The Impact of Stability Exercises on Core Muscle Imbalances and Subsequent Low Back Pain

by

Connor Brian Lusk

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 7, 2021

Keywords: Muscular Imbalance, Magnetic Resonance Imaging, Low Back Pain, Musculoskeletal Disorders, Muscular Asymmetry

Approved by

Richard Sesek, Chair, Tim Cook Associate Professor, Industrial and Systems Engineering
Sean Gallagher, Hal N. and Peggy S. Pennington Professor, Industrial and Systems Engineering
Mark Schall, Associate Professor, Industrial and Systems Engineering
Wei Liu, Associate Professor, Dean Health Professions School, University of Texas Health Science Center San Antonio

Abstract

The pathology of low back pain (LBP) is often unclear, despite the fact that it is the most common musculoskeletal disorder (MSD) with hundreds of thousands of workers afflicted. One underlying mechanism that may contribute to LBP is muscular imbalance (MI) among the lumbar paraspinal and core muscles**.** It has been hypothesized that MI contributes to LBP, and that MI may be more pronounced in subjects that present with LBP than those without. It follows that, if MI can be reduced, LBP may subsequently be mitigated. It is possible that certain exercise regimens may reduce imbalance and therefore LBP related to such imbalances. The purpose of this doctoral work was to examine this relationship between MI and LBP. Specifically, this work sought to establish a novel method of quantifying MI, assess the linear relationship between MI and LBP, investigate physiological changes in trunk musculature and its relationship with MI-related LBP over time, and evaluate the effects of various forms of MI on MSDs using an epidemiological database of workers while controlling for psychosocial factors.

Magnetic Resonance Imaging (MRI) was used to collect scans of the low back and core muscles in subjects to precisely measure cross-sectional areas (CSAs) and mechanical lever arm lengths (MLALs). These scans were then used to quantify the degree to which muscles were imbalanced. Data regarding pain and exercise were collected via weekly subject survey on exercise intensity and duration, and LBP ratings. A cross-sectional analysis of the data examined MRI-derived lumbar paraspinal and core muscle CSAs from female subjects was conducted to assess the correlation between MI and LBP. A prospective analysis was used to evaluate how MI and LBP may change over time. A cross-sectional analysis was conducted to validate the proof of concept of physical imbalance and its impact on MSDs using an epidemiological ergonomic

database consisting of health data on several measures of imbalance and their associations with LBP and the likelihood of LBP related medical attention sought.

A new measure of MI was established (MI_{new}) and compared to previously accepted measures of MI (MI_{CSA}). MI_{new} incorporates MLALs in combination with CSAs to correct for the individual mechanical advantages of paraspinal and core muscles to provide a more inclusive measure of MI than CSA difference alone. Linear regression found that exercise was not significantly related to LBP development and symptoms. Linear regressions determined that the L3/L4 spinal level was more associated with LBP than other levels. Tai Chi exercise was found to have some protective effect for MI and LBP. Different definitions of MI were investigated to test the underlying hypothesis that MI is causally related to pain. Significant odds ratios were found with respect to LBP and imbalance in an occupational setting, Age was shown to be strongly associated with imbalance.

This work is important in that it investigated novel models for measuring core muscle imbalances to provide input for evidence-based practice (EBP) guidelines. Establishing a model for measuring MI may help improve biomechanical models by introducing a new type of personal characteristic that may impact MSD risk, and subsequent pain. Exercises designed to stabilize and strengthen the core muscles have been shown to not only strengthen the paraspinal muscles but may also reduce LBP. This work adds to the growing body of literature suggesting the clinical benefits of incorporating low impact exercise in daily life to prevent/treat LBP. Meaningful results such as these provide evidence to conduct larger, more inclusive research studies on MI related LBP, and potential MI exercise interventions to prevent or alleviate LBP symptoms.

Acknowledgments

To my parents: James Lusk and Louise Lusk, thank you for instilling in me from a very early age the importance of education and becoming a lifelong learner.

To my advisor: Richard Sesek, thank you believing in me and spending countless hours preparing me to become an educator and researcher on my own with a passion to continuously learn and improve.

To my committee members: Mark Schall, Sean Gallagher, Wei Liu, and Thomas Denney; thank you for supporting me always and providing me with the knowledge to better myself as a researcher and a writer.

To Robert Thomas, Ron Beyers, Fehmi Capanoglu, and all OSE faculty, students, family, and friends; thank you for never failing to cheer me on throughout the doctoral process and providing me with any assistance or guidance that I needed, ensuring that my time at Auburn would be an unforgettable experience.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

A/P	Anterior/Posterior
BCF	Back Compressive Force
BMI	Body Mass Index
CSA	Cross-Sectional Area
DRA	Diastasis Rectus Abdominus
IAP	Intra-Abdominal Pressure
LBP	Low Back Pain
MI	Muscular Imbalance
MLAL	Mechanical Lever Arm Length
MRI	Magnetic Resonance Imaging
MSD	Musculoskeletal Disorder
QL	Quadratus Lumborum
SD	Standard Deviation
VAS	Visual Analog Scale
WMSD	Work-Related Musculoskeletal Disorder

Chapter 1

Introduction

1.1 Musculoskeletal Disorders and Low Back Pain

Musculoskeletal disorders (MSDs) are among the most prevalent injuries across a variety of individuals and age groups. The Center for Disease Control (CDC) defines an MSD as a disease or disorder of the musculoskeletal system and its connective tissue due to an event or exposure resulting in a bodily reaction (CDC). MSDs are not only painful, but are very costly, and a hindrance to both workers and the environments in which they work (Bhattacharya, 2014). MSDs impact more than just work, they also influence quality of life and can persist after retirement. MSDs have consistently been the occupational injury that results in the greatest days away from work (Bhattacharya, 2014).

According to the Bureau of Labor Statistics (BLS), there were 272,780 total cases with days away from work in private industry in the United States due to MSDs, the incidence rate of MSDs was 27.2 per 10,000 full time workers, and the median days away from work was 12 in 2018 alone (BLS, 2020). Occupational exposure to physical risk factors is commonly associated with MSDs. These physical risk factors include bending, climbing, crawling, reaching, twisting, repetitive motions, and working for extended periods of time with highly repetitive tasks at non-neutral postures. Examples of MSDs include overexertion, sprains/strains/tears in muscle ligaments and tissues, low back pain (LBP), cumulative trauma disorders and disc herniations (CDC).

LBP is the most common MSD from which individuals suffer (Vos, Theo, et al. 2017). In 2010, the prevalence rate of self-reported LBP was 25.7% (Yang, Haiou, et al., 2016). The prevalence of LBP was over one-fourth of the population in the USA in the year 2006 (Deyo, et al, 2006). The lifetime prevalence of LBP in the USA was 80% in 2007 (Rubin 2007).

LBP is one of the most common MSDs resulting in disability and days away from work (Ekman et al, 2001). The prevalence of LBP has been estimated to be more than one-quarter of the United States population (Deyo et al, 2006). In 2014, OSHA reported that the cost of workers compensation was about $1 billion per week. The National Health Interview Survey reported that at least 50% of adults in the United States had MSDs, with 20.3% of those experiencing LBP.

In 2016, the back was the most common body part associated with MSDs resulting in days away from work (BLS, 2016). Back-related MSDs made up 38.5% of MSDs that occurred in 2016 (BLS, 2016). Out of 349,550 total cases, 134,550 were back related cases (BLS, 2016). Back injury rates have remained relatively high for the past 50 years (BLS). Back-related MSDs had an incidence rate of 9.6 per 10,000 full time workers with 98,540 cases in 2019 (BLS, 2019).

The number of cases of LBP incidents resulting in emergency hospital visits from 2004 and 2008 was 2.06 million (Waterman et al, 2012). The BLS indicated that the body part most often affected by MSDs was the trunk and low back (52%) of all MSD cases, and 43% of all trunk-related MSDs were related to the low back. It is estimated that two-thirds of adults will experience LBP in their life (Deyo, 2001). The cause of LBP remains unclear for 85% of cases (Deyo, 2001). It is very likely that LBP will reoccur in people who suffer from it. Approximately 60% to 84% of people will experience recurrent symptoms (Bergquist-Ullman et al, 1977; Von Korff et al, 1993; Hides et al, 2001).

Work in the automotive manufacturing industry have been highly associated with MSDs (Punnett, et al 2004). Ergonomic programs have been implemented in automobile assembly plants to protect workers from working for long periods of time in awkward, extended, or stooped postures (Fowler, 2010). MSDs were deemed the worst occupational hazard in an occupational epidemic in the 1990s (Herrington and Morse, 1995). Workers who are required to perform manual material handling (MMH) spend a substantial amount of time lifting, holding, moving with, and lowering materials of different weights.

1.2 Cost of Musculoskeletal Disorders and Low Back Pain

There are many costs associated with occupational injuries and illnesses. The Department of Labor (DOL) reported on the different types of costs associated with occupational injury and illnesses in 2016 (DOL, 2016). The total cost of accidents arising from occupational injuries and illnesses is comprised of both the direct and indirect costs. Workers' compensation, legal fees, and medical expenses only account for the direct costs. Indirect costs, such as retraining, accident investigation, maintenance and repairs, loss of productivity, abatements, diminished employee morale, absenteeism and decreases in production substantially increase the cost associated with occupational injuries (DOL, 2016).

MSDs make up approximately 30% of all workers compensation costs, with almost 400,000 injuries per year (BLS, 2020). The direct costs associated with MSDs are estimated to equal $20 billion a year, with total (direct and indirect costs) costs estimated to be $45-$54 billion per year (The Occupational Health and Safety Administration (OSHA)). MSD related indirect costs may be up to five times the direct costs, due to lost productivity, product defects, and days away from work. MSD injuries and illnesses result in 38% more lost time on average than other injuries and illness cases (BLS).

The societal cost of LBP is very high, with money needed to pay doctors' fees, to purchase medicine, and for diagnostic processes. X-Rays, Computed tomography (CT) and magnetic resonance imaging (MRI) are frequently used to help diagnose and treat LBP. The number of people suffering from LBP has not decreased despite the billions of dollars spent on LBP relief every year. LBP is a chronic debilitating illness that severely hampers the quality of life and capability of sufferers, even though it isn't considered lethal. Back injuries are expensive, with an average of $8,000 in direct costs (Webster and Snook, 1994).

Back injuries make up about half of the MSD cases reported each year (BLS). LBP costs make up a third of all workers compensation costs (Webster and Snook, 1994). It has been estimated that the annual cost due to LBP is $100 billion (Katz, 2006). Despite the high occurrences, hazards, and costs of LBP, workplaces still appear resistant to altering workstations and modifying work tasks to prevent it.

1.3 Muscular Imbalance and Low Back Pain

MSDs develop as a result of how the body responds to the forces that act on it over time (CDC). When forces act upon the body as with lifting and material handling, the body exerts its own force to counteract those loads; this can result in reaction forces that exceed the body's capabilities at certain levels and locations (National Research Council (US) and Institute of Medicine (US) Panel on MSDs and the Workplace). Psychophysical studies have been conducted by asking subjects to adjust their work to a self-perceived acceptable level of work (Kolstrup, 2012).

There are numerous physical changes to the human body, that can contribute to the development of MSDs. These changes include exercise induced muscular development (hypertrophy), muscular loss (atrophy) from lack of activity and sedentary lifestyle, and disorders related to physical overuse. There have been many causal factors related to LBP including sprains and strains of the paraspinal muscles, applied forces, and intervertebral disc (IVD) degeneration (National Institutes of Health (NIH), 2013). Muscular imbalances (MI) have been hypothesized to contribute to the development of LBP, however, this mechanism is not as well understood and has not been investigated as thoroughly as other factors (Nadler, 2002; Oddsson et al, 2003; Fredricksburg Chiropractic).

Since most causes of LBP remain unknown, studies have been conducted to determine possible causal contributors to LBP. MI has been hypothesized to be a contributor and/or risk factor for LBP (Hides et al, 2008; Hides et al, 1996; Hides et al, 1994; Danneels et al, 2000; Kamaz et al, 2007; Mengiardi et al, 2006; Kjaer et al, 2007; Ploumis et al, 2011; Barker et al, 2004; Kulig et al, 2009; Beneck et al, 2012; Kader et al, 2000; Kang et al, 2007; Kim et al, 2011; Wallwork et al, 2009; Chan S- et al, 2012; Engstrom et al., 2007; Stewart et al, 2010; Lavender et al,1989).

Previous research aimed to determine how asymmetry resulting from a difference in the left and right cross-sectional areas (CSAs) of the paraspinal muscles creates a MI (Hides et al, 2008; Engstrom et al., 2007; Stewart et al, 2010; Lavender et al,1989). Several studies have shown that symptomatic patients with LBP have relatively smaller paraspinal muscles than those who are asymptomatic with no LBP (Hides, et al 2008; Beneck, et al 2012; Chan et al, 2012; Danneels et al, 2000; Cooper et al, 1992; Kamaz et al, 2007). In other studies, this finding has been contradicted (Danneels et al, 2000; Lee S- et al, 2006; McLoughlin et al, 1994). To date, there have been no LBP studies that have quantified MI using mechanical muscle lever arm lengths (MLALs) or effective moment generating capability, such as the product of MLALs with CSAs.

Several studies have demonstrated that asymptomatic subjects tend to have symmetrical paraspinal muscle CSAs by (Hides et al, 2008; Hides et al, 1994; Stokes et al, 2005). However, for those with asymmetry, the painful side of the back may or may not have been the side with smaller CSAs. For example, in some studies, the symptomatic side tended to have smaller paraspinal CSAs (Hides et al, 2008; Hides et al, 1994; Stokes et al, 2005) while in others, the symptomatic side may or may not have had smaller paraspinal CSAs (Kader et al 2000; Hyun et al, 2007; Battié et al, 2012; Stokes et al, 1992).

However, asymmetry has not always been linked to LBP. For example, significant multifidus asymmetry in an MRI-based study was reported by Niemeläinen (2011) in asymptomatic men (Niemeläinen et al, 2011). In fact, several studies have reported paraspinal and core muscle asymmetry in asymptomatic athletes (Engstrom et al, 2007; Hides et al, 2010; Ranson et al, 2008; Sanchis-Moysi et al, 2010; Sanchis-Moysi et al, 2011). It should be noted that in many of those studies, the athletes performed sports requiring asymmetrical activities such as cricket, bowling, and racquet sports. In all the aforementioned studies, only lateral (left/right) imbalance of the paraspinal muscles was considered and all used muscle CSA as the determinant of MI.

1.4 Measuring Muscular Imbalance with Magnetic Resonance Imaging

MRI scans provide a reliable means for the quantification of biological parameters such as CSAs of muscle tissues in a non-invasive manner. In the more recent decades, there has been an increase in published research investigating the morphometric parameters of the paraspinal muscles in patients reporting LBP using MRI. Several MRI studies have been conducted to measure spinal geometry, muscular CSAs, MLALs vertebrae heights and lengths, and to identify spinal disc degeneration (Tang, et al, 2015, 2016).

Previous work (Salar, 2017; Pentikis, 2017) has determined reliable means for estimating CSAs and MLALs using MRI and subsequently demonstrating how this information can be used to improve the prediction of low back forces in biomechanical models. That research found average absolute left-right percentage differences across the lower lumber CSAs of ~5-20% for asymptomatic healthy subjects (Pentikis, 2017).

A new method to measure MI may help assess the relationship between MI and LBP using both CSAs and MLALs, and combinations of CSAs and MLALs. Imbalances have commonly only been measured laterally, and anterior/posterior (A/P) MI measurements should be introduced into a new MI measure for all core and trunk muscles individually and in functional groups to provide a more accurate MI estimation than using CSA alone. This new method may correct for the effective force production capability of paraspinal and core muscles.

1.5 Objectives of the Research

The broad goal of this dissertation is to establish whether MI, more specifically, of the core and paraspinal muscles, is related to LBP and whether such imbalance can be meaningfully reduced by core stability exercises. This study evaluates how specific individual muscular balance characteristics impact LBP and if these factors can be modified to decrease LBP. This work is significant as it will provide vital scientific knowledge regarding MIs and their relationship to LBP and whether these imbalances can be reduced via systematic exercise. It is important to determine whether or not MI can be reduced, even if they are not directly related to LBP, so that a new type of personal characteristic that may impact MSD, risk and subsequent pain may be introduced to future biomechanical models to prevent and reduce MSD risk.

Limited published research exists on the potential causes of paraspinal muscle asymmetry (Hides et al, 2008; Hides et al, 1994). Due to the high number of possible determinants to paraspinal muscular asymmetry, it is not known if changes in muscular morphology and asymmetry are caused by LBP, are only risk factors for LBP; or if changes in musculature and muscular asymmetry are both causes of LBP and risk factors for LBP. The relationship between

LBP and its progression along with possible risk factors of paraspinal muscular asymmetry may be important for understanding these relationships.

To date, there is no published research that has quantified muscle imbalance using MRI-derived measurements of CSAs *and* MLALs of the paraspinal and core muscles (psoas, erector spinae, quadratus lumborum, rectus abdominus, and oblique muscles). This innovative approach will relate ratings of LBP with lateral (right and left) as well as anterior posterior imbalances. Imbalances will be quantified as in previous studies, but also by utilizing novel quantification methods (A/P, the multiple muscles, and incorporate MLALs).

The objective of this doctoral work was to examine this relationship between MI and LBP. To achieve this objective, we addressed the following specific aims:

- Specific Aim 1: Establish a novel method of quantifying MI and assess the linear relationship between MI and LBP.

- Specific Aim 2: Investigate physiological changes in trunk musculature and its relationship with MI-related LBP over time.

- Specific Aim 3: Evaluate the effects of various forms of MI on MSDs using an epidemiological database of workers while controlling for psychosocial factors.

Chapter 2

Review of the Literature

2.1 Low Back Pain Etiology

LBP is currently one of the main health care problems both occupationally and non-occupationally. It is estimated that up to 80% of the population report experiencing LBP at some point in their life (Ruas et al, 2017). Many LBP cases are non-specific, having no obvious precipitating event (Riihimäki, 1991). A subset of these LBP cases may be due to muscle imbalance (Ruas et al, 2017; Nadler et al, 2001). MIs in the low back and core/trunk have been referred to by various descriptors in the scientific literature including lower cross syndrome (LCS), flexion-intolerant LBP, distal crossed syndrome, anterior pelvic crossed syndrome, and posterior pelvic crossed syndrome.

> According to Ruas et al. (2017),
>
> "low levels of strength and/or flexibility of trunk, spine and hips have been pointed out as either causes, consequences or influencing factors for the prevalence of the chronic lower back pain condition."

This was concluded after reviewing 14 studies conducted between 1983 and 2016 that demonstrated that strength imbalances might be associated with LBP. The literature review also called for more inclusive research to be conducted of diverse populations as most published studies on the topic of MI and LBP investigate younger, male athletes. To date, most published research has also been limited to cross-sectional studies, and further longitudinal studies are needed to determine the potential associations and causal factors of MI induced LBP.

Typically, once an MI has started to develop in the pelvic and low back area, pain begins to occur. Posture and movement are compromised and change with the introduction of a MI and pain. An anterior pelvic tilt, hip flexion, and hyper lordosis (excessive lordotic curve of the low back) result from inhibited abdominal muscles and “tight,” inflexible psoas muscles, resulting in a chronic stress load acting upon the lumbar spine (Norris et al, 1995; Milias, 2015; Janda et al, 1996).

2.2 Low Back Pain Related Injuries

MIs can occur when muscles are repeatedly shortened or lengthened in relation to one another (Physiopedia, 2019). To put it more simply, MIs occur when opposing forces between muscles provide different directions of tension (Muscle Imbalance Syndromes, 2019). These imbalances may be contributed to by repeated movements or sustained postures, but they can also result from a predisposition of specific muscle groups to tightness or weakness (Muscle Imbalance Syndromes, 2019). Studies indicate that imbalances due to weakness can be corrected via exercise and physical therapy.

Muscle tightness is defined as a muscle that feels stiff and has lost flexibility. MIs can become dangerous when they lead to alternate patterns of movement or joint dysfunction, resulting in injuries (Hutt, 2014). As tight muscles adapt to postures and movements, it is common for individuals to develop imbalances. It is important to note that not all imbalances lead to chronic pain or injury and that asymptomatic individuals have also been found to have varying degrees of imbalance (Pentikis, 2017). However, as the level of imbalance increases, the likelihood of pain generally increases (Fortin, 2014).

Mitchell (2008) at Curtin University of Technology hypothesized that LBP was influenced directly by regional differences in habitual lumbar spine posture and movement, rather than the entire spine. Kim Hutt, in Dance UK, studied frequent movements and injuries of dancers. Their report concluded that common dance specific faults could be *a symptom or a consequence* of MIs that could predispose dancers to injury (Hutt, 2014).

The crossing and interaction of these muscles together can create joint dysfunction (Das, et al. 2017). The weak muscles involved are typically the abdominals and the gluteus maximus, while the tight muscles are generally the thoracolumbar extensors and hip flexors. Hamstrings are typically tight when this syndrome occurs due to apparent compensation for pelvic tilt. Untreated MIs in the low back may also contribute to further imbalances and subsequent pain and injury in other body regions (Miller, 2017).

Examination for MI includes observation of the pelvis position as well as the shape, size, and tone of inhibited muscles. Consequences of MI include overstress of hips and thoracolumbar junction from muscular overcompensation, and an impairment of stature (slouching) and function (Kerger, et al, 2016). Common treatments for MI include chiropractic manipulation, stretches intended to reduce tension in some muscles, and exercises to build strength in others.

A study by Shriya Das measured weakness of abdominals and hip extensors, and tightness of hip flexors and spinal extensors on 117 healthy male adults and 83 healthy female adults. Results of this study concluded that prevalence of developing LCS is more likely to be found in young women rather than young men (Das et al. 2017).

A flexed position of the back can result from many activities, for example, bending over to pick something up, sitting at a computer at work, or driving an automobile. Those who suffer from MI may have a type of "flexion-intolerant LBP," or are sometimes referred to as "chronically flexed people" (Dionne, 2018). Chronic flexing of any region of the spine can result in LBP (Mitchell, 2008). This type of flexion-intolerant lower back pain resulting from MI can be a difficult to quantify without medical imaging (Heller, 2014). In addition, the condition of the discs themselves (i.e., disc degeneration) cannot be assessed without such imaging because of the location of the disc (surrounded by muscles) (Heller, 2014). It should be noted that some disc degeneration may also be due to aging in older patients (Heller, 2014).

Several types of stretching are documented and demonstrated in "Evaluation and Management of the Upper and Lower Crossed Syndromes" by Shawn Kerger and Richard Schuster (Kerger, et al, 2016). Some of the stretches explained include iliopsoas stretch, rectus femoris stretch, quadratus lumborum stretch, and gluteus maximus retraining. Another method found to provide relief is activating/strengthening muscles and lengthening the duration of static stretching (Miller, 2017). Therefore, stretching and exercise routines that involve these activities should theoretically prevent and/or reduce MI and the subsequent pain associated with such MIs.

The development of MI can eventually lead to further physiological change in the morphometric measurements of the paraspinal and core musculature. Several studies have been published that indicate an association between lateral CSA differences of the paraspinal muscles and LBP. Goubert and Fortin both found evidence that a smaller multifidus CSA is associated with and predictive of LBP in their respective MRI studies. Systematic literature reviews have previously only reported on studies that measured the CSA of the paraspinal muscles (Wan, et al, 2015; Fortin, Suri, Wan, Goubert, and Ranger). To date, no study has been published that investigates the association between both the CSA of the paraspinal muscles *AND* the core/trunk muscles (rectus abdominus and obliques) with LBP.

Paraspinal muscle CSA asymmetry has been associated with LBP in patients in several MRI studies (Hides, et al 2008; Beneck, et al 2012; Chan et al, 2012; Danneels et al, 2000; Cooper et al, 1992; Kamaz et al, 2007). Those with LBP had different sized muscles on the left versus right sides of their bodies. In several studies, the symptomatic side had the smaller CSA, resulting in unilateral LBP on the smaller CSA side. To date, research has only studied MIs as quantified by measuring paraspinal muscle CSAs. No studies have considered non-paraspinal core MI nor have any studies considered the MLALs for any core muscles including the paraspinal muscles, nor have any studies considered the A/P imbalances. In addition, most studies have focused on single muscles or related muscle groups. None have considered all the core muscles together.

2.3 Potential Mechanisms of Physiological Changes in Trunk Musculature

Core strength has been shown to be an important element in preventing or reducing LBP. Individuals that present with LBP typically have low core control and stability. Hodges suggested that when spinal pain presents, the central nervous system (CNS) alters its responses for spinal support, postural control, and balance (Hodges, 1999, 2000, 2001). Hodges also suggested that in subjects with LBP, the response of the transverse abdominus, diaphragm, pelvic floor, and multifidus were delayed or diminished during movement.

Pilates type exercise is generally thought of as an effective core strengthening exercise. However, these exercises include high-load movements with lumbar flexion and abdominal activation, which are difficult to execute and can risk lumbo-pelvic pain syndromes developing (Key, 2013). Lewit (2008) suggested that postural patterns depend upon balanced activity levels and good coordination in the core. Pilates and similar exercises may strengthen the core, however, those lacking the baseline physical condition to perform such exercises may be at risk given the relatively high spinal loads associated with these exercises.

While the spine is the "support column" of the trunk, it requires the assistance of other mechanisms, primarily the muscles, to support and stabilize it during loading stresses (Key, 2013). Intra-abdominal pressure (IAP) has been suggested to be important for the stabilization of the back when exposed to biomechanical stresses. IAP cannot be generated without trunk muscle co-activation.

IAP generation and trunk muscle co-activation increase proportionally to each other, therefore, the higher the forces generated, the stiffer the spine (Cholewicki et al, 1997). Studies have shown that low IAP contributes to poor postural control and support mechanisms (Cresswell, Hodges, Gandevia 2000). These studies suggest that activity levels in the core need to be well-balanced to avoid injury (Key, 2013). Injuries are more likely to occur when any element, such as a muscle, is overactive or underactive, interfering with the balanced pattern of coordination (Key, 2013).

IAP provides internal stability to support the psoas and trunk muscles (Kolar, 2010). If the IAP is deficient or excessive, MI may be present (Key, 2013). The obliques and rectus muscles respond to externally imposed torques to help maintain the spatial relationship between the pelvis and the spine during posture-movement (Bergmark. 1989). The abdominal muscles have varying activation patterns depending on the activity performed (Vera-Garcia et al, 2011).

Kendall found that the differences in the activity levels of the upper and lower abdominals typically resulted in stronger upper abdominal muscles and weaker lower abdominal muscles (Kendall et al, 1993). Healthy spinal control can be inhibited by "excessively activated" abdominal muscles, resulting in too much spinal rigidity and stiffness (Key, 2013).

Ideal IAP and postural control result from balanced activity between all abdominal muscles. The transversus needs to have the capacity to match the activity of the rectus and obliques. Attempting to activate single muscles can create dysfunctional spines (McGill, 2004). Good core control comes from muscles working synergistically, co-activating and coordinating to produce desired movements (Key, 2013). MI occurs in the core when there is dyscoordination and imbalance between muscles (Hodges, 2001). This MI causes more trunk stiffness, less spinal movement, and more LBP (Key, 2013).

2.4 Asymmetrical Lifting

When a person cannot share the load of an object equally between their hands, due to awkward posture and/or load position, an asymmetric lift occurs. MMH tasks may be asymmetric. Asymmetric lifts have been determined to be more stressful than symmetric lifts (Ayoub, 1989). Low back and trunk muscle activity and both shear and compressive forces increase during an asymmetrical task (Anderson et al., 1985). It is important to attempt to maintain a neutral spine posture during such tasks. A neutral posture decreases the shear forces that act upon the spine.

There have been multiple studies published on asymmetric, or asymmetrical, lifting. Most published research studies on asymmetric lifting place an emphasis on the twisting of the low back (Parikh et al., 1997; Wu, 2000; Dolan et al., 2001; Bobick et al., 2001; Cheng and Lee, 2003). Pentikis (2017) found that lateral asymmetric lifts (held laterally in one hand) significantly increased back compressive force (BCF) as compared to symmetrical lateral lifts which had an average of a 70% decrease in BCF for a given total load as compared to asymmetric one-handed lifting. It was also determined that symmetrical lateral lifting of twice as much weight had 24% less BCF as compared to asymmetrical lateral lifting (Pentikis, 2017).

When forces act upon the body, it biomechanically reacts in order to withstand the stresses that have been applied. Lateral shear forces increased during one-hand lifts, A/P shear forces decreased, and BCF remained the same, according to Marras and Davis (1998). To prevent increasing the spinal load, loads should ideally be lifted symmetrically (equally between the left and right sides) with two hands and carried that way.

Many research studies found asymmetrical lifting to be a risk factor for injury and pain. Asymmetrical tasks are commonplace, but the risks can reduced by eliminating or minimizing such tasks. To mitigate the risk for developing an injury from an asymmetric lift, the load should be balanced and carried evenly, and twisting should be avoided, particularly twisting during the lift itself. Females typically have lower spinal strength than males, spinal strength decreases with age, and moments produced by trunk muscles can be estimated using spinal strength age regression relationships (Gallagher and Marras, 2012).

2.5 Asymmetry and Back Compressive Force

There can be differences between the right and left sides of the body, creating a bilateral asymmetry (Krishan, 2011). These bilateral differences can result in force asymmetries during lifting, even if the lift itself appears to be symmetrical. Valen (1962) described directional asymmetry as when the dimensions of one side of the body are greater than the opposite side consistently, and fluctuation asymmetry as a random difference between the quantitative measurements of bilateral body parts (Valen, 1962). The body's ability to adapt and compensate for stressors is one reason that imbalances can develop (Livshits et al, 1994; Otremski et al, 1993).

Unilateral activity for extended durations and at rigorous levels has been shown to be associated with muscular asymmetry (Kannus et al, 1996; Kannus et al, 1995). For example, prolonged twisting of the spine as with driving a forklift in reverse can result in the body compensating for this twisting by overdeveloping one side with respect to the other. These changes can be both muscular tightness or laxity as well as hypertrophy or atrophy. Relative hypertrophy/atrophy can be detected via MRI or other medical imaging equipment. Tightness, however, cannot be detected by imaging technologies.

Muscular asymmetry is commonly presented in athletes that participate in unilateral sports, such as racket sports. There have been several studies that suggest that asymmetrical sports are associated with higher risk of injuries and MI (Hides et al 2008; Elliot et al, 1993; McLean et al, 1993). As a result of this, symmetrical activities or core strengthening exercises have been suggested as a possible intervention to avoid the development of or correction of asymmetry (McLean et al, 1993).

MI can cause hypertrophy due to over-recruitment of one group of muscles and might be the cause of a decrease in CSA or recruitment of the corresponding opposing muscles. MI is also possible when considering groups of muscles, (such as all torso flexion muscles combined, rather than considering them individually). (Hides et al, 2012).

MI is undesirable since torque-producing muscles of the trunk generate large forces on the spine (Cholewicki et al, 1997). Cholewicki et al (1997), using a biomechanical in vivo model, suggested that these forces might induce instability of the lumbar spine if deeper muscles, such as the multifidus and transverse abdominus (TrA), were not activated. Atrophy of the multifidus muscles can occur in people with LBP (Hides et al, 2001) and those who experience prolonged bed rest (Belavy et al, 2011; Hides et al, 2007).

2.6 Paraspinal Muscles

The paraspinal muscles run parallel on both sides of the spine and are attached directly to the vertebrae to provide mobility, stability, and trunk movement (Wilke, et al, 1995; Solomonow et al, 1998). The paraspinal muscles refer to the erector spinae group, which includes the illocostalis and longissimus muscle, multifidus, psoas, and the quadratus lumborum.

The lumbar erector spinae are present on the lumbar spine to assist in posture and lateral flexion (side bending) (Moore et al, 2006). According to McGill, the line of action from the erector spinae is almost perpendicular to the spinal compression axis, creating posterior shear forces with an extensor moment on the superior vertebrae (McGill, 2002). Figure 2.1 illustrates the erector spinae muscles.

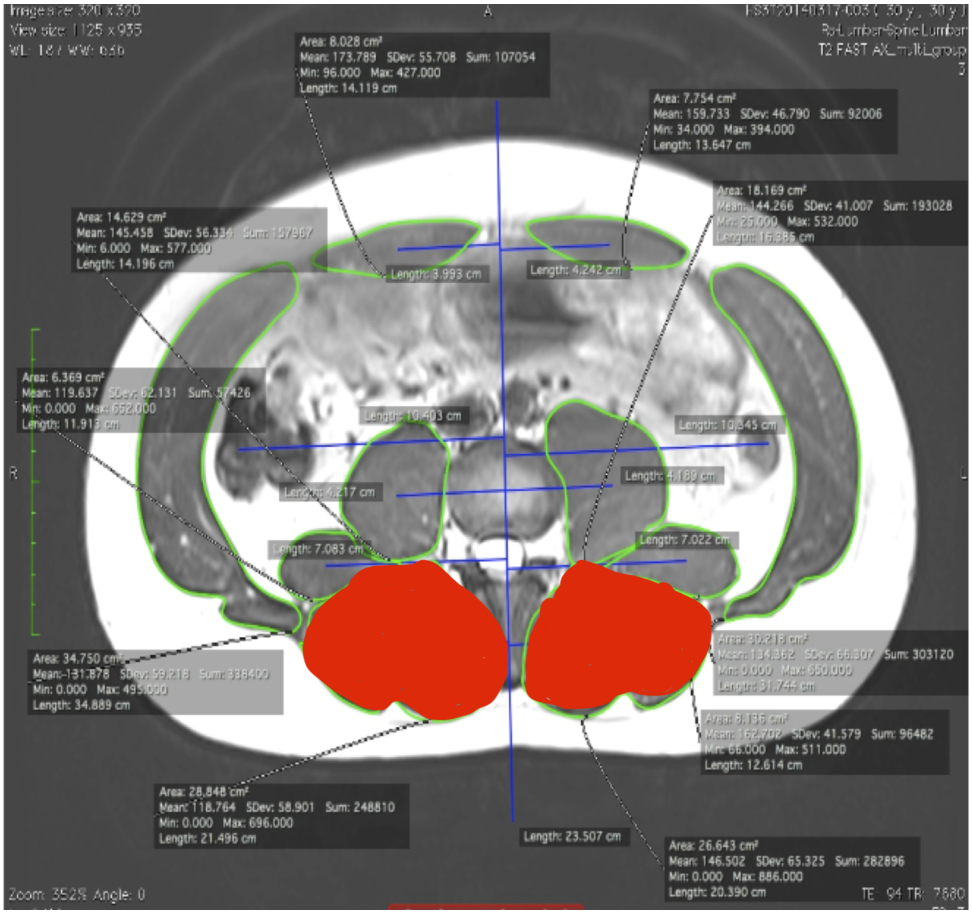


Figure 2.1: MRI Axial View of the Erector Spinae Muscles

The multifidus, another extensor of the lumbar spine, is involved with control of the vertebral segments and stiffening of the intervertebral discs (Wilke et al, 1996). The multifidus is directly attached to the lumbar vertebrae, so the forces generated by the multifidus put pressure directly on the spine (McGill, 2002). The multifidus also can compensate for spinal stresses by generating twisting and side-bending torque (McGill, 2002). The multifidus line of action is usually parallel to the longitudinal compressive axis.

The psoas muscles, commonly referred to as the hip flexors, cross the spine and the hip and attach on every lumbar vertebra and act as a stabilizer to the spine (Penning, 2000). Andersson and Nachemson demonstrated that there is minimal psoas activity in a relaxed upright position (Andersson et al, 1977; Nachemson, 1966). McGill used intramuscular electrodes to show psoas activation only during hip flexion, leading to the belief that the psoas is a spine stabilizer, providing shear stiffness when needed to compensate for hip torque present (McGill, 2002). Figure 2.2 illustrates the psoas muscles.

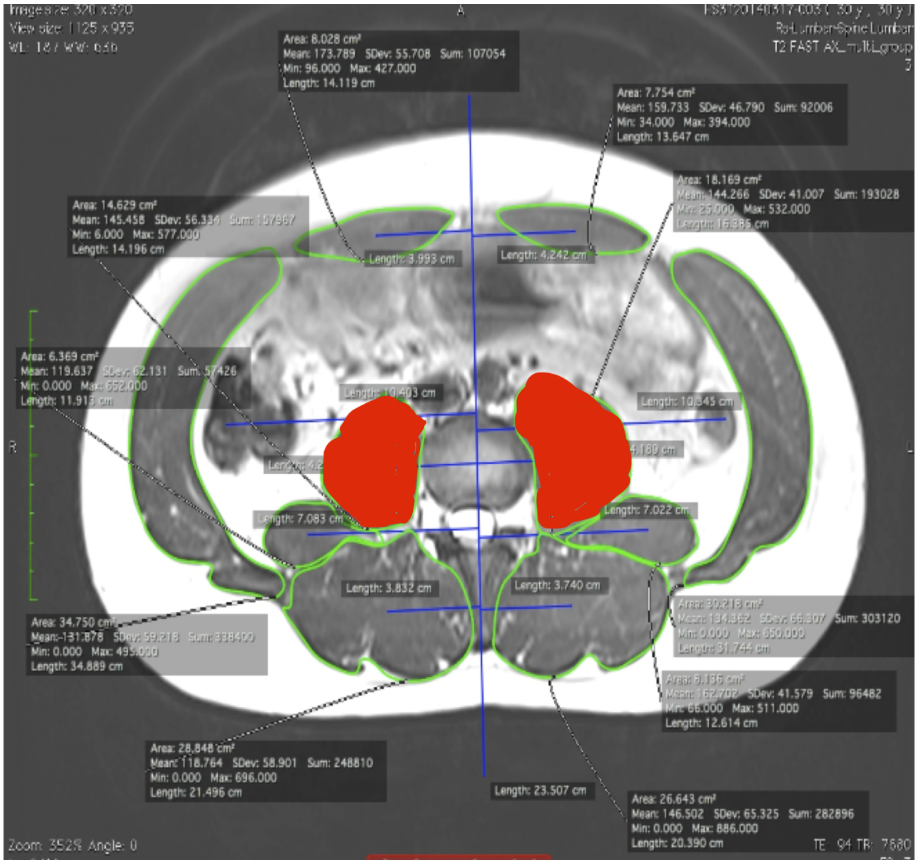


Figure 2.2: MRI Axial View of the Psoas Muscles

The quadratus lumborum (QL) is present on each of the lumbar vertebrae (Bergmark, 1989). the QL provides for extension. It has been shown that the QL is more active than extensors during lateral bending (McGill, 1996). It was also found that QL activity increased as axial spinal compression was increased (McGill, 1996). Due to these studies, the QL has been found to be a powerful lumbar lateral flexor (side flexor) that provides frontal plane segmental stabilization as the spine moves (McGill, 1996). Figure 2.3 illustrates the quadratus lumborum muscles.

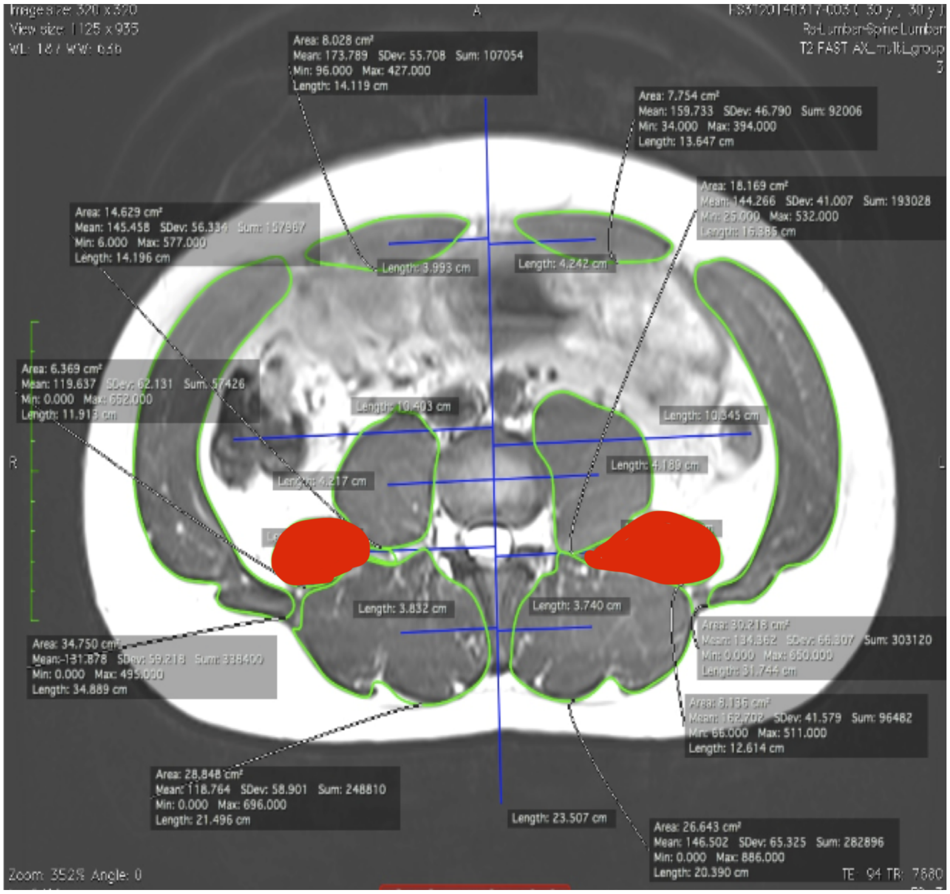


Figure 2.3: MRI Axial View of the QL Muscles

2.7 Core Muscles

The trunk muscles in the abdomen area are often referred to as the core muscles. The external oblique is the largest lateral group of muscles present on both sides of the body.

