Correlation of Selected Trunk and Hip Muscle Cross-Sectional Areas with Incidence and Severity of Low Back Pain in Adult Males and Females

Dissertation

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By

Amy Helen Amabile

Graduate Program in Anatomy

The Ohio State University

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Dissertation Committee:

John Bolte IV, PhD, Advisor

Amanda Agnew, PhD

Laura Boucher, PhD

Sue Ferguson, PhD

Safdar Khan, MD
ABSTRACT

Study Design: This was a 3-part, retrospective, observational, cross-sectional study.

Objective: The objective of the study was to examine the association between muscle morphometry of selected trunk and hip muscles, and various measures of low back pain (LBP) in adult males and females.

Background: LBP is a huge cause of human suffering and expense in the United States and worldwide. Understanding the causes of, and developing successful interventions to address LBP, requires an understanding of certain morphometric and LBP-related variables, and how they interact with each other.

Methods: Muscle cross-sectional area (CSA) was measured using computed tomography and magnetic resonance imaging scans of selected hip and trunk muscles in a cadaver model, and in living human participants through retrospective review of patient records. LBP-related variables were obtained from medical records and correlated with muscle CSA and with LBP surgical outcomes.

Results: Multifidus (MF), gluteus maximus (GM), and erector spinae (ES) CSAs showed a correlation with LBP incidence and severity. Psoas major (PM), while correlated with MF atrophy in one component of the present research, overall did not demonstrate a relationship to LBP. Pre-surgical MF CSA was positively correlated with 6-month post-surgical outcomes. Pre-surgical Oswestry Disability Index (ODI) scores demonstrated the
ability to differentiate between surgical and non-surgical participants, and were correlated with post-surgical outcomes.

**Conclusion:** This research supports prior research indicating MF and ES vary with LBP. A previously unexplored relationship between GM and LBP was demonstrated. Pre-surgical ODI scores may have clinically useful predictive value for post-surgical outcomes.

**Key Words:** back pain, multifidus, gluteus maximus, psoas major, Oswestry Disability Index, cross-sectional area.
Dedication

This document is dedicated to the individuals who donated their bodies to science and made this research, and my graduate work in anatomy, possible.
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Vita

1986..........................................................B.A. in History, Grinnell College

1994 ......................................................M.P.A. in Public Administration, New York University

2004 ........................................................M.P.T. in Physical Therapy, University of Texas at El Paso

2006 to 2011 ..........................................Lecturer, Physical Therapy Program, University of Texas at El Paso

2004 to 2016 ..........................................Physical Therapist, Las Cruces, NM and Columbus, OH

Publications


Fields of Study

Major Field: Anatomy

Minor Field: Neuroscience
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CHAPTER 1: INTRODUCTION
Goal of the Present Research

The overall goal of the present research was to determine whether an association exists between the size of muscles, as measured by cross-sectional area (CSA), and incidence and severity of low back pain (LBP) in adult human males and females. The muscles of interest were: multifidus (MF), gluteus maximus (GM), psoas major (PM), and erector spinae (ES). Incidence and severity of LBP were measured by numbers of LBP-related medical visits, treatment recommendations, medical diagnoses, numbers of comorbidities, scores on numeric pain scales, Oswestry Disability Index scores, peripheralization of LBP symptoms, and time since onset of LBP. In addition, CSA and other variables were correlated with medical decision-making regarding surgical and non-surgical treatment, and with patient outcomes after back surgery.

Previous research on the relationship between LBP and CSA in the identified muscles has ranged from virtually non-existent (for GM) to very well-studied (for MF). Understanding the relationship of the CSA of the above muscles to LBP will potentially increase our understanding of the etiology of LBP, and may provide a rationale for the development of interventions targeting strength deficits in these muscle groups in LBP patients.

The study consisted of 3 separate components as outlined under Specific Aims. 1) A cadaver-based study assessing the relationship between MF CSA and the CSAs of GM and PM. 2) An examination of the relationship of GM CSA to incidence and severity of LBP in adult females. This component used de-identified patient medical records and imaging from the Ohio State University (OSU) Wexner Medical Center through the Center for Clinical and Translational Science (CCTS). 3) A comparison of muscle
morphometry, medical history, and various LBP-related variables and test scores from patients with LBP referred for surgical consultation to the OSU Carepoint East Comprehensive Spine Center.

