andrew, or both. I found that towards the end my overall fitness and performance went up considerably however I was concerned with cardio more so than anything else because I wanted to avoid the adrenalin dump.

Week 4
Most of this week I did not notice much change from the previous physically, but I do notice that I am more aware of how to activate certain muscles in my body and use them during my training periods such as spreading the floor with my feet to brace myself during muay thai drills and such.

Week 5
I find it easier to move during training and shadow boxing, meaning I find it less challenging to explosively 'stop' and 'go'. Even when throwing a punch or a knee I can turn on my core better which results in more explosiveness I guess. I also feel like my swing has become a lot stronger on both legs my balance is definitely improved a lot because I can throw a descent swing from both legs and with descent power. I can also throw a better punch to kick combination expending less energy to do so as before and it 'flows' better, although Andrew has been teaching us a pivot type of footwork to throw combinations with so it could be that more so than the core attributing to this but still a change. I had a demo on May 4th in which I cut 9 pounds for but continued cutting losing a total of 18 pounds. Being lighter could be why my movement is easier, I also find it less of a hassle to move for example during tech sparring sessions im more inclined to chase someone down or put in the effort to stay in front of them than before, before it would require more effort and expend more energy for the same movement than now, so moving is easier.

I also noticed that during my training sessions when I am balancing on one leg I notice that my glute on my support leg is active more of the time when I am not actively thinking about activating it, I also have noticed that bringing my leg up to block a low kick comes up a lot faster and with less effort than before beginning the training. Doing this routine of exercises no longer leaves me sore in the slightest and sometimes feels more difficult than I expected, for example the wood chops would always be harder than I think they would be requiring more effort from me to stay stable and resist rotating.

Week 6

I found that performing some of the exercises felt like two different sections of my core were being used. For example the half kneeling wood chop made me feel like

Also I found it less challenging to perform the exercises when I had to actively think about what I was doing, for example when doing the brief case walk as I actively thought about activating the glute on the planted leg I found that it was easier to maintain balance. Also I noted that after doing the wood chops walking up the stairs my knees felt as if they had something pushing them inwards though I looked at them and they did not appear to be doing so.

The following day my shoulders were the most sore from these exercises but as for my core the 'V cut' muscles were the most sore along with a little bit of soreness from the lats. These aren't much soreness at all on the posterior part of my core if any. But a good overall description of my core the day after beginning this new set of exercises would be that my core feels 'rusted'. The day after my athletic performance would definitely suffer due to soreness.

The second day of performing these routines did not leave me sore like the first session did. During the rows I felt more strain on my lower back than the previous session. Also the briefcase walk was less difficult to stay balanced. I have noticed from the second – third week of training that I find it easier to maintain balance whilst training especially during stretches where I am required to stand on one leg.

During shadow boxing the ease of which I throw my punches is still surprising to me I don't have to lean into more of them than before to get the speed and explosiveness I want, though its not a major improvement because I find myself leaning in still with some punches this observation comes purely from a few jabs that caught Richard off guard.

Also I noticed that push kicks do not push me as far back as the used to, well timed ones still get me like before where my core would go flying away before my head kind of making me bend forward however a few more push kicks will not have that same effect on me I'm better able to allow it to glance off or catch them, I haven't worked on defending pushkicks or it could be that I've been practicing working on establishing my range but still worth noting.

Subject ID: S05
Training Group: Isometric naive

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

Weight lifting on and off for 2 years

Past injuries (within last year):

Minor knee pain when I squat

Current physical training (physical activity performed during study aside from assigned training protocol):

Weight training (squats, deadlifts, bench press, bodybuilding)

Comments (weekly observations/changes in physical performance):

I used to lift weights on and off but would stop for a few months at a time before going at it again. My goals for lifting were to get stronger and look better. I never trained my core before even when I was doing squats and deadlifts since I didn't think it would do too much for my strength. We tested my endurance when I was in the lab and all my times were under a minute.

The first week of training was a bit hard since I had to learn how to hold my body straight without my back bending or twisting too much for the plank, side plank and bird dog. Ben had me put a foam roller on my back when I did bird dogs to make sure I wasn't twisting or else the foam roller would fall off. The second week was easier after I learned how to control my body. I wasn't as sore and it was easier to finish the workouts.

In the third week I noticed heavier squats and deadlifts are a lot easier. The core exercises changed I am using cables for Pallof Press, holding the cable handles above my head facing forward and backward, and to the side. I am also doing suitcase holds where I hold the cable handle at my side and prevent it from pulling me to the side. When I squat I used to feel unstable when coming out from the bottom position and it would feel like I am going to fall forward or backward. Now I can spread the floor and brace my core and coming out of the same position in my squat feels much easier.

Week 5 exercises changed and they are much more tiring and I have to think more to stay stable while I'm moving my limbs. I feel tired like I had a hard workout and my core and arms got sore during the early part of the week. As the week went on and into the next week they got a lot easier.