The external oblique is essential in rotating and flexing the trunk. The direction of rotation is inversely related to the pull of the muscle. The obliques function to counteract the moment occurring on each side of the body. The internal oblique muscle lies inferior to and runs diagonally to the external oblique, forming an “X”. The internal oblique is also essential for trunk rotation, but its direction of rotation is directly related to the pull of the muscle.

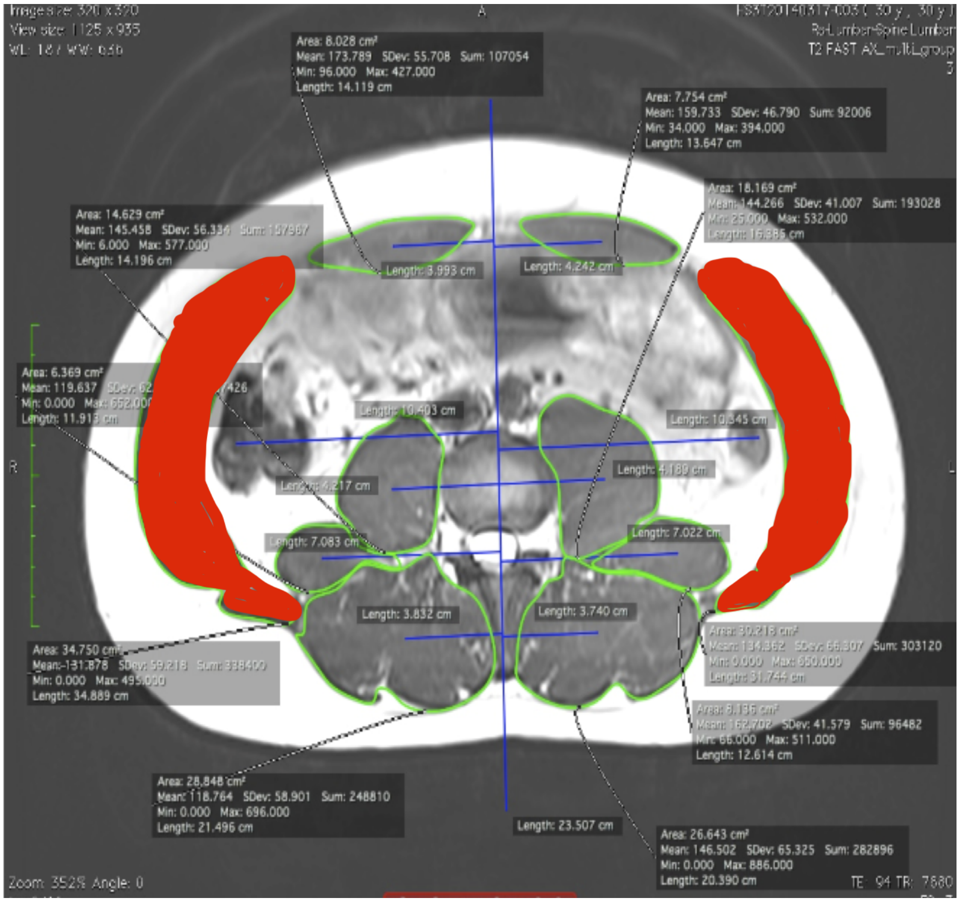


Figure 2.4: MRI Axial View of the Oblique Muscles

Rankin (2005) investigated the importance of abdominal muscles for LBP prevention, since these muscles play a significant role in lumbar spine stabilization. Gathering these muscle sizes can be used as an indirect measurement for their force-generating capacity which has been demonstrated in several studies (Rankin, 2005; Maughan et al., 1983; Kanehisa et al., 1994; Rankin et al., 2006; Ishida et al., 2014).

Nemeth and Ohlsen (1986) used CT scans to obtain muscle moment arms in vivo for biomechanical model use with the geometric center of the rectus abdominis muscle to estimate the muscle force vector (lever arm). Smaller moment arm values were found by Reid and Costigan (1987) for rectus abdominis muscles. In 2006, Rankin (2005) suggested that the assessment of each abdominal muscle size relative to the others is important when evaluating imbalance within the abdominal muscle group. Figure 2.5 illustrates the rectus abdominus muscles.

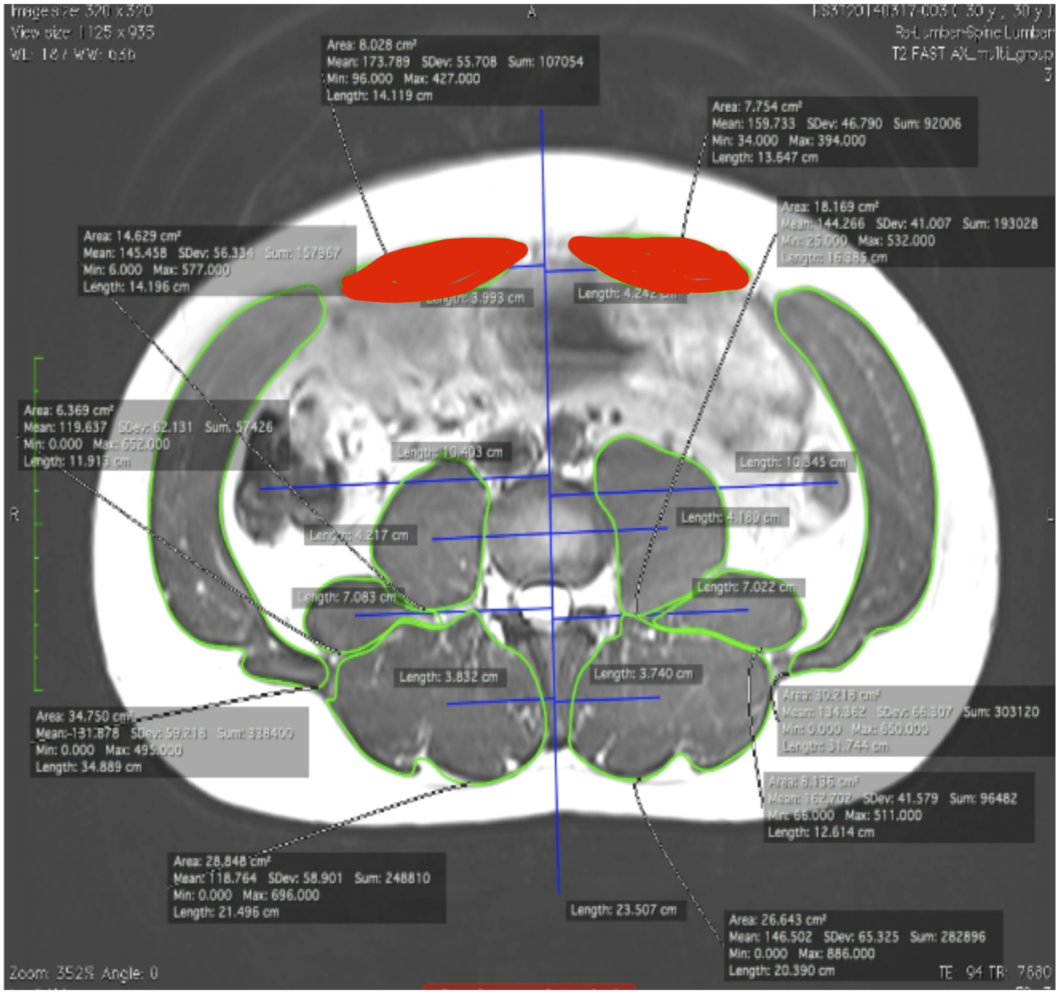


Figure 2.5: MRI Axial View of the Rectus Abdominus Muscles

2.8 Diastasis Recti

Abdominal muscles are spinal stabilizers, and proper coordination of them is important to prevent LBP. Poor coordination of the abdominal muscles is seen in the diastasis (separation of the muscles) and has been associated with LBP. Diastasis of the rectus abdominus is known as DRA. While the separation can be a small vertical gap between the left and right erectus abdominus muscles (Alamer et al, 2019), this muscle separation impedes full muscular function which can contribute to LBP (Candido et al, 2005). DRA may contribute to muscle lever arm changes, causing an imbalance. DRA can be associated with LBP creating non-optimal load transfer due to compromised posture, trunk instability and movement (Lee et al, 2008). In a study by Parker, findings suggested that women with DRA reported an increase in abdominal and pelvic pain, which lead to LBP (Parker et al, 2009).

Mechanical stresses loaded on the abdominal wall are believed to cause the rectus muscle to separate (Alamer et al, 2019). When the support system for the back is compromised due to abdominal muscle separation such as DRA, some support can then be transferred to relatively weak connective tissue rather than the muscles, contributing to LBP (Thornton, 1993; Benjamin et al, 2014). Cumulative mechanical stress on the abdominal wall connective tissue can contribute to changes in the musculoskeletal morphology of the trunk, resulting in an increase in the distance between the muscle insertions and generating muscle stretching (Rett et al, 2009).

DRA was found to be 2.5 times more common in individuals with LBP in a study by Doubkova (2018). This study also found a strong correlation between body mass index (BMI) and DRA. Increased torso diameter resulting from obesity and/or pregnancy can further stretch the abdominal muscles. The relationship between DRA and LBP may be explained due to the compensatory overuse of back musculature due to lost abdominal wall stability (Cheesborough et al, 2015). DRA has been studied mostly in pregnant women and post-cesarean section women. DRA has also been found in men, particularly in men with higher BMIs. The presence of DRA in men supports the hypothesis of stress-induced DRA, as men are more likely to participate in strenuous activity, increasing the chance of paraspinal muscle overload (Doubkova, 2018).

Abdominal wall muscle coordination is important for providing support for posture and spinal stabilization (Lee et al, 2008; Bitnar et al, 2015). The abdominal wall muscles work in sync with the diaphragm and pelvic floor muscles to regulate IAP which has been suggested to further increase lumbar spine stiffness (Hodges et al, 2005). Trunk stabilization is essential to balanced upright posture and relies on the rectus abdominus muscles and other coordinating trunk muscles to regulate IAP (Tayashiki et al, 2016).

This relationship supports the hypothesis that DRA may influence IAP and spinal stabilization, subsequently contributing to LBP (Doubkova, 2018). A relationship between IAP and LBP has been found (Stokes et al, 2011; Hagins et al, 2011). Abdominal strength is needed to mechanically control the abdomen and provide for spinal stability involving the co-activation of trunk flexors and extensor muscles which is believed to help prevent abdominal separation (Keeler et al, 2012).

Research supports the notion that physical exercise can be used as an intervention for DRA (Benjamin et al (2014), Mesquita et al (1999), Mommers et al (2017), and Lee et al (2016)). DRA has been surgically corrected in some patients with LBP, resulting in some LBP alleviation, most likely due to the postural change from the tightening of the thoracolumbar fascia (Doubkova, 2018). DRA has been measured and evaluated by a variety of methods, some manual and some relying on medical imaging such as MRI (Van de Water et al, 2016). Elkhatib et al (2011) compared DRA measurements from MRI scans of subjects pre- and post-operative abdominal surgery. Surgery was effective in reducing DRA.

2.9 Quantitative Measurement of Muscles with Magnetic Resonance Imaging Modeling

MRI uses combinations of tissue images which are created via a magnetic field gradient; these gradients are combined to produce maps of tissues within the body. Nuclear magnetic resonance (NMR) was discovered in 1937 (Rabi, 1937). The first MRI image was created from the gradients in magnetic fields about 2 decades later by Carr, (1950). The MRI scanner was created and continually improved upon between 1960 and 1974 (Isanov, 1960; Damadian, 1974). Damadian (1971) suggested using MRI to visually diagnose tumors from normal human tissue and performed the first MRI scan on a human in 1977, which took about 5 hours to complete.

MRI processes have been improved substantially over the years, making it one of the most common diagnosis tools currently used in medical practice. MRI is also used for research purposes to investigate the human body and, as in the case of this dissertation, aid in the development of biomechanical models by providing more accurate estimates of biomechanically relevant structure sizes and relative positions.

CT uses ionizing radiation to produce images of the CSAs of human tissue in vitro. CT was a popular tool used to develop back models before MRI became the preferred method. MRI uses magnetic fields and radio waves, which are not dangerous to humans at the magnitudes used, versus the ionizing radiation of the CT. In 1989, Tracey et al, used MRI scans of the lumbar spine to create a regression analysis with position and CSA measurements (Tracey et al, 1989). MRI has been used in many studies since then to analyze human tissues with the express purpose of improving biomechanical models.

Physical factors, such as lifting, carrying and awkward postures are among the main factors contributing to LBP (Plowman, 1992). Physical factors are not the only factors that can contribute to LBP. Individual age, gender, height, and weight all vary significantly among individuals and significantly influence the incidence and severity of LBP. These influences are both direct and indirect. For example, medical conditions such as diabetes contribute directly to MSDs while an individual's anthropometric differences also impact the magnitude of the forces experienced.

MLAL differences from individual to individual, for instance, will result in different exposures for a given MMH task. Many ergonomic models used to predict LBP do not consider individual characteristics. The lack of individualization in ergonomic models presents problems, specifically when assessing an individual's risk for LBP. MRI derived measurements can be used to personalize ergonomic and biomechanical models.

MRI is a useful tool for identifying potential pathological causes of LBP (e.g., bulging discs, nerve impingements, etc.). However, it is also often used in a qualitative manner (e.g., Pffirrmann ratings of disc degeneration) (Salar, 2017). MRI has great promise for providing more detailed quantitative data regarding precise sizes and locations of relevant low back structures. Precise quantification of muscle CSAs and MLALs will provide better descriptions of MIs to test the hypotheses that imbalances are associated with LBP, and that imbalances can be reduced via intervention such as exercise programs.

2.10 Exercise as a Muscular Imbalance Intervention

Exercise is often prescribed as part of a rehabilitation program for chronic pain (Sullivan et al, 2012). Strengthening the core muscles through exercise has been shown to reduce LBP (Wang et al, 2012). Stabilization exercises have been linked to a strengthened and, therefore, a more stabilized core (Wang et al, 2012). The literature suggests an underlying model (imbalances lead to tension and then pain) that can be rigorously tested via MRI.

Tai Chi exercise focuses specifically on core stability. It has been shown to improve strength, stability, and reduce pain (Wang et al, 2012, Weifen et al, 2013, Wu et al 2004, Wang et al 2013). Previous research has demonstrated the positive benefits of performing Tai Chi exercises (Wang et al 2012, Weifen et al, 2013, Wu et al 2004, Wang et al 2013). It is possible that Tai Chi exercises could reduce MI associated with LBP. In several studies, an intervention group was selected from a group of controls to participate in Tai Chi intervention classes (Wang et al 2012, Weifen et al, 2013, Wu et al 2004, Wang et al 2013) where they found Tai Chi to be an effective alternative and low-cost treatment for chronic pain conditions, specifically LBP. Therefore, it is logical that intervention-based experimental designs studying Tai Chi prospectively could quantitatively compare MIs prior to and after practicing Tai Chi.

Chenghu Deng and Wei Xia (2017) studied the effects of Tai Chi on degeneration within lumbar vertebrae and discs. This study followed two groups of subjects: 24 participants with no Tai Chi training or experience and 27 who have practiced Tai Chi for more than four years. After reviewing the MRI scans, Deng and Xia found that those who have been practicing Tai Chi had significantly fewer degenerated lumbar vertebrae and discs than the control group. In both groups, the L5 disc was the most affected for both vertebrae and discs. While this study compared low back health and disc degeneration cross-sectionally, it did not prospectively follow subjects using Tai Chi as an intervention.

Chapter 3

A Novel Approach for Quantifying Muscular Imbalances and its Relationship to Low Back Pain

3.1 Introduction

Muscle asymmetry resulting in an MI in the paraspinal muscles has been identified as a likely contributor to LBP development (Danneels et al, 200; Hides et al, 2008; Kader et al, 2000; Mengiardi et al, 2006; Parkkola et al, 1993). Side specific CSA spinal morphometry has been investigated in previous research through the lumbar spine levels (L2-S1) to determine if spinal level or side specific muscular atrophy may be a contributor to LBP (Hides et al, 2008; Barker et al, 2004; Campbell et al 1998; Hides et al, 1994; Hyuan et al, 2007; Ploumis et al, 2011; Hayashi et al, 2002; Hides et al, 2002). Paraspinal muscle asymmetry has been found in individuals with LBP, and thought to most likely be caused by disuse, denervation, or reflex inhibition (Hodges et al, 2006).

The mechanism behind paraspinal MI may be a symptom *or* a consequence of LBP, or *both* a symptom and a consequence of LBP. This may create a vicious cycle of trauma to muscles causing injury due to poor muscle control, leaving the muscles unable to heal after exercise or stress, resulting in accelerated degeneration and subsequent pain. The mechanism of MI needs to be further explored to better assess the association of MI and LBP. Theoretically, balance is created through equal moment generation capability in both the forward/back and side-to-side hemispheres of the low back. Imbalances disrupt coordinated moment generations created by the paraspinal muscles and unevenly load the spine, which may contribute to further MI and result in LBP.

Efforts to better understand the degree of MI present in people with and without LBP, have increasingly relied on medical imaging, such as MRI. These medical imaging techniques have been used to precisely measure muscles in the low back and have typically used muscle CSA side-to-side differences of paraspinal muscles to quantify MI. An asymmetry of greater than 10% was proposed as an abnormality, as studies have shown that paraspinal muscles are typically symmetric (i.e., ≤ 10% MI) in people that do not suffer from LBP (Hides et al, 2008; Hides at al, 1994; Stokes et al, 2005). However, in 2011, it was found that 40% of 126 men without LBP had a multifidus MI over 10% (Hides et al, 2008).

There are other factors to consider when studying the mechanism of MI and MI related LBP. In addition to paraspinal muscle CSA differences, core muscle CSA differences should also be incorporated into MI models. Also, not only should CSA lateral differences be considered as MI factors, but also A/P CSA differences, as paraspinal muscles work in coordination with the core muscles to distribute loads as symmetrically as possible throughout the low back to relieve pressure on the spine. MLALs should also be introduced into the MI model to account for muscle moment generating capacity.

There is no known, published research that has quantified MI using MRI-derived measurements of CSAs *and* MLALs of both the paraspinal and core muscles (psoas, erector spinae, QL, rectus abdominus, and oblique muscles). Thus, the objective of this experiment was to assess the relationship between MI and LBP using established MI evaluation techniques as well as via a newly developed measure of MI (MI_{new}). MIs were measured in terms of muscle CSAs, MLALs, and combinations of CSAs and MLALs both laterally and anteriorly/posteriorly for all core muscles individually and groups.

3.2 Materials and Methods

3.2.1 Study Sample Characteristics

Lumbar spine MRI scans were obtained from 28 subjects. Characteristics of study participants are found in Table 3.1 below. All subjects were female. Subjects were aged 51-81 (mean 62.79, standard deviation (SD) 8.37) (Table 3.1). Lumbar IVD segments from L2-S1 (L2/L3, L3/L4, L4/L5, L5/SI) and trunk/core musculature were gathered from the MRI scans taken on a Siemens Verio open-bore 3T scanner.

Table 3.1: Characteristics of Subjects, Means and SD

Factor	Mean	SD
Age (Years)	62.79	8.37
Height (m)	1.66	0.14
Weight (kg)	69.91	17.04
BMI (kg/m^2)	25.67	6.10
Typical Amount of Exercise (Hour/Week)	4.38	4.24
LBP (0 - 10)	1.96	2.42

Subjects had to meet the inclusion criteria of being female, age 50 or over, able to ambulate unaided (without walkers, canes, or other assistive devices), possessed the unrestricted use of all four limbs and were free of metal implants that could interfere with MRI collection. Recruitment for study participants was carried out through word-of-mouth on campus at Auburn University (AU), community group exercise classes, book clubs, doctors' offices, and local hospital-run facility recreational centers that also acted as rehabilitation clinics. Flyers were also posted to advertise the study at these venues and were distributed among the members of these organizations to share with other potential eligible participants. Twenty-eight subjects met these criteria and participated in the study. CSAs, MLALs, and MI measurements were taken from the axial MRI scans. A sagittal view was used to ensure that the measurements taken were at the correct level from L2-S1.

Subject personal demographics/characteristics on age, height, weight, and BMI were measured at the time of the MRI scan by study personnel. Age was confirmed by birthdate; weight was measured by a scale in pounds (lbs.) and converted to kilograms (kg); and height was measured using an anthropometric measuring device in inches (in) which were then converted to meters (m). BMI was calculated by dividing the weight in kg by the height in m^2.

Subjects were administered an intake medical questionnaire (Appendix 1) that provided information on potentially related physical activities, and pain in the following body regions: low back, neck/head, shoulder and upper arm, upper back, distal upper extremities, hip and buttocks, thigh, knee, and ankle/feet. The level of pain or discomfort in each region below was gathered via a visual analog scale (VAS) from zero to ten each body region depicted on the figure on the questionnaire (Figure 3.1).

Other health data collected for the subjects included: whether there was any history of hysterectomy, oophorectomy, smoking, and osteoporosis; any history and the severity/effect on daily life of heart attacks, blood clots, hypertension, high cholesterol, diabetes, obesity, and sciatica; the number of any biological children; whether they are pre- or post-menopausal; and how much exercise (hours/week) is typical. Exercisers were defined as those who reported typically participating in at least one or more hour of physical activity per week on their intake medical questionnaire. This questionnaire was administered to subjects to provide information on other factors that might influence or contribute to MI and LBP.

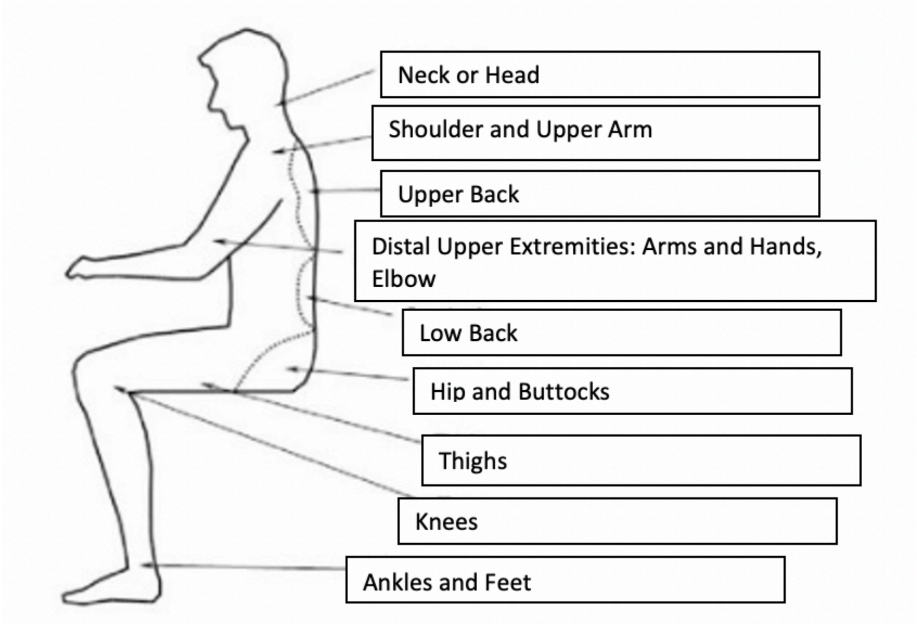


Figure 3.1: Medical Questionnaire Body Diagram for Self-Reported VAS Pain Ratings

3.2.2 Measuring Methods

3.2.2.1 Magnetic Resonance Imaging Methodology

Scans of the lumbar spine from L2-S1 were collected with a standardized T2 weighted protocol. A localizer scan was first performed in the MRI procedure sequence (Figure 3.2). The localizer scan is a preview scan that helps operators determine if the correct body segments are being scanned and if the subject appears to be positioned as straight as possible (e.g., minimal lateral flexion or twisting to one side or the other). Subjects were scanned in the supine position (lying on their back), seen in Figure 3.3.

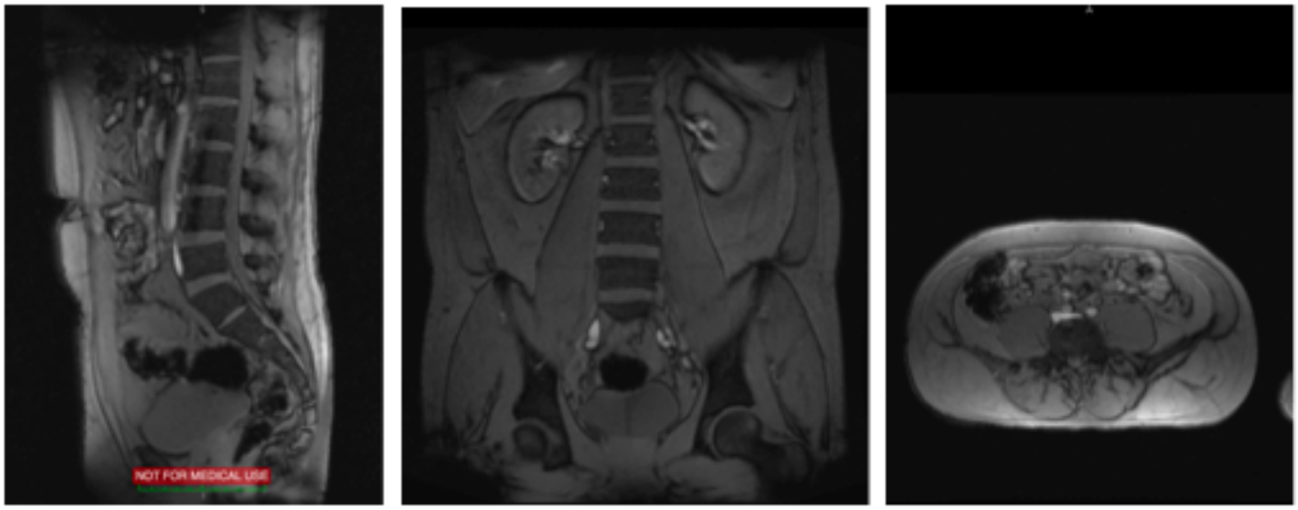


Figure 3.2: Localizer MRI Scan

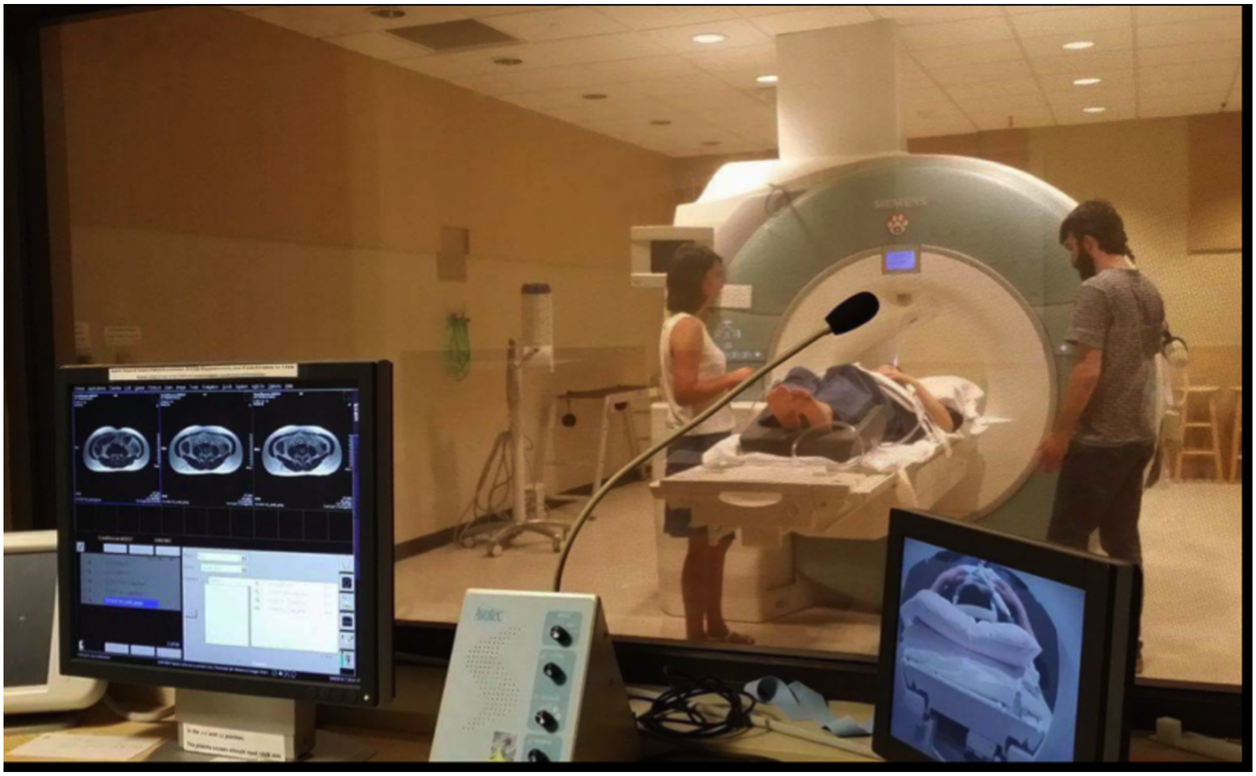


Figure 3.3: MRI Setup with Subject

After performing any necessary adjustments to the localizer scan and/or the subject position, the MRI scans were carried out as per protocol: L2-S1 for both sagittal continuous, axial continuous, and multi-group T2-weighted images. MRI scans on the lumbar spine were performed at the AUMRIRC using the 3T Siemens Verio open-bore MRI scanner with the supplemental abdomen coil to improve the quality of scan in the abdominal region.

The protocol used was sagittal continuous T2-weighted, axial continuous T2-weighted, axial multi-group T2-weighted at parameters of T2-weighted spin-echo (TR 3440 ms; TE 41ms) at 3mm thickness slice, 385 FOV read, and 100% FOV phase (Tang et al, 2016; Gungor et al, 2016; Pentikis, 2017; Salar, 2017). Complete morphological analyses of the IVD and core musculature were completed with this T2 weighted protocol that has been shown effective at visualizing the needed aspects of the MRI scans collected in several previous studies (Tang et al, 2016; Gungor et al, 2016; Pentikis, 2017; Salar, 2017).

Subject MRI and survey data were anonymized using a subject code to protect personal information (Appendix 2). The AU Institutional Review Board (IRB) approval email is found in Appendix 3, and the promotional IRB approved flyer distributed to promote recruitment is found in Appendix 4. IRB and the state of Alabama approval was obtained to gather MRI scans. No data collection occurred prior to IRB approval. Signed, IRB approved informed consent forms were collected from each subject (Appendix 5), as well as the MRI Pre-Entry Screening Form (Appendix 6).

3.2.2.2 Muscle Cross-Sectional Areas and Mechanical Lever Arm Lengths

Muscle CSAs and MLALs measurements from paraspinal and core muscles from L2-S1 were gathered from the MRI images using OsiriX software (v10.0.6, Pixmeo SARL, 266 Rue de Bernex, CH133 Bernex, 2021, Switzerland). To calculate CSAs using OsirX, the perimeter of the disc and muscles were traced with a reference length (a line of known length), and for each shape, points were placed around the perimeter with lines drawn at opposite points, creating an intersection of the lines creating the shapes centroid. Measurements were made of CSAs of paraspinal and core muscles following the measurement protocols established by Tang and Gungor (2013), and each corresponding MLAL (generated by the horizontal location of the disc and muscle centroid) for the core muscles was assessed following the measurement protocols established by Pentikis (2017).

The previously used measurement protocols have all demonstrated excellent intra-and-inter-rater reliabilities as evaluated using inter-class coefficients (ICCs) (Tang et al, 2016; Gungor et al, 2016; Pentikis, 2017; Salar, 2017). Therefore, current study scans are expected to be similarly reliable. In Figure 3.4, muscle group CSAs calculated with OsiriX are shown on a traced MRI.

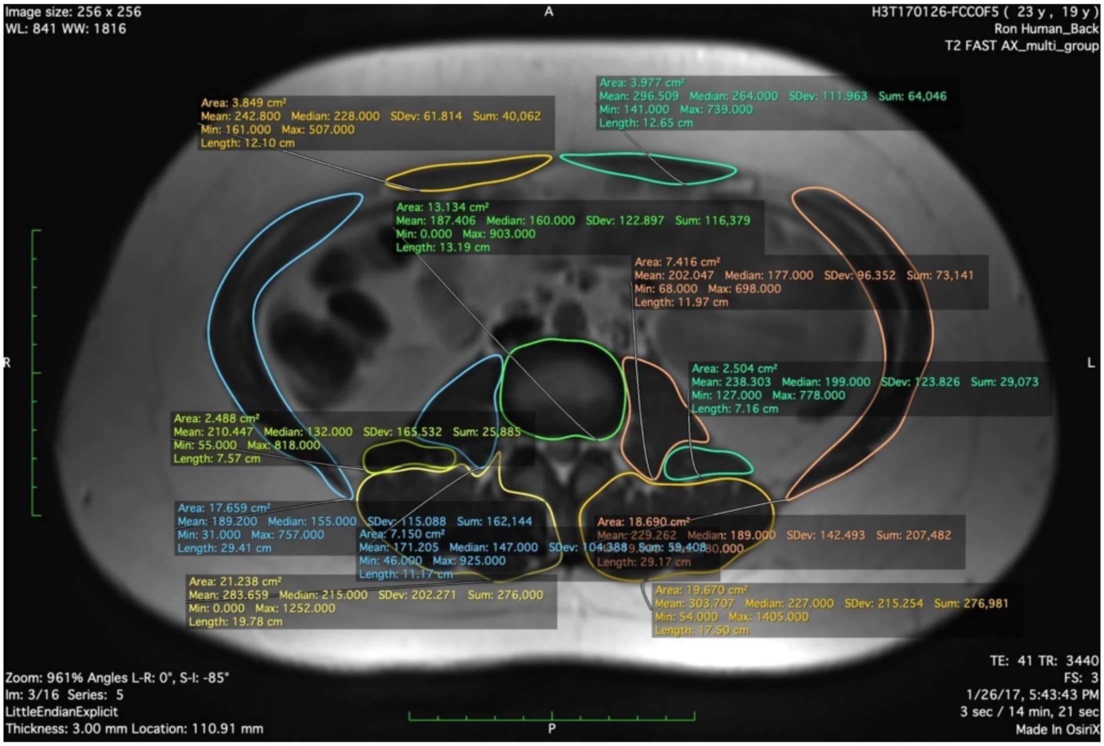


Figure 3.4: Traced MRI with Muscle CSAs Calculated in OsiriX

3.2.2.3 Muscular Imbalance

The measurements for each trunk muscle gathered were used in a summation across two planes: sagittal and frontal. This facilitated comparison of the hemisphere pairs of left/right (lateral) and A/P (fore/aft). To calculate the lateral MLALs, a 90° MLAL from a sagittal plane bisecting the spinal disc was used. To calculate the A/P MLALs, a 90° MLAL from a frontal plane bisecting the spinal disc was used.

Previous studies have suggested that both the lateral and A/P moment arms should be used as predictors in biomechanical models of the spine. The moment arms suggested are illustrated in Figures 3.5 and 3.6 and were used by Jorgenson et al, (2000) and Pentikis (2017). MI can be measured in absolute terms or in terms of percentage difference. Others have measured imbalances based solely on the CSA difference (MI_{CSA}). To date, the MLALs has not been factored into assessments of MI.

In addition to MI based solely on CSA (MI_{CSA}), this dissertation also introduces and explores a novel measure of MI (MI_{New}) as a function of the product of CSAs with corresponding MLALs. In Figure 3.6 lateral MLALs are shown on an MRI scan which are calculated from the centroid of the spinal disc to the centroid of the muscle for each muscle. In Figure 3.7 A/P MLALs are shown on an MRI scan which are calculated from the centroid of the spinal disc to the centroid of the muscle for each muscle.

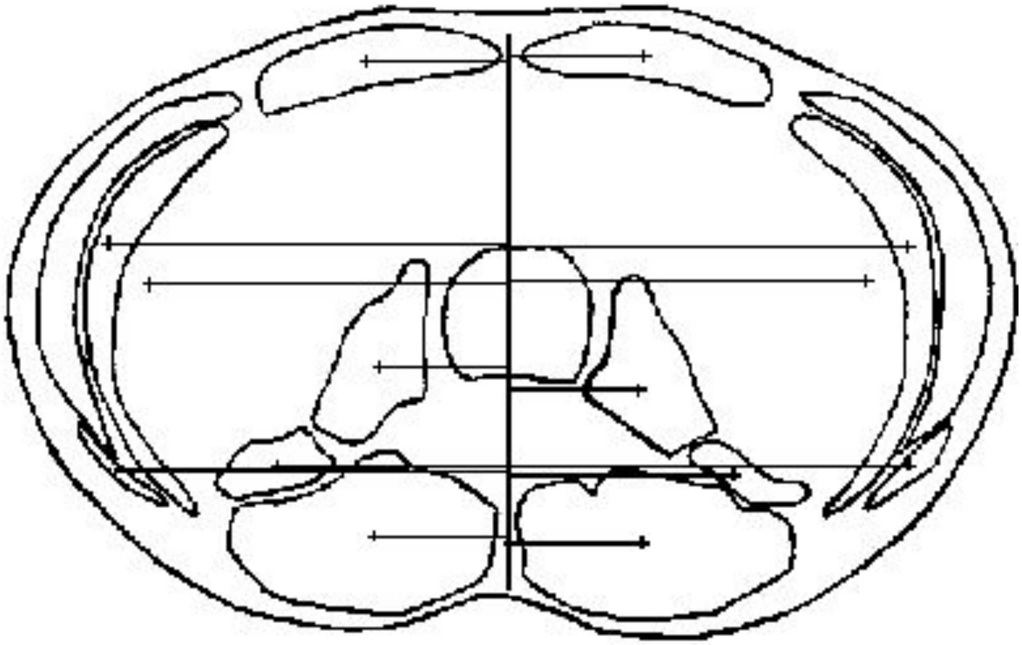


Figure 3.5: Proposed Axial MRI with Lateral MLALs (Jorgenson et al, 2000).