Rationale for the Structure of the Present Research

A cadaver-based study was initially planned to assess possible covariation of GM and PM with a muscle (MF) already known to vary with LBP, to help determine if a more complex study on actual LBP patients was indicated. The cadaver study also allowed for development of the research techniques and methodology used in subsequent components.

The second component allowed for a detailed analysis of GM CSA and its relation to LBP, on a targeted, well-controlled, sample with minimal covariates.

The third component allowed for detailed analysis of MF, PM and ES CSAs, and for their correlation with multiple variables related to LBP. In addition, the relationship between these variables and surgical outcomes was assessed.

Specific Aims and Hypotheses

Aim 1: Determine whether there is a correlation between the CSA of GM and PM, and the CSA of MF, in a sample of adult human male and female cadavers.

Hypothesis: Both PM and GM CSA will show an atrophy pattern that is significantly correlated with that of MF.
Aim 2: Determine whether there is a correlation between the CSA of GM, and incidence and severity of chronic LBP, in adult females with and without LBP, as determined from de-identified patient data accessed through the OSU CCTS.

Hypothesis: Participants with chronic LBP will have greater atrophy in their GM muscles than control participants.

Aim 3: Determine whether there is a correlation between the CSA of PM, ES and MF and severity of LBP in adult males and females referred for LBP surgery, as measured by treatment recommendations, medical diagnoses, comorbidities, scores on numeric pain scales, Oswestry Disability Index (ODI) scores, peripheralization of LBP symptoms, and time since onset of LBP.

Hypotheses: 1) Muscle CSA for MF, PM and ES will be significantly lower in the surgery group, and positively correlated with favorable surgical outcomes.

2) Numeric pain score, chronicity, number of affected vertebral levels, percent of peripheralization of LBP, number of comorbidities, ODI scores and percent of fatty infiltration will all be significantly higher in the surgery group, and will be negatively correlated with favorable surgical outcomes.

3) Muscle CSA will be smaller on the affected side of participants with unilateral LBP.
CHAPTER 2: REVIEW OF LITERATURE
Scope of the Problem of Low Back Pain

Low back pain (LBP) is a significant health problem in the United States and
worldwide. According to the National Health Interview Survey conducted in 2012, 27% of all Americans over the age of 18 had experienced LBP in the prior 3 months, with the highest incidence (32%) among 45 to 64 year olds.\textsuperscript{1} Worldwide prevalence of LBP has been estimated at 38\% annually for all age groups.\textsuperscript{2}

LBP is a major cause of workplace disability, absenteeism, and expense, and its impact is felt among workers throughout the private sector, and at all levels and branches of the military.\textsuperscript{2,3,4,5,6} Stewart et al\textsuperscript{6} surveyed 28,902 randomly sampled workers from a variety of industries, and found that the second most common cause of lost work time, and the highest rate of absenteeism, was for workers with LBP. Lincoln et al\textsuperscript{4} also found that LBP-related conditions were responsible for the highest 5-year cumulative risk of disability among active duty US Army personnel.

Defining Low Back Pain

Definition of Pain and Overview of Basic Nociception

Pain is a sensation felt by an individual after a noxious stimulus (mechanical, thermal or chemical) is perceived by free nerve endings in tissues. The mechanism by which this stimulus is transformed into an action potential involves ion channels on the nerve endings, which open and close preferentially depending on the type of stimulus, thus leading to depolarization.\textsuperscript{7} Tissue types that contain pain receptors that are relevant to the present research include: muscle, tendon, ligament, bone, vertebral endplate, outer annulus fibrosus, dura mater and joint capsule.\textsuperscript{8,9}
Actual tissue damage is not required; rather, the threat of tissue damage, reaching a high enough threshold, may be sufficient to cause pain. Some nociceptors respond primarily to one type of stimulus; others are polymodal and respond to all 3 types of noxious stimuli. Slow pain nerve fibers, categorized as type IV C (C fibers), are unmyelinated and tend to have more polymodal nerve endings. Fast pain fibers, known as type III A delta (delta fibers), are lightly myelinated and tend to respond to just one type of pain stimulus.¹⁰