My squat and deadlift feel even stronger. Ben showed me how to punch someone and using the glute and core activation I learned I felt like punching was much faster and harder than how I punched before, but I never used any trained technique when punching before. I will be doing these core workouts even after the study because I feel they have helped my strength in the gym go up and I feel more stable.

Subject ID: S10
Training Group: Dynamic naïve

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
Basketball
Volleyball
Weights

Past injuries (within last year):
None

Current physical training (physical activity performed during study aside from assigned training protocol):
Basketball
Volleyball
Weights

Comments (weekly observations/changes in physical performance):
I followed the core program exactly as what Ben showed me when we met up every week. Overall I felt faster and my muscles could twitch faster especially after the last 2 weeks. The medicine ball throws were my favourite since I could whip the ball and use my hips as hard as I could. I think my jumping has gotten better too but I'm not sure if its because I have been working on jumping or because I can activate my muscles quicker.

Subject ID: S11
Training Group: Dynamic naïve

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
None

Past injuries (within last year):
None

Current physical training (physical activity performed during study aside from assigned training protocol):
None

Comments (weekly observations/changes in physical performance):
Week 1: Learned how to do the basic exercises. Core muscles feel warm and activated after training and not very tired.
Week 2: Exercises are a lot easier, not feeling as much in my core muscles as the week before.
Week 3: New exercises started. The exercises looked a lot harder when Ben was demonstrating them but they weren't too hard to perform. The Russian Barbell Twist makes me pretty sore after the workout but it got easier through the week. The hardest part was making sure the arms don't push the barbell and to make sure my core is tight so my hips and shoulders don't twist away.
Week 4: Exercises feel a lot easier. I noticed before that when picking things up or carrying heavy things my back would hurt after. This week I helped my friend move all of his stuff. I was helping him move his couch and my back didn't hurt after. I felt like I had better control of my core muscles because when I lifted anything I would brace my core and could feel the muscles activate. I think the core training is helping me turn my core on and off better and that might be why my back doesn't hurt after helping my friend move.
Week 5: The new exercises were hard to do. Not that it was too heavy but learning how to quickly turn my core on and off was new to me and challenging to do. Ben said to just keep practicing and gave me some tips on how to stay relaxed so I will try to remember and use them. I like the medicine ball throws. I can feel my sides activate when I to the bending and rotation throws.
Week 6: It feels easier now to turn my muscles on and off quickly. We made the exercises harder by adding 5 lbs to the curl up twitch and Superman twitch. I can feel the muscles turn on sharply and to a higher degree. The throws also feel a lot faster.

Subject ID: S12
Training Group: Isometric savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
Muay Thai – 10+ amateur fights, provincial welterweight champion (WAMTAC)
Weight training

Past injuries (within last year):
Broken nose, shin damage
Some shoulders rounding and forward head that I'm trying to fix

Current physical training (physical activity performed during study aside from assigned training protocol):
Muay Thai
Weiht training

Comments (weekly observations/changes in physical performance):
I am accustomed to traditional muay thai style core work with lots of crunches, sit ups, side bends and twisting having done them for years while training as a fighter. I signed up for Ben's study after having known him and talked to him about core training for fighters and athleticism. More recently I have adopted the isometric style exercises (plank, side bridge) and stopped doing situps to see what would happen.

The first 2 weeks I didn't feel much from the plank, bird dog and side bridge, mostly because I do these almost every day in training. Ben did add some cues that I'm not used to (squeezing my core, glutes, fists, pulling my elbows toward my waist during plank and side bridge, pointing my heel during bird dogs). These did make the exercises a little more challenging but not much. I did feel some more activation and warmth in my core and glutes during these cues though.

The next 2 weeks were more challenging since these were exercises I've never done before – all of these used external load in the cable stack machine. With the extra weight I had to concentrate harder to activate my core and glutes to make sure the weight didn't pull me around. I feel I can activate my core and glute muscles a lot easier during this period and the contraction feels stronger.

The last 2 weeks were the hardest and I did them as their own workout; previously I did the other core workouts after lifting weights. I am using all the cues I've learned (tight fists, spread the floor) to control my movement and it feels a lot easier to do it now, especially for the suitcase walk with the high step. When we added the step I had a tendency to cross my feet and lose balance but by keeping tight I got better at it, and it became easier. The anti-rotation exercises were the hardest but I think that's because I've never trained anti-rotation much before.

Subject ID: S13
Training Group: Dynamic Savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
Muay Thai
Squash (recreational)

Past injuries (within last year):
Blunt trauma to head, shins

Current physical training (physical activity performed during study aside from assigned training protocol):

Muay Thai

Comments (weekly observations/changes in physical performance):
For the first set I followed it to a tee. I remember feeling more energized after the drills. Usually if I enter the gym feeling 6/10 the drills will bring me up to 8/10. But if i'm already feeling 8/10, the drills don't increase it by much.