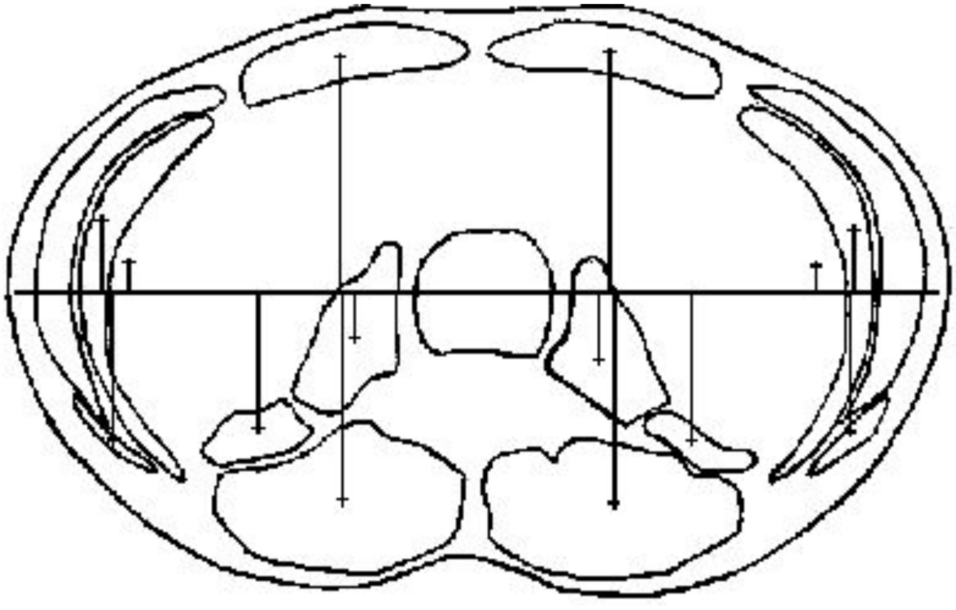


Figure 3.6: Proposed Axial MRI with A/P MLALs (Jorgenson et al, 2000)

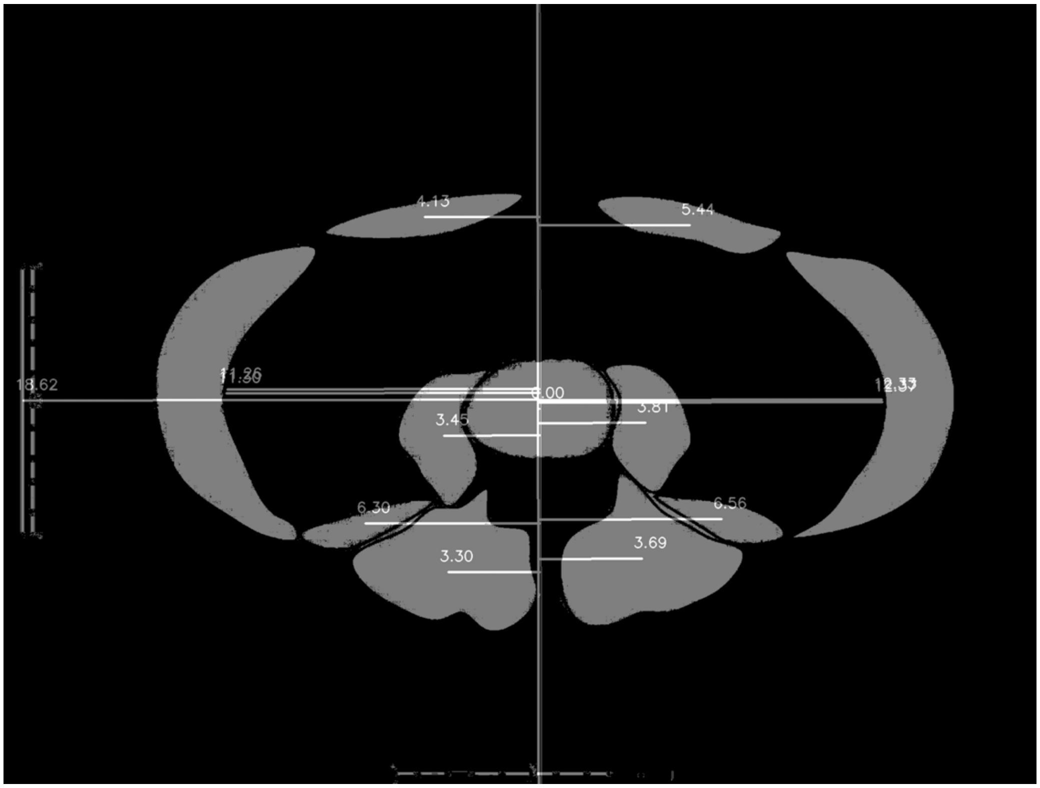


Figure 3.7: Lateral 90° L/R MLALs

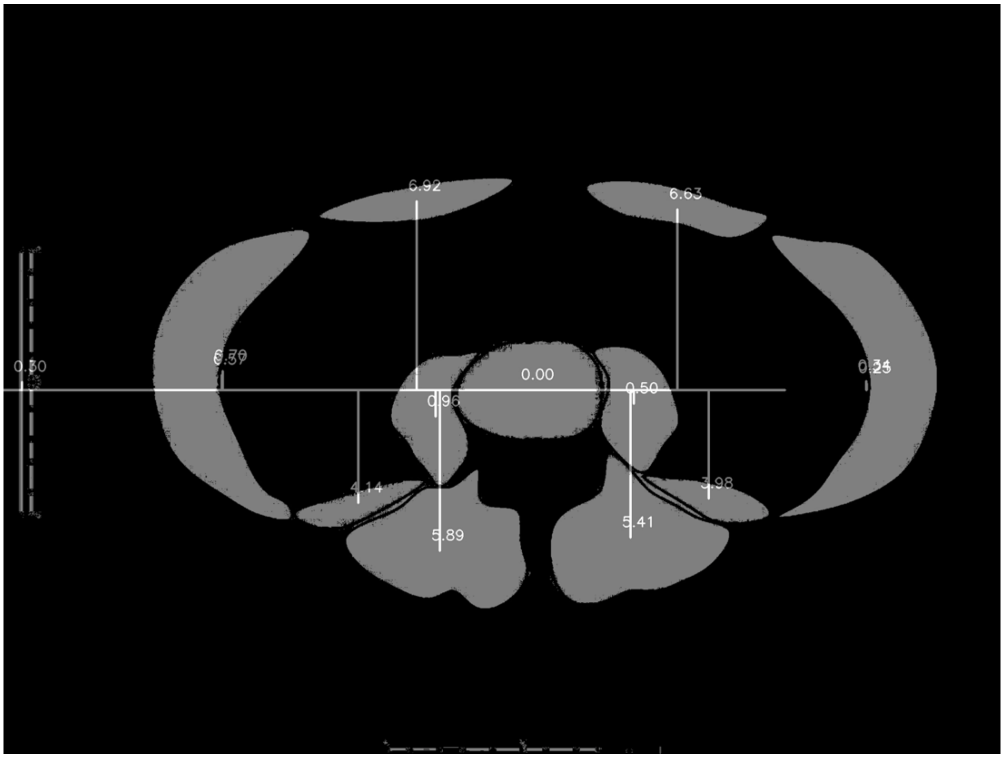


Figure 3.8: A/P MLALs

MI was evaluated muscle-by-muscle in individual pairs, by functional muscle groups, and by hemisphere (lateral and A/P) for MI_{CSA} and MI_{New}. The older MI model, MI_{CSA}, only takes the absolute differences between the two muscles, muscle groups, or hemisphere, as shown in equation 3.1 below. To calculate the percentage of imbalance for MI_{New}, the smaller side was subtracted from the larger side and subsequently divided by the larger side as shown in equation 3.2 below. This assessment of MI_{New} in terms of percentage was proposed by Fortin (Fortin, 2014). This process was repeated for all individual muscles, functional muscle groups, and for each hemisphere.

$$MI_{CSA} = \frac{Larger\ MI_{CSA} - Smaller\ MI_{CSA}}{Larger\ MI_{CSA}} \times 100 \quad Eq,\ 3.1$$

$$MI_{New} = \frac{Larger\ MI_{CSA*MLAL} - Smaller\ MI_{CSA*MLAL}}{Larger\ MI_{CSA*MLAL}} \times 100 \quad Eq,\ 3.2$$

3.3 Statistical Analysis

Measurements of CSAs and MLALs were used to calculate the imbalance assessments, MI_{CSA} and MI_{New}. CSA units are in cm^2, MLAL units are in cm, and MI_{New} units are in cm^3 as it is the product of the CSA (cm^2) and MLAL (cm). However, since the average absolute percentage difference is used, MI becomes unitless after calculation.

MI models were checked for assumptions of linear regression. Model diagnostics were run for the verification of assumptions of normality, linearity, homoscedasticity, and absence of multicollinearity. Both the MI_{CSA} and MI_{New} models were used to create a regression of MI against LBP and exercise. Correlations were found for LBP, typical weekly exercise duration, BMI, weight, and age and MI at each spinal level. T-tests were performed between groups of exercisers (exercisers were defined as those who reported typically participating in at least one or more hour of physical activity per week on their intake medical questionnaire) and non-exercisers and groups of those with LBP and those without LBP for LBP, exercise, and MI. Linear regressions were run for each MI measurement at each muscle, muscle group, and hemisphere at each lumbar spine level to see which muscle, muscle groups, hemispheres, or spinal level had the greatest association with LBP.

3.4 Results

Average absolute percentage differences of MI_{CSA} and MI_{New} are shown in Tables 3.2 and 3.3 for each muscle, muscle group, and hemisphere at each lumbar spine level in the lateral hemisphere.

Table 3.2: MI_{CSA} - Average Absolute Percentage Differences of Paraspinal and Core Muscles, Muscle Groups, and Hemispheres Across All Lumbar Spinal Levels, Means and SD for All Subjects

MI_{CSA}	L2/L3		L3/L4		L4/L5		L5/S1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Erector Spinae	7.23	5.04	8.50	7.31	6.86	5.76	11.20	6.81
Psoas	15.60	13.41	10.37	5.75	9.75	7.02	15.00	12.13
Oblique	13.10	8.91	7.65	11.48	13.29	14.91	21.87	12.68
Rectus Abdominus	20.32	13.40	18.99	12.53	15.55	13.15	15.20	13.53
Quadratus Lumborum	26.19	18.27	18.93	12.82	25.45	23.30	---†	---†
Paraspinal Group	7.11	4.82	6.82	5.39	6.93	5.22	9.72	6.38
Core Group	11.18	8.05	8.78	9.09	11.65	13.17	14.15	10.10
Lateral Hemisphere	7.64	5.43	6.01	5.67	7.49	5.83	9.68	5.86
† QL does not extend to this level in most subjects and therefore was not used								

Table 3.3: MI$_{New}$ - Average Absolute Percentage Differences for Paraspinal and Core Muscles, Muscle Groups, and Hemispheres, Across All Lumbar Spinal Levels, Means and SD for All Subjects

MI$_{New}$	L2/L3		L3/L4		L4/L5		L5/S1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Erector Spinae	16.46	9.29	17.97	14.14	14.02	9.97	18.39	9.17
Psoas	23.81	14.03	15.94	11.27	12.43	10.87	16.37	12.93
Oblique	14.93	11.94	11.65	11.79	13.75	13.38	23.86	13.38
Rectus Abdominus	30.46	17.36	33.02	14.93	23.02	13.57	28.83	20.56
Quadratus Lumborum	28.23	19.26	19.93	12.68	26.61	25.55	---†	---†
Paraspinal Group	14.81	10.18	14.40	12.36	12.03	8.43	13.95	10.08
Core Group	14.51	11.18	12.82	11.72	14.12	12.17	18.73	14.58
Lateral Hemisphere	13.40	10.63	13.18	10.30	11.56	9.56	13.11	9.74
† QL does not extend to this level in most subjects and therefore was not used								

Personal characteristics were correlated to investigate any potentially signficant relationships. Statistically significant correlations are bolded and denoted with an asterisk in Table 3.4.

Table 3.4: Correlation Matrix of Subject Personal Characteristics,
Correlation (Significance)

	LBP (0 - 10)	Exercise (Hour/Week)	Age (Years)	Height (m)	Weight (kg)	BMI (kg/m^2)
LBP (0 - 10)	1					
Exercise (Hour/Week)	-0.08 (0.34)	1	0.17 (0.28)			
Age (Years)	-0.01 (0.31)	0.12 (0.28)	1			
Height (m)	-0.06 (0.39)	0.15 (0.23)	-0.17 (0.19)	1		
Weight (kg)	-0.26 (0.09)	-0.21 (0.14)	-0.03 (0.43)	**0.40*** (0.02)	1	
BMI (kg/m^2)	-0.20 (0.16)	**-0.33*** (0.05)	0.14 (0.24)	**-0.42*** (0.01)	**0.67**** (0.00)	1
* Correlation is significant at the 0.05 level ** Correlation is significant at the 0.01 level						

There were twenty-two exercisers and six non-exercisers in the subject population with sixteen subjects reporting LBP, and twelve that did not report LBP. Of the exercisers, fourteen reported LBP and eight did not. Of the non-exercisers, two reported LBP, and four did not. The average LBP rating of those who exercised was 2.1 versus a LBP rating of 1.4 for those who did not exercise. However, this LBP difference was not statistically significant ($p = 0.55$). Of the exercisers, those who had reported LBP exercised an average of 4.2 hours per week, while those without LBP exercised slightly more with 4.7 hours of exercise per week. Exercise was not found to be significant with respect to LBP development when evaluated via linear regression ($p = 0.67$).

T-tests indicated only one statistically significant difference between exercisers and non-exercisers. At the L4/L5 level using the MI_{CSA}, the exercisers had significantly more MI than their non-exercisering peers (8% vs. 2%, $p=0.01$). There were no other apparent differences in MI between exercisers and non-exercisers (Appendix 8).

Using the MI_{CSA} measure, T-tests showed only one statistifally significant difference in MI_{CSA} for those with LBP vs. those with no LBP. This occurred at the L4/L5 level with MI more than double for those with LBP vs. those without LBP (9% vs. 4%, $p=0.02$) (Appendix 8).Table 3.5 shows the significant relationships found related to MI for those with and without LBP.

Table 3.5: Significant Relationships Found Related to MI for LBP Symptomatic/Asymptomatic Subjects

Symptomatic (LBP Present) Have Higher MI_{New}			
Spinal Level	MI_{New} Measurement	P-Value	(MI_{New} Mean Symptomatic, MI_{New} Mean Asymptomatic)
L4/L5	Erector Spinae	**0.05**	(17%, 10%)
L4/L5	Paraspinal Muscle Group	**0.08****	(14%, 9%)
Asymptomatic (LBP *Not* Present) Have Higher MI_{New}			
L2/L3	Erector Spinae	**0.05**	(13%, 20%)
L5/S1	Paraspinal Muscle Group	**0.00**	(9%, 21%)
L5/S1	Lateral Hemisphere	**0.03**	(10%, 18%)
L3/L4	Quadratus Lumborum	**0.09****	(25%, 29%)
L5/S1	Psoas	**0.09**	(13%, 21%)
*Significant at the 0.05 level ** Trending towards significance at the 0.05 level			

Linear regression was used to explore the relationship of MI to LBP. Several signifiant associations between and MI and LBP were found. No MI_{CSA} regressions were statistically significant. However, several of the MI_{New} regressions indicated statistically signifcant, positive relationships to LBP. The L2/L3 level was found to be most associated with LBP based on CSA alone (MI_{CSA}). MI_{New} established that the L2/L3 (p=0.36) and L3/L4 (p=0.27) levels were most associated with LBP development. The erector spinae (p=0.03), paraspinal muscle group (p=0.01), and lateral hemisphere (p=0.05) were all found statistically significant for predicting LBP. These relationships are plotted in Figures 3.9 – 3.11 and Tables 3.6 and 3.7 display the regression coefficients and their significances.

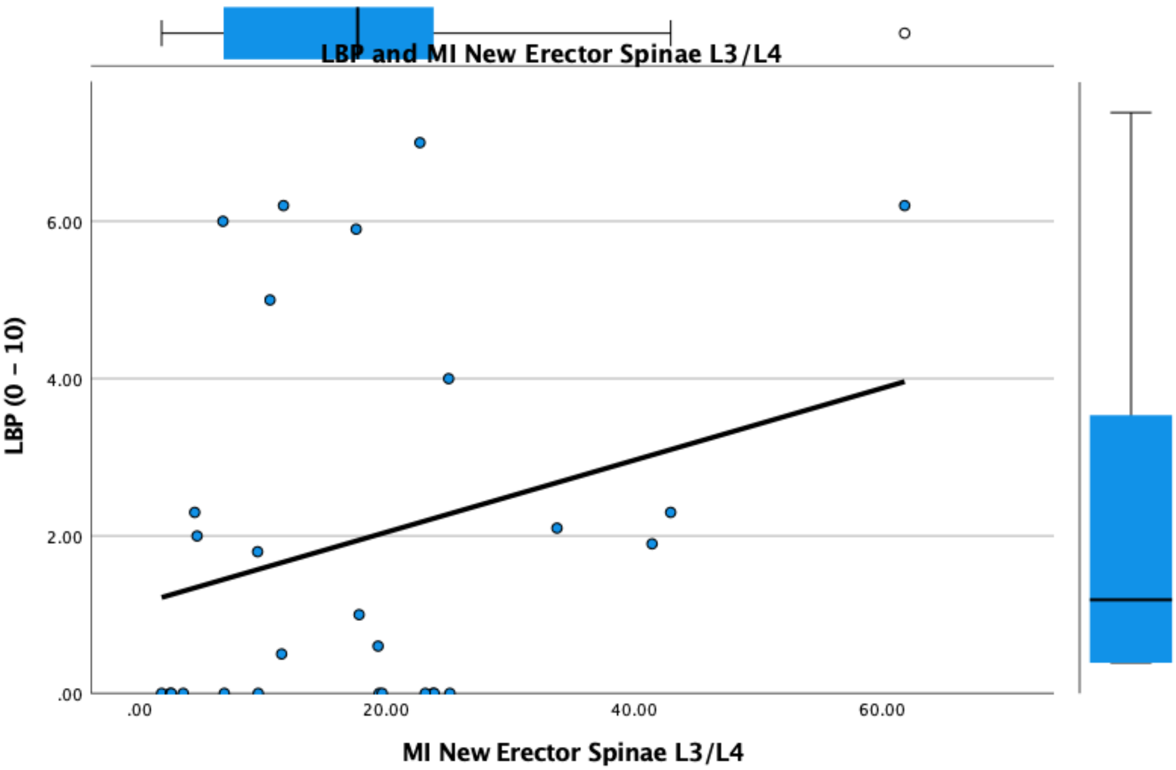


Figure 3.9: LBP and MI_{New} Erector Spinae L3/L4

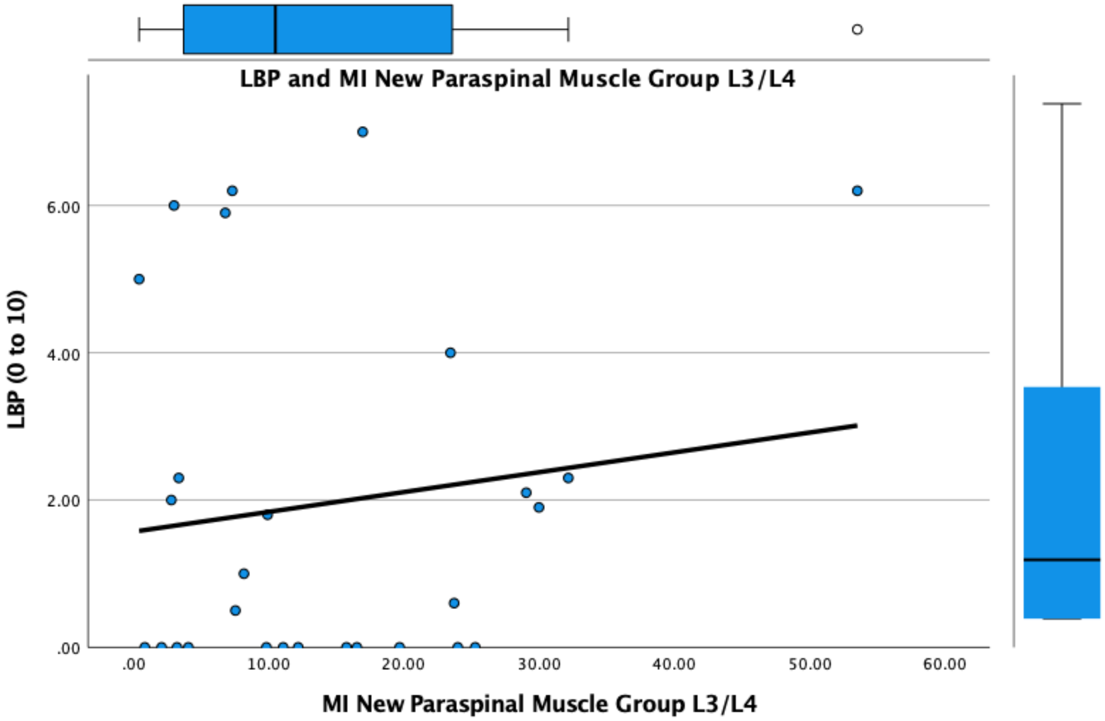


Figure 3.10: LBP and MI_{New} Paraspinal Muscle Group L3/L4

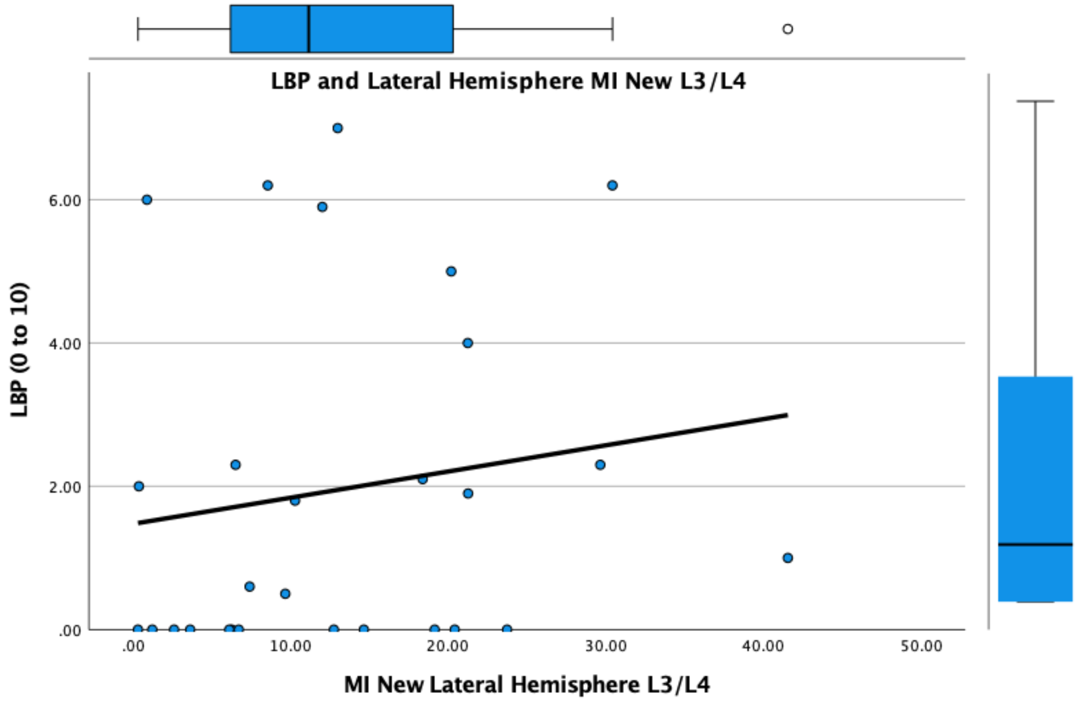


Figure 3.11: LBP and MI$_{New}$ Lateral Hemisphere L3/L4

Table 3.6: LBP and MI$_{CSA}$ Linear Regression, Coefficient (Significance)

MI$_{CSA}$	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	-0.150 (0.15)	0.016 (0.89)	0.096 (0.46)	-0.067 (0.64)
Psoas	0.025 (0.52)	-0.096 (0.28)	0.079 (0.41)	-0.062 (0.24)
Oblique	0.182 (0.09)	-0.090 (0.62)	0.112 (0.38)	0.016 (0.80)
Rectus Abdominus	-0.030 (0.47)	-0.76 (0.24)	0.065 (0.19)	0.058 (0.54)
Quadratus Lumborum	0.027 (0.36)	0.000 (0.99)	-0.018 (0.60)	---†
Paraspinal Group	0.014 (0.92)	0.200 (0.21)	0.158 (0.34)	0.302 (0.29)
Core Group	-0.154 (0.34)	0.209 (0.41)	-0.095 (0.55)	0.006 (0.95)
Lateral Hemisphere	-0.003 (0.99)	-0.223 (0.19)	-0.122 (0.66)	-0.395 (0.24)

† QL does not extend to this level in most subjects and therefore was not used

Table 3.7: LBP and MI_{New} Linear Regression, Coefficient (Significance)

MI_{New}	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	-0.130 (0.17)	**0.219** **(0.03*)**	0.027 (0.67)	0.047 (0.53)
Psoas	0.047 (0.22)	0.014 (0.82)	**0.099** **(0.04*)**	-0.017 (0.70)
Oblique	0.238 (0.26)	-0.243 (0.26)	-0.116 (0.66)	0.027 (0.69)
Rectus Abdominus	0.005 (0.86)	-0.003 (0.93)	-0.038 (0.44)	0.024 (0.40)
Quadratus Lumborum	0.017 (0.53)	0.021 (0.61)	**-0.069** **(0.05*)**	---†
Paraspinal Group	0.007 (0.94)	**-0.533** **(0.01*)**	0.140 (0.15)	-0.115 (0.25)
Core Group	-0.226 (0.42)	-0.426 (0.25)	0.244 (0.43)	-0.008 (0.89)
Lateral Hemisphere	0.053 (0.82)	**0.909** **(0.05*)**	-0.092 (0.56)	-0.044 (0.70)
† QL does not extend to this level in most subjects and therefore was not used * Correlation is significant at the 0.05 level				

Raw MRI data obtained from a previous MRI study of weightlifters was used to compute the erector spinae MI_{CSA} at L3/L4 for a comparison to this MRI study. The previous research did not investigate MI, but a subsect was extracted and evaluated in the same manner to establish MI for a younger population including vigorous resistance training subjects. Women were less likely to be weightlifters, but no statistically significant difference was found between weightlifters and non-weightlifting female controls with respect to erector spinae muscle size (CSA). Both weightlifters and controls had asymmetry present. There was no significant difference between MI_{CSA} for these subjects. Lifters and non-lifters had virtually identical levels of imbalance.

The inclusion criteria for the weightlifting study were no LBP at present time, no LBP history, no previous back surgery, and included both genders. Subjects were recruited from AU with ages ranging from (19-29) (Table 3.8). There was a statistically significant difference in muscle size between male and female subjects.

Table 3.8: Weightlifting Study Subject Personal Characteristics

	Mean (All Subjects)	SD (All Subjects)	Mean (Women Only)	SD (Women Only)
Age (Years)	24	3.34	23	3.63
Height (m)	1.73	8.53	1.68	6.41
Weight (kg)	73.17	13.32	64.71	10.16
BMI (kg/m^2)	24.47	3.36	23.08	3.98

The average L3/L4 erector spinae CSA of female subjects was 19.6 cm^2 (SD=1.32), and male erector spinae CSA was 31.0 cm^2 (SD= 2.97) in the previous study, and the current study (female subjects average age = 63 years) erector spinae CSA average was 21.0 cm^2 (SD 3.55). Average percent asymmetry in the young population of both controls and weightlifters was just 2.12% (SD=2.25), and after intervention the average was 1.98% (SD = 2.25).

Women in the weightlifting study were much younger at 23 years of age, weighed less and had a lower BMI than the older population of women. The women over 50 had an average MI_{CSA} of 8.50%, as opposed to the younger population of women who had similar muscle size, but approximately one-fourth as much MI at 2.12%.

An A/P MI ratio was developed by dividing the anterior hemisphere MI by the posterior hemisphere. A/P MI has not been previously studied, therefore there is no known “ideal” ratio established. The A/P ratios for MI_{CSA} and MI_{New} are presented in Tables 3.9 and 3.10, respectively. A/P MI_{New} was significantly correlated with weight and BMI at all lumbar spinal levels. Increasing A/P ratios were associated with increasing weight and BMI. At the L2/L3 level, A/P MI_{CSA} was negatively correlated with correlated with exercise. A/P MI_{New} was negatively correlated with exercise at both the L3/L4 and L4/L5 levels, and height. Increasing A/P ratios were associated with shorter stature and fewer hours/week of exercise. Significant correlations are presented in Tables 3.11 and 3.12.

Table 3.9: A/P MI_{CSA} Hemisphere Ratio

Spinal Level	Minimum	Maximum	Mean	SD
L2/L3	0.77	1.39	1.06	0.14
L3/L4	0.67	1.26	0.85	0.13
L4/L5	0.53	1.33	0.77	0.19
L5/S1	0.68	1.66	0.95	0.22

Table 3.10: A/P MI_{New} Hemisphere Ratio

Spinal Level	Minimum	Maximum	Mean	SD
L2/L3	0.21	1.61	0.73	0.38
L3/L4	0.17	1.50	0.49	0.34
L4/L5	0.09	1.69	0.64	0.39
L5/S1	0.48	1.87	0.90	0.33

Table 3.11: Correlation Matrix of Subject Personal Characteristics and A/P MI_{CSA}, Correlation (Significance)

	LBP (0 to 10)	Height (m)	Weight (kg)	BMI (kg/m^2)	Exercise (Hour/Week)
Height (m)	-0.06 (0.39)	1.00	**0.39*** **(0.02)**	**-0.42*** **(0.01)**	0.15 (0.23)
Weight (kg)	-0.26 (0.09)	**0.39*** **(0.02)**	1.00	**0.67**** **(0.00)**	-0.21 (0.14)
BMI (kg/m^2)	-0.20 (0.16)	**-0.42*** **(0.01)**	**0.67**** **(0.00)**	1.00	**-0.33*** **(0.05)**
Exercise (Hour/Week)	-0.08 (0.34)	0.15 (0.23)	-0.21 (0.14)	**-0.33*** **(0.05)**	1.00
A/P MI_{CSA} L2/L3	**-0.41*** **(0.02)**	-0.05 (0.41)	**0.423*** **(0.01)**	**0.44*** **(0.01)**	**-0.45**** **(0.01)**
A/P MI_{CSA} L3/L4	-0.11 (0.28)	0.06 (0.38)	0.27 (0.09)	0.20 (0.15)	-0.31 (0.06)
A/P MI_{CSA} L4/L5	-0.10 (0.31)	0.02 (0.47)	**0.41*** **(0.02)**	**0.39*** **(0.02)**	-0.27 (0.09)
A/P MI_{CSA} L5/S1	0.17 (0.19)	-0.08 (0.35)	0.23 (0.12)	0.27 (0.09)	0.01 (0.48)

* Correlation is significant at the 0.05 level (1-tailed).
** Correlation is significant at the 0.01 level (1-tailed).

Table 3.12: Correlation Matrix of Subject Personal Characteristics and A/P MI_{New}, Correlation (Significance)

	Height (m)	Weight (kg)	BMI (kg/m^2)	Exercise (Hour/Week)
Height (m)	1.00	**0.39* (0.02)**	**-0.42* (0.01)**	0.15 (0.23)
Weight (kg)	**0.04* (0.02)**	1.00	**0.67** (0.00)**	-0.21 (0.14)
BMI (kg/m^2)	**-0.42* (0.01)**	**0.67** (0.00)**	1.00	**-0.33* (0.05)**
Exercise (Hour/Week)	0.15 (0.23)	-0.21 (0.14)	**-0.33* (0.05)**	1.00
A/P MI_{New} L2/L3	**-0.48** (0.01)**	**0.34* (0.04)**	**0.71** (0.00)**	-0.31 (0.06)
A/P MI_{New} L3/L4	**-0.36* (0.03)**	**0.40* (0.02)**	**0.67** (0.00)**	**-0.38* (0.02)**
A/P MI_{New} L4/L5	-0.22 (0.13)	**0.49** (0.00)**	**0.65** (0.00)**	**-0.33* (0.05)**
A/P MI_{New} L5/S1	0.14 (0.24)	**0.55** (0.00)**	**0.41* (0.02)**	-0.32 (0.06)
* Correlation is significant at the 0.05 level (1-tailed). ** Correlation is significant at the 0.01 level (1-tailed).				

While there are relatively few data points, a plot of the A/P MI_{New} ratio at L3/L4 vs. LBP seems to indicate that a ratio between 0.5 and 1.0 is associated with the lowest levels of pain (Figure 3.12).

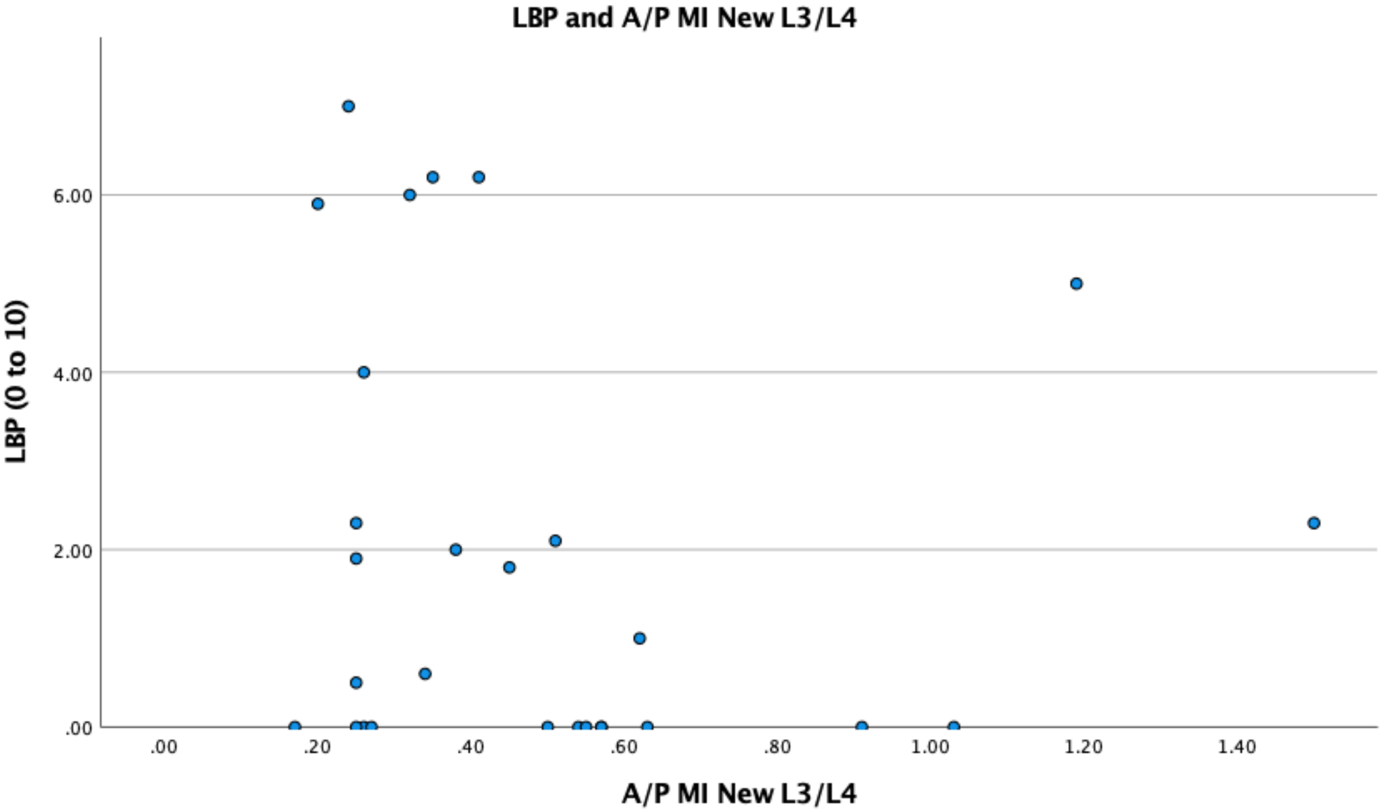


Figure 3.12: LBP and A/P MI_{New} Ratio L3/L4

3.5 Discussion

The age of participants is higher as compared to the typical age ranges in previous studies conducted on MI and subsequent LBP. Most studies on MI have been conducted with younger, male athletes (Franettovich et al, 2011). A significant scientific contribution of this work is the evaluation of the associations between LBP and MI for the understudied population of older women. It should be noted that this aspect of the study may be considered for older workers, as there is an increasingly aging workforce in the United States, as more workers are delaying retirement and continuing to work. The sample size (n=28) is relatively small to assess an association between MI and LBP, however, small-n experimental designs are considered very effective for randomized control trial (RCT) studies (Graham et al, 2012).

MI was measured in terms of CSA (MI_{CSA}) and MLAL*CSA (MI_{New}). MI was measured anteriorly/posteriorly (by hemisphere) and laterally for all core muscles individually, in functional groups, and by hemisphere. Various quantitative indices of imbalance were explored including a novel approach for quantifying MIs. Relationships to LBP and MI were explored. The new way of quantifying MI, MI_{New}, assumed that MLALs may correct for some imbalance, resulting in a better overall assessment than CSA alone.

MI measurements were normalized by finding the absolute percentage differences, rather than considering absolute area differences. Percentages may be more meaningful in showing size differences in the data, specifically muscular size differences, particularly when subject size and stature vary. MI_{CSA} described the average absolute percentage differences between muscle sizes using only CSAs, while MI_{New} described the average absolute percentage differences in moment generating capability (product of muscle areas and corresponding muscle lever arms) between muscles, muscle groups, and hemispheres.

MI_{New} values were larger than the CSA model, as they were a product (CSA*MLAL). The new model appears to be more sensitive to imbalance possibly because it incorporates the MLAL distance factor. Interestingly, it was determined that when considering groups of muscles rather than individual muscles, less MI was observed. This natural "correcting" for individual muscle differences may explain the lower MI with groups and hemispheres than with individual muscles. For example, MI_{CSA} for the lateral hemisphere was less than 10% at all levels. However, most individual muscle MI_{CSAs} were greater than 10% at all levels.

Both MI measurement models were checked for the appropriate assumptions via model diagnostics. Case-wide diagnostics of the MI model data were inspected to identify any outliers that may have been present in the data. There were no residuals that were three or more SDs from the mean, which may have been considered outliers. It was determined that valid inferences could be made from the models, as the residuals of regression followed normal distributions. The normal probability plot (P-P) residuals were normally distributed and conformed to the diagonal normality line in the P-P plot. Homoscedasticity showed residuals were equally distributed via plotted predicted values and residuals on scatterplot. Linearity was demonstrated by a straight-line relationship between the predictor values in the regression and outcome variables for both MI models and multicollinearity was checked with variation inflation factors (VIF) that were each below 10.

Not surprisingly, BMI was positively correlated with weight and negatively correlated with height. Exercise was negatively corrlated with BMI.

In the present study, no clear relationship was established where MI is always associated with LBP. Inconsistent differences resulted from the unusual patterns of MI and LBP. The MI_{New} measaure indicated mixed results with respect to the link between MI and LBP. In some cases, those with LBP had higher MI, in others MI was higher in those without LBP, depending on the spinal level considered. It should be noted these comparisons are for no LBP (0 on scale from 0 to 10) vs. any pain (>0 pain rating). The spinal level considered appeared to impact whether or not the relationship would be positive or negative. Therefore, imbalance location may play an important role in LBP.

The linear regression findings also appear to suggest that the location of imbalance may play an important role in LBP. One data point fell outside the whiskers of the box plots, and was explored in greater detail. It belonged to a subject with severe scoliosis who had both high LBP and MI. This data point supports the hypothesis that increased MI presented with increased LBP; although it was higher than most of the other data, it was expected and explained.

However, based on this potential outlier, it was suggested that this scoliotic subject may be driving the relationship between MI and LBP, skewing results.The linear regressions were run again without this particular scoliotic subject. The relationship between MI and LBP remianed significant for the ES and Paraspianl muscle groups. The lateral hemisphere, however, was no longer statistically significant (p=0.08). This suggests that scoliotic subjects warrant further study.

It is worth exploring further because MI may be exacerbated by scoliosis and or scoliosis could be a cause of LBP. In a study of volleyball players, volleyball players were five times more likely to have scoliosis than non volleyball playing controls which is a compelling odds ratio (Modi et al, 2008). It was not determined whether scoliosis or imbalance were leading to pain. To further investigate and determine the linear relationship between MI and LBP, it may be more meaningful to study scoliotic subjects and or unilateral sport athletes as these populations have been found to have the highest levels of LBP and MI. exercise in general may not be the most important relationship to investigate with respect to LBP and MI, Since it was not found to be a good predictor of the relationship.

Certain types of exercise, like unilateral sports, have been shown to be more predictive of LBP and MI. Certain muscle contractions in the core muscles (whether voluntary or involuntary) may impact movement and subsequent LBP. In the future, these contractions might be investigated in scoliotic subjects and unilateral sport athletes in tandem with MI and LBP to better determine the relationship between them.

The relationship between MI and LBP appears to be a function of spinal level and the grouping of muscles analyzed. While the MI relationship to LBP appeared to vary by spinal level, the L3/L4 level appeared to be most significantly and consistently related to LBP. Groups of muscles in aggregate are better at predicting LBP. The muscle groups and the complete hemisphere appeared most related to LBP. The hemispheres appeared to "balances out" when investigating differences in muscles and muscle groups, resulting in lower estimates of MI for both MI_{CSA} and MI_{New}.

The previous weightlifting study population was quite different from the current MI study, as no one was excluded for having LBP and subject inclusion criteria specifically included being female and 50 or more years of age. The weightlifting study average age was significantly less than the current study at 24 years and included both male and female subjects.

In this study, an increase in MI did not always lead to an increase in LBP. The spinal lever and MI type (e.g., individual muscles, groups, hemispheres) were important. In this study, the exercisers had greater MI than non-exercisers. Whereas, in the weightlifting study, there were no MI differences between exercisers and non-exercisers with both groups exhibiting very low MI_{CSA} levels of ~2%. The exercisers in this study did have more pain (2.1 vs. 1.4), but the differences were not statistically significant and may be the result of exercise related discomfort. This was somewhat surprising as it was hypothesized that exercise may impart a protective effect with respect to both MI and corresponding LBP.

Age plays appears to play a role in the development of MI. Analysis showed a significant difference in MI between younger and older populations. The muscle sizes (actual CSA sizes) were not that different between the groups (young vs. old females), but the MI was significantly greater for the older population of women.

It can be assumed that lateral MI is optimized when differences are small (i.e., the sides are symmetrical). However, a similar assumption cannot be made with respect to the A/P hemispheres. To date, A/P MI, specifically the A/P ratio, has not been studied. Therefore, there are not established "ideal" or desirable ranges for this ratio. However, it appears that ratios between 0.5 and 1.0 were associated with the lowest levels of LBP. Theoretically, perfect balance would occur at an MI of 0.0 laterally, but when considering A/P imbalance, more research is needed to determine the optimal fore/aft balance. The posterior hemisphere is larger than the anterior hemisphere and it has more moment generating capability, which is beneficial since most lifting occurs in the front of the body (on the anterior side).

Very low A/P MI_{New} ratio may be indicative of weak abdominal muscles which literature indicates is related to LBP (Nourbakhsh et al, 2002). In fact, there is a cluster of high pain subjects at the lowest observed A/P MI_{New} levels. A/P MI_{New} levels greater than 1.0 may be indicative of obesity (e.g., protruding abdominal cavity). Since persons with relatively weak abdominal muscles will tend to have lower A/P ratios. interventions targeting core muscles may impact the A/P ratio favorably.

Pregnancy may influence lateral MI, due to its tendency to cause diastasis recti, which is a separation between the two rectus abdominus muscles. This separation increases lateral MLALs and increases spinal load because of the loss of stability and function in the rectus abdominus muscles, causing the erector spinae muscles to withstand more forces during tasks with loads. Pregnancy-related changes to the rectus abdominus may also significantly impact the A/P ratio. Similarly, obesity may also significantly impact the abdominal muscles, altering the A/P ratio as well as lateral balance.

The exploration of the A/P ratio considered both MI_{CSA} and MI_{New} models. The first three spinal levels include the psoas in the posterior hemisphere, but at the L5/S1, the psoas is included in the anterior hemisphere. Also, this hemispheric change may vary somewhat from subject to subject both in terms of when (level) and the degree (how far) to which the shift occurs. Generally, the psoas muscles shift to the anterior side of the trunk at the L5/S1 level. How the core and paraspinal muscles contribute to the A/P ratio is a function of spinal level. However, it appears that with respect to the rectus abdominus and oblique muscles, smaller "weak" muscles contribute to lower A/P ratios that may be related to increased levels of LBP.

3.6 Conclusion

A novel quantitative index for MI was established and its relationship to pain was explored laterally and anteriorly/posteriorly for all core and paraspinal muscles individually, in muscle groups, and by hemisphere. The A/P ratio was explored to determine what ratios were associated with the most and the least pain. MI muscle, and muscle group measurements were higher on average for the new model, since it is the product of the CSA and MLAL. In general, the MI_{New} was more significantly related to LBP than MI_{CSA}. This may be attributed to the strength of the MLALs correcting for imbalance directionally, particularly in the hemisphere's measurements.

The regression correlation coefficients allowed relationships of various factors to MI to be determined. While there were not many significant relationships found, there were several that were found to be trending towards significance. There was a mixture of body types in the population, some subjects had bigger muscles than others, so we controlled for this by normalizing the MI measurements with the average absolute percentage differences.