Both types of pain fibers have their cell bodies in the dorsal root ganglia of spinal nerves, and these typically synapse in laminae I to V of the dorsal horn of the spinal cord, on cell bodies of second-order neurons.¹¹,¹² Fibers from these second order neurons typically then cross to the contralateral side of the spinal cord and ascend in the lateral spinothalamic tract (LSTT). Fibers of the LSTT terminate primarily in the ventral posterolateral nucleus of the thalamus, but also in the reticular formation, superior colliculus, periaqueductal gray (PAG), and hypothalamus.¹² Those second order neurons of the LSTT that terminate in the thalamus synapse on cell bodies of third-order neurons projecting to the primary somatosensory cortex, and other areas of the cortex including the insula, and the anterior cingulate gyrus.¹¹,¹³

Chronic pain, defined commonly as pain lasting longer than 12 weeks,¹⁴,¹⁵,¹⁶ is perpetuated by inflammatory mechanisms and peripheral/central sensitization, which is discussed below. Referred pain is a diffuse, achy pain felt in sites distant from the actual location of noxious stimulus, achieved through convergence of pain fibers on common second-order neurons in the spinal cord.⁹ Radicular pain is a well-defined sharp, shooting pain resulting from compression or traction of previously inflamed nerve roots or spinal
nerves, occurring in the distribution of the affected nerve root. It is important to note that the term “radiculopathy” refers to sensory or motor losses caused by the same mechanisms as radicular pain; however radiculopathy can occur in the absence of radicular pain, and vice versa.\textsuperscript{9}

**Definition of Low Back Pain**

Defining LBP has been challenging due to its multifactorial nature, the often subjective criteria used to define it, and the plethora of LBP diagnostic codes available to clinicians. Sixty-six different International Classification of Diseases (ICD-9) codes have been identified that pertain to either non-surgical or surgical LBP.\textsuperscript{17} In addition to the many diagnostic codes available, numerous other LBP classification systems exist\textsuperscript{18} including: the Quebec Task Force’s (QTF) 7 category system based on pain peripheralization and presence of neurological symptoms;\textsuperscript{19} McKenzie’s\textsuperscript{20} derangement, dysfunction and postural syndromes; pain mechanism-based systems such as the one proposed by Hensley and Courtney;\textsuperscript{21} and treatment-based classification systems such as the one proposed by Delitto et al.\textsuperscript{22}

**Causes of and Risk Factors for Low Back Pain**

There are several known extrinsic and intrinsic causes of LBP.\textsuperscript{5,23,24,25} There is typically not one exclusive factor, but rather an interaction of multiple causal factors, which leads to LBP. It is also relevant to note that many, if not most, episodes of LBP are of unknown etiology, and are considered “non-specific” back pain.\textsuperscript{26} Marras\textsuperscript{27} concluded that although LBP is caused by force or load-stimulated pain-sensing tissues, the force/load threshold differs among individuals. The tolerance to varying tissue loads
varies among individuals depending upon fitness, strength, age, genetics, cumulative loading, and muscle responses to compensate for pain. Among dozens of identified causes of LBP, Ferguson and Marras\textsuperscript{28} identified 5 overarching categories of LBP risk factors (personal, physical, exposure, psychological and psychosocial) with each category having one to 2 dozen different risk factors. The risk factors most relevant to the present research are described below.

**Age/Sex**

Increased age and female sex have been consistently correlated with LBP.\textsuperscript{23,27,29} In general, LBP incidence increases with age until approximately age 70, after which incidence decreases.\textsuperscript{2} Only one identified study, by Roy et al,\textsuperscript{30} found male sex was more correlated with LBP; however this was likely due to differing job descriptions among males and females in their active-duty Army cohort.

**Muscle Strength/Endurance/Motor Control**

Decreased muscle strength, endurance, and motor control have all been implicated in the genesis of LBP. The relative importance of each of these factors is disputed and varies widely based on individual researcher beliefs, and on the measurement techniques used in individual studies.

**Trunk/Hip Muscle Strength** Decreased trunk and hip muscle strength has been identified in persons with LBP, yet it is unknown if these strength deficits are a cause or an effect of LBP. Nourbakashsh and Arab\textsuperscript{31} assessed back and hip muscle strength and endurance in 600 males and females with and without LBP. They found decreased back extensor endurance, and decreased gross strength in abdominal muscles, hip flexors, extensors, abductors and adductors in LBP participants. Cho et al\textsuperscript{29} assessed trunk muscle
strength in 48 individuals in a prospective study and found that maximum isometric and isokinetic trunk flexor and extensor strength were negatively correlated with LBP.