Subject ID: S18
Training Group: Dynamic Savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):
Judo, weightlifting, Muay Thai,

Past injuries (within last year):
Patellar Tendonitis

Current physical training (physical activity performed during study aside from assigned training protocol):

Muay Thai and Judo, with some weightlifting mixed in

Comments (weekly observations/changes in physical performance):
Training Journal:
Week 1 - 5sets x 10 reps
Exercises: Curlup, Side curlup, twisting curlup, superman
Completed 4x in the first week
Weekly observation: slightly strenuous during the exercises, but no noticeable fatigue after completing each days exercises

Week 2 - inconsistently training

Week 3
Completed 6 days of exercises
5 sets x 10 reps
Exercises: (same as week one) (Phase 1)
Weekly observation: Exercises were becoming slightly easier, again no noticeable fatigue after completing each days exercises

Week 4
Phase 2 exercises started, 5x that week
5 sets x 10 reps
Weekly observation: exercises had a noticeable different in difficulty, especially those with weight, slight fatigue after completing the days exercises

Week 5/6
No exercises completed, was in England for grandfathers funeral
Ben told my to revert to Phase 1 if needed but I did not have time to

Week 7
Completed Phase 2's exercises 5x that week
5 sets x 10 reps
Weekly observations: exercises again caused a slight fatigue, noticeable different for those with weight

Week 8/9
Phase 3 Dynamic exercises completed 5x in both weeks
5 sets x 10 reps
Weekly observations: only noticeable fatigue when tossing the ball against the wall

Subject ID: S20
Training Group: Dynamic savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

-muay Thai
-Brazilian Jiu-jitsu
-Weight training
-Volleyball

Past injuries (within last year):
-None

Current physical training (physical activity performed during study aside from assigned training protocol):

-muay Thai
-Weight lifting
-Volleyball

Comments (weekly observations/changes in physical performance):

Workout Routine 1

During the first week of the training schedule, the recommended exercises required the use of unfamiliar movements which caused difficulty when trying to activate the correct muscles. Unlike typical workouts where the most exhaustion occurs after the first couple workouts, I found that this set of core exercises caused more exhaustion as I became more familiar with the necessary movements. A couple days into the workout, I began to feel more and more exhaustion as I was able to better control the activation of the targeted muscles. After more days of conducting the exercises, my body was not only able to properly engage the required muscle groups, I was able to reduce rest times and increase reps. After completing this portion of the training schedule, my core was able to better perform these specific workouts but no observable differences in physical performance were observed.

Workout Routine 2

During the last set of training, the exercises involved more kinetic linkages and resulted in more exhaustion post-training. Each movement had to be done slow during the first week to ensure proper technique. After sets were performed with inadequate technique, muscular exhaustion was more distributed around the body compared to sets with proper execution, which, caused exhaustion to be focused around the core. Following the first week, the exercises became more familiar and the individual reps were able to be performed with more speed and power. The sheer difference in sound when the medicine ball hit the wall was indicative of such increase in speed and power. Post-training exhaustion was much like the first set of exercises where more was felt after the first couple run-throughs as the correct muscles were able to be activated with greater intensity. This set of workouts did seem to show a difference in my physical performance. During muay Thai training, I was able to throw punches and kicks with less preparation (both mental and physical). For a lack of a better term, my strikes were more ‘quick-release’ than ever before.

Subject ID: S21
Training Group: Isometric savvy

Past physical history (sports, weight lifting, physical activity performed regularly in the last year):

Current Training; Mon-Fri, Weightlifting and Kettlebells 30+mins, Martial arts training 90+mins 3 x week
Example: Snatch 5x2, Front Squat up to a heavy single, KB swings 1x20

Past injuries (within last year):
-None

Current physical training (physical activity performed during study aside from assigned training protocol):

-muay Thai
-Weight lifting
-Volleyball

Comments (weekly observations/changes in physical performance):
Week 1- all training was done at home, before martial arts class if training that evening, exercises were done in a circuit fashion
5 days; plank, side bridge, bird dog, 10s x 4 times through
Week 2- all training was done at home, before martial arts class if training that evening, exercises were done in a circuit fashion
3 days; plank, side bridge, bird dog, torsional buttress 10s x 4 times through
*I experienced an abdominal cramp that I was concerned may be a hernia and took 3 days off all training
Week 3- all training was done at gym after weightlifting, exercises were done one at a time 4x10s, Day 1, 2
Anterior pallof press 22.5, Posterior pallof press 17.5, Anti rotation pallof press 22.5, Suitcase hold 42.5
Was unable to complete this weeks training at gym so copied week 2 routine for two evenings at home
Week 4
Day 1, Anterior pallof press 27.5, Posterior pallof press 22.5, Anti rotation pallof press 27.5, Suitcase hold 52.5
Day 2, Anterior pallof press 27.5, Posterior pallof press 22.5, Anti rotation pallof press 27.5, Suitcase hold 62.5
Day 3, Anterior pallof press 27.5, Posterior pallof press22.5, Anti rotation pallof press 27.5, Suitcase hold 72.5
Week 5 all training was done at gym after weightlifting, exercises were split in pairs and alternated daily
Day 1,demo day with Ben,   Stir the pot 4x 5rotations/side, half kneeling woodchop 4x5/side, inverted row 4x5, Unilateral KB walk 50lb x 40yard