The hypothesis of the experiment that higher levels of MI would be associated with higher self-reported LBP ratings was not conclusively supported. The plots of MI against LBP reported pattern are not exactly as expected, with MIs positively or negatively correlating with LBP depending on the spinal level and the measure (MI_{CSA} or MI_{New}). Some statistically significant differences were relatively small and most correlations, while significant, were modest. Possible explanations include small size and potential biases in subject recruitment (e.g., many of the subjects were recruited from the same gym/rehab center). Future studies should consider both a larger and more diverse cohort of subjects.

Expanding on previous studies on trunk asymmetry, this novel MI index was evaluated at each spinal level between L2-S1, rather than at a single level as in most studies. It was determined from the current study that the L3/L4 level showed the promise for use in evaluating the association between MI and LBP. Future studies on MI should ensure this spinal level is included in the analysis. These data are important because they may be used to build and improve upon biomechanical models with estimates of trunk/spinal/core pain and measurements using factors such as: age, height, weight, and exercise intensity and duration. The MRI data may also be used to build models of relative positions of muscles and sizes. This is particularly important for this population, older women, which is typically not included in studies of this type. Overall, MI does appear to be related to discomfort, however the relationship between MI and exercise did not appear to be supported.

A more inclusive study is needed to follow this pilot study. It was hard to establish a clear relationship between MI and LBP, but a repeated measure was established that can be incorporated into future studies. Post hoc analyses on the power of the relationships between LBP and exercise, LBP and MI, and exercise and MI all were below 0.8, indicating that the sample size needs to be larger to have sufficient subjects to detect the actual effect found. It can be assumed that CSA represents muscle force capability, and MLAL is the relative mechanical advantage of muscles. Together, CSA and MLAL provide moment generating capability. The larger MI switched between the left and right sides of the lateral measurements throughout the spinal levels without apparent pattern.

The mechanism behind how MI occurs and subsequent LBP is not known for certain, but it may be caused by asymmetric loading of the spine which introduces tension, causing muscle pain fibers to become irritated, ultimately leading to pain sensation caused by electrical signals being sent to the brain. The mechanism may be muscle related pain, leading to lateral shifts, leading to shear compression and uneven/asymmetric loading of the spine. Stresses need to be distributed symmetrically so that stress concentrations do not become too high at some locations in the spinal motion segments. Asymmetrical loads can create shear compression in the spine, causing nociceptors in and around the disc to produce a signal that travels through the muscle and nerve fibers to the brain, indicating pain.

This finding brought attention to a priori considerations for potential follow-up analyses based on limitations of the current study. There is a level of muscle efficiency that is present, coordinating motor units to allow muscle contractions in the muscle fiber. This study did not control for muscle fiber types. Some muscle fiber types respond better to different types of exercise. There is a difference in chronic pain and muscle pain. Future studies should control for the type of pain subjects experience. The subjects that were recruited for this study came from an exercise environment, introducing a fundamental bias. The exercisers may have had greater LBP, but they were established in their exercise routines. Subjects of both genders with more diverse age ranges, BMIs, and fitness levels should be included in future studies. Data should also be collected on handedness and participation in sports that are inherently asymmetric such as racket sports, which may be found to contribute to lateral MIs.

Chapter 4

Effects of Exercise on Muscular Imbalance and Low Back Pain: A Pilot Study

4.1 Introduction

There are many proposed ways to decrease the likelihood of developing an MSD. Stretching has been shown in studies to increase flexibility through viscoelasticity of muscle tendon units (Kubo, 2001). However, stretching has not been consistently shown to have a significant impact on reducing the risk of developing an MSD (Hess and Heckler, 2003; van Poppel, 1997; CDC; Thacker et al, 2004).

Exercise ameliorates atrophy of the paraspinal and core muscles. Exercise is often prescribed as part of a rehabilitation program for chronic pain (Sullivan et al, 2012). Strengthening the core muscles through exercise has been shown to reduce LBP (Wang et al, 2012). The literature suggests an underlying model: imbalances lead to tension and then pain. This concept can be rigorously tested via MRI.

It is hypothesized that as imbalances increase, so will ratings of LBP discomfort. MI in the torso and pelvic regions has also been referred to as LCS, pelvic cross syndrome, and flexion intolerance. This theory hypothesizes that LBP can be caused by MIs across the torso and lower back. The theory suggests that imbalances can be exacerbated by repetitive shortening and tightening of the muscles, which subsequently results in chronic tightening patterns across the body which can result in some muscles weakening, increases in hip flexion, and subsequent LBP. Persons that maintain prolonged static postures are at risk for developing this type of MI (Anghel, 2007). It should be noted that unless and until such tightening patterns weaken muscles, the muscles will not change in size and therefore *cannot* be detected using MRI or other imaging techniques. However, as muscle atrophy or hypertrophy occurs, such changes can be detected via MRI.

Tai Chi exercise is symmetric in nature (working both sides of the body equally) and low impact. It combines balance, strengthening, and stretching. Tai Chi is often prescribed as an exercise intervention for people suffering from arthritis and osteoporosis (Han et al, 2004; Lee et al, 2008). It is also used as a method to help reduce falls in older people by improving physical function and coordination (Logghe et al, 2010). The research regarding Tai Chi as an intervention support its potential efficacy as a form of exercise that may reduce LBP or help manage it.

In a 2011 study, Hall et al, demonstrated the benefits of Tai Chi from a patient perspective. Their study found significant reductions in LBP symptoms and included multiple positive subject testimonials. This and other studies called for more research to be conducted on Tai Chi interventions to add to the literature demonstrating its clinically worthwhile benefits, specifically as a LBP alleviator. The objective of this study was to investigate physiological changes in trunk musculature and its relationship to MI related LBP over time.

4.2 Materials and Methods

4.2.1 Study Sample Characteristics

Chapter 3 was Phase I of this study and consisted of a cross-sectional analysis. This chapter (4) includes a prospective analysis (Phase II) conducted based upon the previous cross-sectional analysis, with a new aspect added to the previous cross-sectional phase (subject groups). This prospective analysis investigated LBP, MI, exercise, and related changes from 3 different groups (control, intervention, Tai Chi) with weekly surveys over a six-month period. All subjects met the same inclusion criteria as in Chapter 3 and their personal characteristics are shown in Table

4.1. At baseline, all subjects (n=28) had a mean age of 62.8 years (SD=8.37), weight of 69.9 kg (SD=17.04), and BMI of 25.7 kg/m^2 (SD=6.10).

Table 4.1: Characteristics of Subjects at Baseline, Means and SD

Factor	Mean	SD
Age (Years)	62.79	8.37
Height (m)	1.66	0.14
Weight (kg)	69.91	17.04
BMI (kg/m^2)	25.67	6.10
Typical Amount of Exercise (Hour/Week)	4.38	4.24
LBP (0 - 10)	1.96	2.42

Phase I included a baseline MRI and symptom survey from all participants consisting of both Tai Chi practitioners, and control subjects, who at the outset of the study did not practice Tai Chi. Phase II included a prospective study of a randomized subset from the baseline enrollment. Two analyses were done on the subjects followed in time.

The first was of the participants placed in a subset of one of five intervention groups. Table 4.2 provides characteristics of the subset of participants followed over time, with respect to their intervention group classification. The second analysis was a comparison of Tai Chi practitioners and non-Tai Chi practitioners during the intervention. Table 4.3 provides characteristics of this subset of participants followed over time, with respect to their status as a Tai Chi practitioner. The subject sample size decreased from n=28 at baseline to n=25 during the intervention due to COVID-19 restrictions and the loss of the ability to collect additional follow up data.

Table 4.2: Characteristics of Intervention Group Subjects, Means and SD

	Intervention Group	N	Mean	SD
Age (Years)	Control No Exercise	3	66.00	2.65
	Control Exercise	3	55.33	1.53
	Exercise Plus Tai Chi	7	58.71	5.96
	No Exercise Plus Tai Chi	2	54.00	4.24
	Tai Chi	10	70.30	7.20
	Total	25	63.44	8.51
Height (m)	Control No Exercise	3	1.74	0.04
	Control Exercise	3	1.65	0.03
	Exercise Plus Tai Chi	7	1.69	0.08
	No Exercise Plus Tai Chi	2	1.63	0.16
	Tai Chi	10	1.60	0.21
	Total	25	1.65	0.15
Weight (kg)	Control No Exercise	3	97.57	12.69
	Control Exercise	3	56.10	3.86
	Exercise Plus Tai Chi	7	63.57	10.61
	No Exercise Plus Tai Chi	2	69.50	0.71
	Tai Chi	10	62.50	9.22
	Total	25	66.80	14.79
BMI (kg/m^2)	Control No Exercise	3	32.48	5.47
	Control Exercise	3	20.64	2.02
	Exercise Plus Tai Chi	7	22.16	3.19
	No Exercise Plus Tai Chi	2	26.49	4.77
	Tai Chi	10	25.21	6.54
	Total	25	24.78	5.85
LBP (0 - 10)	Control No Exercise	4	0.40	0.61
	Control Exercise	4	1.08	0.38
	Exercise Plus Tai Chi	8	2.75	2.11
	No Exercise Plus Tai Chi	2	0.60	0.84
	Tai Chi	10	1.53	1.61
	Total	28	1.59	1.68

Table 4.3: Characteristics of Subjects Tai Chi Practitioners and Non-Tai Chi Practitioners, Means and SD

	Tai Chi Group	N	Mean	SD
Age (Years)	No Tai Chi	6	60.67	6.15
	Tai Chi	19	64.32	9.09
	Total	25	63.44	8.51
Height (m)	No Tai Chi	6	1.69	0.06
	Tai Chi	19	1.64	0.16
	Total	25	1.65	0.15
Weight (kg)	No Tai Chi	6	76.83	24.21
	Tai Chi	19	63.63	9.20
	Total	25	66.80	14.79
BMI (kg/m^2)	No Tai Chi	6	26.56	7.46
	Tai Chi	19	24.22	5.37
	Total	25	24.78	5.85
LBP (0 - 10)	No Tai Chi	8	0.74	0.59
	Tai Chi	20	1.92	1.86
	Total	28	1.59	1.68

The control group of non-Tai Chi practitioners were asked to not perform any activities beyond their normal daily life activities. Specifically, if the subjects in the control group were exercisers, they were asked to maintain their current exercise routines. The Tai Chi intervention group subjects practiced Tai Chi regularly for at least two days a week participating in one-hour sessions during the six-month duration of the study. Subjects from the Tai Chi group to be followed prospectively and received no intervention but were periodically (weekly) surveyed regarding any low back symptoms and their activity level (e.g., participation in Tai Chi as well as other forms of exercise) (Appendix 7). The Tai Chi intervention group, and the control group acted as controls (no intervention).

4.2.2 Measuring Methods

4.2.2.1 Magnetic Resonance Imaging and Image Measurements

Follow up lumbar spine standardized T2 weighted sagittal continuous, axial continuous, and multi-group MRI scans of L2-S1 were gathered at AUMRIRC on a Siemens Verio open bore 3T MRI scanner with the abdomen coil from the participants following the same MRI procedure protocol stablished and described in Chapter 3. Images were also assessed in the same manner as established in Chapter 3 to obtain including CSAs, MLALs, and MI_{New}. MI_{New} was previously established as the better method of quantifying MIs and assessing its relationship to LBP; therefore, MI_{New} will solely be used for MI calculations in this prospective analysis.

Data on types of exercise and duration and self-reported pain ratings from weekly surveys were used to investigate physiological changes in trunk musculature and its relationship with MI-related LBP over time with respect to exercise, specifically Tai Chi.

4.3 Statistical Analysis

The average absolute percentage differences for MI_{New} change across the core and paraspinal muscles through the lumbar spine levels (L2-S1) at baseline for all subjects (n=28) was found using the Δ MI_{New} individually and as a group, like previously.

Paired t-tests were performed to find any significant changes in MI_{New} change from baseline to follow up for all subjects. Weekly survey exercise type/duration and self-reported pain ratings baseline data and average (during six-month intervention period) data were compared across all subjects and within each intervention group and Tai Chi group via Analysis of Variance (ANOVA). A between group analysis was done to determine if any of the intervention groups had significant personal characteristic, MI_{New}, or LBP differences over the study period.

4.4 Results

4.4.1 Baseline Groups

Table 4.4 shows the average absolute percent longitudinal change in MI_{New} for all subjects in the study, across all groups.

Table 4.4: ΔMI_{New} Average Absolute Percentage Change for All Subjects

ΔMI_{New} Change	L2/L3		L3/L4		L4/L5		L5/S1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Erector Spinae	0.37	11.45	3.34	11.41	-2.63	11.79	-4.49	12.18
Psoas	0.15	10.36	-1.46	9.76	-0.87	7.42	-2.35	18.03
Oblique	2.22	15.64	-0.80	8.44	-2.75	16.13	2.59	20.60
Rectus Abdominus	7.23	21.20	-8.17	19.14	-2.95	21.96	-1.66	15.93
Quadratus Lumborum	-0.50	20.11	-1.75	10.80	-4.76	23.91	---†	---†
Paraspinal Group	1.89	10.79	1.28	11.23	-1.62	9.45	-0.57	12.13
Core Group	2.55	14.81	-2.27	9.69	-2.89	15.05	4.47	17.37
Lateral Hemisphere	3.49	12.05	-1.43	8.89	-1.58	10.09	-1.13	11.55
† QL does not extend to this level in most subjects and therefore was not used								

Table 4.5 is the paired t-test results for the change in MI for all subjects across all groups.

Table 4.5: ΔMI_{New} Change Paired T-Test Results for All Subjects

ΔMI_{New} Change	Significance (P-Value)			
	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	0.97	0.16	0.28	**0.09****
Psoas	0.92	0.46	0.56	0.67
Oblique	0.40	0.64	0.40	0.46
Rectus Abdominus	**0.08****	**0.04***	0.51	0.57
Quadratus Lumborum	0.84	0.43	0.33	---†
Paraspinal Group	0.45	0.58	0.40	0.99
Core Group	0.34	0.25	0.35	0.18
Lateral Hemisphere	0.14	0.43	0.44	0.78
† QL does not extend to this level in most subjects and therefore was not used * Significant at the 0.05 level ** Trending towards significance at the 0.05 level				

The L3/L4 rectus abdominus was the only muscle found to have a significant ΔMI_{New} change over time for all subjects, via paired t-test.

Table 4.6 is the $\Delta A/P\ MI_{New}$ ratio changes and the paired t-test significances for ΔMI_{New} change. No $\Delta A/P\ MI_{New}$ ratios were found to have a significant difference from baseline to follow up.

Table 4.6: ΔA/P MI Ratio Change and Paired T-Test Results for All Subjects

$\Delta A/P\ MI_{New}$ Change	Mean	SD	Minimum	Maximum	Significance (P-Value)
L2/L3	0.07	0.41	-0.82	0.74	0.45
L3/L4	0.05	0.27	-0.57	1.01	0.31
L4/L5	0.03	0.21	-0.45	0.48	0.49
L5/S1	0.08	0.25	-0.22	0.67	0.14

At baseline, there were six non-exercisers, twelve exercisers, and ten Tai Chi practitioners. Table 4.7 shows the personal characteristics of these three groups.

Table 4.7: Baseline Personal Characteristics of Non-Exercisers, Exercisers, and Tai Chi Practitioners

Factor (At Baseline)	Group	Mean	SD
LBP (0 - 10)	Non-Exerciser	1.42	2.52
	Exerciser	2.03	2.69
	Tai Chi	2.20	2.22
	Total	1.96	2.42
Exercise (Hour/Week)	Non-Exerciser	0.00	0.00
	Exerciser	5.54	4.51
	Tai Chi	5.60	3.57
	Total	4.38	4.24
Age (Years)	Non-Exerciser	60.33	6.74
	Exerciser	57.75	5.15
	Tai Chi	70.30	7.20
	Total	62.79	8.37
Height (m)	Non-Exerciser	1.67	0.11
	Exerciser	1.70	0.08
	Tai Chi	1.60	0.21
	Total	1.66	0.14
Weight (kg)	Non-Exerciser	85.58	15.14
	Exerciser	67.92	18.92
	Tai Chi	62.90	9.07
	Total	69.91	17.04
BMI (kg/m^2)	Non-Exerciser	30.73	5.29
	Exerciser	23.42	5.01
	Tai Chi	25.34	6.42
	Total	25.67	6.10

Only one statistically significant difference between Tai Chi practitioners, non-exercisers, and exercisers for MI_{New} was found at L5/S1 for the rectus abdominus (42% vs. 29% (non-exercisers) and 19% (exercisers), p=0.03). Appendix 9 contains all descriptive statistics and ANOVA results for this comparison. Table 4.8 contains significant relationships between the three groups at baseline.

Table 4.8: Significant Relationships Between Tai Chi Practitioners,

Non-Exercisers, Exercisers at Baseline

Tai Chi Practitioners Have Higher Measurements		
Factor	P-Value	(Tai Chi Practitioners, Non-Exercisers, Exercisers)
Exercise (Hour/Week)	**0.01***	(5.6, 0, 5.5)
Age (Years)	**0.00***	(70, 60, 58)
Controls (Non-Exercisers and Exercisers) Have Higher Measurements		
Weight (kg)	**0.03***	(63, 86, 68)
BMI (kg/m2)	**0.05***	(25, 31, 24)
*Significant at the 0.05 level		

Tai Chi practitioners had a higher LBP at baseline, even though they exercised more hours per week (Figure 4.1). Tai Chi practitioners exercised more (Figure 4.2) and were older. Controls weighed more and had a higher BMI (Figure 4.3).

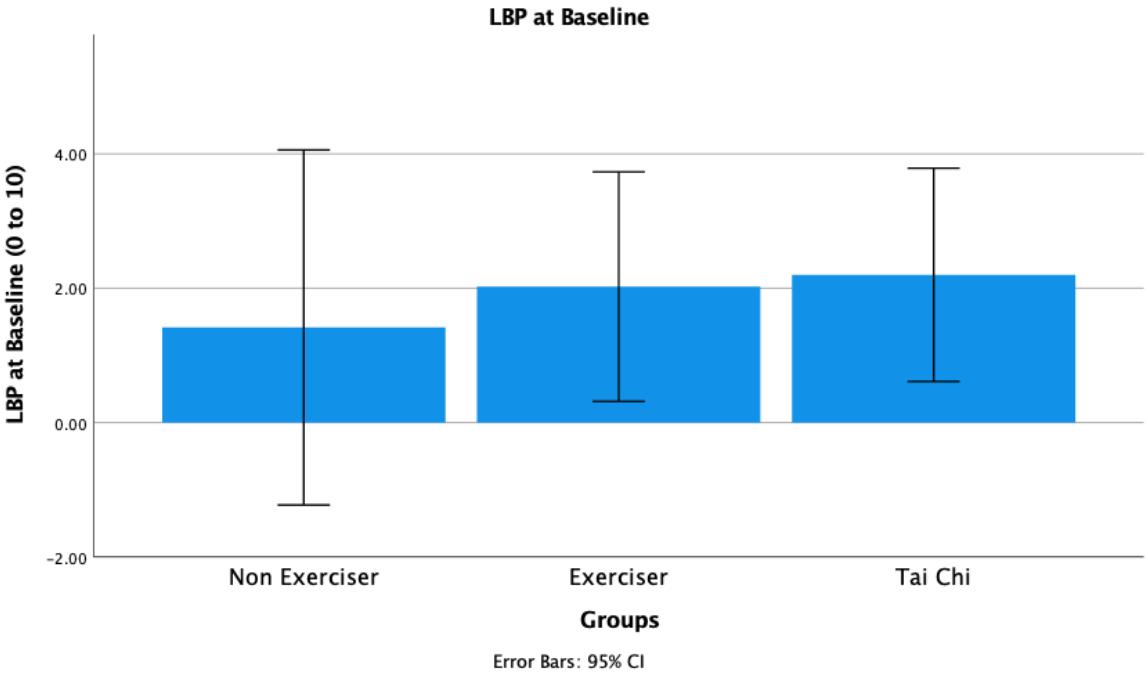


Figure 4.1: LBP at Baseline for Non-Exercisers, Exercisers, and Tai Chi Practicioners

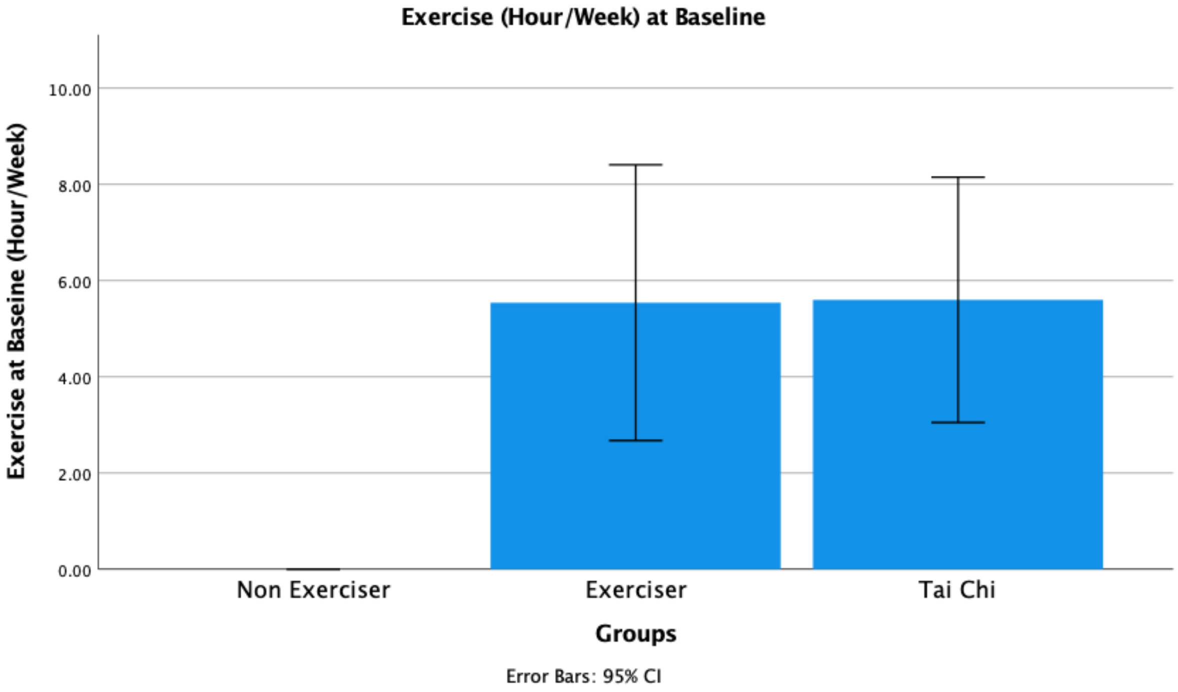


Figure 4.2: Exercise at Baseline for Non-Exercisers, Exercisers, and Tai Chi Practicioners

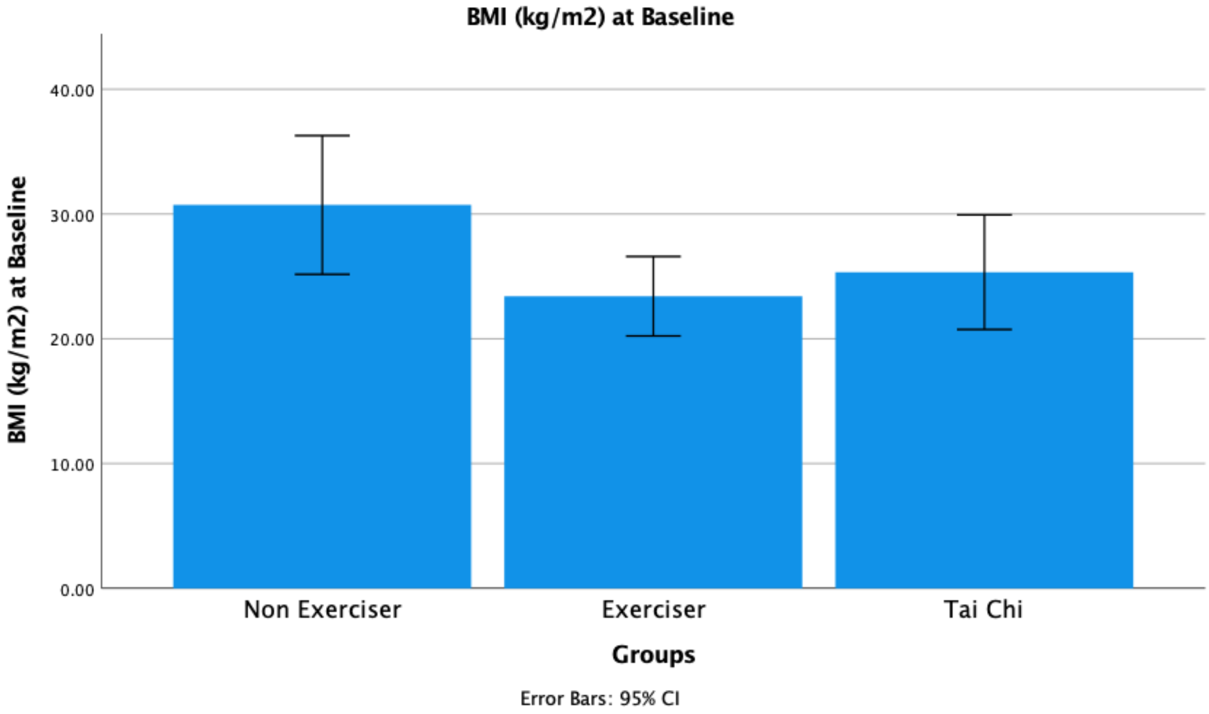


Figure 4.3: BMI at Baseline for Non-Exercisers, Exercisers, and Tai Chi Practicioners

4.4.2 Intervention Groups

There were five intervention groups ${}^{\ni}$(n=28) in the Tai Chi prospective study:

Controls (Non-Exerciser) (n=4)

Controls (Exerciser) (n=4)

Exerciser (PLUS Tai Chi Practitioner) (n=8)

†Non-Exerciser (PLUS Tai Chi Practitioner) (n=2)

Tai Chi Practitioner (n=10)

> †There were only n=2 non-exercising controls that participating in the Tai Chi intervention.
>
> ${}^{\ni}$Data was able to be gathered from weekly surveys over the study duration for the three subjects that were not able to receive a follow up MRI. Follow up MI_{New} has n=25, but the survey data (exercise/pain info) has n=28.

Appendix 10 includes all descriptive statistics and ANOVA results of MI_{New} change for the intervention groups. The average LBP each intervention group reported and the average amount of Tai Chi they participated in each week is seen below in Table 4.9. There were no other apparent differences in MI between the intervention groups.

Table 4.9: Intervention Study Groups Characteristics

Factor	Group	Mean	SD
LBP Rating Average (0 - 10)	Controls (Non-Exerciser)	0.40	0.61
	Controls (Exerciser)	1.08	0.38
	Exerciser (Plus Tai Chi Practitioner)	2.75	2.11
	Non-Exerciser (Plus Tai Chi Practitioner)	0.60	0.84
	Tai Chi Practitioner	1.53	1.61
	Total	1.59	1.68
Tai Chi Average (Hour/Week)	Controls (Non-Exerciser)	0.00	0.00
	Controls (Exerciser)	0.00	0.00
	Exerciser (Plus Tai Chi Practitioner)	1.59	0.57
	Non-Exerciser (Plus Tai Chi Practitioner)	1.81	0.27
	Tai Chi Practitioner	1.98	1.77
	Total	1.29	1.36

The exercise plus Tai Chi group had the highest average LBP; the control (no exercise) and the no exercise plus Tai Chi group had the lowest LBP (Figure 4.4).

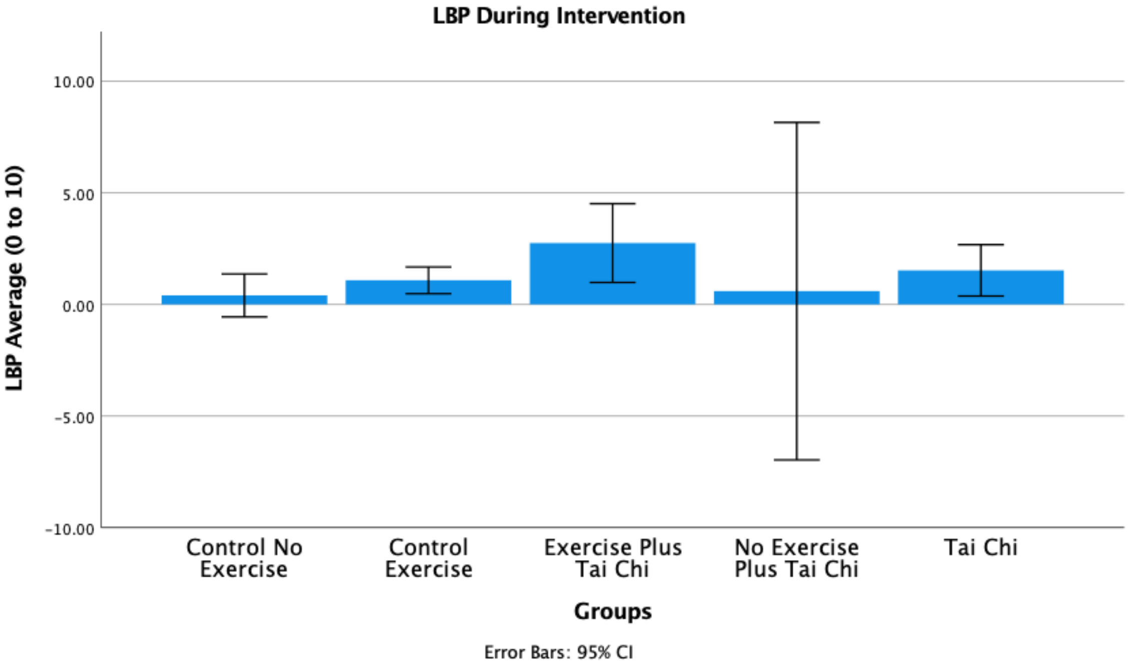


Figure 4.4: Average LBP For Intervention Groups

Siginificant personal characteristics relationships for the intervention groups showed that Tai Chi practitioners were older and practiced more Tai Chi per week, while controls weighed more and had a higher BMI (Table 4.10).

Table 4.10: Significant Relationships Among Intervention Groups

Tai Chi Practitioners (Exercisers Plus Tai Chi, Non-Exercisers Plus Tai Chi, Current Tai Chi Practitioners) Have Higher Measurements		
Factor	P-Value	(Exercisers Plus Tai Chi, Non-Exercisers Plus Tai Chi, Current Tai Chi Practitioners, Non-Exercisers, Exercisers)
Age (Years)	**0.00***	(**59, 54, 70**, 66, 55)
Tai Chi (Hour/Week)	**0.02***	(**2, 2, 2**, 0, 0)
Controls (Non-Exercisers and Exercisers) Are Heavier and Have Larger BMIs		
Weight (kg)	**0.00***	(64, 70, 63, **98, 56**)
BMI (kg/m2)	**0.06****	(22, 26, 25, **32, 21**)
* Significant at 0.05 **Trending Towards Significance at 0.05		

Figures 4.5 – 4.7 show the ΔMI_{New} change for intervention groups at the L3/L4 for the erector spinae, paraspinal muscle group, and lateral hemisphere, respectively.

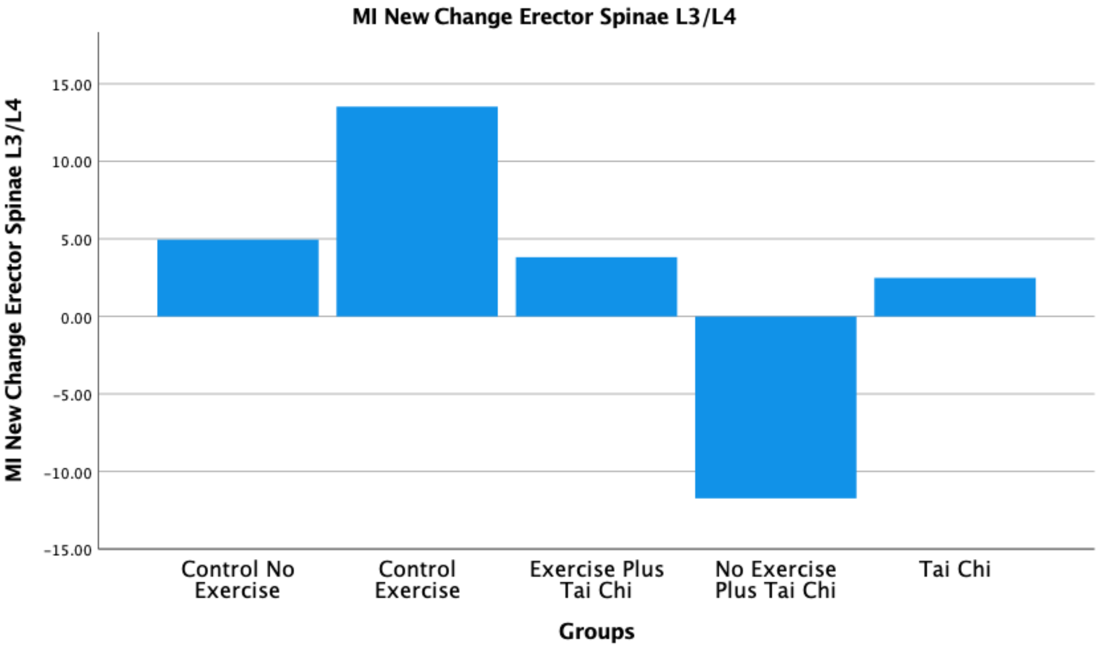


Figure 4.5: ΔMI_{New} Change for Intervention Groups Erector Spinae L3/L4

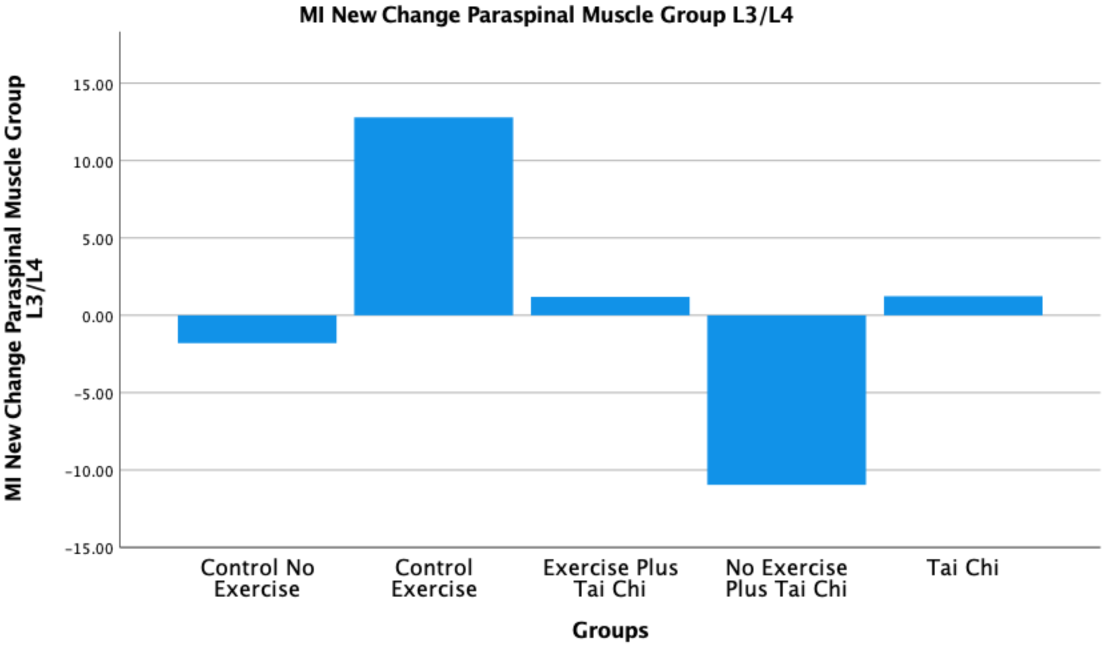


Figure 4.6: ΔMI_{New} Change for Intervention Groups Paraspinal Muscle Group L3/L4

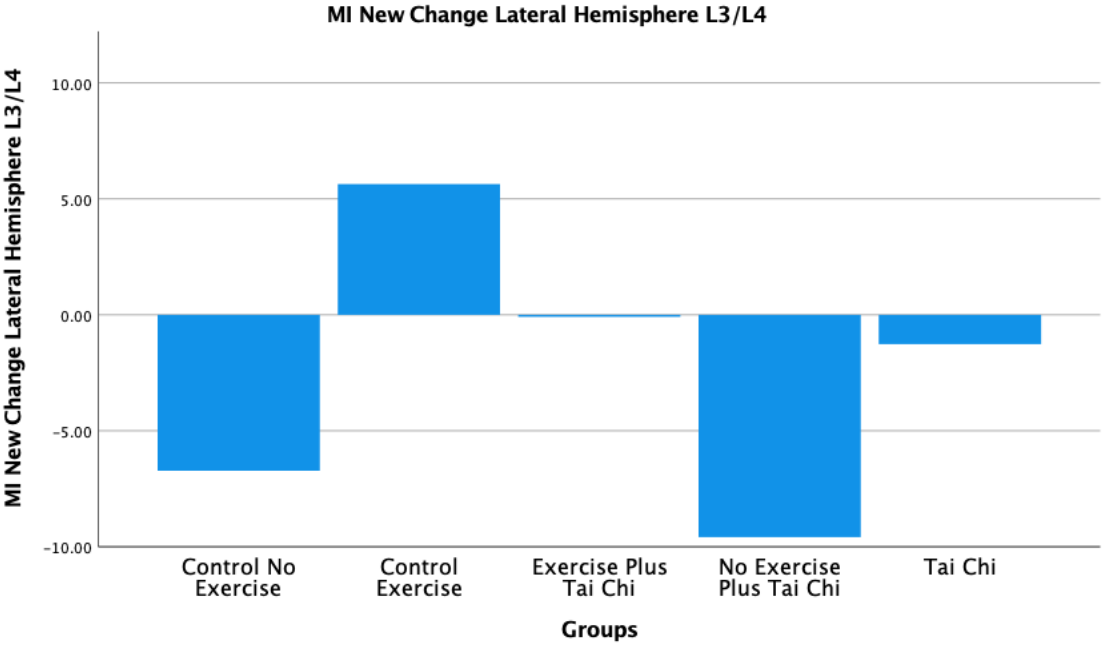


Figure 4.7: ΔMI_{New} Change for Intervention Groups Lateral Hemisphere L3/L4

4.4.3 Tai Chi Groups

A between groups comparison was run for intervention groups that either practiced Tai Chi or did not practice Tai Chi. Subjects were considered Tai Chi practitioners whether they were already current Tai Chi practitioners at the start of the study or became one in an intervention group. Non-Tai Chi practitioners served as controls for this group comparison. Appendix 11 includes all descriptive statistics and ANOVA results for the analysis of MI_{New} change during the intervention study for Tai Chi practitioners (n=8) and Non-Tai Chi practitioners (n=20). Data was able to be gathered from weekly surveys over the study duration for the three subjects that were not able to receive a follow up MRI. Follow up MI_{New} has n=25, but the survey data (exercise/pain info) has n=28.Table 4.11 shows the descriptive analysis of LBP and average Tai Chi exercise per week for Tai Chi groups.

Table 4.11: Intervention Study Groups (Tai Chi and Non-Tai Chi) Characteristics

	Tai Chi Group	Mean	SD
LBP Rating Average (0 - 10)	No Tai Chi	0.74	0.59
	Tai Chi	1.92	1.86
	Total	1.59	1.68
Tai Chi Average (Hour/Week)	No Tai Chi	0.00	0.00
	Tai Chi	1.80	1.28
	Total	1.29	1.36

It was found that Tai Chi practitioners had a higher average LBP during the study (Figure 4.8); however, Tai Chi LBP was 1.9 vs. non-Tai Chi LBP of 0.74, which was not a significant difference. Tai Chi practitioners weighed less than the non-Tai Chi controls (64 kg vs. 77 kg, p=0.055).

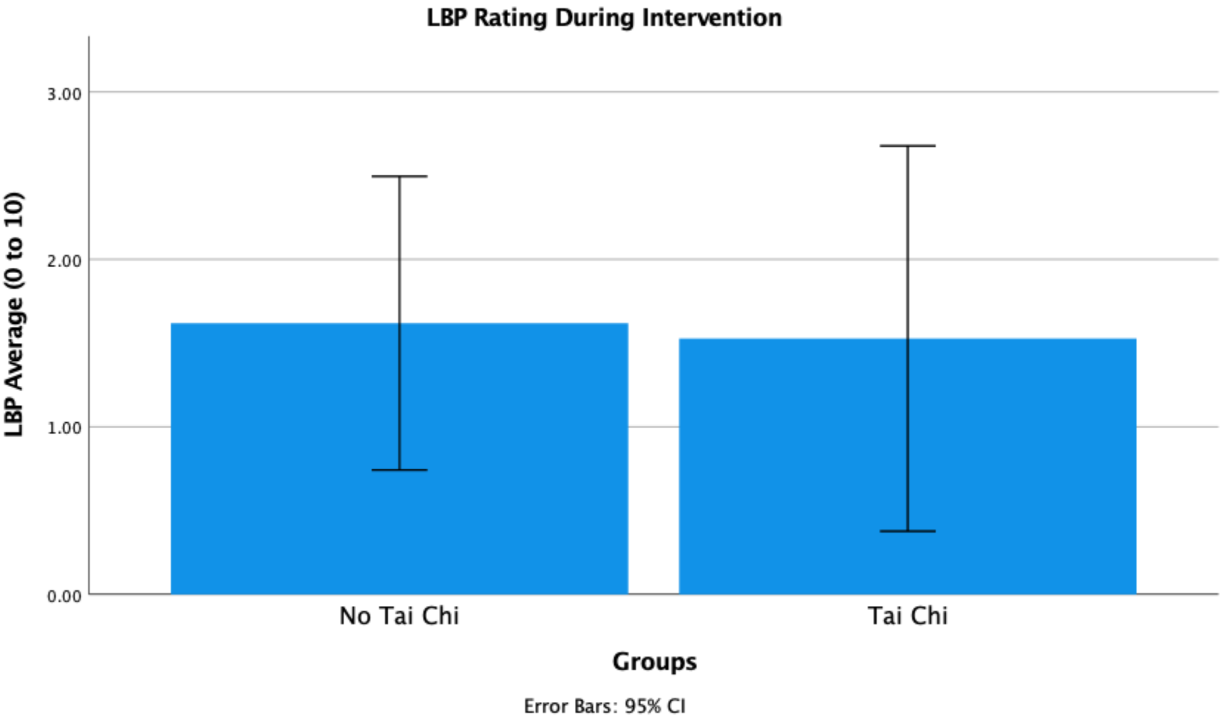


Figure 4.8: Average LBP for Tai Chi and Non-Tai Chi Groups

Tai Chi practitioners had a larger decrease in ΔMI_{New} at several locations at the L5/S1 level. The erector spinae (p=0.05), paraspinal muscle group (p=0.03), and lateral hemisphere (p=0.01) all had significantly decreased ΔMI_{New} than Non-Tai Chi. These relationships are plotted in Figures 4.9 – 4.11.