**Trunk Muscle Endurance** The muscle atrophy seen with LBP can be considered a manifestation of decreased endurance, rather than decreased strength. The greater proportion of type I fibers in multifidus (MF) and erector spinae (ES), reflecting their tonic functions, supports the notion that muscle atrophy would present as decreased endurance in these muscles.\textsuperscript{32,33} The general trend toward transition of slow to fast-twitch fibers with disuse atrophy also provides a rationale for interpreting atrophy as decreased endurance.\textsuperscript{34,35} Da Silva et al\textsuperscript{36} used electromyography (EMG) to measure trunk muscle endurance in younger and older adults with and without LBP, and found significantly increased fatigue in the LBP groups of both young and older adults compared with healthy controls, but no fatigue differences based on age. De Pozeo-Cruz et al\textsuperscript{37} found decreased trunk muscle extension and flexion endurance among LBP participants compared with healthy controls among a population of sedentary office workers.

**Motor Control Impairments** Normal CNS control of stabilizing muscles can involve preparatory, feedback and continuous motor control mechanisms, and both an excessive and an insufficient muscular response to postural demands may lead to pain.\textsuperscript{38} Co-contraction of the ES with the abdominal musculature provides gross control to the spinal column; and graded contractions of the deep muscles such as the MF control individual segmental movement.\textsuperscript{39} The basic mechanism underlying motor control in the spine is a type of reflex whereby proprioceptive and nociceptive afferents from the muscles, ligaments, disks and capsules project to the cell bodies of paraspinal muscle motor efferents in the spinal cord, which then contract and ultimately stabilize the
intervertebral joints. The proprioceptive function of the deep back muscles, which are richly endowed with muscle spindles, is very important in motor control. Muscle spindles signal alpha motor neurons (AMN) and gamma motor neurons (GMN), and are then calibrated by the GMNs to remain sensitive to muscle length, thereby maintaining overall muscle stiffness. Alterations to this mechanism due to chronic pain, excessive load and inflammatory mediators may result in either LBP and/or insufficient intersegmental stabilization.

Paraspinal muscle proprioception has been shown to be altered in LBP. Hodges and Ebenbichler et al discussed the evidence for motor control impairments in the genesis of LBP and argued that impairments in timing, sequencing and amplitude of contractions of the spinal stabilizers are an important cause of LBP. It is at or near a neutral posture that these motor control mechanisms become most important, as the soft tissues, such as ligaments and capsules, are most slack near neutral, requiring the spine to rely on agonist/antagonist muscle contraction to maintain stability. Prolonged passive loading of soft tissues, such as happens with prolonged sitting, has been shown to desensitize the muscle spindles and Golgi tendon organs and lead to altered motor programs controlling stabilization. Conversely, muscle contraction increases proprioceptive acuity, which may explain why exercises targeting these deep muscles seem to be effective in treating LBP. When this system is impaired due to injury, stability falls out of physiological limits and results in stretch or compression of pain sensitive structures. Desscarreaux et al showed that pain itself causes significantly decreased accuracy in both trunk flexion and extension, and greater torque variability. However, the cause of lasting impairments in motor control, long after acute insults have had time to
heal, is not known, and may be due in part to peripheral and central sensitization mechanisms discussed below. 38,39

**Lifting**

Lifting has been correlated with LBP due to the excessive loads placed on the lumbar intervertebral discs (IVD) with improper lifting techniques, heavy loads, and extended amount of time spent lifting. 30 In particular, leaning forward while holding a load has been shown to increase the effective load on the lumbar IVDs substantially. 25,43 Nachemson 25 found that holding a 20 kilogram load while bending forward 20 degrees increased the load on the third lumbar IVD by over 200 percent.