Day 2, Stir the pot 4x 5rotations/side, half kneeling woodchop 4x10/side
Day 3, inverted row 1x10, 3x5, Unilateral KB walk 50lb x 40yard
Day 4, Stir the pot 4x 5rotations/side, half kneeling woodchop 4x10/side
Week 6 all training was done at gym after weightlifting, exercises were split in pairs and alternated daily
Day 1, inverted row 1x5,1x6,1x7,1x6, Unilateral KB walk 50lb x 40yard
Day 2, Stir the pot 4x 5rotations/side, half kneeling woodchop 4x10/side
Day 3, inverted row 4x6, Unilateral KB walk 50lb x 40yard
Day 4, Stir the pot 4x 5rotations/side, half kneeling woodchop 4x10/side
Day 5, inverted row 4x7, Unilateral KB walk 50lb x 40yard
Comments;
Overall I really enjoyed the program. Some really interesting exercises presented in a logical progression. I particularly liked the bodyweight exercises from weeks one and two and the unilateral KB walk from week five and six. I will continue to use these exercises in my future training. I personally found the volume a bit on the high side given my current workout routine. For example I'm not sure I require specific anterior/posterior exercises when I'm also training heavy pulls and squats. The most beneficial aspect of the program was the coaching cues provided by Ben. The ability to create tension throughout the entire body is critical not just for athletic movements but everyday life. Through Ben's coaching cues in each movement I was able to learn where I was leaking stability and correct. Now when I walk with a grocery bag in one hand (unilateral KB walk) I run through all Bens cues in my head just as if it were a 50lb KB.

Bibliography

Adams MA and Hutton WC. 1982. Prolapsed intervertebral disc: A hyperflexion injury. Spine 7(3): 184-191

Akuthota V and Nadler SF. 2004. Core strengthening. Arch Phys Rehab Med 85(1): 86- 92.

Army US. Physical Fitness Training: Field Manual 21–20. Washington (DC): Headquarters, United States Army; 1992. p.14-20.

Avela, Janne, Heikki Kyröläinen, and Paavo V. Komi. "Altered reflex sensitivity after repeated and prolonged passive muscle stretching." *Journal of Applied Physiology* 86.4 (1999): 1283-1291.

Aultman CD, Scannell J, McGill SM. 2004. Predicting the direction of nucleus tracking in porcine spine motion segments subjected to repetitive flexion and simultaneous lateral bend. Clin Biomech 20:126 - 129

Axler CT, McGill SM. 1997. Low back loads over a variety of abdominal exercises: searching for the safest abdominal challenge. Med Sci Sports Exerc. 29(6): 804- 11.

Beim GM, Giraldo JL, Pincivero DM, Borror MJ, Fu FH. 1997. Abdominal Strengthening Exercises: A comparative EMG study. J Sport Rehab 6: 11- 20. J Orthop Sports Phys Ther 6: 11 - 20

Bellemare, F., et al. "Effect of tension and timing of contraction on the blood flow of the diaphragm." *Journal of Applied Physiology* 54.6 (1983): 1597-1606.

Bergmark A. 1987. Stabilityof the lumbar spine A study in mechanical engineering. ACTA ORTHOPAEDICA SCANDINAVICA SUPPLEMENTUM 230(60): 25- 38

Bonde-Petersen, F., A. L. Mørk, and E. Nielsen. "Local muscle blood flow and sustained contractions of human arm and back muscles." *European journal of applied physiology and occupational physiology* 34.1 (1975): 43-50.

Brereton LC and McGill SM. 1998. Frequency response of spine extensors during rapid isometric contractions: Effects of muscle length and tension. J Electromyogr Kinesiol. 8(4): 227- 32.

Brown, T., Hansen, R. J., & YORRA, A. J. (1957). Some mechanical tests on the lumbosacral spine with particular reference to the intervertebral discs a preliminary report. *The Journal of Bone & Joint Surgery*, *39*(5), 1135-1164.

Brown SHM and McGill SM. 2005. Muscle force– stiffness characteristics influence joint stability: A spine example. Clin Biomech. 20(9): 917 - 922

Brown SHM and McGill SM. 2009. The intrinsic stiffness of the in vivo lumbar spine in response to quick releases: Implications for reflexive requirements. J. Electro. Kin. 19: 727- 736

Brown SHM and McGill SM. 2009. Transmission of muscularly generated force and stiffness between layers of the rat abdominal wall. Spine 34(2), 70 - 75.