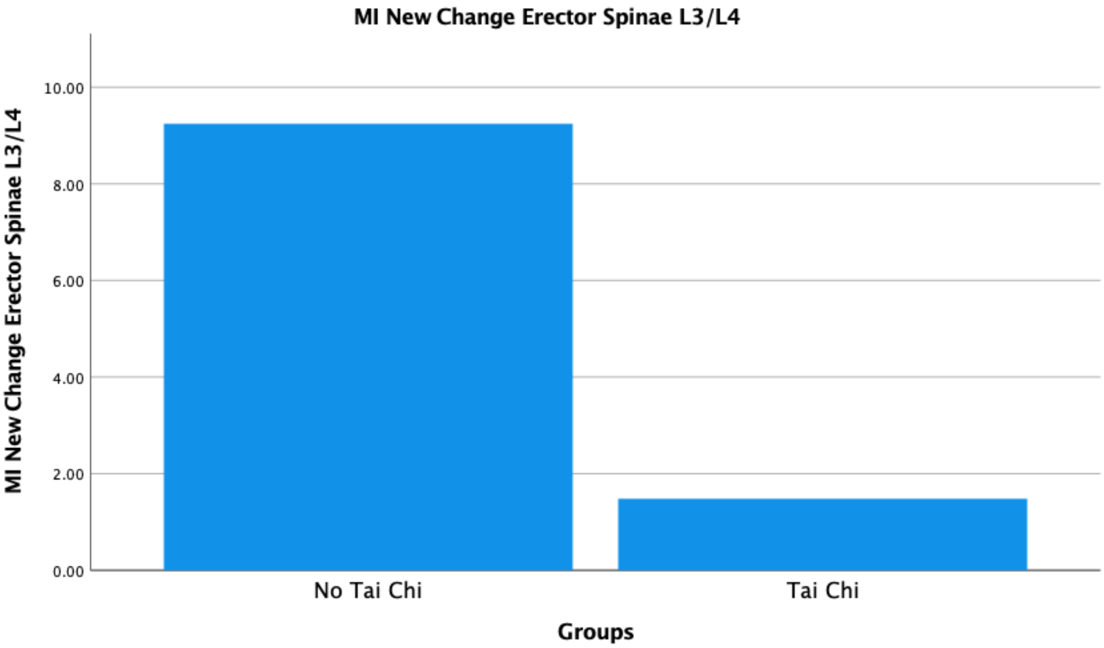


Figure 4.9: ΔMI$_{New}$ Change Tai Chi Groups Erector Spinae L3/L4

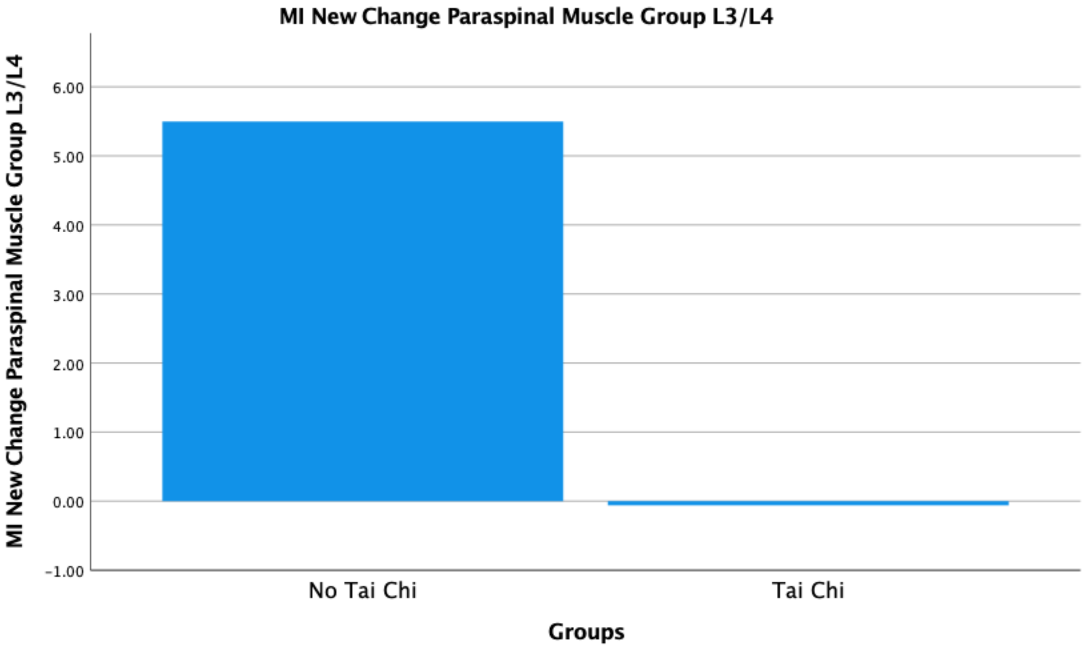


Figure 4.10: ΔMI$_{New}$ Change Tai Chi Groups Paraspinal Muscle Group L3/L4

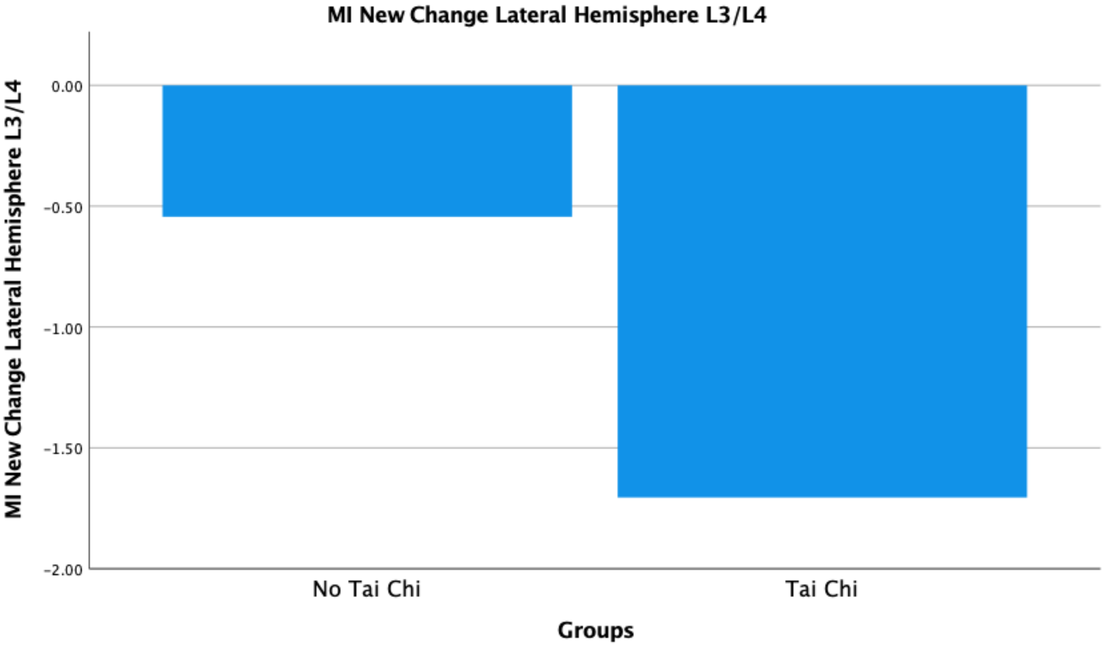


Figure 4.11: ΔMI_{New} Change for Tai Chi Groups Lateral Hemisphere L3/L4

Only one ΔMI_{New} change measure was found significant. The psoas at L4/L5 decreased more for Tai Chi practitioners than controls (p=0.03). The opposite relationship occurred at L5/S1 for the lateral hemisphere MI. Control subjects (Non-Tai Chi) had a larger decrease in ΔMI_{New} than Tai Chi practitioners (-4% vs. 7%, p=0.05).

4.4.4 Anterior/Posterior Ratio

A/P MI_{New} ratios at baseline were found significant for all four spinal levels (Table 4.12). ΔA/P MI_{New} change was found to have a significant difference between groups only at the L5/S1 level for the intervention groups (Table 4.13). The Tai Chi group was following this pattern at L5/S1 for ΔA/P MI_{New} change (p=0.07), trending towards significance (Table 4.14).

Table 4.12: A/P MI_{New} Ratio at Baseline, Means and P-Values

	A/P MI_{New}			
Group	L2/L3	L3/L4	L4/L5	L5/S1
Non-Exerciser	1.10	0.77	0.97	1.18
Exerciser	0.64	0.39	0.49	0.81
Tai Chi Practitioner	0.60	0.45	0.62	0.82
P-Value	**0.02***	**0.05***	**0.03***	**0.05***
*Significant at the 0.05 level				

Table 4.13: ΔA/P MI_{New} Ratio Change for Intervention Groups, Means and P-Values

	ΔA/P MI_{New} Change
Group	L5/S1
Controls (Non-Exerciser)	+0.40
Controls (Exerciser)	+0.09
Exerciser (Plus Tai Chi Practitioner)	+0.02
Non-Exerciser (Plus Tai Chi Practitioner)	+0.33
Tai Chi Practitioner	-0.03
P-Value	**0.05***
*Significant at the 0.05 level	

Table 4.14: ΔA/P MI_{New} Ratio Change for Tai Chi Groups, Means and P-Values

	ΔA/P MI_{New} Change
Group	L5/S1
No Tai Chi	+0.24
Tai Chi	+0.03
P-Value	**0.07****
**Trending Towards Significance at the 0.05 level	

4.5 Discussion

The age of participants is rather high as compared to previous studies conducted on MI and subsequent LBP; most studies on MI have been conducted with younger, male athletes

(Franettovich et al, 2011). A significant scientific contribution of this work is this evaluation of the associations between LBP and MI for the understudied population of older women.

Studying older subjects is important since the overall age of the workforce is increasing, for a variety of reasons. The sample size is relatively small to assess an association between changes in MI and LBP due to exercise, however, small-n experimental designs are considered very effective for RCT studies (Graham et al, 2012). When working with narrow populations (i.e., of all similar age, condition, gender, etc), it can be difficult to observe statistical relationships related to those conditions they share.

The statistical methods used in this analysis were selected to follow subjects in time. The longitudinal ΔMI_{New} changes generally followed a decreasing pattern from baseline to follow up. There were some increases in MI_{New} at follow up. But most increases that were present were small. The MI_{New} model produced larger values for MI as it was a product of CSA and MLAL. Differences from baseline to follow up in MI_{New} were not found to be significant. L3/L4 rectus abdominus was the only ΔMI_{New} measure found significant. The study period may have been too short a duration for subjects to accumulate more significant changes in ΔMI_{New}. Here, the L3/L4 again is shown to be the level most associated with ΔMI_{New} change over time. This may suggest that location/level is important in predicting and analyzing MI_{New} development. CSA was more affected than MLAL over the course of the study; CSA increased more than MLAL for both lateral and A/P ΔMI_{New}.

The mean age of the Tai Chi group and average exercisers was higher than controls, and weight and BMI were higher for controls. A significant difference was found for age, weight, and BMI between the groups at baseline. At baseline there were only two ΔMI_{New} measurements found significant between non-exercisers, exercisers, and Tai Chi practitioners. Tai Chi seemed to have a protective effect on subjects – they exercised more and had lower BMIs.

During the intervention, controls once again had higher weight and BMI than Tai Chi practitioners. L2/L3 erector spinae and paraspinal muscle group ΔMI_{New} were approaching significance. There were only significant ΔMI_{New} decreases found for Tai Chi practitioners at L4/L5 psoas muscles. These results show that Tai Chi seemed to have a protective effect on subjects. Tai Chi intervention subjects had the most reduction in ΔMI_{New} from baseline to follow up. Tai Chi practitioners had overall less increase in ΔMI_{New} than controls (those not doing Tai Chi).

Cohen's d for the intervention groups (the five groups) ΔMI_{New} change, and LBP indicated a small effect size with an alpha of 0.05. There is not a defined "meaningful effect" for this new measure of ΔMI_{New} yet; therefore, this pilot study provides some context for what the expected effect might be. A priori power analysis conducted after the study determined a sample size of n=52 subjects would be needed to have the statistical power to detect a meaningful effect size in relation to ΔMI_{New} change and LBP.

The A/P MI_{New} ratio was significant at baseline between non-exercisers, exercisers, and Tai Chi practitioners for all levels. Tai Chi practitioners had lower A/P MI_{New} ratios at L2/L3 and L5/S1, the same as controls at L3/L4, and was only slightly more at L4/L5. Current Tai Chi practitioners had larger A/P MI_{New} decreases than the other intervention groups and non-Tai Chi practitioners at L5/S1. These results again seem to show that Tai Chi may be beneficial for maintaining healthy weight and reducing MI. However, it did not seem to be as effective for preventing or mitigating LBP, but this may be due to the significantly higher age of Tai Chi practitioners as compared to the other groups. Age has been attributed as a large and important role in developing LBP.

4.6 Conclusion

It can be assumed that CSA represents muscle force capability, and MLAL is the relative mechanical advantage of muscles. Together, CSA and MLAL provide moment generating capability and can be used to identify and calculate MI in a perhaps more meaningful way.

In this pilot study, Tai Chi seemed to have some effect on the development and change of MI_{New}. It was difficult to demonstrate the benefit of an exercise regimen with a small sample size and the primary hypothesis is that MI causes pain, but the data are such that we can only show an association of pain. This study investigated important relationships that should be considered in future biomechanical models, such as: the progression of changes in trunk muscle over time (six months in the present case); the relationship between personal characteristics, physical activity, and LBP; and an evaluation of trunk muscle parameters as risk factors for LBP or its development and determined if CSA, MLAL, and MI at baseline are predictors of LBP at follow-ups.

Building muscle gradually is less harmful on the body than quickly building muscle. Tai Chi is prescribed for patients with LBP due to its symmetric and deliberate movements. Increasing muscle strength too quickly may increase compression forces, which increases damage accumulated, and high spinal compression. Distributing stresses symmetrically may counteract the mechanism behind MI from occurring, since it allows stress concentrations to be balanced, preventing too high of concentrations at various points.

There are several a priori considerations for potential follow-up analyses based on limitations of the current pilot study. A sample of subjects of both genders with a more diverse age range and BMI should be considered in future studies with data collected on handedness, which may be found to contribute to lateral MIs. The sample size in the study was so small that the difference may have been too small to notice in the analysis. The experimental design was appropriate, but the results indicated more subjects needed to be analyzed to determine the true effect. The current study was confounded by intervention subjects that were exercising individually (unsupervised), in addition to the intervention exercise (instructor-led Tai Chi classes).

Muscle fiber type was not controlled for, which should be investigated in future studies as some muscle fiber types respond better to different types of exercise. There was a fundamental bias present, as people that already exercised were more willing to participate in the study. Also, many of the participants were recruited from a hospital-run facility that was both a gym and a rehab center which could explain some of the LBP in the subjects that were exercisers.

Chapter 5

Impact of Physical Imbalance on Work-Related Musculoskeletal Disorders: An Epidemiological Investigation of Imbalances in a Large Automotive Ergonomic Database

5.1 Introduction

Year after year, the most prevalent and costly types of injuries in the workplace are work related musculoskeletal disorders (WMSDs), leading to significant lost workdays or days away from work (Bernard et al, 1997; Silverstein et al, 2004). Direct and indirect costs associated with WMSDs exceed $100 billion annually. These costs include worker's compensation, medical expenses, as well as loss of productivity and reductions in product quality. WMSDs have also been shown to have a significantly negative impact on quality of life due to the long-term pain from which many workers suffer (Westmorland et al, 2002; Qutubuddin, 2014). Approximately 35% of all occupational injuries and illnesses from 1992-2010 were related to WMSDs (Leigh et al, 2001; Bhattacharya et al, 2014). The estimated economic impact of WMSDs in 1998 was $54 billion, and it is steadily increasing; $796 billion was the total estimated cost of WMSDs in 2009 (Morse et al,1998; Yelin et al, 2016; Yelin et al, 1995).

Some industries have higher prevalence rates of WMSDs than others, such as automotive assembly (Nur et al, 2009). Automotive assembly jobs often require a worker to quickly complete highly repetitive tasks on assembly lines with high forces and awkward postures, affecting their muscles, tendons, and joints (Nurmianto et al, 2015; Punnett, 2004). While it is difficult to determine the exact cause of WMSDs, there are multiple risk factors that have been associated with the likelihood of developing WMSDs.

There have been many studies done that explore the relationship between physical and individual risk factors; however, there have been very few published studies that investigate the relationship of imbalances to occupational LBP outcomes. This study was conducted to address this gap in the literature by investigating possible associations between imbalances and LBP. This study investigated several measures of imbalance. These imbalances were studied individually and as a grouped category (i.e., one or more imbalances) to determine if there were any statistically significant associations with LBP and/or the propensity of subjects to seek medical attention related to that LBP. Various types of asymmetrical lifting or twisting activities were also considered independently and together to explore their possible relationships to LBP. The objective of this experiment was to evaluate the effects of various forms of MI on MSDs using an epidemiological database of workers while controlling for psychosocial factors.

5.2 Materials and Methods

An epidemiological study was conducted in automotive manufacturing facilities performing a variety of tasks (Sesek, 1999). This study produced a database linking job-specific ergonomic data to personal injury and symptom data for a variety of manufacturing jobs from 6 different automotive manufacturing facilities. Self-reported symptoms and medical data (obtained by occupational medicine physicians (OMPs)) were collected for 1,016 subjects. This database was used to test and validate a variety of imbalance concepts in an occupational setting. Odds ratios were computed to demonstrate the relative risk of LBP for several imbalance conditions.

Of the 1,016 subjects participating, there were 56 subjects with one or more imbalances and 960 without imbalance; 34 subjects met one imbalance criterion, while 20 met two imbalance criteria, and two met three criteria.

These imbalances were evaluated by a physical medical examination given by an OMP. The medical exam was blinded of history, so only symptoms and physical characteristics were reported. This medical examination included questions on physical abnormalities, tenderness to palpation at various locations on the body, motor power, and range of motion.

An imbalance was defined by the presence of one or more of the following criteria as evaluated and reported by OMPs.

Spine not straight (n=32 subjects): This was determined through a physical examination of the spine. OMPSs first observed subjects for abnormal gait and posture, then inspected for the types of spine curvature disorders: lordosis (spine curves inward at the low back), kyphosis (rounded upper back >50 degrees of curvature), and scoliosis (sideways curved spine in an S- or C-shape). The OMP evaluated this by having the subject bend forward – postural curvatures go away, but structural spinal curvature does not in this position. If kyphosis was suspected, the subject was asked to extend their lower back.

Shoulders and/or pelvis not level (n=26 subjects): The shoulders and pelvis were examined with the spine as they are linked and may be causes of symptoms. When checking for spinal curvature, shoulder asymmetry and pelvic tilt are assessed. The subjects' posture was observed while walking to determine gait abnormalities, and during standing and sitting. If an antalgic limp is present, it may be an attempt to decrease stress on the hips/pelvis. This may cause some one side of the body to overcompensate for the lack of support from the opposite side, which may lead to muscle deterioration. Shoulders were examined for symmetry (function and position).

Lateral deviation difference from left to right (n=6 subjects): The spine was inspected for scoliosis, which is the lateral deviation of the spine from left to right. These subjects' sideways curve in the spine did not resolve after bending over.

Rotational difference from left to right (n=3 subjects): The subjects were seated and asked to twist around to each side. The OMP reported the range of motion (normal is 40°).

Motor power difference in lower extremities (n=13 subjects): This examination tested muscle strength of the lower extremities. The OMP pushed on the lower extremities while the subject attempted to resist the force, and then reported a score out of five points from 0/5 to 5/5 based on the amount of resistance the subject produced.

During a structured interview administered by an occupational health nurse, subjects were asked to provide their LBP experienced on the day of the interview, and, retrospectively, the peak pain experienced during the previous year. Medical visits, whether they be one or more, related to LBP for the last year were also collected. Cases in this study were those who reported LBP symptoms in the past year, and those who had a medical visit related to their LBP symptoms in the past year. First time office visits (FTOVs) and follow-ups used a VAS to obtain a rating of LBP. Non-cases did not have an imbalance that met the established imbalance criteria. Data were collected by OMPs and occupational health nurses (OHNs) that were blinded to the ergonomic analyses. Similarly, doctors and nurses were also blinded regarding their respective examinations.

5.3 Statistical Analysis

The evaluation of the data selected for analysis was completed using a 2x2 outcome matrix, which was used to calculate sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). Sensitivity divides true positives by the sum of true positives and false negatives and is the percentage of actual cases that were classified as cases (pain, FTOV, etc.), in this case imbalance was the “test” to predict health status outcome. Specificity divides true negatives by the sum of true negatives and false positives and is the percentage of controls properly classified as controls (no pain, no FTOV, etc.). PPV is the probability that a having an imbalance results in a health outcome (pain, FTOV, etc.). Whereas NPV is the probability that a person without an imbalance will be a control (i.e., pain free).

Odds ratios were developed to show the relative risk associated with imbalance and pain. Significant odds ratios had a confidence interval (CI) range that did not include one. Kappa scores demonstrated reliability, with a score of one for perfect agreement, zero for random chance agreement, and negative scores predicting an agreement worse than expected.

5.4 Results

Table 5.1 shows the outcome of seeking medical treatment due to imbalance. Table 5.2 shows average pain today was found to be significantly higher for cases with imbalance than those without imbalance (16.1 and 8.7, respectively). Likewise, average worst pain in the last year was also found to be significantly higher for those with imbalance than those without (39.6 and 26.2, respectively).

Table 5.1: Imbalance - Pain Ratings and Medical Treatment Sought

	Pain Today		Pain in the Last 7 Days	Pain in the Last Year				
Pain Rating Threshold	15/100	50/100		15/100	25/100	50/100	Continuous Pain	Seek Medical Treatment
Odds Ratio	2.0	2.7	2.1	2.1	2.1	1.7	3.1	1.8
95% CI	(1.11, 3.56)	(1.28, 5.82)	(1.1, 3.62)	(1.20, 3.54)	(1.23, 3.62)	(1.01, 3.00)	(1.66, 5.82)	(0.99, 3.18)
Kappa Value	0.06	0.08	0.06	0.05	0.05	0.04	0.11	0.05
Sensitivity	0.09	0.13	0.09	0.08	0.08	0.08	0.13	0.08
Specificity	0.95	0.95	0.96	0.96	0.96	0.95	0.95	0.95
PPV	0.32	0.16	0.38	0.52	0.52	0.45	0.27	0.32
NPV	0.81	0.93	0.78	0.66	0.66	0.68	0.89	0.79

Table 5.2: Imbalance (Case) versus No Imbalance (Controls) Pain Ratings

Case	Average Pain Today		Average Worst Pain in the Last Year	
	Rating	P-Value	Rating	P-Value
Imbalance	16.1	**0.04***	39.6	**0.02***
No Imbalance	8.7		26.2	
*Significant at the 0.05 level				

Based on an overall assessment of the job for the 933 subjects who performed some type of lifting, gender was significant in predicting the risk for LBP for jobs that require twisting while lifting. In that study, the OSHA Checklist was used to estimate time lifting and twisting. Females were found to be less likely to be performing lifting jobs with an odds ratio of 0.6 (CI 0.45-0.81). However, females that were lifting, were more likely than their male colleagues to experience LBP. There are increased odds to develop LBP when performing lifting tasks.

While twisting, lifting, and twisting while lifting did not appear to be strongly related to pain today (Table 5.3), there did appear to be some relationship to likelihood to seek medical attention (Table 5.4). Data determined that 22.6% of subjects were recorded as having twisted for one hour or more/day, 46.7% of subjects lifted according to the OSHA checklist, 14.0% of subjects twisted while lifting, and 20.8% of subjects performed one-handed lifting. Tables 5.3 and 5.4 show the association and risk associated with twisting, lifting, and combinations and variations of these two. Twisting was not found to be a significant for the likelihood of imbalance (Table 5.5).

Table 5.3: Twisting and Pain Today

	Twist >= One hour/day	Lift	Twist While Lifting	One-Handed Lifting
Pain Rating Threshold	15/100	15/100	15/100	15/100
Odds Ratio	1.27	0.95	1.15	0.88
95% CI	(0.88, 1.84)	(0.69, 1.31)	(0.73, 1.80)	(0.59, 1.32)
Kappa Value	0.04	-0.01	0.02	-0.02
Sensitivity	0.26	0.46	0.15	0.19
Specificity	0.78	0.53	0.86	0.79
PPV	0.23	0.2	0.22	0.19
NPV	0.81	0.79	0.8	0.79

Table 5.4: Twisting and Seeking Medical Attention

	Twisting	Lifting	Twisting While Lifting	One-Handed Lifting
Odds Ratio	1.37	1.5	1.53	1.38
95% CI	(0.96, 1.95)	(1.10, 2.05)	(1.01, 2.31)	(0.96, 1.98)
Kappa Value	0.06	0.07	0.06	0.06
Sensitivity	0.27	0.18	0.18	0.25
Specificity	0.79	0.87	0.87	0.8
PPV	0.27	0.29	0.29	0.27
NPV	0.79	0.79	0.79	0.79

Table 5.5: Twisting and Likelihood of Imbalance

Odds Ratio	0.77
95% CI	(0.38, 1.55)
Kappa Value	-0.02
Sensitivity	0.19
Specificity	0.77
PPV	0.05
NPV	0.94

Following on the previous analysis and findings, more data were extracted from the epidemiological study to further investigate and improve the preliminary findings. Personal characteristics were factored in to adjust odds ratios and likelihood, such as gender, age, BMI, exercise, additional pain data, lost work time, job difficulty, and additional data on seeking medical attention.

Descriptive statistics were found for comparisons between imbalance and the factors mentioned above (gender, age, BMI, exercise, additional pain data, lost work time, job difficulty, and additional data on seeking medical attention) following the initial statistical analysis to further investigate the occupational effect of physical imbalance. More males were found to have imbalances than females of the total population studied (Table 5.6). However, the sample was skewed heavily towards males (~75% of the study population) and proportionally, neither males nor females were more likely to have an imbalance as measured in the study. The percent of males and females were not found to be statistically significantly different from one another.

Table 5.6: Descriptive Statistics, Comparison Between Imbalance and Gender

		Imbalance		Total	Percent (%) With Imbalance
Gender	Male	694	41	735	5.6%
	Female	261	13	274	4.7%
Total		955	54	1009	5.5%

Most people with imbalances were in the age range of 45-60, accounting for 24 of the 56 subjects with imbalances (Table 5.7). The results of an ANOVA on imbalance and age were found significant (p=0.00), (shown in Figures 5.1 – 5.2).

Table 5.7: Age Classifications of Subjects with Imbalances

		Imbalance		Total	Percent (%) With Imbalance
		No	Yes		
Age-Classification	< 25	53	2	55	3.6%
	25 - 35	268	11	279	3.9%
	35 - 45	259	12	271	4.4%
	45 - 60	342	24	366	6.6%
	>60	38	7	45	15.6%
Total		960	56	1016	5.5%

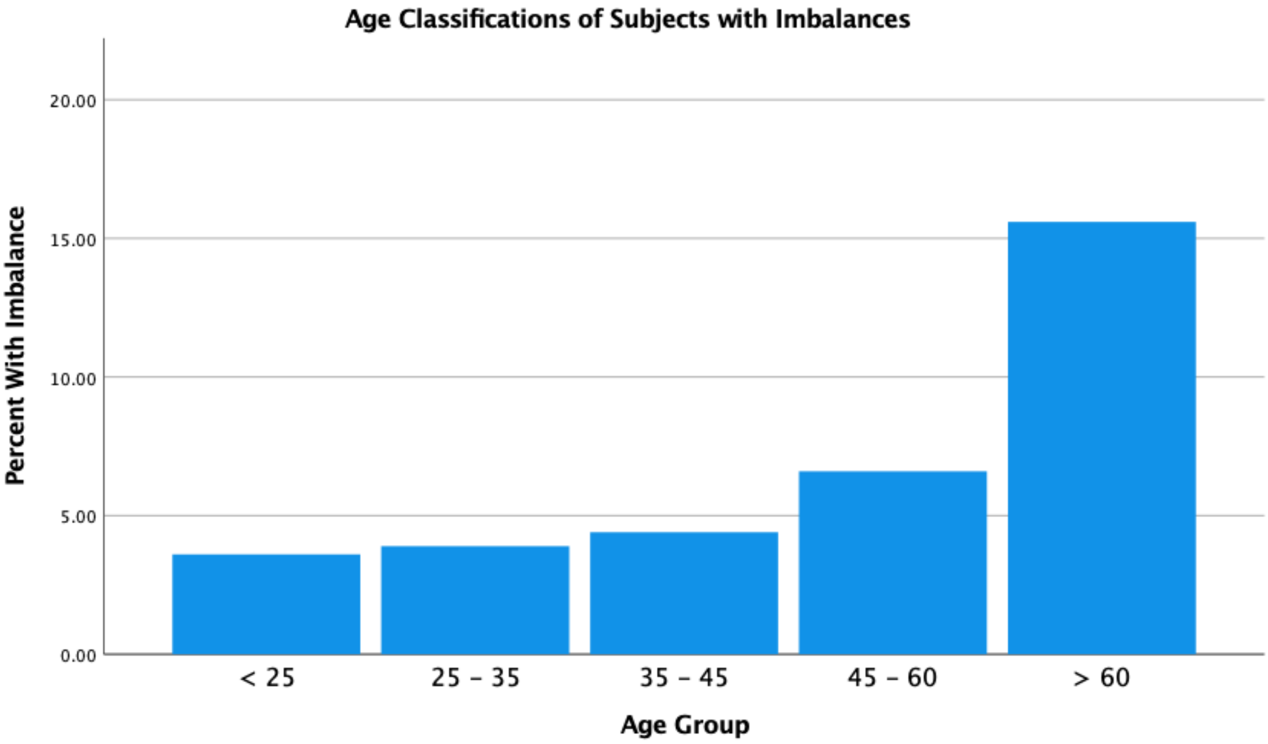


Figure 5.1: Relationship to Imbalance with Age

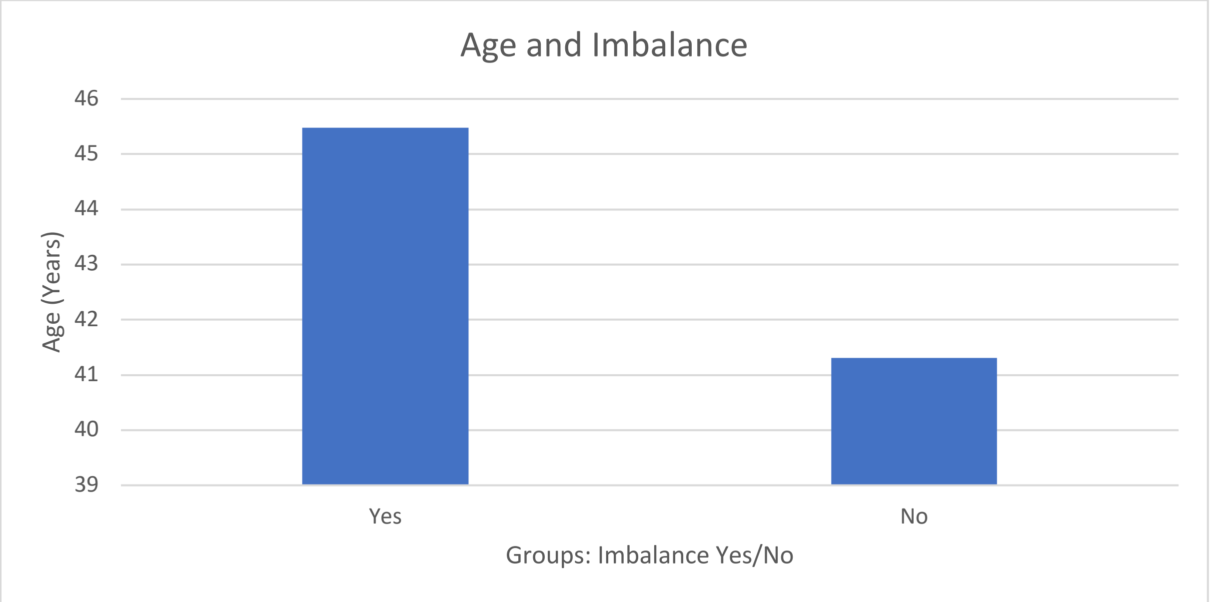


Figure 5.2: Age and Imbalance

BMI did not appear to be associated with imbalance, as its ANOVA significance was found (p=0.99). Overall, just under 10% of subjects exercised with 7.2% lifting weights. Table 5.8 describes the percentage of subjects who exercised with respect to imbalance.

Table 5.8: Descriptive Statistics, Comparison Between Imbalance and Any Exercise

		Imbalance		Total	Percent (%) Participation	
		No	Yes		No	Yes
Exercise	No	835	48	883	95%	5%
	Yes	88	6	94	94%	6%
Total		923	54	977	94%	6%

The results of ANOVA between imbalance and pain today out of 100 was significant at p=0.00 (plotted in Figure 5.3).

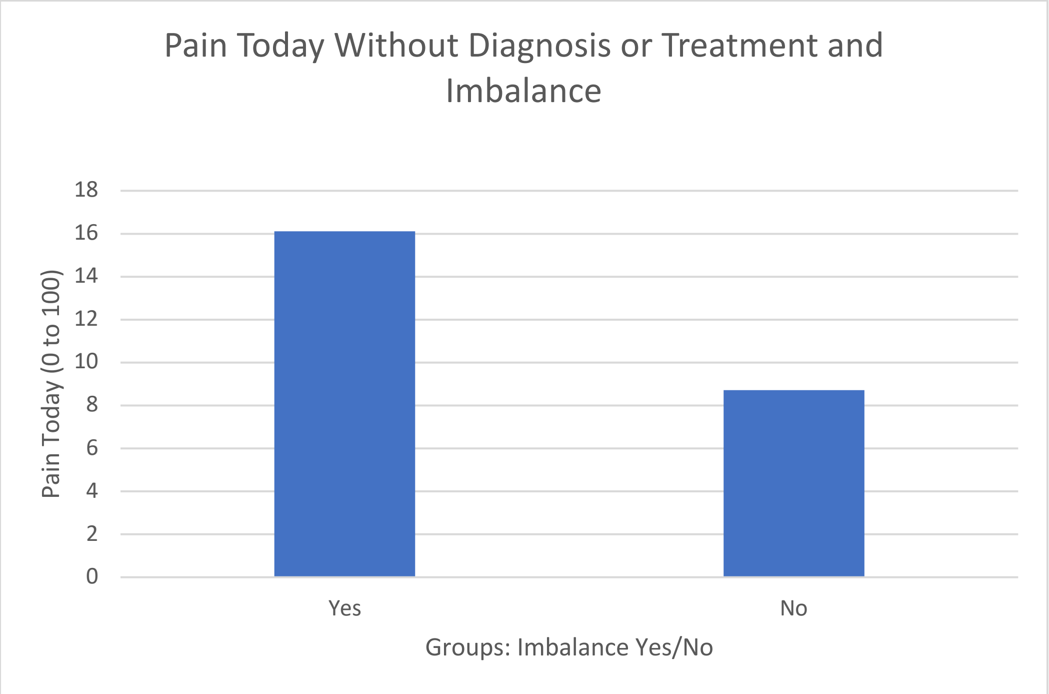


Figure 5.3: Imbalance and Pain Today out of 100 Without Diagnosis or Treatment

Results of the ANOVA between imbalance and worst pain in the last year out of 100, without diagnosis or treatment, was significant at p=0.01 (plotted in Figure 5.4).

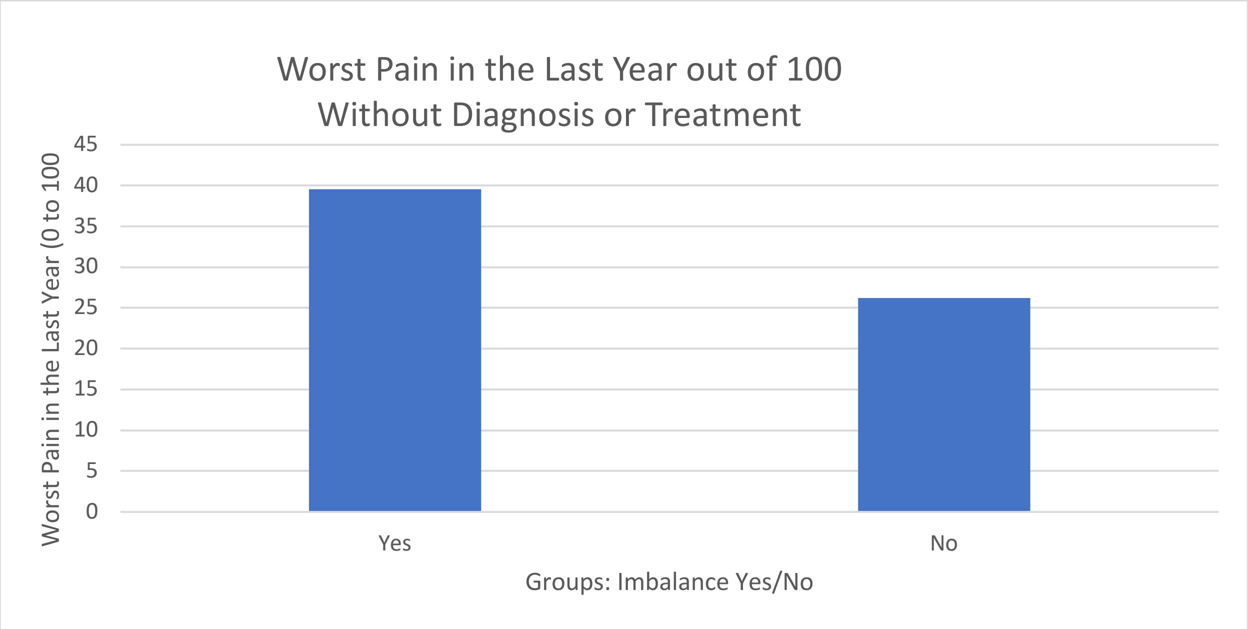


Figure 5.4: Imbalance and Worst Pain in the Last Year out of 100

More than one-fourth of subjects with an imbalance were in continuous pain which was significantly higher than the subjects without imbalance (26.8% vs. 10.5%, p=0.02) (Table 5.9).

Table 5.9: Binary Log Regression (Odds Ratios) – Continuous Pain Versus Imbalance Crude Odds Ratio

		B	S.E.	Wald	df	Sig.	Exp (B)	95% Lower	95% Upper
Step 1[a]	Imbalance (Yes/No)	0.90	0.39	5.27	1	**0.02***	2.450	1.14	5.27
	Constant	-0.83	0.12	48.10	1	0.00	0.437		

a. Variable(s) entered on step 1: Imbalance (Yes/No)
*Significant at 0.05 level

Imbalanced people were less likely to seek medical attention through office visits but were significantly more likely to experience lost work time (p=0.09) (Tables 5.10 – 5.11).

Table 5.10: Chi-Square Test Results for Imbalance and Seeking Medical Attention

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	0.85[a]	1	0.36		
Continuity Correction[b]	0.55	1	0.46		
Likelihood Ratio	0.80	1	0.37		
Fisher's Exact Test				0.36	0.23
Linear-by-Linear Association	0.85	1	0.36		
N of Valid Cases	1016				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 9.48.
b. Computed only for a 2x2 table

Table 5.11: Binary Log Regression (Odds Ratios) – Lost Work Time and Imbalance (Crude)

		B	S.E.	Wald	df	Sig.	Exp (B)	95% Lower And Upper	
Step 1[a]	Imbalance (Yes/No)	0.68	0.40	2.85	1	**0.09****	1.97	0.90	4.31
	Constant	-2.47	0.12	421.17	1	0.00	0.09		

a. Variable(s) entered on step 1: Imbalance (Yes/No)
*Significant at 0.05 level
**Trending Towards Significance at 0.05 level

When adjusted for personal factors and job difficulty, the relationship between imbalance and lost work time becomes even more significant at p=0.04 (Table 5.12).