The weight of a load, and the vertical and horizontal lifting distances are all positively correlated with incidence of LBP, 44 and changing the alignment of the lower extremity joints has been shown to decrease the load on the lumbar spine. Cholewicki et al 45 found that moments at the hip and lumbar spine decreased significantly when the lifter’s lifting style allowed him to keep the weight closer to the body. Yoon 46 found that increasing both knee flexion and base of support required significantly less activation of the trunk and hip muscles involved in lifting. Increased intraabdominal pressure achieved through activation of the transverse abdominus muscle, is thought to increase spinal stability and thus assist in lifting. 47 Marras et al 23 assessed the role of trunk motions in 3 dimensions in workers doing high risk manual materials handling at 48 different companies. Jobs were stratified into low and high risk for back injury. They found that 5 factors correlated positively with increased risk for LBP including: maximum moment, lifting frequency, lateral trunk velocity, sagittal trunk angle, and trunk twisting velocity.
Normal Biomechanics of Lifting When arising from full trunk flexion into extension, most movement happens at the hip joint and is accomplished by gluteus maximus (GM) and the hamstrings during the first 50% of the movement cycle. By 75% of extension, contributions from hip extensors and ES are about equal. In the last 25% of extension to neutral, lumbar extension predominates.\cite{48,49,50} During lifting of asymmetric loads, significant contralateral activation of the MF and ES muscles and significant ipsilateral activation of GM occurs.\cite{51} GM is more active during a wide stance lift, but only with heavier weights.\cite{52}

Altered Biomechanics Found in LBP Importantly, altered trunk and hip kinematics have been noted in individuals with LBP, although there are conflicting results from different studies. Arab et al\cite{53} found significantly greater EMG activity in LBP participants in both ipsilateral and contralateral ES muscles during prone trunk extension, but no difference in GM or hamstring activity. Leinonen et al\cite{50} found that both ES and GM were activated for substantially less time of both the flexion and extension cycle in LBP participants, and activated later in the cycle for trunk extension, in the LBP participants versus controls. After 5 weeks of physical therapy, the ES flexion/extension cycle activation time in LBP participants was equal to the controls; but the GM made no such recovery. Ferguson et al\cite{54} found that both the left and right erector spinae activated significantly earlier during various lifting activities and fired significantly longer in LBP participants versus healthy controls. Luoto et al\cite{55} used force platforms and found a significant decrease in single limb postural control in LBP participants compared to healthy controls. Newcomer et al\cite{56} assessed EMG of ES and rectus abdominus in various perturbations using force platforms in LBP patients and healthy controls, and found
significantly less activation of RA, and more left/right asymmetry in ES and rectus abdominus activation in LBP patients. Marras et al\textsuperscript{57} found that individuals with LBP performing bending and rotational movements had altered velocity, acceleration and lumbar range of motion compared with healthy controls. Marras was able to make these measurements using his lumbar motion monitor (LMM), which provides a quantitative measurement of LBP-related motion impairment. Danneels et al\textsuperscript{58} found that MF showed significantly decreased EMG activity in LBP patients during performance of coordination and strengthening exercises. Freddolini et al\textsuperscript{59} found significantly increased co-contraction of trunk extensor muscles with flexor muscles in LBP participants compared with control participants during perturbation of sitting balance.

**Sitting/Posture/Sedentary Lifestyle**

Sitting for extended periods of time has been implicated in discogenic back pain.\textsuperscript{60} Nachemson\textsuperscript{25} measured loads on lumbar IVDs in various postures and found that sitting unsupported and leaning forward caused the greatest load, followed by standing and leaning forward; holding weights in one’s hands dramatically increased the loads on the IVDs in both sitting and standing. Assuming a lordotic posture while sitting, however, has been shown to decrease discogenic LBP.\textsuperscript{61}

A sedentary lifestyle in general has been implicated in LBP, but this may be due to time spent sitting, as well as other covariates that may be related to LBP. Heneweer et al\textsuperscript{62} found in a study of over 3000 Dutch adults that sedentary lifestyle was associated with increased incidence of LBP. Lis et al\textsuperscript{60} performed a meta-analysis on LBP and sitting. They found an increased incidence of LBP in those occupational groups that sat for more than half of their work day.
Psychological and Emotional Factors

Psychological and emotional factors have been demonstrated to lower pain threshold in LBP patients. For example, based on personality type, there can be greater coactivation of antagonist muscles during a lifting activity leading to increased spinal loading and ultimately increased LBP. Emotional stress during a lifting task has also been shown to increase compression and lateral shear forces in the lumbar spine, particularly in individuals with an introverted personality. Fear-avoidance behavior is a well-known psychological phenomenon in chronic LBP, whereby fear of exacerbation of existing LBP leads to decreased overall activity and sedentary lifestyle, which further exacerbates the LBP and leads to social isolation.

Work Exposure and Biomechanical/Ergonomic Factors

The aforementioned risk factors of lifting, postural, and sedentary lifestyle are all implicated in work-related LBP. Many studies have been performed showing specific risk factors for LBP in the workplace.