Brown, Stephen HM, Francisco J. Vera-Garcia, and Stuart M. McGill. "Effects of abdominal muscle coactivation on the externally preloaded trunk: variations in motor control and its effect on spine stability." *Spine* 31.13 (2006): E387-E393.

Brundin, T. "Circulatory effects of isometric muscle contractions, performed separately and in combination with dynamic exercise." *European journal of applied physiology and occupational physiology* 36.1 (1976): 7-17.

Burgess, K., Connick, M., Graham- Smith, P., & Pearson, S. (2007). Plyometric vs. isometric training influences on tendon properties and muscle output. J. Strength Cond. Res., 21(3), 986- 989.

Callaghan JP and McGill SM. 2001. Intervertebral disc herniation: Studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive fo rce. Clin. Biom. 16(1): 28- 37.

Callaghan JP, Gunning JL, McGill SM. 1998. Relationship between lumbar spine load and muscle activity during extensor exercises. Physical Therapy 78(1): 8- 18

Carolan, B., and E. Cafarelli. "Adaptations in coactivation after isometric resistance training." *Journal of Applied Physiology* 73.3 (1992): 911-917.

Childs, J., Teyhen, D., Benedict, T., Morris, J., Fortenberry, A., McQueen, R., Preston, J., & Wright, A., Dugan J., George S. 2009. Effects of sit-up training versus core stabilization exercises on sit-up performance. Med. Sci. Sports Exerc., 41(11), 2072- 2083.

Chiu LZ and Schilling BK. 2005. A primer on weightlifting: From sport to sports training. J. Strength Cond. Res. 27(1): 42- 48.

Cholewicki J, McGill SM and Norman RW. 1991 Lumbar Spine loads during lifting extremely heavy weights. Med. Sci. Sports Exerc. 23(10): 1179 - 1186.

Cholewicki, Jacek, Manohar M. Panjabi, and Armen Khachatryan. "Stabilizing Function of Trunk Flexor-Extensor Muscles Around a Neutral Spine Posture."*Spine* 22.19 (1997): 2207-2212.

Corcondilas, Adrian, Gabriel T. Koroxenidis, and John T. Shepherd. "Effect of a brief contraction of forearm muscles on forearm blood flow." *Journal of applied physiology* 19.1 (1964): 142-146.

Costi, J. J., Stokes, I. A., Gardner-Morse, M., Laible, J. P., Scoffone, H. M., & Iatridis, J. C. (2007). Direct measurement of intervertebral disc maximum shear strain in six degrees of freedom: motions that place disc tissue at risk of injury.*Journal of biomechanics*, *40*(11), 2457-2466.

Cripton P, Berlemen U, Visarino H, Vegeman PC, Nolte LP, Prasad P. 1995. Response of the liumbar spine due to shear loading. In: Injury prevention through biomechanics (p. 111). Detroit: Wayne State University.

De Luca, C. J., et al. "Behaviour of human motor units in different muscles during linearly varying contractions." *The Journal of physiology* 329.1 (1982): 113-128.

De Luca CJ. 1997. The use of surface electromyography in biomechanics. J Appl Biomech. 13: 135-63.

Durkin JL and Callaghan JP. 2005. Effects of minimum sampling rate and signal reconstruction on surface electromyographic signals. J Electromyogr Kinesiol. 15(5): 474- 81.

Edin, Benoni B., and A. B. Vallbo. "Stretch sensitization of human muscle spindles." *The Journal of physiology* 400.1 (1988): 101-111.

Edin, BENONI B., and A. B. Vallbo. "Dynamic response of human muscle spindle afferents to stretch." *Journal of Neurophysiology* 63.6 (1990): 1297-1306.

Eklund, Brita, L. Kaijser, and E. Knutsson. "Blood flow in resting (contralateral) arm and leg during isometric contraction." *The Journal of physiology* 240.1 (1974): 111-124.

Ekstrom RA, Donatelli RA, Carp KC. 2007. Electromyographic Analysis of Core Trunk, Hip, and Thigh Muscles During 9 Rehabilitation Exercises. J Orthop Sports Phys Ther 37(12): 754- 762.

Escamilla RF, McTaggart MS, Fricklas EJ, Dewitt R, Kelleher P, Taylor MK, Hreljac A, Moorman CT. 2006. An electromyographic analysis of commercial and common abdominal exercises: Implications for rehabilitation and training. J Orthop Sports Phys Ther 36(2): 45 - 57.

Fahey, Thomas D., and C. A. Chico. "Adaptation to exercise: progressive resistance exercise." *Sportsci. org, last update: April* (1998).

Farfan, H. F. "Muscular mechanism of the lumbar spine and the position of power and efficiency." *The Orthopedic clinics of North America* 6.1 (1975): 135.

Farfan, Harry F. "Biomechanics of the lumbar spine." *Managing low back pain*(1988): 15-27.