Table 5.12: Binary Log Regression (Odds Ratios) – Lost Work Time and Imbalance (Crude)
(Adjusted for Personal Characteristics & Job Difficulty)

		B	S.E.	Wald	df	Sig.	Exp(B)	95% CI for EXP(B)	
								Lower	Upper
Step 1[a]	Gender	-0.03	0.28	0.01	1	0.91	0.97	0.56	1.68
	BMI-Classification	0.21	0.16	1.64	1	0.20	1.23	0.90	1.69
	Age-Classification	-0.11	0.12	0.78	1	0.38	0.90	0.71	1.14
	ExpOp_Total	0.13	0.13	1.01	1	0.32	1.14	0.88	1.47
	Imbalance (Yes/No)	**0.84**	**0.41**	**4.18**	**1**	**0.04***	**2.31**	**1.04**	**5.14**
	Constant	-2.81	0.70	16.19	1	0.00	0.06		

a. Variable(s) entered on step 1: Gender, BMI-Classification, Age-Classification, ExpOp_Total, Imbalance (Yes/No)
*Significant at the 0.05 level

5.5 Discussion

The number of imbalances did not appear to impact the likelihood or severity of pain and the relatively small sample of subjects with multiple imbalances did not permit a statistical analysis relating the number of imbalances to health outcomes. There were several variables that appeared to be trending towards significance that may have been elucidated with a larger sample size. Possible confounding variables were explored statistically. Not all imbalances were "equal" with some demonstrating stronger apparent relationships than others. Imbalance was investigated for each imbalance type independently and as a group.

It should be noted that the intent of the original study (automotive study) was not to specifically study imbalances, but rather to consider many factors that could be related to WMSDs. Therefore, only fairly significant or "obvious" imbalances were detected, and it is unclear what percentage of subjects would have quantifiable imbalances had medical imaging technology been employed such as in this dissertation. For example, rotational differences were only observed 3 times and lateral deviation differences 13 times. Had the intent been to study imbalances, perhaps more sophisticated measures would have been used. For example, in the Tai Chi study, all subjects at baseline had paraspinal MIs greater than 10 percent. Likely, there is a threshold above which negative health outcomes become more likely. In the automotive study, only significant (apparent by simple exam and observation) differences were considered.

When considering individual imbalance types, lateral deviation difference and motor imbalance appeared to be the strongest predictors. Using this definition (one or more types of imbalance), 56 of the 1,016 subjects were considered to have an imbalance. Various imbalance measures were considered independently and together. Many of the imbalance measures were found to be effective by themselves (though the small "n" made it hard to reach statistical significance – odds ratios that bounded 1.0 There was no greater likelihood of imbalance occurring in a man or woman, with an odds ratio of approximately 1.0. People with imbalances had greater pain on the day of interview and suffered greater peak pain during the previous year than did those without imbalances.

Also, clearly observable imbalances represented only 5.5% of the study population (56/1,016). It should also be noted that subjects with imbalances were ~4 years older than those without imbalances (45.5 years vs. 41.3 years, p=0.02). It can be determined that imbalances increase or are more likely with older age groups.

Populations did not differ in their propensity to exercise. While imbalanced people did not exercise frequently, nor did the non-imbalanced. In fact, they were slightly more likely to participate in exercise and slightly less so in weight training. However, the percentage rates of participation were very similar and were not statistically significantly different.

5.6 Conclusion

The underlying hypothesis that MI is associated with LBP outcomes was supported by the study of automotive workers. Indeed, those with imbalances were more likely to have pain and seek medical attention related to LBP. Specifically, imbalance related to differences in left/right lateral flexion was found to be very predictive of LBP. The increase of age should hypothetically increase risk of imbalance, and it was shown that age did increase risk of imbalance. This is not surprising as the findings of previous studies have also associated age with imbalance (Bansal et al, 2014; McDonald et al, 1995; Janda et al, 1996; Rupp et al, 1995; Roth et al, 2006; Iwasaki et al; 2015).

The facilities studied in the automotive plants were union environments that gave priority to workers with more seniority when assigning jobs. Therefore, there is a strong tendency for older workers to be performing easier jobs. Therefore, the MI concept analysis was improved by the inclusion of factors to control for job difficulty, age, gender, and psychosocial factors to determine the impact of these variables on LBP. These results that factor in personal characteristics as covariates could potentially derive a new index derived from the MRI quantitative data could be used to quantify imbalance in future studies like the automotive epidemiological study.

It is possible that this new, highly quantitative measure could be more predictive of such multisite, cascading effects to other body parts. For example, a relative risk matrix could be built to demonstrate the impact of such factors as age and gender based on the assumption that the lowest risk is to young males and the highest risk is to older females. Pain and discomfort in one body part may also be related to pain and discomfort in another body part (Bandekar, 2021). Future studies should investigate if *imbalance* is related to such multisite pain.

Chapter 6

Conclusion

This work considers a new measure that has not been previously studied at Auburn or by other researchers. In fact, many aspects have not been studied *at all* (no literature address imbalances of core or lever arms). Further, this is the first Auburn OSE MRI study to consider symptomatic patients and relates MRI findings to the pain of those subjects. All other studies have had asymptomatic subjects. Previous Auburn MRI-related dissertations have specifically recommended the study of symptomatic subjects as well as older subjects. This work is responding to those recommendations for further study. This work studies a new population, one that is often overlooked in studies: women over 50. This study also introduces a prospective element to measure subjects after an intervention (exercise program). Previous work also studies intervention, but was focused on the impact of weightlifting and primarily on changes in CSA and MLALs, not MI.

Concepts were validated (to the extent possible) against an existing ergonomic database (as have several others). The MRI protocol (scan settings and use of supplemental coil) for muscles collected is the same as used by others. This was done so that data can be aggregated across studies at a later date and to allow larger sample sizes with broader subject characteristics. Also, the reliability of measuring those muscles has been studied extensively, demonstrating that the measurement protocols are robust and repeatable. This study also contributes to the aspect of personalization by introducing new elements (MI) and new populations (older, symptomatic).

LBP is one of the most expensive and common MSDs. Since most causes of LBP remain unknown, studies have been conducted to explore whether MIs may be a possible contributor and/or risk factor for LBP. To date, there is no published research that has quantified MI using MRI-derived measurements of CSAs *and* MLALs of both the paraspinal and core muscles (psoas, erector spinae, quadratus lumborum, rectus abdominus, and oblique muscles). Other studies have considered individual muscles and the paraspinal muscle group in the sagittal plane. However, to our knowledge, there are none that have factored in the MLAL as part of the MI evaluation nor have any quantified the entire torso musculature including all core muscles. Further, we could find any studies that have compared anterior musculature to posterior musculature to determine imbalances between the anterior and posterior hemispheres.

A novel quantitative index for imbalance was established and its relationship to pain was explored. Imbalances were measured both laterally and anteriorly/posteriorly for all core and paraspinal muscles individually, in muscle groups, and by hemisphere. In general, the MI_{New} (CSA * MLAL) was more significantly related to LBP than MI_{CSA}. This may be attributed to the strength of the MLALs correcting for imbalance directionally, particularly in the hemispheric measurements. It can be assumed that CSA represents muscle force capability, and MLAL is the relative mechanical advantage of muscles. Together, CSA and MLAL provide moment generating capability.

Many ergonomic models used to predict LBP do not consider individual characteristics. The lack of individualization in ergonomic models may present problems, specifically when assessing an individual’s risk for LBP. This is particularly true if the individual deviates significantly from the average or reference population. For example, women over 50 have not been extensively studied. Models based on younger subjects or male subjects, may not accurately represent the population of older women. MRI derived measurements can be used to personalize ergonomic and biomechanical models, such as MI. It is possible that MI could be factored into future biomechanical models to more accurately assesses a specific subject's lifting-related risk.

The mechanism behind paraspinal MI may be a symptom *or* a consequence of LBP, or *both* a symptom and a consequence of LBP. This may create a vicious cycle of trauma to muscles causing injury due to poor muscle control, leaving the muscles unable to heal after exercise or stress, resulting in accelerated degeneration and subsequent pain.

Tai Chi exercise did appear to be associated with lower levels of MI and seemed to have generally positive effects on subjects (decreases in MI, lower weight, lower BMI) in this pilot study. However, the age difference in subject groups (i.e., the regular Tai Chi practitioners were ~10 years older than the other study groups) may have obfuscated the relationship between MI and LBP. Future studies with larger sample sizes may help elucidate the relationship between MI and LBP. In a study involving college students (Capanoglu, 2021), MI levels were significantly lower (e.g., ~2%) for the younger subjects. This emphasizes the potential role of aging with respect to MI. A larger study with a broader variety of exercisers and non-exercisers may shed more light on whether exercise is effective in slowing or even improving levels of MI in subjects.

MI is present in the occupational setting among workers, in addition to the general population. Those with imbalances were more likely to have pain and seek medical attention related to LBP based on the epidemiological study of automotive workers, and it was shown that age was significantly associated with the likelihood of imbalance, with older workers experiencing higher rates of MI. The MI analysis was refined with the inclusion of factors to control for job difficulty, age, gender, and psychosocial factors to determine the impact of these variables on LBP.

Expanding on previous studies on trunk asymmetry, this novel MI index was evaluated at each spinal level between L2-S1, rather than at a single level as in most studies. It was determined from the current study that the L3/L4 level showed the most promise for use in evaluating the association between MI and LBP. Future studies of MI should ensure this spinal level is included in the analysis. Future studies should also investigate if *imbalance* is related to multisite pain since, pain and discomfort in 1 body part may also be related to pain and discomfort in other body parts (Bandekar, 2021).

It was difficult to establish a clear relationship between MI and LBP, but a repeatable, highly quantitative measure (MI_{New}) was established that can be incorporated into future studies. Subjects of both genders with more diverse age ranges, BMIs, and fitness levels should be included in future studies. The subjects that were recruited for this study came from an exercise environment, introducing a potential fundamental bias. In this study, the exercisers had greater LBP, but they were recruited from a gym that also acted as a rehabilitation clinic. Many of these women had established regular exercise routines.

A priori data should also be collected on handedness and participation in sports that are inherently asymmetric such as racket sports, which may be found to contribute to lateral MIs. This would also facilitate analysis of side-specific MI related to such asymmetric activities. In the future, these data should be aggregated with other MI datasets to better understand the impact of gender, age, exercise, and other health conditions.

References

Bhattacharya, Anasua. "Costs of occupational musculoskeletal disorders (MSDs) in the United States." *International Journal of Industrial Ergonomics* 44.3 (2014): 448-454.

Bureau of Labor Statistics, BLS https://www.bls.gov/iif/msd_state.htm

Vos, Theo, et al. "Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016." *The Lancet* 390.10100 (2017): 1211-1259.

Yang, Haiou, et al. "Low back pain prevalence and related workplace psychosocial risk factors: a study using data from the 2010 National Health Interview Survey." *Journal of manipulative and physiological therapeutics* 39.7 (2016): 459-472.

"Low Back Pain Fact Sheet". *National Institute of Neurological Disorders and Stroke.* National Institute of Health. Archived from the original on 19 July 2013.

Nadler, Scott F., et al. "Hip muscle imbalance and low back pain in athletes: influence of core strengthening." *Medicine & Science in Sports & Exercise* 34.1 (2002): 9-16.

Oddsson, Lars IE, and Carlo J. De Luca. "Activation imbalances in lumbar spine muscles in the presence of chronic low back pain." *Journal of Applied Physiology* 94.4 (2003): 1410-1420.

Plowman SA. Physical activity, physical fitness, and low back pain. Exerc Sport Sci Rev. 1992;20:221–242. doi: 10.1249/00003677-199200200-00008.

Sullivan, Amy Burleson, et al. "The role of exercise and types of exercise in the rehabilitation of chronic pain: specific or nonspecific benefits." *Current pain and headache reports* 16.2 (2012): 153-161.

Wang, Xue-Qiang, et al. "A meta-analysis of core stability exercise versus general exercise for chronic low back pain." PloS one 7.12 (2012): e52082.

Weifen, Wu, et al. "Effectiveness of tai chi practice for non-specific chronic low back pain on retired athletes: a randomized controlled study." Journal of musculoskeletal pain21.1 (2013): 37-45.

Wu, Ge, et al. "Improvement of isokinetic knee extensor strength and reduction of postural sway in the elderly from long-term Tai Chi exercise." *Archives of physical medicine and rehabilitation* 83.10 (2002): 1364-1369.

Wu, Ge, et al. "Spatial, temporal and muscle action patterns of Tai Chi gait." *Journal of Electromyography and Kinesiology*14.3 (2004): 343-354.

Wang, Jie, et al. "Tai Chi for essential hypertension." *Evidence-Based Complementary and Alternative Medicine*2013 (2013).

Deng, Chenghu, and Wei Xia. “Effect of Tai Chi Chuan on Degeneration of Lumbar Vertebrae and Lumbar Discs in Middle-Aged and Aged People: A Cross-Sectional Study Based on Magnetic Resonance Images.” Journal of International Medical Research, vol. 46, no. 2, Feb. 2018, pp. 578–585, doi:10.1177/0300060517734115.

Salar, M. “Validation of MRI-Derived Morphometric Estimations of Biomechanical Inputs to Improve Low Back Pain Risk Assessment.” Auburn University Dissertation. 2017.

Wan, Q et al. “MRI assessment of paraspinal muscles in patients with acute and chronic unilateral low back pain” *British journal of radiology* vol. 88,1053 (2015): 20140546.

Li, Fuzhong et al. “Translation of an effective tai chi intervention into a community-based falls-prevention program” *American journal of public health*vol. 98,7 (2008): 1195-8.

Pentikis, J. “Determination of Safe Guidelines for One-Hand Lifting.” Auburn University Dissertation. 2017.

Tang, R., Gungor, C., Sesek, R.F., Foreman, K.B., Gallagher, S., Davis, G.A. “Morphometry of the lower lumbar intervertebral discs and endplates: comparative analyses of new MRI data with previous findings." European Spine Journal. February 12, 2016: 1-16. DOI: 10.1007/s00586-016-4405-8

Gungor, C., Tang, R., Sesek, R.F., Foreman, K.B., Gallagher, S., and Davis, G.A. "Prediction models for the erector spinae muscle cross-sectional area" Journal of Biomechanical Engineering. 137(7): 8 pp. 2015.

Gungor, C., Tang, R., Sesek, R.F., Gallagher, S., and Davis, G.A. "Morphological investigation of low back erector spinae muscle: Historical data populations" International Journal of Industrial Ergonomics. Volume 49, September 2015, Pages 108-115.

Solloway, Michele R., et al. "An Evidence Map of the Effect of Tai Chi on Health Outcomes." Systematic Reviews, vol. 5, no. 1, 2016, doi:10.1186/s13643-016-0300-y.

Jancewicz, Andrzej. "Tai Chi Chuan's Role in Maintaining Independence in Ageing People with Chronic Disease." Journal of Bodywork and Movement Therapies, vol. 5, no. 1, 2001, pp. 70–77., doi:10.1054/jbmt.2000.0178.

"Lower crossed syndrome". Physiopedia, 26 Aug 2019, https://www.physio-pedia.com/index.php?title=Lower_crossed_syndrome&oldid=220651

Miller, Kenneth. "Lower Crossed Syndrome Starting from Center." National Academy of SportsMedicine, AmericanFitness, magazine.nasm.org/american-fitness-magazine/issues/american-fitness-magazine-winte r-2017/lower-crossed-syndrome-starting-from-center

Kerger, Shawn R, and Richard G Schuster. "Evaluation and Management of the Upper and Lower Crossed Syndromes." American College of Osteopathic Family Physicians, Sept. 2016, https://www.acofp.org/ACOFPIMIS/Acofporg/PDFs/OMED16/Mon_pm_130_KergerShawn_Evaluation_Management_Upper_Lower%20Crossed_Syndromes.pdf

Heller, Marc, and Phillip Snell. “Flexion-Intolerant Lower Back Pain (Part 1): Diagnosis.” Dynamic Chiropractic, 15 Jan. 2014, www.dynamicchiropractic.com/mpacms/dc/article.php?id=56837

“Lower Cross Syndrome.” Fredericksburg Chiropractic, fredericksburgchiropractic.com/home-therapy/lower-cross-syndrome/

Das, Shriya, et al. “Prevalence of Lower Crossed Syndrome in Young Adults: A Cross Sectional Study.” International Journal of Advanced Research, June 2017, pdfs.semanticscholar.org/a1ab/c3a7fd5a9b3aac9d924ea9d1dab4969fa27b.pdf

Dionne, Cassie. “Why Your Approach to Fixing Your Low Back Is Making It Worse.” Breaking Muscle , 18 Nov. 2018, breakingmuscle.com/fitness/why-your-approach-to-fixing-your-low-back-is-making-it-wor se

Mitchell, Tim, et al. “Regional Differences in Lumbar Spinal Posture and the Influence of Low Back Pain.” BMC Musculoskeletal Disorders, BioMed Central, 18 Nov. 2008, www.ncbi.nlm.nih.gov/pubmed/19014712

“WhatIsMuscleImbalance.”MuscleImbalanceSyndromes, www.muscleimbalancesyndromes.com/what-is-muscle-imbalance/

Hutt, Kim. “Muscular Imbalance Explained.” Dance UK, 2014, www.onedanceuk.org/wp-content/uploads/2017/11/DUK-Info-Sheet-13-Muscle-Imbalanc e-Explained.pdf

Ruas, Cassio Victoria, and Adriane Vieira. “Do Muscle Strength Imbalances and Low Flexibility Levels Lead to Low Back Pain? A Brief Review.” Functional Morphology and Kinesiology, 4 Aug. 2017, www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=19&ved=2ahUKEwizvbfz5_vkAhVjk-AKHfjlAy84ChAWMAh6BAgJEAI&url=https%3A%2F%2Fwww.mdpi.com%2F2411-5142%2F2%2F3%2F29%2Fpdf&usg=AOvVaw2RR960AKzuevogyKHk8YMs

Wilke H-, Wolf S, Claes LE, Arand M, Wiesend A, Bendix T. Stability increase of the lumbar spine with different muscle groups: A biomechanical in vitro study. Spine 1995;20(2):192-198.

Solomonow M, Zhou B-, Harris M, Lu Y, Baratta RV. The ligamento- muscular stabilizing system of the spine. Spine 1998;23(23):2552-2562.

McGill SM, Norman RW. Effects of an anatomically detailed erector spinae model on L4/L5 disc compression and shear. J Biomech 1987;20(6):591-600.

Moore KL, Dalley AF, Agur AMR. Clinically oriented anatomy. 5th ed. Philadelphia: Lippincott Williams & Wilkins; 2006.

McGill S. Low back disorders: evidence-based prevention and rehabilitation. Champaign, IL: Human Kinetics; 2002.

Wilke H-, Wolf S, Claes LE, Arand M, Wiesend A. Influence of varying muscle forces on lumbar intradiscal pressure: An in vitro study. J Biomech 1996;29(4):549-555.

Penning L. Psoas muscle and lumbar spine stability: A concept uniting existing controversies. Critical review and hypothesis. Eur Spine J 2000;9(6):577-585.

Andersson GBJ, Ortengren R, Herberts P. Quantitative electromyographic studies of back muscle activity related to posture and loading. Orthop Clin North Am 1977;8(1):85-96.

Nachemson A. Electromyographic studies on the vertebral portion of the psoas muscle; with special reference to its stabilizing function of the lumbar spine. Acta Orthop Scand 1966;37(2):177-190.

Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. Acta Orthop Scand, Supplement1989;60(230):5-54.

McGill S, Juker D, Kropf P. Quantitative intramuscular myoelectric activity of quadratus lumborum during a wide variety of tasks. Clin Biomech 1996;11(3):170-172.

Krishan K. Marked limb bilateral asymmetry in an agricultural endogamous population of North India. Am J Hum Biol 2011;23(5):674- 685.

Valen LV. A Study of Fluctuating Asymmetry. Evolution 1962;16(2):pp. 125-142.

Livshits G, Otremski I, Kobyliansky E. Biology of aging in an Israeli population. 2. Polymorphic blood markers and fluctuating asymmetry. Anthropol Anz 1994;52(2):97-117.

Otremski I, Katz M, Livshits G, Cohen Z. Biology of aging in an Israeli population. 1. Review of literature and morphological variation analysis. Anthropol Anz 1993;51(3):233-249.

Kannus P, Sievanen H, Vuori I. Physical loading, exercise, and bone. Bone 1996;18(1 SUPPL.):1S-3S.

Kannus P, Haapasalo H, Sankelo M, Sievänen H, Pasanen M, Heinonen A, et al. Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. Ann Intern Med 1995;123(1):27-31.

Hides J, Stanton W, Freke M, Wilson S, McMahon S, Richardson C. MRI study of the size, symmetry and function of the trunk muscles among elite cricketers with and without low back pain. Br J Sports Med 2008;42(10):509-513.

Elliott BC, Davis JW, Khangure MS, Hardcastle P, Foster D. Disc degeneration and the young fast bowler in cricket. Clin Biomech 1993;8(5):227-234.

McLean BD, Tumilty McA. D. Left-right asymmetry in two types of soccer kick. Br J Sports Med 1993;27(4):260-262.

Engstrom CM, Walker DG, Kippers V, Mehnert AJH. Quadratus lumborum asymmetry and L4 pars injury in fast bowlers: A prospective MR study. Med Sci Sports Exerc 2007;39(6):910-917.

Ranson C, Burnett A, O'Sullivan P, Batt M, Kerslake R. The lumbar paraspinal muscle morphometry of fast bowlers in cricket. Clin J Sport Med 2008;18(1):31-37.

Stewart S, Stanton W, Wilson S, Hides J. Consistency in size and asymmetry of the psoas major muscle among elite footballers. Br J Sports Med 2010;44(16):1173-1177.

Hides J, Fan T, Stanton W, Stanton P, Mcmahon K, Wilson S. Psoas and quadratus lumborum muscle asymmetry among elite Australian Football League players. Br J Sports Med 2010;44(8):563-567.

Burnett AF, Barrett CJ, Marshall RN, Elliott BC, Day RE. Three- dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. Clin Biomech 1998;13(8):574-583.

Sanchis-Moysi J, Idoate F, Izquierdo M, Calbet JAL, Dorado C. Iliopsoas and gluteal muscles are asymmetric in tennis players but not in soccer players. PLoS ONE 2011;6(7).

Sanchis-Moysi J, Idoate F, Dorado C, Alayó S, Calbet JAL. Large asymmetric hypertrophy of rectus abdominis muscle in professional tennis players. PLoS ONE 2010;5(12).

McGregor AH, Anderton L, Gedroyc WMW. The trunk muscles of elite oarsmen. Br J Sports Med 2002;36(3):214-217.

Parkin S, Nowicky AV, Rutherford OM, McGregor AH. Do oarsmen have asymmetries in the strength of their back and leg muscles? J Sports Sci 2001;19(7):521-526.

Murtezani A, Ibraimi Z, Sllamniku S, Osmani T, Sherifi S. Prevalence and risk factors for low back pain in industrial workers. Folia Med 2011;53(3):68-74.

Lavender SA, Mirka GA, Schoenmarklin RW, Sommerich CM, Sudhakar LR, Marras WS. The effects of preview and task symmetry on trunk muscle response to sudden loading. Hum Factors 1989;31(1):101-115.

Marras WS, Mirka GA. Trunk strength during asymmetric trunk motion. Hum Factors 1989;31(6):667-677.

Barker KL, Shamley DR, Jackson D. Changes in the cross-sectional area of multifidus and psoas in patients with unilateral back pain: the relationship to pain and disability. Spine 2004;29(22):E515-519.

Hides J, Gilmore C, Stanton W, Bohlscheid E. Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. Man Ther 2008;13(1):43-49.

Ploumis A, Michailidis N, Christodoulou P, Kalaitzoglou I, Gouvas G, Beris A. Ipsilateral atrophy of paraspinal and psoas muscle in unilateral back pain patients with monosegmental degenerative disc disease. Br J Radiol 2011;84(1004):709-713.

Hyun JK, Lee JY, Lee SJ, Jeon JY. Asymmetric atrophy of multifidus muscle in patients with unilateral lumbosacral radiculopathy. Spine 2007;32(21):E598-E602.

Hides JA, Stokes MJ, Saide M, Jull GA, Cooper DH. Evidence of lumbar multifidus muscle wasting ipsilateral to symptoms in patients with acute/subacute low back pain. Spine 1994;19(2):165-172.

Kim WH, Lee S-, Lee DY. Changes in the cross-sectional area of multifdus and psoas in unilateral sciatica caused by lumbar disc herniation. J Korean Neurosurg Soc 2011;50(3):201-204.

Kulig K, Scheid AR, Beauregard R, Popovich Jr. JM, Beneck GJ, Colletti PM. Multifidus morphology in persons scheduled for single-level lumbar microdiscectomy: Qualitative and quantitative assessment with anatomical correlates. Am J Phys Med Rehabil 2009;88(5):355-361.

Battié MC, Niemelainen R, Gibbons LE, Dhillon S. Is level- and side- specific multifidus asymmetry a marker for lumbar disc pathology? Spine J 2012;12(10):932-939.

Stokes MJ, Cooper RG, Morris G, Jayson MIV. Selective changes in multifidus dimensions in patients with chronic low back pain. Eur Spine J 1992;1(1):38-42.

Beneck GJ, Kulig K. Multifidus atrophy is localized and bilateral in active persons with chronic unilateral low back pain. Arch Phys Med Rehabil 2012;93(2):300-306.

Hodges P, Holm AK, Hansson T, Holm S. Rapid atrophy of the lumbar multifidus follows experimental disc or nerve root injury. Spine 2006;31(25):2926-2933.

Stokes M, Rankin G, Newham DJ. Ultrasound imaging of lumbar multifidus muscle: Normal reference ranges for measurements and practical guidance on the technique. Man Ther 2005;10(2):116-126.

Niemeläinen R, Briand M, Battié MC. Substantial asymmetry in paraspinal muscle cross-sectional area in healthy adults questions its value as a marker of LBP and pathology. Spine 2011;36(25):2152-2157.

Chan S-, Fung P-, Ng N-, Ngan T-, Chong M-, Tang C-, et al. Dynamic changes of elasticity, cross-sectional area, and fat infiltration of multifidus at different postures in men with chronic low back pain. Spine J 2012;12(5):381-388.

Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ. CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. Eur Spine J 2000;9(4):266-272.

Cooper RG, St Clair Forbes W, Jayson MIV. Radiographic demonstration of paraspinal muscle wasting in patients with chronic low back pain. Br J Rheumatol 1992;31(6):389-394.

Kamaz M, Kiresi D, Oguz H, Emlik D, Levendoglu F. CT measurement of trunk muscle areas in patients with chronic low back pain. Diagn Interv Radiol 2007;13(3):144-148.

Lee HI, Song J, Lee HS, Kang JY, Kim M, Ryu JS. Association between Cross-Sectional Areas of Lubar Muscles on Magnetic Resonance Imaging and Chronicity of Low Back Pain. Ann Rehabil Med 2011;35:852-859.

Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Bourgois J, Dankaerts W, et al. Effects of three different training modalities on the cross sectional area of the lumbar multifidus muscle in patients with chronic low back pain. Br J Sports Med 2001;35(3):186-191.

Hides J, Stanton W, McMahon S, Sims K, Richardson C. Effect of stabilization training on multifidus muscle cross-sectional area among young elite cricketers with low back pain. J Orthop Sports Phys Ther 2008;38(3):101-108.

Key, Josephine. "'The core': understanding it, and retraining its dysfunction." Journal of bodywork and movement therapies17.4 (2013): 541-559.

Hodges, P.W., Gandevia, S.C., 2000a. Activation of the human diaphragm during a repetitive postural task. J. Physiol. 522.1, 165e175.

Hodges, P.W., Gandevia, S.C., 2000b. Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. J. Appl. Physiol. 89 (3), 967e976.

Hodges, P.W., Richardson, C.A., 1999a. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. Arch. Phys. Med. Rehabil. 80 (9), 1005e1012.

Hodges, P.W., Richardson, C.A., 1999b. Transversus abdominis and superficial abdominal muscles are controlled independently in a postural task. Neurosci. Lett. 265 (2), 91e94.

Hodges, P.W., Heijnen, I., Gandevia, S.C., 2001a. Postural activity of the diaphragm is reduced in humans when respiratory de- mand increases. J. Physiol. 15, 999e1008.

Hodges, P.W., Cresswell, A.G., Daggfeldt, K., Thorstensson, A., 2001b. In vivo measurement of the effect of intra-abdominal pressure on the human spine. J. Biomech. 34 (3), 347e353.

Hungerford, B., Gilleard, W., Hodges, P.W., 2003. Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. Spine 28 (14), 1593e1600.

Lewit, K., 2008. Lessons for the future. Int. Musculoskelet. Med. 30 (3), 133e140.

Hemborg, B., Moritz, U., 1985. Intra-abdominal pressure and trunk muscle activity during lifting, 11. Chronic low back pain pa- tients. Scand. J. Rehabil. Med. 17 (1), 5e13.

Hemborg, b, Moritz, U., Hamberg, J., Holmstro ̈m, E., Lo ̈wing, H., Akesson, I., 1985a. Intra-abdominal pressure and trunk muscle activity during lifting 111: effect of abdominal muscle training in chronic low back pain patients. Scand. J. Rehabil. Med. 17 (1), 15e24.

Hemborg, B., Moritz, U., Lo ̈wing, H., 1985b. Intra-abdominal pressure and trunk muscle activity during lifting. IV. The causal factors of the intra-abdominal pressure rise. Scand. J. Rehabil. Med. 17 (1), 25e38.

Goldish, G.D., Quast, J.E., Blow, J.J., Kuskowski, M.A., 1994. Postural effects on intra-abdominal pressure during Valsalva maneuver. Arch. Phys. Med. Rehabil. 75 (3), 324e327.

Cresswell, A.G., Thorstensson, A., 1994. Changes in intra- abdominal pressure, trunk muscle activation and force during isokinetic lifting and lowering. Eur. J. Appl. Physiol. Occup. Physiol. 68 (4), 315e321.

Cresswell, A.G., Grundstrom, H., Thorstensson, A., 1992. Observa- tions on intra-abdominal pressure and patterns of abdominal intramuscular activity in man. Acta Physiol. Scand. 144, 409e418.

Kolar, P., Sulc, J., Kyncl, M., Sanda, J., Neuwirth, J., Bokarius, A.V., Kriz, J., Kobesova, A., 2010. Stabilizing function of the diaphragm: dynamic MRI and synchronized spirometric assessment. J. Appl. Physiol. 109, 1064e1071.

Cholewicki, J., Panjabi, M., Khachatryan, A., 1997. Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. Spine 22 (19), 2207e2212.

Kolar, P., 2007. Facilitation of agonisteantagonist co-activation by reflex stimulation methods. In: Liebenson, C. (Ed.), Rehabili- tation of the Spine: A Practitioner's Manual, second ed. Lippincott Williams & Wilkins, Baltimore.

McGill, S.M., Sharratt, M.T., 1990. Relationship between intra- abdominal pressure and trunk EMG. Clin. Biomech. 5 (2), 59e67. McGill, S.M., Sharratt, M.T., Seguin, J.P., 1995. Loads on spinal tissues during simultaneous lifting and ventilatory challenge. Ergonomics 38 (9), 1772e1792.

McGill, S.M., 2002. Low Back Disorders. Human Kinetics, Cham-pagne, Illinois.

McGill, S.M., 2004. Ultimate Back Fitness. Wabuno Publishers, Waterloo, Canada.

McGill, S.M., 2009. Quoted In: Reynolds G. "Is Your Ab Workout Hurting You Back?". New York Times June 17, 2009.

Vera-Garcia, F.J., Moreside, J.M., McGill, S.M., 2011. Abdominal muscle activation changes if the purpose is to control thorax motion or pelvis motion. J. Electromyogr. Kinesiol. 21 (6), 893e903.

Kendall, F.P., McCreary, E.K., Provance, P.G., 1993. Muscles: Testing and Function, fourth ed. Williams and Wilkins, Baltimore.

Key, J., 2010b. The pelvic crossed syndromes: a reflection of imbalanced function in the myofascial envelope; a further exploration of Janda's work. J. Bodyw. Move. Ther. 14, 299e301.

Doubkova, Lucie, et al. "Diastasis of rectus abdominis muscles in low back pain patients." Journal of back and musculoskeletal rehabilitation 31.1 (2018): 107-112.

Lee DG, Lee LJ, McLaughlin L. Stability, continence and breathing: the role of fascia following pregnancy and delivery. J Bodyw Mov Ther. 2008 Oct; 12(4): 333–48.

Parker MA, Millar LA, Dugan SA. Diastasis Rectus Abdo- minis and Lumbo-Pelvic Pain and Dysfunction-Are They Re- lated? J Womens Health Phys Ther. 2009; 33(2): 15–22.

van de Water ATM, Benjamin DR. Measurement methods to assess diastasis of the rectus abdominis muscle (DRAM): A systematic review of their measurement properties and meta- analytic reliability generalisation. Man Ther. 2016 Feb; 21: 41–53.

Cheesborough JE, Dumanian GA. Simultaneous prosthetic mesh abdominal wall reconstruction with abdominoplasty for ventral hernia and severe rectus diastasis repairs. Plast Recon- str Surg. 2015 Jan; 135(1): 268–76.

Bitnar P, Stovicek J, Andel R, Arlt J, Arltova M, Smejkal M, et al. Leg raise increases pressure in lower and upper esophageal sphincter among patients with gastroesophageal reflux disease. J Bodyw Mov Ther (Internet). 2015 Dec (cited 2016 Jun 3); Available from: http//linkinghub.elsevier.com/ retrieve/pii/S1360859215002909.

Hodges PW, Eriksson AEM, Shirley D, Gandevia SC. Intra- abdominal pressure increases stiffness of the lumbar spine. J Biomech. 2005 Sep; 38(9): 1873–80.

Tayashiki K, Takai Y, Maeo S, Kanehisa H. Intra-abdominal Pressure and Trunk Muscular Activities during Abdominal Bracing and Hollowing. Int J Sports Med. 2016 Feb; 37(2): 134–43.

Stokes IAF, Gardner-Morse MG, Henry SM. Abdominal muscle activation increases lumbar spinal stability: analysis of contributions of different muscle groups. Clin Biomech Bris- tol Avon. 2011 Oct; 26(8): 797–803.

Hagins M, Lamberg EM. Individuals with low back pain breathe differently than healthy individuals during a lifting task. J Orthop Sports Phys Ther. 2011 Mar; 41(3): 141–8.

Alamer, Abayneh, Gebresilassie Kahsay, and Hariharasudhan Ravichandran. "Prevalence of Diastasis Recti and Associated Factors among Women Attending Antenatal and Postnatal Careatmekelle City Health Facilities, Tigray, Ethiopia." Age 20 (2019): 37.

Candido G, Lo T, Janssen P. Risk factors for diastasis of the recti abdominis. Assoc Chartered Physiotherapists Women's Health. 2005;97:49.

Thornton SL, Thornton SJ. Management of gross divarication of the recti abdominis in pregnancy and labour. Physiotherapy. 1993;79(7):457-8.

Benjamin DR, Van de Water AT, Peiris CL. Effects of exercise on diastasis of the rectus abdominis muscle in the antenatal and postnatal periods: a systematic review. Physiotherapy. 2014;100(1):1-8.

Rett MT, Braga MD, Bernardes NO, Andrade SC. Prevalence of diastasis of the rectus abdominis muscles immediately postpartum: comparison between primiparae and multiparae. Brazilian J Phy Ther. 2009;13(4):275-80.

Keeler J, Albrecht M, Eberhardt L, Horn L, Donnelly C, Lowe D. Diastasis recti abdominis: a survey of women's health specialists for current physical therapy clinical practice for postpartum women. J Women's Health Phy Ther. 2012;36(3):131-42.

Elkhatib H, Buddhavarapu SR, Henna H, Kassem W. Abdominal musculoaponeuretic system: magnetic resonance imaging evaluation before and after vertical plication of rectus muscle diastasis in conjunction with lipoabdominoplasty. Plast Reconstr Surg 2011;128:733ee40e.

Mesquita LA, MachadoAV, AndradeAV. Physiotherapyfor reduction of diastasis of the recti abdominis muscles in the postpartum period. Rev Bras Ginecol Obstet 1999; 21:
267 – 272.

Mommers EHH, PontenJEH,AlOmarAK,deVries Reilingh TS, Bouvy ND, Nienhuijs SW. The general surgeon's perspective of rectus diastasis. A systematic review of treatment options. Surg Endosc 2017; 31: 4934–4949.

Lee D, HodgesPW.Behaviorofthelineaalbaduringa curl-up task in diastasis rectus abdominis: an observational study. J Orthop Sports Phys Ther 2016; 46: 580–589.

Hides, Julie, and Warren Stanton. "Muscle imbalance among elite Australian rules football players: a longitudinal study of changes in trunk muscle size." Journal of Athletic training 47.3 (2012): 314-319.

Hides JA, Jull GA, Richardson CA. Long-term effects of specific stabilizing exercises for first episode low back pain. Spine (Phila Pa 1976). 2001;26(11):E243–E248.

Belavy DL, Armbrecht G, Richardson CA, Felsenberg D, Hides JA. Muscle atrophy and changes in spinal morphology: is the lumbar spine vulnerable after prolonged bed-rest? Spine (Phila Pa 1976). 2011;36(2):137–145.

Ramazzini, B. (2001). De morbis arti_cum diatriba [diseases of workers]. American journal of public health, 91(9):1380{1382.

Punnett et al., 2004. Punnett, L., Gold, J., Katz, J., Gore, R., and Wegman, D. (2004). Ergonomic stressors and upper extremity musculoskeletal disorders in automobile manufacturing: a one year follow up study. Occupational and environmental medicine, 61(8):668{674.

Fowler, 2010. Fowler, B. (2010). Built to last: The strategy behind Ford's manufacturing success.

Herington and Morse, 1995. Herington and Morse (1995). Cumulative trauma{repetitive motion injuries. Occupational Injuries. Evaluation, Management and Prevention. Mosby, 1st edition.

Rubin, 2007. Rubin, D. I. (2007). Epidemiology and risk factors for spine pain. Neurologic clinics, 25(2):353{371.

Deyo et al., 2006. Deyo, R. A., Mirza, S. K., and Martin, B. I. (2006). Back pain prevalence and visit rates: estimates from us national surveys, 2002. Spine, 31(23):2724{2727.

Webster and Snook, 1994. Webster, B. S. and Snook, S. H. (1994). The cost of 1989 workers' compensation low back pain claims. Spine, 19(10):1111{1115.

Deyo RA, Weinstein JN. Low back pain. N Engl J Med 2001;344(5):363-370.

Bergquist-Ullman M, Larsson U. Acute low back pain in industry. A controlled prospective study with special reference to therapy and

confounding factors. Acta Orthop Scand 1977;48(suppl. 170):1-117.

Von Korff M, Deyo RA, Cherkin D, Barlow W. Back pain in primary care: Outcomes at 1 year. Spine 1993;18(7):855-862.

Hides J, Gilmore C, Stanton W, Bohlscheid E. Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. Man Ther 2008;13(1):43-49.

Mengiardi B, Schmid MR, Boos N, Pfirrmann CWA, Brunner F, Elfering A, et al. Fat content of lumbar paraspinal muscles in patients with chronic low back pain and in asymptomatic volunteers: Quantification with MR spectroscopy. Radiology 2006;240(3):786-792.

Kjaer P, Bendix T, Sorensen JS, Korsholm L, Leboeuf-Yde C. Are MRI defined fat infiltrations in the multifidus muscles associated with low back pain? BMC Med 2007;5.

Kader DF, Wardlaw D, Smith FW. Correlation between the MRI changes in the lumbar multifidus muscles and leg pain. Clin Radiol 2000;55(2):145-149.

Kang CH, Shin MJ, Kim SM, Lee SH, Lee CS. MRI of paraspinal muscles in lumbar degenerative kyphosis patients and control patients with chronic low back pain. Clin Radiol 2007;62(5):479-486.

Wallwork TL, Stanton WR, Freke M, Hides JA. The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. ManTher 2009;14(5):496-500.

Lee S-, Chan CK-, Lam T-, Lam C, Lau N-, Lau RW-, et al. Relationship between low back pain and lumbar multifidus size at different postures.Spine 2006;31(19):2258-2262.

McLoughlin RF, D'Arcy EM, Brittain MM, Fitzgerald O, Masterson JB. The significance of fat and muscle areas in the lumbar paraspinal space: A CT study. J Comput Assisted Tomogr 1994;18(2):275-278).

Jorgensen MJ, Marras WS, Granata KP, Wiand JW. MRI-derived moment-arms of the female and male spine loading muscles. Clin Biomech (Bristol, Avon). 2001 Mar;16(3):182-93. doi: 10.1016/s0268-0033(00)00087-5. Erratum in: Clin Biomech (Bristol, Avon) 2001 Jul;16(6):547. PMID: 11240052.

Sesek, R.F. (1999). Evaluation and Refinement of Ergonomic Survey Tools to Evaluate Worker Risk of Cumulative Trauma Disorders (Dissertation).

Marras and Davis, 1998. Marras, W. S. and Davis, K. G. (1998). Spine loading during asymmetric lifting using one versus two hands. Ergonomics, 41(6):817{834.

Ayoub, 1989. Ayoub, M. M. (1989). Manual Materials Handling: Design And Injury Control Through Ergonomics. CRC Press.

Anderson et al., 1985. Anderson, C. K., Cha_n, D. B., Herrin, G. D., and Matthews, L. S. of Biomechanics, 18(8):571{584.

Damadian et al., 1976. Damadian, R., Goldsmith, M., and Minko_, L. (1976). NMR in cancer: XVI. FONAR image of the live human body. Physiological chemistry and physics, 9(1):97{100.

Kubo, Keitaro, Hiroaki Kanehisa, and Tetsuo Fukunaga. "Effect of stretching training on the viscoelastic properties of human tendon structures in vivo." *Journal of applied physiology* 92.2 (2002): 595-601.

Anghel, Mirella, et al. "Músculoskeletal disorders (MSDS) consequences of prolonged static postures." *J Exper Med Surg Res* 4 (2007): 167-172.

Gallagher, Sean, and William S. Marras. "Tolerance of the lumbar spine to shear: a review and recommended exposure limits." Clinical Biomechanics 27.10 (2012): 973-978.