Lifting-related factors are by far the most well-studied job-related risk for LBP. Marras et al. studied workplace risk factors for LBP among workers involved in manual materials handling in 48 different industries. They found that factors correlated positively with increased risk for LBP including: maximum moment, lifting frequency, lateral trunk velocity, sagittal trunk angle, and trunk twisting velocity. In another study Marras et al. found that risk of a clinically meaningful decrease in low back function among distribution center workers was best predicted by age, rest time, load exposure, job satisfaction and prior low back function.
Underlying Medical Conditions

Underlying conditions that can lead to LBP include: degenerative disc disease, spondylosis, spinal stenosis, herniated discs, spondylolisthesis, spondylolysis, osteoporosis, and other less common pathologies.\textsuperscript{24,67} It should be noted that there is often a mismatch between clinical symptoms reported by patients, and findings upon imaging, with many asymptomatic individuals having positive findings for the above conditions on imaging.\textsuperscript{68,69} For example, in the average 50 year-old individual without LBP, 80\% show spondylosis, 60\% show disc bulges and 14\% show spondylolisthesis; these percentages all increase with age.\textsuperscript{69} With this caveat in mind, there are several common findings on MRI or CT scan which are seen in patients diagnosed with LBP, which are relevant to the present research.

Degenerative Disc Disease Disc degeneration is defined as pathological structural failure of the disc that is not age-related. This structural failure includes annular tears, endplate damage, prolapse, and decreased disc height or narrowing of the disk space. One of the components of spondylosis, degenerative disc disease is caused by loading and tissue changes related to altered metabolic and vascular conditions, as well as genetic predisposition. Disc degeneration can lead to spinal stenosis.\textsuperscript{70}

Spondylosis Spondylosis involves disc degeneration as well as the presence of osteophytes on the superior and inferior endplates of the vertebral bodies. This process ultimately closes down on the lateral foramina and can result in nerve compression.\textsuperscript{70} Spondylosis also results in substantial neural arch weight bearing which may be a source of LBP.\textsuperscript{71}
Disc Herniation  IVD bulging, herniation or extrusion involves a partial or complete displacement of annulus or nucleus pulposus tissue into the vertebral canal. This causes varying degrees of spinal stenosis and thus can compress spinal cord tissue or nerve roots.\textsuperscript{72} IVDs have been shown to fail in extreme flexion, and most commonly in the posterolateral direction.\textsuperscript{73,74}

Stenosis  Spinal stenosis, lateral recess stenosis, and lateral foraminal stenosis refer to narrowing of the central canal, the medial foramen, and the lateral foramen, respectively. Causation includes spondylosis, disc degeneration and disc herniation. This narrowing can compress or stretch spinal cord tissue, nerve roots, or spinal nerves.\textsuperscript{68,75,76}

Spondylolisthesis  Spondylolisthesis is the anterior displacement of one vertebrae over the vertebrae below it. It is typically degenerative and associated with aging in the lumbosacral spine, as opposed to the traumatic spondylolisthesis commonly seen in younger patients in the cervical spine. This can lead to fracture of the pars interarticularis (spondylolysis), and also can cause compression and shearing of spinal cord tissue and nerve roots. Many patients with degenerative spondylolisthesis are asymptomatic, but if they have neurological symptoms they may be considered a surgical candidate.\textsuperscript{77} Spondylolisthesis is classified using the Meyerding\textsuperscript{78} system into 4 grades of severity ranging from 25\% to 100\% displacement.

Hyperalgesia and Peripheral/Central Sensitization  An important factor in the perpetuation of chronic LBP is the phenomenon of hyperalgesia, whereby patients experience significant pain from minimal noxious stimulus, due to sensitization of pain receptors in the central nervous system (CNS) and peripheral nervous system (PNS). This can progress to a more extreme form of
hyperalgesia called allodynia, which is the experience of pain from stimuli that are entirely non-noxious under normal circumstances. This sensitization leads people with LBP to believe that they are harming themselves with minimal stresses and loading of the painful tissues, and leads to decreased activity due to fear-avoidance beliefs.