Fleck, Steven J. *Designing resistance training programs*. Human Kinetics 1, 2004.

Flint MM. 1965. An electromyographic comparison of the function of the iliacus and the rectus abdominis muscles: A preliminary report. Phys Ther 45:248-253

Folland, Jonathan P., and Alun G. Williams. "Morphological and Neurological Contributions to Increased Strength." *Sports Medicine* 37.2 (2007): 145-168.

French, Duncan N., William J. Kraemer, and Carlton B. Cooke. "Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions." *The Journal of Strength & Conditioning Research*17.4 (2003): 678-685.

Fortin, JOSEPH D., and FRANK JE Falco. "The Biomechanicai Principles of Preventing Weightlifting Injuries." *Physical medicine and rehabilitation* 11 (1997): 697-716.

Gardner- Morse MG, Stokes IAF. 1998. The effects of abdominal muscle coactivation on lumbar spine stability. Spine 23(1): 86– 92.

Garfinkel, S., and E. Cafarelli. "Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training." *Medicine and science in sports and exercise* 24.11 (1992): 1220.

Gossen, E. Roderich, and Digby G. Sale. "Effect of postactivation potentiation on dynamic knee extension performance." *European Journal of Applied Physiology* 83.6 (2000): 524-530.

GRANHED, HANS, RAGNAR JONSON, and TOMMY HANSSON. "The loads on the lumbar spine during extreme weight lifting." *Spine* 12.2 (1987): 146-149.

Gullich, A., & Schmidtbleicher, D. (1996). MVG induced short term potentiation of explosive force. New Studies in Athletics, 4,67-81.

Häkkinen, K. E. I. J. O., and PAAVO V. Komi. "Electromyographic changes during strength training and detraining." *Medicine and Science in Sports and Exercise* 15.6 (1982): 455-460.

Hakkinen, K., et al. "Neuromuscular and hormonal adaptations in athletes to strength training in two years." *Journal of Applied Physiology* 65.6 (1988): 2406-2412.

Häkkinen, K., M. Alen, and P. V. Komi. "Changes in isometric force-and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining." *Acta Physiologica Scandinavica* 125.4 (1985): 573-585.

Halpern AA and Bleck EE. 1979. Sit- Up Exercises: An Electromyographic Study. Clin Orthop

145: 172 - 178

Hardy WG, Lissner HR, Webster JE, Gurdjian ES. Repeated loading tests of the lumbar spine: a preliminary report. Surg Forum 1958 :IX: 690-5.

Hodges P, Kaigle Holm A, Holm S, Ekström L, Cresswell A, Hansson T, Thorstensson A. 2003. Intervertebral Stiffness of the Spine Is Increased by Evoked Contraction of Transversus Abdominis and the Diaphragm: In Vivo Porcine Studies. Spine 28(23): 2594 - 2601.

Hoffman JR, Cooper J, Wendell M, Kang J. 2004. Comparison of Olympic vs. traditional power lifting training programs in football players. J. Strength Cond. Res. 18(1): 129 - 135.

Hunter, Sandra K., et al. "Human skeletal sarcoplasmic reticulum Ca2+ uptake and muscle function with aging and strength training." *Journal of Applied Physiology* 86.6 (1999): 1858-1865.

Iinuma N et al. Studies on the intra-muscular pressure in erector spinae muscles and intra-abdominal pressure (in Japanese). Acta Scholae Med Univ Gifu 1996;44:70-79

Jackson AW, Morrow JR, Brill PA, Kohl HW, Gordon NF, Blair SN. 1998. Relations of sit-up and sit-and-reach tests to low back pain in adults. J Orthop Sports Phys Ther 2 7(1):22-26.

Jones, B. H., & Knapik, J. J. (1999). Physical training and exercise-related injuries. *Sports Medicine*, *27*(2), 111-125.

Jones, D. A., and O. M. Rutherford. "Human muscle strength training: the effects of three different regimens and the nature of the resultant changes." *The Journal of physiology* 391.1 (1987): 1-11.

Jones, D. A., O. M. Rutherford, and D. F. Parker. "Physiological changes in skeletal muscle as a result of strength training." *Experimental Physiology* 74.3 (1989): 233-256.

Kavcic N, Grenier S, McGill SM. 2004. Determining the Stabilizing Role of Individual Torso Muscles During Rehabilitation Exercises. Spine 29(11): 1254- 1265.

Kraemer, William J., Michael R. Deschenes, and Steven J. Fleck. "Physiological adaptations to resistance exercise." *Sports Medicine* 6.4 (1988): 246-256.

Kraemer, William J., et al. "American College of Sports Medicine position stand. Progression models in resistance training for healthy adults." *Medicine and science in sports and exercise* 34.2 (2002): 364-380.

Kraemer, WILLIAM J., and NICHOLAS A. Ratamess. "Fundamentals of resistance training: progression and exercise prescription." *Medicine and science in sports and exercise* 36.4 (2004): 674-688.