Nourbakhsh, Mohammad Reza, and Amir Massoud Arab. "Relationship between mechanical factors and incidence of low back pain." *Journal of Orthopaedic & Sports Physical Therapy* 32.9 (2002): 447-460.

Nadler, Scott F. DO; Malanga, Gerard A. MD; Feinberg, Joseph H. MD; Prybicien, Michael ATC; Stitik, Todd P. MD; DePrince, Melissa MS Relationship Between Hip Muscle Imbalance and Occurrence of Low Back Pain in Collegiate Athletes: A Prospective Study, American Journal of Physical Medicine & Rehabilitation: August 2001 - Volume 80 - Issue 8 - p 572-577

Whittal, Mitchel C., et al. "High Load With Lower Repetitions vs. Low Load With Higher Repetitions: The Impact on Asymmetry in Weight Distribution During Deadlifting." *Frontiers in Sports and Active Living* 2 (2020).

Hall, Amanda M., et al. "Tai chi exercise for treatment of pain and disability in people with persistent low back pain: a randomized controlled trial." *Arthritis care & research* 63.11 (2011): 1576-1583.

National Research Council (US) and Institute of Medicine (US) Panel on Musculoskeletal Disorders and the Workplace. Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities. Washington (DC): National Academies Press (US); 2001. 6, Biomechanics.Available from: https://www.ncbi.nlm.nih.gov/books/NBK222434/

Kolstrup, C.L. Work-related musculoskeletal discomfort of dairy farmers and employed workers. *J Occup Med Toxicol* **7,** 23 (2012). https://doi.org/10.1186/1745-6673-7-23

Graham, James E et al. “Small sample research designs for evidence-based rehabilitation: issues and methods.” *Archives of physical medicine and rehabilitation* vol. 93,8 Suppl (2012): S111-6. doi:10.1016/j.apmr.2011.12.017

Franettovich, M., et al. "Muscle imbalance among elite athletes." *British journal of sports medicine* 45.4 (2011): 348-349.

Liu, Jing, et al. "Chen-style tai chi for individuals (aged 50 years old or above) with chronic non-specific low back pain: a randomized controlled trial." *International journal of environmental research and public health* 16.3 (2019): 517.

Hall, Amanda, et al. "The effectiveness of Tai Chi for chronic musculoskeletal pain conditions: A systematic review and meta-analysis." *Arthritis Care & Research: Official Journal of the American College of Rheumatology* 61.6 (2009): 717-724.

Hall, Amanda, et al. "Effectiveness of tai chi for chronic musculoskeletal pain conditions: updated systematic review and meta-analysis." *Physical therapy* 97.2 (2017): 227-238.

McDonald, Craig M., et al. "Profiles of neuromuscular diseases. Duchenne muscular dystrophy." *American journal of physical medicine & rehabilitation* 74.5 Suppl (1995): S70-92.

Janda, Vladimir, Clare Frank, and Craig Liebenson. "Evaluation of muscular imbalance." *Rehabilitation of the spine: a practitioner's manual* 6 (1996): 97-112.

Rupp, S., K. Berninger, and T. Hopf. "Shoulder problems in high level swimmers-impingement, anterior instability, muscular imbalance?." *International journal of sports medicine*16.08 (1995): 557-562.

Roth, Stephen M., et al. "Inflammatory factors in age-related muscle wasting." *Current opinion in rheumatology* 18.6 (2006): 625-630.

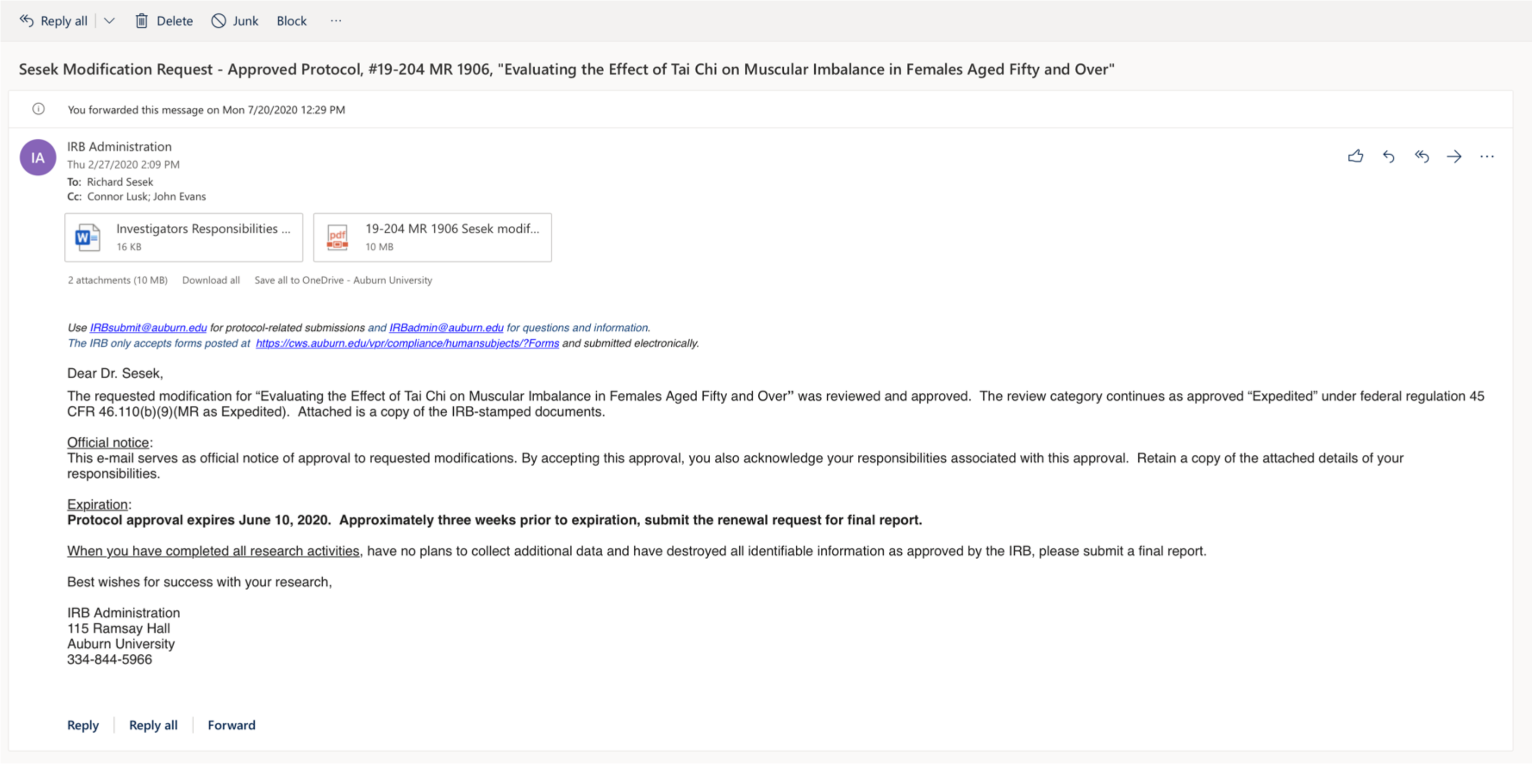
Iwasaki, Shinichi, and Tatsuya Yamasoba. "Dizziness and imbalance in the elderly: age-related decline in the vestibular system." *Aging and disease* 6.1 (2015): 38.

Bansal, Symron, Wendy B. Katzman, and Lora M. Giangregorio. "Exercise for improving age-related hyperkyphotic posture: a systematic review." Archives of physical medicine and rehabilitation 95.1 (2014): 129-140.

Modi, Hitesh, et al. "Muscle imbalance in volleyball players initiates scoliosis in immature spines: a screening analysis." *Asian spine journal* 2.1 (2008): 38.

Appendices

Appendix 1



Sesek Modification Request - Approved Protocol, #19-204 MR 1906, "Evaluating the Effect of Tai Chi on Muscular Imbalance in Females Aged Fifty and Over"

You forwarded this message on Mon 7/20/2020 12:29 PM

IRB Administration
Thu 2/27/2020 2:09 PM
To: Richard Sesek
Cc: Connor Lusk; John Evans

Use IRBsubmit@auburn.edu for protocol-related submissions and IRBadmin@auburn.edu for questions and information.
The IRB only accepts forms posted at https://cws.auburn.edu/vpr/compliance/humansubjects/?Forms and submitted electronically.

Dear Dr. Sesek,

The requested modification for “Evaluating the Effect of Tai Chi on Muscular Imbalance in Females Aged Fifty and Over” was reviewed and approved. The review category continues as approved “Expedited” under federal regulation 45 CFR 46.110(b)(9)(MR as Expedited). Attached is a copy of the IRB-stamped documents.

Official notice:
This e-mail serves as official notice of approval to requested modifications. By accepting this approval, you also acknowledge your responsibilities associated with this approval. Retain a copy of the attached details of your responsibilities.

Expiration:
Protocol approval expires June 10, 2020. Approximately three weeks prior to expiration, submit the renewal request for final report.

When you have completed all research activities, have no plans to collect additional data and have destroyed all identifiable information as approved by the IRB, please submit a final report.

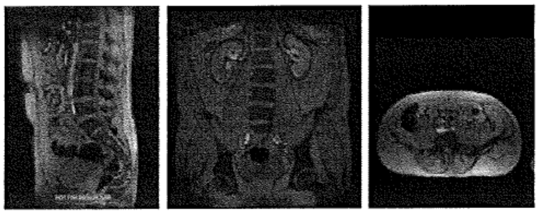
Best wishes for success with your research,

IRB Administration
115 Ramsay Hall
Auburn University
334-844-5966

Appendix 2

Effect of Tai Chi on Low Back and Trunk Muscular Imbalances Research Study

- Are you a female?
- Are you 50 years of age or older?



- Are you willing to participate in an MRI study?
- Are you willing to consider participating in a Tai Chi exercise class?

*If you answered **YES** to these questions, you may be eligible to participate in the following study:*

Evaluating the Effect of Tai Chi on Muscular Imbalance in Females Aged Fifty and Over

The purpose of this study is to establish whether muscular imbalance is related to low back pain (LBP). Previous research has demonstrated the positive benefits of performing Tai Chi exercises. This research seeks to determine if performing Tai Chi exercises reduces these imbalances and if these imbalances are indeed associated with low back pain.

There is no direct benefit to you for participating in the study. Participants will receive monetary compensation for participating. Participants will receive $40.00 for Phase I. Subjects participating in Phase II will be compensated $4.00 per weekly survey and $40.00 for a second MRI at the conclusion of the study. The Tai Chi Intervention group will be compensated $10.00 per class during the six (6) week intervention period.

This study is being conducted by the Industrial and Systems Engineering Department at Auburn University. MRI images will be captured at the Auburn University MRI Research Center. Tai Chi classes will be at Frank Brown Recreation Center.

Please contact Connor Lusk (cbl0020@auburn.edu - (334) 618-6294), or Dr. Richard Sesek (sesek@auburn.edu - (334) 728-1438) for more information.

The Auburn University Institutional
Review Board has approved this
Document for use from
06/11/2019 to 06/10/2020
Protocol # 19-204 MR 1906

Appendix 3

Intake Form

1. Are you currently practicing Tai Chi? yes no

   If yes, please describe for how long (months/years) you have been practicing?

   ____

   If yes, how often do you perform Tai Chi in a typical week?

   ____

2. Have you had a hysterectomy? yes no

3. Have you had an oophorectomy? yes no

4. Do you smoke? yes no ex-smoker

   If yes, how many packs per day? ________________

   If yes, how many packs have you smoked per year?

   ____

   If ex-smoker, how many packs per day for how many years did you smoke (e.g. 1 pack per day for 10 years)? ________________________________

5. Have you been diagnosed with osteoporosis? yes no

6. Have you been diagnosed with heart attacks? yes no

   If yes, to what extent has it had an effect on your daily life?

   |---|

   0 (no effect) 10 (completely debilitating)

   (circle 0 if no effect)

7. Have you been diagnosed with blood clots? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

8. Have you been diagnosed with hypertension? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

9. Have you been diagnosed with high cholesterol? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

10. Have you been diagnosed with diabetes? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

11. Have you been diagnosed with obesity? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

12. Have you been diagnosed with sciatica? yes no

If yes, to what extent has it had an effect on your daily life?

|--|

0 (no effect) 10 (completely debilitating)

(circle 0 if no effect)

13. Have you ever had children? yes no

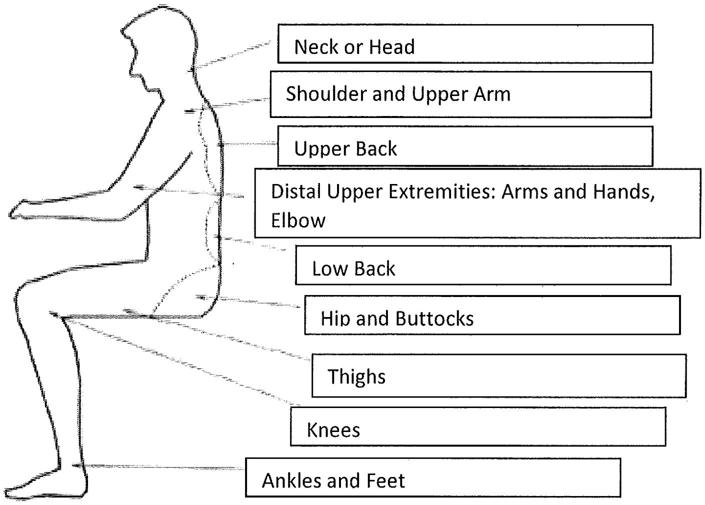
If yes, how many children have you had? ________________

14. Are you pre- or post-menopausal? ________________

15. In a typical week, this is how much I exercise (hours/ week).

____

16. Please indicate on the scales below the level of pain or discomfort in each region indicated.



Neck or Head Pain Rating this past week (maximum discomfort experienced)

|---|

0
(nothing at all)

10
(worst imaginable)

(circle 0 if no discomfort)

Shoulder and Upper Arm Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Upper Back Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Distal Upper Extremities Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Low Back Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Hip and Buttock Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Thigh Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Knee Pain Rating this past week (maximum discomfort experienced)

|--|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Ankles and Feet Pain Rating this past week (maximum discomfort experienced)

|--|

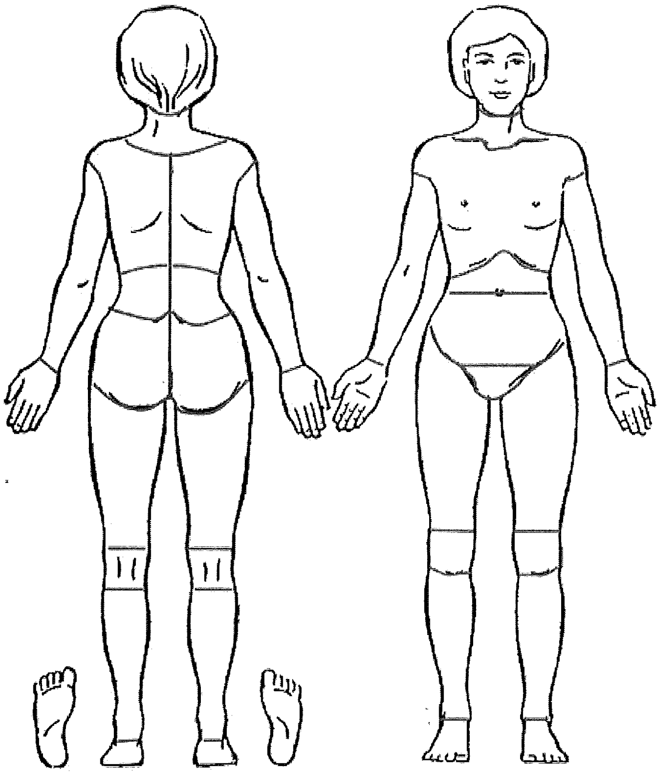
0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

17. Please shade or use X's to denote the parts of the back on the figures below that you are experiencing pain.

    Please indicate whether the pain is to the left, right or both sides of the body with shading or X's.

    If the pain radiates down the leg, please draw an arrow down the leg in which you are experiencing pain in.



NASM™
NATIONAL ACADEMY OF SPORTS MEDICINE

Data Collection Sheet

NAME:______________________________ DATE:______________

HEIGHT:________in. WEIGHT:__________lbs. AGE:_________

PHYSICIANS NAME:____________________ PHONE:__________

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

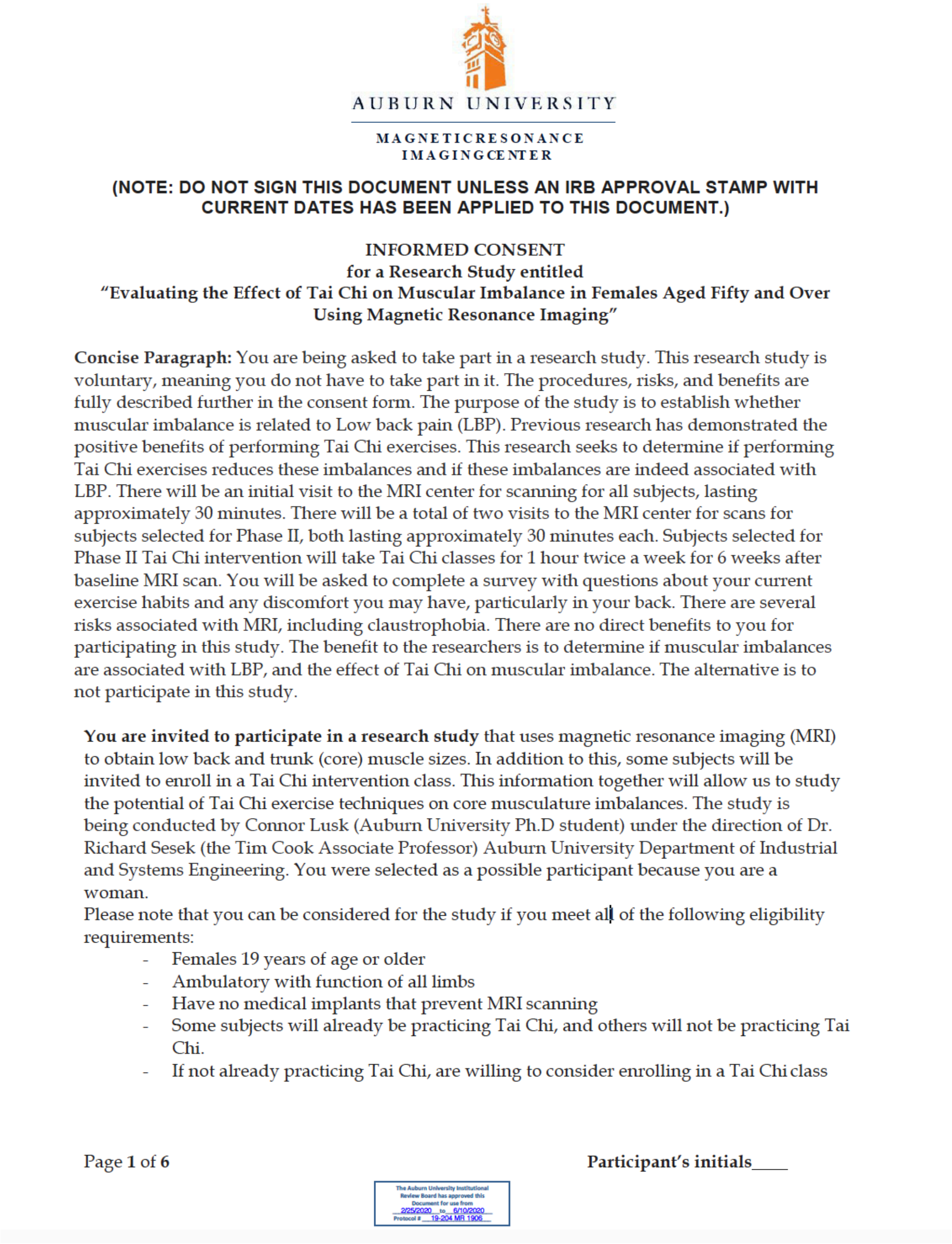
	Questions	Yes	No
1	Has your doctor ever said that you have a heart condition and that you should only perform physical activity recommended by a doctor?		
2	Do you feel pain in your chest when you perform physical activity?		
3	In the past month, have you had chest pain when you were not performing any physical activity?		
4	Do you lose your balance because of dizziness or do you ever lose consciousness?		
5	Do you have a bone or joint problem that could be made worse by a change in your physical activity?		
6	Is your doctor currently prescribing any medication for your blood pressure or for a heart condition?		
7	Do you know of <u>any</u> other reason why you should not engage in physical activity?		

If you have answered "Yes" to one or more of the above questions, you are advised to consult your physician or health care provider before engaging in physical activity. Seek advice from your physician or health care provider on what type of activity is suitable for your current condition. If you have already spoken to your healthcare provider regarding exercises that are suitable for your current condition, please indicate here:

____

Subject Signature

Appendix 4



AUBURN UNIVERSITY

MAGNETIC RESONANCE
IMAGING CENTER

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for a Research Study entitled
"Evaluating the Effect of Tai Chi on Muscular Imbalance in Females Aged Fifty and Over Using Magnetic Resonance Imaging"

Concise Paragraph: You are being asked to take part in a research study. This research study is voluntary, meaning you do not have to take part in it. The procedures, risks, and benefits are fully described further in the consent form. The purpose of the study is to establish whether muscular imbalance is related to Low back pain (LBP). Previous research has demonstrated the positive benefits of performing Tai Chi exercises. This research seeks to determine if performing Tai Chi exercises reduces these imbalances and if these imbalances are indeed associated with LBP. There will be an initial visit to the MRI center for scanning for all subjects, lasting approximately 30 minutes. There will be a total of two visits to the MRI center for scans for subjects selected for Phase II, both lasting approximately 30 minutes each. Subjects selected for Phase II Tai Chi intervention will take Tai Chi classes for 1 hour twice a week for 6 weeks after baseline MRI scan. You will be asked to complete a survey with questions about your current exercise habits and any discomfort you may have, particularly in your back. There are several risks associated with MRI, including claustrophobia. There are no direct benefits to you for participating in this study. The benefit to the researchers is to determine if muscular imbalances are associated with LBP, and the effect of Tai Chi on muscular imbalance. The alternative is to not participate in this study.

You are invited to participate in a research study that uses magnetic resonance imaging (MRI) to obtain low back and trunk (core) muscle sizes. In addition to this, some subjects will be invited to enroll in a Tai Chi intervention class. This information together will allow us to study the potential of Tai Chi exercise techniques on core musculature imbalances. The study is being conducted by Connor Lusk (Auburn University Ph.D student) under the direction of Dr. Richard Sesek (the Tim Cook Associate Professor) Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because you are a woman.

Please note that you can be considered for the study if you meet all of the following eligibility requirements:

- Females 19 years of age or older
- Ambulatory with function of all limbs
- Have no medical implants that prevent MRI scanning
- Some subjects will already be practicing Tai Chi, and others will not be practicing Tai Chi.
- If not already practicing Tai Chi, are willing to consider enrolling in a Tai Chi class

Page **1** of **6** **Participant's initials____**

The Auburn University Institutional
Review Board has approved this
Document for use from
2/25/2020 to 6/10/2020
Protocol # 19-204 MR 1906

Also please be aware that your de-identified data will be shared with the Edward Via School of Osteopathic Medicine (VCOM). VCOM is partnering with Auburn University for this study.

What will be involved if you participate?

If you decide to participate in this research study, you will be asked a undergo magnetic resonance imaging (MRI) scan. You will first be asked screening questions to make sure it is safe for you to undergo an MRI scan. You will then be asked to lie on a bed that slides into the long tube of the scanner. The scanner is a magnet with a small-enclosed space. Radio waves and strong, changing magnetic fields are used to make images of your body. You will be given earplugs and earphones to protect your ears since these changing magnetic fields cause loud knocking, thumping, and pinging noises. You will be asked to remain very still at these times. To help you keep your head perfectly still, we will put cushions around your head. Each scan lasts about 10 minutes and will not exceed 30 minutes in the scanner. Each scan will obtain MRI pictures of the low back and trunk muscles from the lumbar 2 to the lumbar 5 region of your back. Your total time commitment will be approximately 30 minutes for the scan. You will also be asked to complete a short questionnaire (~20 minutes). Total time for this portion of the study should not exceed 1 hour. Please note that none of the scans done during this study are appropriate for clinical interpretation. This means that they are not designed to assess any medical condition you may have. They are not designed to reveal any clinically relevant problems. Rather, they are intended solely for research purposes. The surveys will gather information about your exercise habits, body discomfort, and overall wellness.

Incidental Findings: These procedures are carried out purely for experimental purposes. The MRI scans that are acquired in this study are not the same as those acquired during a clinical examination as requested by a Medical doctor. Therefore they are not useful to investigate any abnormalities or medical condition you may have. Furthermore, the investigators who will analyze these images are not medical doctors and are not trained to evaluate these scans.

It is possible however that an abnormality may be noticed. If this happens, a brief diagnostic scan will be performed and referred to a radiologist for reading. If you choose to provide the name and contact information of your primary physician, the results of the scan will be provided to them. If you no not have primary physician or do not provide contact information for your primary care physician, the results will be provided to Dr. Fred Kam, M.D. at the Auburn University Medical Clinic, who will discuss the results of the scan with you at your expense. If you would like, you may list your primary care physician here:

____

Phase I will include 60 participants scanned at baseline: 30 practitioners and 30 non-practitioners.

Phase II will include 3 subsets of 10 each — 10 practitioners, randomly selected to continue into Phase II, 10 from the non-practitioner group that are invited to and agree to participate in Tai Chi (intervention), and 10 from the non-practitioner group that are asked to continue their normal exercise routines (control).

Phase I: Baseline MRI and Survey

Thirty (30) subjects will be recruited from the community Tai Chi classes. Potential subjects will be screened to ensure that they meet inclusion criteria. Subjects will be given a consent form in person by Ms. Lusk before participation. The Tai Chi group subjects will practice Tai Chi regularly for at least 2 days a week for 1 hour during the duration of the study through the community classes at Frank Brown Recreation Center. Subjects will be administered a weekly survey that includes self-reported low back pain as well as a log of their weekly exercise activities.

Thirty (30) control group subjects will be recruited from church groups, community centers, and by word of mouth. Potential subjects will be screened to ensure that they meet inclusion criteria. Subjects must not be current practitioners of Tai Chi. Subjects will be given a consent form in person by Ms. Lusk before participation. Subjects will be administered a weekly survey that includes self-reported low back pain as well as a log of their weekly exercise activities.

Phase II: Prospective Study with Follow-Up MRI and Weekly Surveys

Phase II will include 3 subsets of 10 each — 10 practitioners, randomly selected to continue into Phase II, 10 from the non-practitioners that are invited to and agree to participate in Tai Chi, and 10 from the non-practitioners that are not asked to do anything different. The current Tai Chi practitioners will continue to do Tai Chi twice a week, and are not asked to do anything additional than their current Tai Chi regimen. The first group of non-practitioners will continue their normal routine, and are asked to continue their normal exercise routines (control). The second group of non-Tai Chi practitioners will participate in a Tai Chi intervention. The Tai Chi intervention will take place at the Frank Brown Recreation center. Participants will be the 10 subjects from the non-practitioners that are invited to and agree to participate in Tai Chi. The Tai Chi intervention will be twice a week for one hour at a time. The intervention only consists of the Tai Chi class under the supervision of the professional instructor.

Are there any risks or discomforts?

The risks associated with participating in this study are:

1. The most obvious personal risk from having an MRI is blunt trauma due to metallic objects being brought into the magnetic field. As such, all necessary steps will be taken to make sure neither you nor anyone else who enters the MRI scanner room is in possession of an unrestrained metal object and no unauthorized person will be allowed to enter the MRI scanner room.
2. Participants who have iron or steel implants or clips from surgery within their body or metallic objects such as shrapnel or metal slivers in their body may be pulled by the magnet and cause injury.

3. The MRI machine produces an intermittent loud noise, which some people find annoying.
4. Some participants may feel uncomfortable being in an enclosed place (claustrophobia) and others find it difficult to remain still.
5. Some people experience dizziness or a metallic taste in their mouth if they move their head rapidly in the magnet.
6. Some people experience brief nausea when being put into or taken out of the scanner.

Although long-term risk of exposure to the magnet is not known, the possibility of any long term risk is extremely low based on information accumulated over the past 30 years.

To minimize these risks, we will:

1. Have you fill out a screening form to determine if you have iron or steel implants, clips from surgery, or other metallic objects in your body. If you have implants, clips, or objects in your body, you will not be able to undergo an MRI scan.
2. Ask you to change into surgical scrubs supplied by the center and remove any watches, rings, earrings, or other jewelry or metallic objects. You will be provided a private place to change and you may retain your undergarments. You will be asked to remove your bra if it has an underwire or metal fasteners.
3. Scan you with a handheld metal detector to detect any unknown metallic objects.
4. Provide you with either earplugs or a set of headphones specifically designed to work in an MRI scanner.
5. Maintain visual and verbal contact with you during the scan and check with you frequently to determine if you are having any negative feelings or sensations.
6. If some unknown risk becomes a safety issue, the research team will immediately stop the scan and remove you from the scanner.
7. You can stop the scan at any time and be immediately removed from the scanner.

Some participants will be asked to participate in Tai Chi exercise. Risk will be mitigated by having a professional instructor teach the classes while watching the participants form, technique, and pace. Participants have time to rest and recover between Tai Chi classes. Our intervention is 2 classes/week. Subjects may do more on their own, but are not asked/required to do so.

The physical activity of the Tai Chi exercise intervention may result in muscle soreness and fatigue for some subjects, as with any exercise regimen. Tai Chi is low impact, and was specifically chosen due to this, and has shown to have physical benefits. Participants in the intervention group will be guided by a professional instructor. Other subjects are not asked to do anything beyond their normal routines.

Are there any benefits to yourself or others? If you participate in this study, you can expect to receive no direct benefits. Your participation, however, provides the investigator with a greater understanding of the effect of Tai Chi exercise on muscular imbalance throughout the trunk/core musculature.

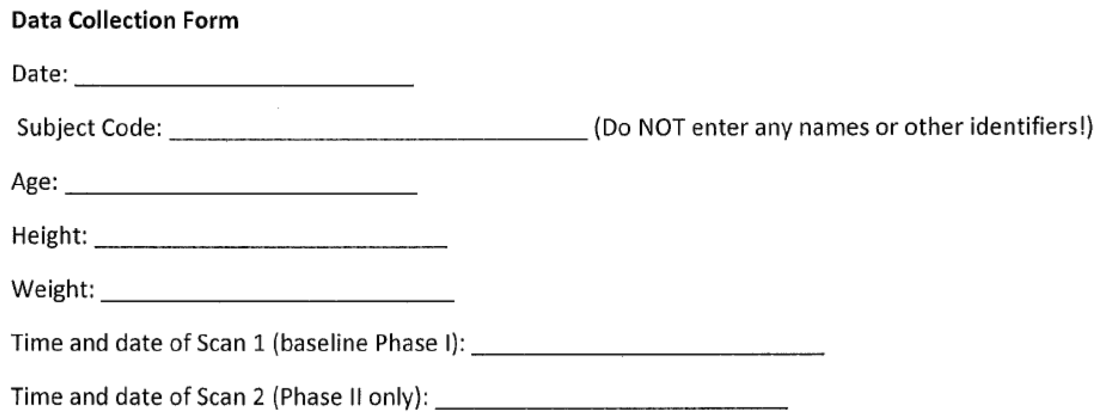
Will you receive compensation for participating?
Participants will receive $40.00 for Phase I (including MRI). Subjects participating in Phase II will be compensated $4.00 per weekly survey and $40.00 for a second MRI at the conclusion of the study. The Tai Chi Intervention group will be compensated $10.00 per class during the six (6) week intervention period.

Are there any costs? If you decide to participate, you will not incur any costs. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose not to participate after the pre-consent procedure or if you are determined not to be eligible for the study after the pre-consent procedure, then the initial pre-consent data will be destroyed. You may cease participation at any time. You will receive prorated compensation for the percentage of the experiment you complete. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, the Samuel Ginn College of Engineering, the Department of Industrial and Systems Engineering, or the Edward Via College of Osteopathic Medicine.

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. Information obtained through your participation may be used to fulfill an educational requirement, published in a professional journal and/or presented at a professional meeting. Your personal information will be linked to the study data using a randomly-generated code. It is possible, that we may contact you about participation in future studies. However, if you do not wish to be contacted in the future, please indicate when signing this consent form and we will delete all links between your personal identifying information and your study data. The confidential link between your personal information and the study data will be stored in a locked filing cabinet in the principal investigator's office.

Appendix 5



Data Collection Form

Date: ______________________________

Subject Code: ______________________________ (Do NOT enter any names or other identifiers!)

Age: ______________________________

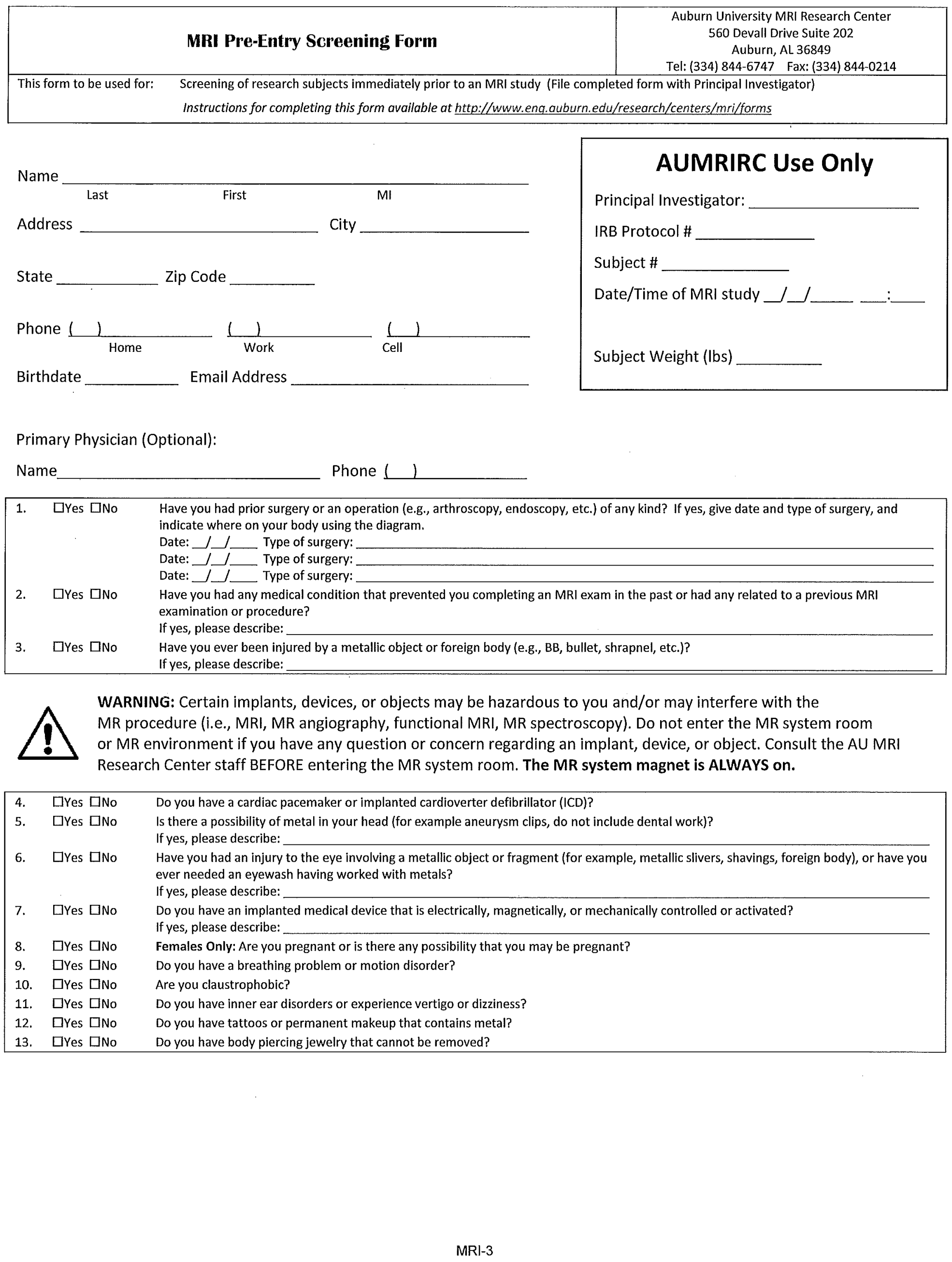
Height: ______________________________

Weight: ______________________________

Time and date of Scan 1 (baseline Phase I): ______________________________

Time and date of Scan 2 (Phase II only): ______________________________

Appendix 6



MRI Pre-Entry Screening Form

Auburn University MRI Research Center
560 Devall Drive Suite 202
Auburn, AL 36849
Tel: (334) 844-6747 Fax: (334) 844-0214

This form to be used for: Screening of research subjects immediately prior to an MRI study (File completed form with Principal Investigator)

Instructions for completing this form available at http://www.eng.auburn.edu/research/centers/mri/forms

Name ____
Last First MI

Address ________________________ City ________________

State __________ Zip Code _________

Phone (__)__________ (__)__________ (__)__________
Home Work Cell

Birthdate __________ Email Address ________________________

AUMRIRC Use Only

Principal Investigator: __________________

IRB Protocol # ____________

Subject # ____________

Date/Time of MRI study __/__/____ ___:___

Subject Weight (lbs) _________

Primary Physician (Optional):

Name____________________________ Phone (__)___________

1. ☐Yes ☐No Have you had prior surgery or an operation (e.g., arthroscopy, endoscopy, etc.) of any kind? If yes, give date and type of surgery, and indicate where on your body using the diagram.
Date: __/__/____ Type of surgery: ______________________
Date: __/__/____ Type of surgery: ______________________
Date: __/__/____ Type of surgery: ______________________
2. ☐Yes ☐No Have you had any medical condition that prevented you completing an MRI exam in the past or had any related to a previous MRI examination or procedure?
If yes, please describe: ______________________
3. ☐Yes ☐No Have you ever been injured by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc.)?
If yes, please describe: ______________________

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). Do not enter the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the AU MRI Research Center staff BEFORE entering the MR system room. **The MR system magnet is ALWAYS on.**

4. ☐Yes ☐No Do you have a cardiac pacemaker or implanted cardioverter defibrillator (ICD)?
5. ☐Yes ☐No Is there a possibility of metal in your head (for example aneurysm clips, do not include dental work)?
If yes, please describe: ______________________
6. ☐Yes ☐No Have you had an injury to the eye involving a metallic object or fragment (for example, metallic slivers, shavings, foreign body), or have you ever needed an eyewash having worked with metals?
If yes, please describe: ______________________
7. ☐Yes ☐No Do you have an implanted medical device that is electrically, magnetically, or mechanically controlled or activated?
If yes, please describe: ______________________
8. ☐Yes ☐No **Females Only:** Are you pregnant or is there any possibility that you may be pregnant?
9. ☐Yes ☐No Do you have a breathing problem or motion disorder?
10. ☐Yes ☐No Are you claustrophobic?
11. ☐Yes ☐No Do you have inner ear disorders or experience vertigo or dizziness?
12. ☐Yes ☐No Do you have tattoos or permanent makeup that contains metal?
13. ☐Yes ☐No Do you have body piercing jewelry that cannot be removed?

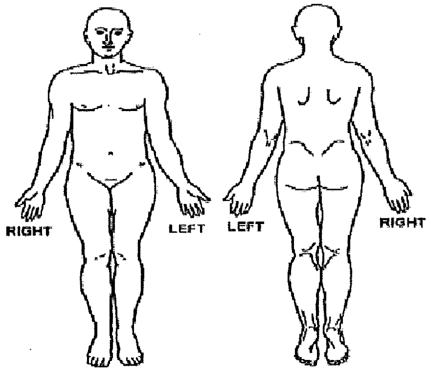
MRI-3

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). Do not enter the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the AU MRI Research Center staff BEFORE entering the MR system room. **The MR system magnet is ALWAYS on.**

Please indicate if you have any of the following:

14. ☐Yes ☐No Neurostimulation system
15. ☐Yes ☐No Spinal cord stimulator
16. ☐Yes ☐No Internal electrodes or wires
17. ☐Yes ☐No Bone growth/bone fusion stimulator
18. ☐Yes ☐No Cochlear, otologic, or other ear implant
19. ☐Yes ☐No Insulin or other infusion pump
20. ☐Yes ☐No Implanted drug infusion device
21. ☐Yes ☐No Any type of prosthesis (eye, penile, etc.)
22. ☐Yes ☐No Heart valve prosthesis
23. ☐Yes ☐No Eyelid spring or wire
24. ☐Yes ☐No Artificial or prosthetic limb
25. ☐Yes ☐No Metallic stent, filter, or coil
26. ☐Yes ☐No Shunt (spinal or intraventricular)
27. ☐Yes ☐No Vascular access port and/or catheter
28. ☐Yes ☐No Radiation seeds or implants
29. ☐Yes ☐No Swan-Ganz or thermodilution catheter
30. ☐Yes ☐No Medication patch (Nicotine, Nitroglycerine)
31. ☐Yes ☐No Any metallic fragment or foreign body
32. ☐Yes ☐No Wire mesh implant
33. ☐Yes ☐No Tissue expander (e.g., breast)
34. ☐Yes ☐No Surgical staples, clips, or metallic sutures
35. ☐Yes ☐No Joint replacement (hip, knee, etc.)
36. ☐Yes ☐No Bone/joint pin, screw, nail, wire, plate, etc.
37. ☐Yes ☐No IUD, diaphragm, or pessary
38. ☐Yes ☐No Dentures or partial plates
39. ☐Yes ☐No Tattoo or permanent makeup
40. ☐Yes ☐No Body piercing jewelry
41. ☐Yes ☐No Hearing aid (*Remove before entering MRI scanner room*)
42. ☐Yes ☐No Other implant ____________________

Please mark on the figure(s) below the location of any implant or metal inside of or on your body.