**Peripheral Sensitization** Peripheral sensitization is a complex process whereby release of molecules by nociceptors, and by injured and adjacent tissues, ultimately increases pain by increasing neuronal firing rate, and decreasing the necessary threshold required to elicit action potentials in C-fiber neurons. The production of pain is intimately related to the inflammatory response in tissues. The mechanisms by which pain is generated and perpetuated are complicated and multifactorial, and the chemical factors involved include, among many others, prostaglandins, substance P, and histamine. Non-steroidal anti-inflammatory drugs (NSAIDs) work by indirectly impeding the production of these chemical mediators and thereby having an analgesic effect.

**Central Sensitization** Central sensitization involves changes that occur in synapses in the dorsal horn of the spinal cord and at higher levels in the CNS. This happens in the spinal cord through mechanisms where ascending pain fibers are pushed into a sustained excitatory state by glutamate receptors that have been stimulated over a period of time by actual noxious input lasting from weeks to months. This increased glutamate receptor activation causes presynaptic neurons to release substance P, which leads to increased nociception. Sustained noxious stimulus also ultimately leads to increased transcription of genes that code for glutamate receptors on the dendrites of post synaptic membranes, resulting in increased numbers of receptors and a stronger pain response.
It is important to recognize that central sensitization applies to hyperalgesia produced at sites distant from the area of the primary complaint. For example, Giesecke et al\textsuperscript{82} found that pressure applied to the thumb produced pain reports in participants with chronic LBP and fibromyalgia, that significantly exceeded the reports of pain in healthy control participants. Similarly, Jason et al\textsuperscript{83} found that participants with chronic LBP had decreased pressure point pain thresholds (PPT) with stimulus applied distant to the low back when compared with healthy controls.

**Measuring Low Back Pain Severity**

There are many methods of measuring LBP, and this has made it challenging to compare the results of different studies. Some common LBP measurement methods that are relevant to the present study are described below. These include: pain scales, chronicity, functional scales, degree of peripheralization, and functional motion.

**Pain Scales**

A variety of numeric pain scales were found by Herr et al\textsuperscript{84} and Lee et al\textsuperscript{85} to be valid in both younger and older adults. Although there are numerous pain scales in use, the numeric pain scale, used in the present research, is easiest to administer and commonly used by clinicians with adult patients.\textsuperscript{84,86,87}

**Chronicity**

Time since onset is commonly used as a way to measure LBP severity. Although the cutoff points vary from study to study, 12 weeks is consistently used as a cut-off point between acute and chronic LBP,\textsuperscript{14,15,16,88,89} and is so used in the present study. One caveat
in using chronicity as a measure of LBP severity is that it can be related to other factors, such as active Workers Compensation claims.90

**Functional/Impairment Scales**

There are numerous functional assessment tools available to assess severity of LBP.91 However, use of such tools varies greatly among clinicians and has been found to be highly dependent on time constraints in the clinic due to high patient loads.92 The Oswestry Disability Index (ODI) is among the most widely used scales to assess functional disability related to LBP,89,93,94,95,96 and was used by the clinicians participating in the present research. The ODI, in use for almost 40 years, has 10 items which are each scored from zero to 5, with the final score doubled to obtain a possible total score of 100, representing the most extreme disability related to LBP. It has been found to be a reliable and valid tool for estimating LBP-related disability.22,91,97 Although the ODI has been validated as a tool to measure LBP, it does not consistently correlate with muscle cross-sectional area (CSA), another measure of LBP used in the present study and described in detail below.14

**Peripheralization of Symptoms**

Peripheralization - referral of LBP symptoms into the buttocks and lower extremity - has been used as a measure of severity of LBP. The QTF developed a well-known classification system based on the level of peripheralization of LBP, and this has been shown to correlate with symptom severity.19 Konsted et al98 studied pain, activity limitation and sick leave in a group of 1,752 patients with LBP over a 12-month period. They divided study participants into 4 QTF categories based on presence and severity of pain in the low back versus pain above and below the knee. They found that patients with
reported pain only in the low back and not in the leg, had improved activity and less sick leave than those with leg pain. Konstantinou et al\textsuperscript{99} performed a meta-analysis of studies assessing the impact of leg pain in LBP patients, and found greater disability and poorer quality of life in those individuals reporting greater percentages of leg pain. Cook et al\textsuperscript{100} performed a retrospective analysis of outcomes in 1,108 patients undergoing lumbar discectomy and found that greater percent of lower extremity pain versus back pain was significantly correlated with positive surgical outcomes after one year.