Komi, Paavo V., and Jukka T. Viitasalo. "Changes in motor unit activity and metabolism in human skeletal muscle during and after repeated eccentric and concentric contractions." *Acta Physiologica Scandinavica* 100.2 (1977): 246-254.

Korthuis, RJ. Skeletal muscle circulation. Morgan & Claypool Life Sciences, San Rafael (2011)

Kubo, K., Kanehisa, H., Ito, M., & Fukunaga, T. 2001. Effects of isometric training on the elasticity of human tendon structures in vivo. J. Appl. Physiol. , 91, 26 - 32

Levine, David, et al. "Sagittal lumbar spine position during standing, walking, and running at various gradients." *Journal of athletic training* 42.1 (2007): 29.

Kubo, Keitaro, et al. "Effects of repeatedx muscle contractions on the tendon structures in humans." *European journal of applied physiology* 84.1-2 (2001): 162-166.

Kukulka, Carl G., and H. Peter Clamann. "Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions." *Brain research* 219.1 (1981): 45-55.

Laughlin, M. Harold, et al. *Control of blood flow to cardiac and skeletal muscle during exercise*. John Wiley & Sons, Inc., 1996.

Liebenson, Craig, ed. *Rehabilitation of the spine: a practitioner's manual*. Lippincott Williams & Wilkins, 2007.

Lindblom, K. (1957). Intervertebral-disc degeneration considered as a pressure atrophy. *The Journal of*

Bone & Joint Surgery, *39*(4), 933-945.

Ma SP and Zahalak GI. 1991. A distribution-moment model of energetics in skeletal muscle. J Biomech 24: 21– 35.

Marshall LW and McGill SM. 2010. The role of axial torque in disc herniation. Clin Biomech 25(1): 6 - 9

Medvedyev, A.S. A System of Multi - Year Training in Weightlifting. Moscow: Fizkultura i Sport, 1986.

McGill SM. 1992. A myoelectrically based dynamic three- dimensional model to predict loads on lumbar spine tissues during lateral bending. J Biomech. 25(4): 395- 414.

McGill SM. 1997. The biomechanics of low back injury: Implications on current practice and the clinic. J Biomech 30(5): 456 - 475

McGill SM. 2007. Low back disorders. 2nd ed. Windsor (ON): Human Kinetics

McGill, SM. 2009. Ultimate back fitness and performance . (4 ed.). Waterloo: Backfitpro Inc.
McGill SM., McDermott A. and Fenwick C. 2008. Comparison of Different Strongman Events: Trunk Muscle Activation and Lumbar Spine Motion, Load and Stiffness. *Journal of Strength and Conditioning Research*, 23(4): 1148–1161.

McGill SM, Childs A, Liebenson C. 1999. Endurance times for stabilization exercises: Clinical targets for testing and training from a normal database. Arch. Phys. Med. Rehab. 80: 941 - 944

McGill SM, Juker D, Kropf P. 1996. Appropriately placed surface EMG electrodes reflect deep muscle activity (psoas, quadratus lumborum, abdominal wall) in the lumbar spine.J Biomech. 29(11): 1503- 1507.

McGill SM and Karpowicz A. 2009. Exercises for spine stabilization: motion/motor patterns, stability progressions, and clinical technique. Arch Phys Med Rehabil. 90(1):118- 26.

Meyerding HW. 1931. Spondylolisthesis. J Bone Joint Surg 13(1): 39- 48

Michna H. 1984. Morphometric analysis of loading- induced changes in collagen - fibril populations in young tendons. Cell Tissue Res. 236:465 – 470

Miyamoto, Kei, et al. "Effects of abdominal belts on intra-abdominal pressure, intramuscular pressure in the erector spinae muscles and myoelectrical activities of trunk muscles." *Clinical Biomechanics* 14.2 (1999): 79-87.

Moritani, Toshio. "Neural factors versus hypertrophy in the time course of muscle strength gain." *American Journal of Physical Medicine & Rehabilitation*58.3 (1979): 115-130.

Morrissey, MATTHEW C., EVERETT A. Harman, and MICHAEL J. Johnson. "Resistance training modes: specificity and effectiveness." *Medicine and Science in Sports and Exercise* 27.5 (1995): 648-660.

Natarajan, R. N., Williams, J. R., Lavender, S. A., An, H. S., & Andersson, G. B. (2008). Relationship between disc injury and manual lifting: a poroelastic finite element model study. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *222*(2), 195-207.

Nesser, T.W., Huxel, K.C., Tincher, J. L., & Okdada, T. (2008). The relationship between core stability and performance in division i football players. J. Strength Cond. Res., 22(6), 1750-1754.

Norman R, Wells R, Neumann P, Frank J, Shannon H, Kerr M and the Ontario Universities Back Pain Study (OUBPS) Group. 1998. A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. Clinical Biomechanics 13, 561-573

Norris CM. 1993. Abdominal muscle training in sport. Br. J. Sports Med. 27:19- 27.