IMPORTANT INSTRUCTIONS

Before entering the MR scanner room, you must remove all metallic objects including hearing aids, dentures, partial plates, keys, beeper, cell phone, eyeglasses, hair pins, barrettes, jewelry, body piercing jewelry, watch, safety pins, paperclips, money clip, credit cards, bank cards, magnetic strip cards, coins, pens, pocket knife, nail clippers, tools, clothing with metal fasteners, & clothing with metallic threads.

Please consult the research staff if you have any question or concern BEFORE you enter the MR scanner room.

NOTE: You may be advised or required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.

I attest that the above information is correct to the best of my knowledge. I read and understand the contents of this form and had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that I am about to undergo.

This form is valid only on the day it is completed.

Signature of Person Completing Form: ______________________________ Signature ______________ Date

Form Completed By: ☐ Subject ☐ Relative ______________________ Print Name ______________ Relationship to Subject

Form Information Reviewed By: ______________________ Print Name ______________ Signature

Form Information Reviewed By: ______________________ Print Name ______________ Signature

Appendix 7

Weekly Survey

SUBJECT IDENTIFICATION #: __________ DATE: ______

WEIGHT: ________

For this past week, including today:

Please describe your current, regular exercise activities (please include Tai Chi) that go beyond normal activities of daily life (such as walking to the store, work, church, etc.)

Tai Chi this past week: yes no (if yes, please describe)
times per week _____
duration of exercise per session _____

Calisthenics/stretching (yoga, stretching, etc.) this past week: yes no (if yes, please describe)
times per week _____
duration of exercise per session _____

Weightlifting or resistance training this past week: yes no (if yes, please describe)
times per week _____
duration of exercise per session _____

Aerobic/cardiovascular training (including running, exercise classes, martial arts, etc.): this past week: yes no (if yes, please describe)
times per week _____
duration of exercise per session _____

Discomfort

Visual Analog Scales

Low Back Pain Rating this past week (maximum discomfort experienced)

|---|

0 10
(nothing at all) (worst imaginable)

(circle 0 if no discomfort)

Leg/lower extremity this past week (maximum discomfort experienced)

|---|

0 10
(nothing at all) (worst imaginable)

Neck/shoulder this past week (maximum discomfort experienced)

|---|

0 10
(nothing at all) (worst imaginable)

Wellness

With regard to my **health,** this past week, I felt_______ overall.

|---|

0 10
(terrible) (really great)

Rest/Recovery

This past week, I slept an average of _____ hours/night. The overall quality of my sleep was.

|---|

0 (terrible)   10 (really great)

Appendix 8

Chapter 3 T-Test Results

Table 8.1 MI_{CSA} and Exerciser Status T-Test Results

	MI_{CSA} P-Values			
	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	0.84	0.95	**0.01***	0.16
Psoas	0.68	0.16	0.83	0.25
Oblique	0.72	0.80	0.35	0.78
Rectus Abdominus	0.48	0.29	0.26	0.40
Quadratus Lumborum	0.28	0.54	0.83	---†
Paraspinal Group	0.53	0.15	0.64	0.46
Core Group	0.79	0.87	0.25	0.52
Lateral (Left/Right) Hemisphere	0.73	0.23	0.15	0.49

† QL does not extend to this level in most subjects and therefore was not used
*Correlation is significant at the 0.05 level
** Correlation is trending towards significance at the 0.05 level

Table 8.2: MI_{New} and Exerciser Status T-Test Results

	MI_{New} P-Values			
	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	0.38	0.12	0.57	0.67
Psoas	0.97	0.93	0.94	0.15
Oblique	0.57	0.96	0.42	0.56
Rectus Abdominus	0.85	**0.09****	0.40	0.96
Quadratus Lumborum	0.50	0.79	0.87	---†
Paraspinal Group	0.16	0.45	0.73	0.91
Core Group	0.43	0.92	0.56	0.58
Lateral (Left/Right) Hemisphere	0.69	0.88	0.72	0.43

† QL does not extend to this level in most subjects and therefore was not used
*Correlation is significant at the 0.05 level
** Correlation is trending towards significance at the 0.05 level

.

Table 8.3: MI_{CSA} and LBP T-Test Results

	MI_{CSA} P-Values			
	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	0.19	0.82	**0.02***	0.30
Psoas	0.70	0.43	0.97	0.20
Oblique	0.30	0.53	0.63	0.31
Rectus Abdominus	0.45	0.21	0.66	0.52
Quadratus Lumborum	0.31	0.47	0.63	---†
Paraspinal Group	0.92	0.79	0.24	0.49
Core Group	0.53	0.72	0.49	0.12
Lateral (Left/Right) Hemisphere	0.51	0.68	0.85	0.13

† QL does not extend to this level in most subjects and therefore was not used
*Correlation is significant at the 0.05 level
** Correlation is trending towards significance at the 0.05 level

Table 8.4: MI_{New} and LBP T-Test Results

	MI_{New} P-Values			
	L2/L3	L3/L4	L4/L5	L5/S1
Erector Spinae	**0.05***	0.15	**0.04***	0.41
Psoas	0.49	0.50	0.36	**0.08****
Oblique	0.13	0.38	0.86	0.47
Rectus Abdominus	0.95	0.74	0.37	0.70
Quadratus Lumborum	0.82	**0.08****	0.73	---†
Paraspinal Group	0.25	0.40	**0.07****	**0.00***
Core Group	0.11	0.23	0.94	0.27
Lateral (Left/Right) Hemisphere	0.21	0.14	0.55	**0.03***

† QL does not extend to this level in most subjects and therefore was not used
*Correlation is significant at the 0.05 level
** Correlation is trending towards significance at the 0.05 level

Appendix 9

Chapter 4 ANOVA Baseline Results

MI$_{New}$ Comparison Between Tai Chi Practitioners, Non-Exercisers, Exercisers at Baseline

Descriptive Statistics

		Mean	Std. Deviation
MI New Erector Spinae L2/L3	Non-Exerciser	19.48	11.76
	Exerciser	16.24	9.89
	Tai Chi	14.88	7.40
	Total	16.46	9.29
MI New Erector Spinae L3/L4	Non-Exerciser	10.01	7.43
	Exerciser	17.44	8.82
	Tai Chi	23.40	19.96
	Total	17.97	14.14
MI New Erector Spinae L4/L5	Non-Exerciser	16.15	14.13
	Exerciser	12.33	7.72
	Tai Chi	14.77	10.34
	Total	14.02	9.97
MI New Erector Spinae L5/S1	Non-Exerciser	16.97	12.20
	Exerciser	18.88	9.17
	Tai Chi	18.69	7.90
	Total	18.39	9.17

		Mean	Std. Deviation
MI New Psoas L2/L3	Non-Exerciser	24.03	8.85
	Exerciser	22.15	12.09
	Tai Chi	25.51	18.88
	Total	23.81	14.03
MI New Psoas L3/L4	Non-Exerciser	15.56	7.47
	Exerciser	13.76	9.20
	Tai Chi	18.79	15.21
	Total	15.94	11.27
MI New Psoas L4/L5	Non-Exerciser	12.14	7.73
	Exerciser	9.56	8.70
	Tai Chi	16.06	14.26
	Total	12.43	10.87
MI New Psoas L5/S1	Non-Exerciser	9.55	6.15
	Exerciser	20.02	8.51
	Tai Chi	16.04	19.11
	Total	16.37	12.93

		Mean	Std. Deviation
MI New Oblique L2/L3	Non-Exerciser	12.45	8.21
	Exerciser	16.85	14.61
	Tai Chi	14.32	11.30
	Total	14.93	11.94
MI New Oblique L3/L4	Non-Exerciser	11.42	4.89
	Exerciser	12.43	15.94
	Tai Chi	10.87	9.56
	Total	11.65	11.79
MI New Oblique L4/L5	Non-Exerciser	9.77	10.75
	Exerciser	13.84	10.26
	Tai Chi	16.01	18.10
	Total	13.75	13.38
MI New Oblique L5/S1	Non-Exerciser	20.96	14.42
	Exerciser	23.18	10.95
	Tai Chi	26.70	16.46
	Total	23.86	13.38

		Mean	Std. Deviation
MI New Rectus Abdominus L2/L3	Non-Exerciser	29.27	19.19
	Exerciser	38.52	17.55
	Tai Chi	22.32	13.03
	Total	30.46	17.36
MI New Rectus Abdominus L3/L4	Non-Exerciser	42.15	6.17
	Exerciser	26.62	14.85
	Tai Chi	35.21	16.19
	Total	33.02	14.93
MI New Rectus Abdominus L4/L5	Non-Exerciser	27.29	13.09
	Exerciser	20.61	16.77
	Tai Chi	23.36	9.66
	Total	23.02	13.57
MI New Rectus Abdominus L5/S1	Non-Exerciser	29.26	13.31
	Exerciser	18.63	18.61
	Tai Chi	42.13	20.77
	Total	28.83	20.56

		Mean	Std. Deviation
MI New Quadratus Lumborum L2/L3	Non-Exerciser	23.47	20.38
	Exerciser	28.17	17.81
	Tai Chi	31.15	21.54
	Total	28.23	19.26
MI New Quadratus Lumborum L3/L4	Non-Exerciser	21.21	13.41
	Exerciser	23.83	14.72
	Tai Chi	14.50	7.96
	Total	19.93	12.68
MI New Quadratus Lumborum L4/L5	Non-Exerciser	28.14	17.46
	Exerciser	20.97	24.72
	Tai Chi	32.46	30.98
	Total	26.61	25.55

		Mean	Std. Deviation
MI New Paraspinal Muscle Group L2/L3	Non-Exerciser	20.02	11.20
	Exerciser	15.96	10.31
	Tai Chi	10.42	8.40
	Total	14.81	10.18
MI New Paraspinal Muscle Group L3/L4	Non-Exerciser	10.94	8.58
	Exerciser	12.85	8.36
	Tai Chi	18.33	17.41
	Total	14.40	12.36
MI New Paraspinal Muscle Group L4/L5	Non-Exerciser	10.96	5.03
	Exerciser	11.22	8.88
	Tai Chi	13.65	9.91
	Total	12.03	8.43
MI New Paraspinal Muscle Group L5/S1	Non-Exerciser	14.39	11.17
	Exerciser	12.79	11.76
	Tai Chi	15.19	7.64
	Total	13.95	10.08

		Mean	Std. Deviation
MI New Core Muscle Group L2/L3	Non-Exerciser	11.26	6.72
	Exerciser	16.97	14.03
	Tai Chi	13.76	10.10
	Total	14.51	11.18
MI New Core Muscle Group L3/L4	Non-Exerciser	13.25	5.66
	Exerciser	12.83	15.16
	Tai Chi	12.56	10.64
	Total	12.82	11.72
MI New Core Muscle Group L4/L5	Non-Exerciser	11.50	9.30
	Exerciser	13.94	9.00
	Tai Chi	15.90	17.01
	Total	14.12	12.17
MI New Core Muscle Group L5/S1	Non-Exerciser	21.69	14.03
	Exerciser	15.24	12.94
	Tai Chi	21.41	17.45
	Total	18.73	14.58

		Mean	Std. Deviation
MI New Lateral Hemisphere L2/L3	Non-Exerciser	11.85	7.24
	Exerciser	15.96	13.10
	Tai Chi	11.53	9.63
	Total	13.40	10.63
MI New Lateral Hemisphere L3/L4	Non-Exerciser	12.59	6.35
	Exerciser	12.55	11.52
	Tai Chi	14.29	11.47
	Total	13.18	10.30
MI New Lateral Hemisphere L4/L5	Non-Exerciser	10.29	8.72
	Exerciser	11.86	5.57
	Tai Chi	11.97	13.88
	Total	11.56	9.56
MI New Lateral Hemisphere L5/S1	Non-Exerciser	10.28	4.49
	Exerciser	12.16	10.92
	Tai Chi	16.28	10.64
	Total	13.11	9.74

ANOVA Results: Personal Characteristics, MI_{CSA}, and MI_{New} Comparison Between Tai Chi Practitioners, Non-Exercisers, Exercisers at Baseline

	Sum of Squares	df	Mean Square	F	Sig.
LBP	2.398	2	1.199	0.193	0.826
Exercise	146.183	2	73.092	5.404	**0.011**
Age	905.031	2	452.515	11.477	**0.000**
Height	0.049	2	0.025	1.235	0.308
Weight	2011.435	2	1005.717	4.316	**0.025**
BMI	215.582	2	107.791	3.422	**0.049**

	Sum of Squares	df	Mean Square	F	Sig.
MI New Erector Spinae L2/L3	80.250	2	40.125	0.446	0.646
MI New Erector Spinae L3/L4	678.403	2	339.201	1.797	0.186
MI New Erector Spinae L4/L5	66.936	2	33.468	0.320	0.729
MI New Erector Spinae L5/S1	15.861	2	7.931	0.088	0.916

	Sum of Squares	df	Mean Square	F	Sig.
MI New Psoas L2/L3	59.457	2	29.729	0.141	0.869
MI New Psoas L3/L4	139.618	2	69.809	0.530	0.595
MI New Psoas L4/L5	231.183	2	115.591	0.976	0.391
MI New Psoas L5/S1	439.987	2	219.994	1.351	0.278

	Sum of Squares	df	Mean Square	F	Sig.
MI New Oblique L2/L3	80.970	2	40.485	0.268	0.767
MI New Oblique L3/L4	13.684	2	6.842	0.046	0.955
MI New Oblique L4/L5	146.401	2	73.201	0.391	0.681
MI New Oblique L5/S1	128.728	2	64.364	0.341	0.714

	Sum of Squares	df	Mean Square	F	Sig.
MI New Rectus Abdominus L2/L3	1387.103	2	693.552	2.580	**0.097****
MI New Rectus Abdominus L3/L4	1039.999	2	519.999	2.612	**0.093****
MI New Rectus Abdominus L4/L5	180.254	2	90.127	0.470	0.630
MI New Rectus Abdominus L5/S1	2842.539	2	1421.269	4.185	**0.028**

	Sum of Squares	df	Mean Square	F	Sig.
MI New Quadratus Lumborum L2/L3	221.231	2	110.615	0.282	0.757
MI New Quadratus Lumborum L3/L4	486.784	2	243.392	1.579	0.226
MI New Quadratus Lumborum L4/L5	737.951	2	368.975	0.546	0.586

	Sum of Squares	df	Mean Square	F	Sig.
MI New Paraspinal Muscle Group L2/L3	369.618	2	184.809	1.909	0.170
MI New Paraspinal Muscle Group L3/L4	255.216	2	127.608	0.825	0.450
MI New Paraspinal Muscle Group L4/L5	40.960	2	20.480	0.273	0.764
MI New Paraspinal Muscle Group L5/S1	31.380	2	15.690	0.144	0.866

	Sum of Squares	df	Mean Square	F	Sig.
MI New Core Muscle Group L2/L3	135.196	2	67.598	0.521	0.600
MI New Core Muscle Group L3/L4	1.748	2	0.874	0.006	0.994
MI New Core Muscle Group L4/L5	73.389	2	36.694	0.234	0.793
MI New Core Muscle Group L5/S1	263.791	2	131.896	0.601	0.556

	Sum of Squares	df	Mean Square	F	Sig.
MI New Lateral Hemisphere L2/L3	121.423	2	60.712	0.518	0.602
MI New Lateral Hemisphere L3/L4	19.268	2	9.634	0.085	0.919
MI New Lateral Hemisphere L4/L5	12.439	2	6.219	0.063	0.939
MI New Lateral Hemisphere L5/S1	149.298	2	74.649	0.772	0.473

Appendix 10

Chapter 4 ANOVA Results (MI Change from Intervention)

MI$_{New}$ Comparison Between:

Controls (Non-Exerciser)

Controls (Exerciser)

Exerciser (PLUS Tai Chi Practitioner)

Non-Exerciser (PLUS Tai Chi Practitioner)

Tai Chi Practitioner

Descriptive Statistics

MI$_{New}$ Change	Group	Mean	Std. Deviation
Change New Erector Spinae L2/L3	Control No Exercise	-11.78	17.43
	Control Exercise	1.33	5.18
	Exercise Plus Tai Chi	4.89	6.25
	No Exercise Plus Tai Chi	-13.54	13.49
	Tai Chi	3.36	10.55
	Total	0.37	11.45
Change New Erector Spinae L3/L4	Control No Exercise	4.95	1.03
	Control Exercise	13.54	9.78
	Exercise Plus Tai Chi	3.82	15.08
	No Exercise Plus Tai Chi	-11.73	14.42
	Tai Chi	2.49	8.01
	Total	3.34	11.41
Change New Erector Spinae L4/L5	Control No Exercise	-12.29	24.78
	Control Exercise	-1.50	3.15
	Exercise Plus Tai Chi	-1.21	11.62
	No Exercise Plus Tai Chi	-0.48	7.91
	Tai Chi	-1.50	9.98
	Total	-2.63	11.79
Change New Erector Spinae L5/S1	Control No Exercise	-18.08	11.24
	Control Exercise	5.13	7.14
	Exercise Plus Tai Chi	-5.55	9.29
	No Exercise Plus Tai Chi	-4.99	2.02
	Tai Chi	-2.47	14.15
	Total	-4.49	12.18

		Mean	Std. Deviation
Change New Psoas L2/L3	Control No Exercise	-7.43	9.00
	Control Exercise	7.30	16.65
	Exercise Plus Tai Chi	-2.79	9.44
	No Exercise Plus Tai Chi	7.36	2.11
	Tai Chi	0.89	9.57
	Total	0.15	10.36
Change New Psoas L3/L4	Control No Exercise	-6.17	15.41
	Control Exercise	-0.30	14.02
	Exercise Plus Tai Chi	-0.09	9.43
	No Exercise Plus Tai Chi	-2.49	2.78
	Tai Chi	-1.16	9.37
	Total	-1.46	9.76
Change New Psoas L4/L5	Control No Exercise	4.93	4.97
	Control Exercise	4.54	8.11
	Exercise Plus Tai Chi	-5.18	6.83
	No Exercise Plus Tai Chi	1.10	1.75
	Tai Chi	-1.62	7.63
	Total	-0.87	7.42
Change New Psoas L5/S1	Control No Exercise	17.28	16.80
	Control Exercise	-7.07	15.99
	Exercise Plus Tai Chi	-5.50	13.54
	No Exercise Plus Tai Chi	-0.17	1.10
	Tai Chi	-5.06	21.72
	Total	-2.35	18.03

		Mean	Std. Deviation
Change New Oblique L2/L3	Control No Exercise	9.27	11.95
	Control Exercise	-10.90	14.78
	Exercise Plus Tai Chi	-4.06	13.87
	No Exercise Plus Tai Chi	3.65	26.72
	Tai Chi	8.15	14.83
	Total	2.22	15.64
Change New Oblique L3/L4	Control No Exercise	-6.85	4.47
	Control Exercise	3.08	7.88
	Exercise Plus Tai Chi	-0.73	8.04
	No Exercise Plus Tai Chi	-5.33	1.33
	Tai Chi	0.70	10.20
	Total	-0.80	8.44
Change New Oblique L4/L5	Control No Exercise	0.28	16.42
	Control Exercise	-1.75	8.96
	Exercise Plus Tai Chi	-7.29	15.13
	No Exercise Plus Tai Chi	-0.51	4.84
	Tai Chi	-1.24	20.92
	Total	-2.75	16.13
Change New Oblique L5/S1	Control No Exercise	10.14	20.48
	Control Exercise	21.49	27.32
	Exercise Plus Tai Chi	5.57	16.83
	No Exercise Plus Tai Chi	-6.43	9.36
	Tai Chi	-5.64	20.87
	Total	2.59	20.60

		Mean	Std. Deviation
Change New Rectus Abdominus L2/L3	Control No Exercise	16.08	25.31
	Control Exercise	1.29	33.41
	Exercise Plus Tai Chi	0.28	12.30
	No Exercise Plus Tai Chi	-3.71	1.90
	Tai Chi	13.41	23.72
	Total	7.23	21.20
Change New Rectus Abdominus L3/L4	Control No Exercise	-10.87	11.45
	Control Exercise	0.29	12.82
	Exercise Plus Tai Chi	-1.91	14.41
	No Exercise Plus Tai Chi	-17.61	15.95
	Tai Chi	-12.40	25.47
	Total	-8.17	19.14
Change New Rectus Abdominus L4/L5	Control No Exercise	10.10	12.57
	Control Exercise	-11.29	32.86
	Exercise Plus Tai Chi	0.13	25.16
	No Exercise Plus Tai Chi	-18.89	22.40
	Tai Chi	-3.34	19.73
	Total	-2.95	21.96
Change New Rectus Abdominus L5/S1	Control No Exercise	6.04	17.80
	Control Exercise	4.81	14.79
	Exercise Plus Tai Chi	-2.05	19.47
	No Exercise Plus Tai Chi	3.04	15.67
	Tai Chi	-6.57	14.56
	Total	-1.66	15.93

		Mean	Std. Deviation
Change New Quadratus Lumborum L2/L3	Control No Exercise	-2.40	31.05
	Control Exercise	3.09	42.28
	Exercise Plus Tai Chi	1.56	9.83
	No Exercise Plus Tai Chi	9.83	36.85
	Tai Chi	-4.53	14.18
	Total	-0.50	20.11
Change New Quadratus Lumborum L3/L4	Control No Exercise	1.72	15.08
	Control Exercise	-3.84	15.37
	Exercise Plus Tai Chi	0.60	9.36
	No Exercise Plus Tai Chi	-6.77	3.25
	Tai Chi	-2.80	11.50
	Total	-1.75	10.80
Change New Quadratus Lumborum L4/L5	Control No Exercise	-19.45	29.28
	Control Exercise	-1.53	15.64
	Exercise Plus Tai Chi	-5.07	25.05
	No Exercise Plus Tai Chi	-0.49	4.47
	Tai Chi	-1.96	27.77
	Total	-4.76	23.91

		Mean	Std. Deviation
Change New Paraspinal Muscle Group L2/L3	Control No Exercise	-11.71	12.39
	Control Exercise	6.30	15.71
	Exercise Plus Tai Chi	1.92	5.00
	No Exercise Plus Tai Chi	-7.30	17.48
	Tai Chi	6.46	7.81
	Total	1.89	10.79
Change New Paraspinal Muscle Group L3/L4	Control No Exercise	-1.80	6.10
	Control Exercise	12.79	13.38
	Exercise Plus Tai Chi	1.19	13.95
	No Exercise Plus Tai Chi	-10.95	10.38
	Tai Chi	1.24	8.10
	Total	1.28	11.23
Change New Paraspinal Muscle Group L4/L5	Control No Exercise	-5.55	11.53
	Control Exercise	0.81	5.05
	Exercise Plus Tai Chi	-3.45	9.58
	No Exercise Plus Tai Chi	0.03	3.78
	Tai Chi	-0.21	11.29
	Total	-1.62	9.45
Change New Paraspinal Muscle Group L5/S1	Control No Exercise	-5.83	18.12
	Control Exercise	6.81	9.19
	Exercise Plus Tai Chi	1.49	12.24
	No Exercise Plus Tai Chi	-5.48	4.41
	Tai Chi	-1.68	12.70
	Total	-0.57	12.13

		Mean	Std. Deviation
Change New Core Muscle Group L2/L3	Control No Exercise	9.78	15.46
	Control Exercise	-7.02	6.78
	Exercise Plus Tai Chi	-5.09	13.82
	No Exercise Plus Tai Chi	4.60	22.41
	Tai Chi	8.19	14.45
	Total	2.55	14.81
Change New Core Muscle Group L3/L4	Control No Exercise	-6.90	1.38
	Control Exercise	3.12	12.54
	Exercise Plus Tai Chi	-2.35	9.89
	No Exercise Plus Tai Chi	-8.02	0.25
	Tai Chi	-1.29	11.17
	Total	-2.27	9.69
Change New Core Muscle Group L4/L5	Control No Exercise	1.77	13.78
	Control Exercise	-3.97	11.89
	Exercise Plus Tai Chi	-6.20	14.00
	No Exercise Plus Tai Chi	-2.52	1.79
	Tai Chi	-1.73	19.53
	Total	-2.89	15.05
Change New Core Muscle Group L5/S1	Control No Exercise	9.38	10.73
	Control Exercise	16.43	18.33
	Exercise Plus Tai Chi	10.59	10.49
	No Exercise Plus Tai Chi	0.13	7.16
	Tai Chi	-4.00	21.36
	Total	4.47	17.37

		Mean	Std. Deviation
Change New Lateral Hemisphere L2/L3	Control No Exercise	4.08	9.17
	Control Exercise	-3.19	8.47
	Exercise Plus Tai Chi	-2.74	10.30
	No Exercise Plus Tai Chi	6.14	20.03
	Tai Chi	9.14	12.44
	Total	3.49	12.05
Change New Lateral Hemisphere L3/L4	Control No Exercise	-6.72	1.16
	Control Exercise	5.64	12.44
	Exercise Plus Tai Chi	-0.09	10.17
	No Exercise Plus Tai Chi	-9.59	2.02
	Tai Chi	-1.26	8.02
	Total	-1.43	8.89
Change New Lateral Hemisphere L4/L5	Control No Exercise	-0.13	12.39
	Control Exercise	-2.03	7.77
	Exercise Plus Tai Chi	-3.83	7.73
	No Exercise Plus Tai Chi	0.23	5.13
	Tai Chi	-0.67	13.23
	Total	-1.58	10.09
Change New Lateral Hemisphere L5/S1	Control No Exercise	10.90	11.48
	Control Exercise	2.99	9.05
	Exercise Plus Tai Chi	-1.87	10.15
	No Exercise Plus Tai Chi	-3.36	5.66
	Tai Chi	-5.01	12.81
	Total	-1.13	11.55

ANOVA Results Between:

Controls (Non-Exerciser)

Controls (Exerciser)

Exerciser (PLUS Tai Chi Practitioner)

Non-Exerciser (PLUS Tai Chi Practitioner)

Tai Chi Practitioner

MI_{New}

	Sum of Squares	df	Mean Square	F	Sig.
LBP	19.461	4	4.865	1.973	0.132
TaiChi Hr/Week	19.275	4	4.819	3.613	**0.020**
Calisthenics Stretching Hr/Week	16.740	4	4.185	4.647	**0.007**
Weightlifting Hr/Week	1.820	4	0.455	0.613	0.657
Aerobic Cardio Hr/Week	69.284	4	17.321	3.671	**0.019**

$\mathrm{MI}_{\mathrm{New}}$	Sum of Squares	df	Mean Square	F	Sig.
Change New Erector Spinae L2/L3	1064.934	4	266.234	2.560	**0.070****
Change New Erector Spinae L3/L4	782.813	4	195.703	1.670	0.196
Change New Erector Spinae L4/L5	319.724	4	79.931	0.530	0.715
Change New Erector Spinae L5/S1	880.602	4	220.151	1.644	0.203

	Sum of Squares	df	Mean Square	F	Sig.
Change New Psoas L2/L3	495.711	4	123.928	1.192	0.345
Change New Psoas L3/L4	86.865	4	21.716	0.198	0.937
Change New Psoas L4/L5	332.404	4	83.101	1.682	0.194
Change New Psoas L5/S1	1375.722	4	343.931	1.071	0.397

	Sum of Squares	df	Mean Square	F	Sig.
Change New Oblique L2/L3	1296.556	4	324.139	1.418	0.264
Change New Oblique L3/L4	218.680	4	54.670	0.734	0.580
Change New Oblique L4/L5	207.392	4	51.848	0.172	0.950
Change New Oblique L5/S1	2144.144	4	536.036	1.334	0.292

	Sum of Squares	df	Mean Square	F	Sig.
Change New Rectus Abdominus L2/L3	1300.307	4	325.077	0.685	0.611
Change New Rectus Abdominus L3/L4	868.295	4	217.074	0.548	0.703
Change New Rectus Abdominus L4/L5	1295.706	4	323.926	0.630	0.647
Change New Rectus Abdominus L5/S1	589.813	4	147.453	0.536	0.711

	Sum of Squares	df	Mean Square	F	Sig.
Change New Quadratus Lumborum L2/L3	454.981	4	113.745	0.246	0.909
Change New Quadratus Lumborum L3/L4	149.452	4	37.363	0.282	0.886
Change New Quadratus Lumborum L4/L5	794.129	4	198.532	0.307	0.870
	Sum of Squares	df	Mean Square	F	Sig.
Change New Paraspinal Muscle Group L2/L3	990.806	4	247.701	2.744	**0.057****
Change New Paraspinal Muscle Group L3/L4	725.279	4	181.320	1.577	0.219
Change New Paraspinal Muscle Group L4/L5	112.959	4	28.240	0.278	0.888
Change New Paraspinal Muscle Group L5/S1	336.697	4	84.174	0.527	0.717

	Sum of Squares	df	Mean Square	F	Sig.
Change New Core Muscle Group L2/L3	1166.176	4	291.544	1.423	0.263
Change New Core Muscle Group L3/L4	226.953	4	56.738	0.559	0.695
Change New Core Muscle Group L4/L5	158.996	4	39.749	0.151	0.961
Change New Core Muscle Group L5/S1	1518.734	4	379.684	1.327	0.294

	Sum of Squares	df	Mean Square	F	Sig.
Change New Lateral Hemisphere L2/L3	740.698	4	185.174	1.351	0.286
Change New Lateral Hemisphere L3/L4	379.784	4	94.946	1.253	0.321
Change New Lateral Hemisphere L4/L5	57.250	4	14.312	0.120	0.974
Change New Lateral Hemisphere L5/S1	649.064	4	162.266	1.270	0.315

Appendix 11

Chapter 4 ANOVA Results (In Intervention: Non-Tai Chi Practitioner and Tai Chi Practitioner)

Descriptive Statistics of MI Change (New)

In Intervention: Non-Tai Chi Practitioner and Tai Chi Practitioner

MI New		Mean	Std. Deviation
Change New Erector Spinae L2/L3	No Tai Chi	-5.23	13.56
	Tai Chi	2.14	10.48
	Total	0.37	11.45
Change New Erector Spinae L3/L4	No Tai Chi	9.25	7.80
	Tai Chi	1.48	11.90
	Total	3.34	11.41
Change New Erector Spinae L4/L5	No Tai Chi	-6.89	16.87
	Tai Chi	-1.29	9.92
	Total	-2.63	11.79
Change New Erector Spinae L5/S1	No Tai Chi	-6.47	15.25
	Tai Chi	-3.87	11.46
	Total	-4.49	12.18

		Mean	Std. Deviation
Change New Psoas L2/L3	No Tai Chi	-0.06	14.43
	Tai Chi	0.21	9.23
	Total	0.15	10.36
Change New Psoas L3/L4	No Tai Chi	-3.24	13.56
	Tai Chi	-0.91	8.63
	Total	-1.46	9.76
Change New Psoas L4/L5	No Tai Chi	4.74	6.02
	Tai Chi	-2.64	7.04
	Total	-0.87	7.42
Change New Psoas L5/S1	No Tai Chi	5.11	19.82
	Tai Chi	-4.71	17.31
	Total	-2.35	18.03

		Mean	Std. Deviation
Change New Oblique L2/L3	No Tai Chi	-0.82	16.32
	Tai Chi	3.17	15.75
	Total	2.22	15.64
Change New Oblique L3/L4	No Tai Chi	-1.89	7.90
	Tai Chi	-0.46	8.78
	Total	-0.80	8.44
Change New Oblique L4/L5	No Tai Chi	-0.74	11.88
	Tai Chi	-3.39	17.49
	Total	-2.75	16.13
Change New Oblique L5/S1	No Tai Chi	15.82	22.47
	Tai Chi	-1.59	18.67
	Total	2.59	20.60

		Mean	Std. Deviation
Change New Rectus Abdominus L2/L3	No Tai Chi	8.69	27.72
	Tai Chi	6.77	19.62
	Total	7.23	21.20
Change New Rectus Abdominus L3/L4	No Tai Chi	-5.29	12.47
	Tai Chi	-9.08	21.02
	Total	-8.17	19.14
Change New Rectus Abdominus L4/L5	No Tai Chi	-0.60	25.15
	Tai Chi	-3.70	21.56
	Total	-2.95	21.96
Change New Rectus Abdominus L5/S1	No Tai Chi	5.42	14.65
	Tai Chi	-3.89	16.02
	Total	-1.66	15.93

		Mean	Std. Deviation
Change New Quadratus Lumborum L2/L3	No Tai Chi	0.35	33.31
	Tai Chi	-0.77	15.19
	Total	-0.50	20.11
Change New Quadratus Lumborum L3/L4	No Tai Chi	-1.06	13.95
	Tai Chi	-1.97	10.07
	Total	-1.75	10.80
Change New Quadratus Lumborum L4/L5	No Tai Chi	-10.49	23.17
	Tai Chi	-2.95	24.47
	Total	-4.76	23.91

		Mean	Std. Deviation

Change New Paraspinal Muscle Group L2/L3	No Tai Chi	-2.70	16.05
	Tai Chi	3.34	8.63
	Total	1.89	10.79
Change New Paraspinal Muscle Group L3/L4	No Tai Chi	5.50	12.26
	Tai Chi	-0.06	10.88
	Total	1.28	11.23
Change New Paraspinal Muscle Group L4/L5	No Tai Chi	-2.37	8.69
	Tai Chi	-1.38	9.89
	Total	-1.62	9.45
Change New Paraspinal Muscle Group L5/S1	No Tai Chi	0.49	14.60
	Tai Chi	-0.91	11.69
	Total	-0.57	12.13

		Mean	Std. Deviation
Change New Core Muscle Group L2/L3	No Tai Chi	1.38	14.09
	Tai Chi	2.92	15.38
	Total	2.55	14.81
Change New Core Muscle Group L3/L4	No Tai Chi	-1.89	9.68
	Tai Chi	-2.39	9.96
	Total	-2.27	9.69
Change New Core Muscle Group L4/L5	No Tai Chi	-1.10	11.93
	Tai Chi	-3.46	16.15
	Total	-2.89	15.05
Change New Core Muscle Group L5/S1	No Tai Chi	12.90	13.98
	Tai Chi	1.81	17.80
	Total	4.47	17.37

		Mean	Std. Deviation
Change New Lateral Hemisphere L2/L3	No Tai Chi	0.45	8.84
	Tai Chi	4.45	12.95
	Total	3.49	12.05
Change New Lateral Hemisphere L3/L4	No Tai Chi	-0.54	10.41
	Tai Chi	-1.71	8.65
	Total	-1.43	8.89
Change New Lateral Hemisphere L4/L5	No Tai Chi	-1.08	9.31
	Tai Chi	-1.74	10.57
	Total	-1.58	10.09
Change New Lateral Hemisphere L5/S1	No Tai Chi	6.94	10.21
	Tai Chi	-3.68	10.98
	Total	-1.13	11.55

ANOVA Results Non-Tai Chi Practitioner and Tai Chi Practitioner

MI (CSA and New)

	Sum of Squares	df	Mean Square	F	Sig.
LBP	7.963	1	7.963	3.035	**0.093****
Tai Chi Hr/Week	18.600	1	18.600	15.424	**0.001**
Calisthenics Stretching Hr/Week	0.344	1	0.344	0.241	0.628
Weightlifting Hr/Week	0.551	1	0.551	0.782	0.385
Aerobic Cardio Hr/Week	1.103	1	1.103	0.162	0.690

Mi New Change	Sum of Squares	df	Mean Square	F	Sig.
Change New Erector Spinae L2/L3	247.638	1	247.638	1.966	0.174
Change New Erector Spinae L3/L4	274.872	1	274.872	2.217	0.150
Change New Erector Spinae L4/L5	143.302	1	143.302	1.033	0.320
Change New Erector Spinae L5/S1	30.865	1	30.865	0.201	0.658

	Sum of Squares	df	Mean Square	F	Sig.
Change New Psoas L2/L3	0.350	1	0.350	0.003	0.956
Change New Psoas L3/L4	24.786	1	24.786	0.252	0.620
Change New Psoas L4/L5	248.452	1	248.452	5.330	**0.030**
Change New Psoas L5/S1	439.245	1	439.245	1.373	0.253

	Sum of Squares	df	Mean Square	F	Sig.
Change New Oblique L2/L3	72.647	1	72.647	0.288	0.596
Change New Oblique L3/L4	9.303	1	9.303	0.126	0.726
Change New Oblique L4/L5	32.144	1	32.144	0.119	0.733
Change New Oblique L5/S1	1381.296	1	1381.296	3.610	**0.07****

	Sum of Squares	df	Mean Square	F	Sig.
Change New Rectus Abdominus L2/L3	16.761	1	16.761	0.036	0.852
Change New Rectus Abdominus L3/L4	65.518	1	65.518	0.173	0.682
Change New Rectus Abdominus L4/L5	43.859	1	43.859	0.087	0.770
Change New Rectus Abdominus L5/S1	395.839	1	395.839	1.599	0.219

	Sum of Squares	df	Mean Square	F	Sig.
Change New Quadratus Lumborum L2/L3	5.730	1	5.730	0.014	0.908
Change New Quadratus Lumborum L3/L4	3.746	1	3.746	0.031	0.862
Change New Quadratus Lumborum L4/L5	259.460	1	259.460	0.443	0.512

	Sum of Squares	df	Mean Square	F	Sig.
Change New Paraspinal Muscle Group L2/L3	166.395	1	166.395	1.455	0.240
Change New Paraspinal Muscle Group L3/L4	140.801	1	140.801	1.123	0.300
Change New Paraspinal Muscle Group L4/L5	4.499	1	4.499	0.048	0.828
Change New Paraspinal Muscle Group L5/S1	8.959	1	8.959	0.058	0.811

	Sum of Squares	df	Mean Square	F	Sig.
Change New Core Muscle Group L2/L3	10.832	1	10.832	0.047	0.830
Change New Core Muscle Group L3/L4	1.148	1	1.148	0.012	0.915
Change New Core Muscle Group L4/L5	25.401	1	25.401	0.108	0.745
Change New Core Muscle Group L5/S1	561.429	1	561.429	1.933	0.178

	Sum of Squares	df	Mean Square	F	Sig.
Change New Lateral Hemisphere L2/L3	73.066	1	73.066	0.493	0.490
Change New Lateral Hemisphere L3/L4	6.156	1	6.156	0.075	0.787
Change New Lateral Hemisphere L4/L5	2.026	1	2.026	0.019	0.891
Change New Lateral Hemisphere L5/S1	514.314	1	514.314	4.398	**0.047**

Appendix 12

Chapter 5 Statistical Analysis Results

Analysis Between Age and Imbalance

	N	Mean	SD	Std. Error	95% CI Lower	95% CI Upper	Min	Max
No	955	41.31	10.83	0.35	40.62	42.00	20.3	70.90
Yes	56	45.48	12.26	1.64	42.19	48.76	24.0	67.00
Total	1011	41.54	10.95	0.34	40.87	42.22	20.3	70.90

Analysis of Variance (ANOVA) Between Age and Imbalance

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	919.15	1	919.15	7.72	**0.00***
Within Groups	120076.95	1009	119.01		
Total	120996.09	1010			
*Significant at the 0.05 level					

Analysis Between Body Mass Index and Imbalance

	N	Mean	SD	Std. Error	95% CI Lower	95% CI Upper	Min	Max
No	948	27.56	4.75	0.15	27.26	27.86	16.00	54.80
Yes	53	27.57	4.37	0.60	26.37	28.78	17.00	37.30
Total	1001	27.56	4.73	0.15	27.27	27.85	16.00	54.80

Analysis of Variance (ANOVA) Between Body Mass Index and Imbalance

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.00	1	0.00	0.000	0.99
Within Groups	22385.48	999	22.41		
Total	22385.49	1000			

Descriptive Statistics, Comparison Between Imbalance and Weightlifters

		Imbalance		Total
		No	Yes	
Weightlifters	No	857	50	907
	Yes	66	4	70
Total		923	54	977

Analysis Between Imbalance and Pain Today out of 100 (Without Diagnosis or Treatment)

	N	Mean	Std. Deviation	Std. Error	95% CI Lower	95% CI Upper	Min	Max
No	960	8.70	18.77	0.61	7.51	9.89	100.00	100.00
Yes	56	16.11	25.77	3.44	9.20	23.01	100.00	82.00
Total	1016	9.11	19.28	0.61	7.92	10.29	100.00	100.00

ANOVA Between Imbalance and Pain Today out of 100

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2905.58	1	2905.58	7.87	**0.00***
Within Groups	374336.15	1014	369.17		
Total	377241.73	1015			
*Significant at the 0.05 level					

Analysis Between Imbalance and Worst Pain in the Last Year out of 100 (Without Diagnosis or Treatment)

	N	Mean	Std. Deviation	Std. Error	95% CI Lower	95% CI Upper	Min	Max
No	960	26.19	38.05	1.23	23.7797	28.60	0.00	100.00
Yes	56	39.57	41.11	5.49	28.5621	50.58	0.00	100.00
Total	1016	26.93	38.32	1.20	24.5678	29.29	0.00	100.00

ANOVA Between Imbalance and Worst Pain in the Last Year out of 100(Without Diagnosis or Treatment)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9475.40	1	9475.40	6.486	**0.01***
Within Groups	1481275.21	1014	1460.82		
Total	1490750.61	1015			
*Significant at the 0.05 level					

Propensity to Seek Medical Attention for First Time Office Visit Versus Imbalance

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Case/Control – Office Visits * Imbalance (Yes/No)	1016	100.0%	0	0.0%	1016	100.0%

Imbalance and Office Visits

		Imbalance		Total
		No	Yes	
Case/Control – Office Visits	0	800	44	844
	1	160	12	172
Total		960	56	1016