Panjabi MM. 2003. Clinical spinal instability and low back pain. J Electromyogr Kin esiol 13(4): 371-379.

Parkinson, Robert J., Tyson AC Beach, and Jack P. Callaghan. "The time-varying response of the in vivo lumbar spine to dynamic repetitive flexion."*Clinical Biomechanics* 19.4 (2004): 330-336.

Ranawat VS, Dowell JK, Heywood- Waddington MB. 2003. Stress fractures of the lumbar pars interarticularis in athletes: a review based on long- term results of 18 professional cricketers. Injury 34(12): 915 - 919

Rutherford, O. M., and D. A. Jones. "The role of learning and coordination in strength training." *European journal of applied physiology and occupational physiology* 55.1 (1986): 100-105.

Sale, Digby G. "Neural adaptation to resistance training." *Med Sci Sports Exerc*20.5 Suppl (1988): S135-45.

Scannell JP and McGill SM. 2003. Lumbar posture - should it, and can it, be modified? a study of passive tissue stiffness and lumbar position during activities of daily living. Phys. Ther. , 83, 907-917

Schache, Anthony G., et al. "Three-dimensional angular kinematics of the lumbar spine and pelvis during running." *Human movement science* 21.2 (2002): 273-293.

Schafer, Richard C., and Leonard Schroeder. *Chiropractic management of sports and recreational injuries*. Baltimore: Williams & Wilkins, 1986.

Stodden DF, Campbell BM, Moyer TM. 2008. Comparison of Trunk Kinematics in Trunk Training Exercises and Throwing. J. Strength Cond. Res. 22(1): 112 - 118

Stokes IAF and Iatridis JC. 2004. Mechanical Conditions That Accelerate Intervertebral Disc Degeneration: Overload Versus Immobilization. Spine 29(23): 2724 - 2732

Sutarno CG and McGill SM. 1995. Isovelocity investigation of the lengthening behaviour of the erector spinae muscles. Eur J Appl Physiol 70: 146 – 153

Taanila, H., Suni, J., Pihlajamäki, H., Mattila, V. M., Ohrankämmen, O., Vuorinen, P., & Parkkari, J. (2009). Musculoskeletal disorders in physically active conscripts: a one-year follow-up study in the Finnish Defence Forces.*BMC musculoskeletal disorders*, *10*(1), 89.

Tampier, C., Drake, J., Callaghan, J., McGill, S.M. (2007) Progressive disc herniation: An investigation of the mechanism using radiologic, histochemical and microscopic dissection techniques. Spine, 32(25): 2869-2874.

Turman, Paul D. "Coaches and cohesion: The impact of coaching techniques on team cohesion in the small group sport setting." *Journal of Sport Behaviour* 26.1 (2003): 86-104.

Twomey LT and Taylor JR. 1987. Lumbar posture, movement and mechanics. In: Twomey LT (ed) Physical therapy of the low back. Churchill Livingstone, New York

Van Dieen JH, Cholewicki J, Radebold A. 2003. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine 23(8): 834 - 841.

Vandervoort, A. A., J. Quinlan, and A. J. McComas. "Twitch potentiation after voluntary contraction." *Experimental neurology* 81.1 (1983): 141-152.

Verkhoshansky YV. Fundamentals of special strength training in sport: 1977. In: Supertraining. Siff MC, ed. Denver, CO: Supertraining Institute, 2003. pp.113.

Viru, M. "Differences in effects of various training regimens on metabolism of skeletal muscles." *The Journal of sports medicine and physical fitness* 34.3 (1994): 217.

Wilson GJ, Murphy AJ, Pryor JF. 1994. Musculotendionus stiffness: Its relationship to eccentric, isometric, and concentric performance. J. Appl. Physiol. 76:2714–2719.

Willardson JM. 2007. Core Stability Training: Applications to sports conditioning programs. J. Strength Cond. Res. 21(3): 979 - 985.

Willett GM, Hyde JE, Uhrlaub MB, Wendel CL, Karst GM. 2001. Relative Activity of Abdominal Muscles During Commonly Prescribed Strengthening Exercises. J. Strength Cond. Res. 15(4); 480-485.

Winter DA. 2009. Biomechanics and Motor Control of Human Movement (4th ed.). Hoboken (NJ): John Wiley & Sons, p. 78.

Winter DA and Patla AE. 1997. Signal processing and linear systems for the movement sciences. Waterloo (ON): Waterloo Biomechanics, p. 22- 31.

Yingling VR and McGill SM. 1999. Mechanical properties and failure mechanics of the spine under posterior shear load: observations from a porcine model. J. Spinal Disorders 12(6): 501- 508.

Zahalak G. 1986. A comparison of the mechanical behaviour of the cat soleus muscle with a Distribution - Moment Model. J Biomech Eng 108:131- 140