Mckenzie\textsuperscript{20} developed an approach to LBP assessment and treatment that depends largely on assessing changes in symptom peripheralization and centralization. Werneke and Hart\textsuperscript{101} used a McKenzie approach to categorize 287 adult males and females with non-specific neck and LBP, as centralizers and non-centralizers. They found that patient reported-centralization, was correlated with relief of symptoms, and that, when assessed over a multi-visit period, the accuracy of the centralization label was significantly greater.

Kader et al\textsuperscript{102} assessed MF atrophy in 78 adult patients with back pain. They graded the level of atrophy on lumbar MRI subjectively based on visually estimated percentages of fat and fibrous infiltration into the muscle belly. They correlated CSA with participant-reported radicular symptoms and with observed disk degeneration, herniation, and nerve root impingement as seen on MRI. The only significant finding was that atrophy correlated positively with reported peripheralization of symptoms.

**Functional Motion**

Marras et al\textsuperscript{23,57,65} and Ferguson et al\textsuperscript{103,104} have used the LMM to assess the probability of LBP-related motion impairment in a number of studies on working populations with and without LBP. This device, a lightweight exoskeleton or harness
connected to a computer, measures range of motion, velocity and acceleration of movements in a sagittal, transverse and coronal plane. It then derives a “probability of normal” value, normalized to age and sex, between zero and one; values of less than 0.5 indicate impaired low back function. They found that the LMM accurately differentiated healthy from LBP participants, and is also able to differentiate sincere from insincere efforts.

**Treatment Interventions for Low Back Pain**

**Exercise**

Up to 90% of physical therapists use exercise as part of their treatment plan for LBP patients. A number of different forms of exercise have been shown to be effective in decreasing LBP, the most common of which are described below.

**Multifidus/Lumbar Stabilization/Motor Control Exercises** Exercises targeting the MF muscle can be performed in sitting, standing, supine, or quadruped and typically involve isometric co-contraction of MF and transversus abdominus. More advanced MF exercises involve concurrent upper and lower extremity exercises while performing this co-contraction. Such exercises are referred to clinically and in the literature also as lumbar stabilization, motor control and core stabilization exercises. Hides et al were some of the earliest researchers to assess the effectiveness of LBP interventions targeting the MF. They found that MF CSA increased significantly in patients with acute unilateral LBP after one month of performing only one exercise: isometric co-contraction of MF and transverse abdominus. After ten weeks the CSAs in the treatment group had increased further, while the control group’s CSAs remained unchanged. They followed
up with all 39 of the pain-free participants with a questionnaire at one-year post completion of the study, and with 36 of the participants at 3 years. At 3 years, patients in the control group showed a 9 times increased recurrence of LBP compared with patients from the treatment group. The number of individuals still performing the exercises was not noted in the report.

Rabin et al\textsuperscript{109} assessed lumbar stabilization targeting the MF versus manual therapy as treatments for LBP in 104 adults with LBP. They found that both treatments were effective, but lumbar stabilization exercises were significantly more effective. Kim et al\textsuperscript{95} found that functional mobility, MF CSA, and psoas major (PM) CSA increased, while pain decreased, in 33 patients with LBP lasting more than 20 weeks. This was after the participants underwent an exercise program consisting of cardiovascular, lumbar stabilization, and some PM-specific exercises. Franca et al\textsuperscript{108} assessed the effects of MF exercises versus general strengthening exercises in 30 individuals with LBP over a 6-week treatment period and found significantly greater improvement in LBP as measured by pain and ODI scores in the MF exercise group. Wang et al\textsuperscript{110} performed a meta-analysis comparing the effects of core stability exercises versus general non-specific exercises on LBP. They found that core stabilization significantly decreased LBP immediately following treatment compared with general exercises; but that both forms of exercise had the same effect at 6 months follow up. They also found that functional status as measured by the ODI and other tools was significantly greater in the core stability group. Macedo et al\textsuperscript{111} performed a meta-analysis of 14 studies on the effectiveness of motor control exercises targeting MF and transverse abdominus in the treatment of LBP versus minimal treatment, manual therapy, other exercise, and surgery. They found motor
control exercises were significantly more effective in reducing LBP than minimal or no treatment in the short, intermediate and long term.

Some studies have shown a lack of significance for MF exercises and LBP. Daneels et al\textsuperscript{16} studied paravertebral muscle CSA at 3 levels in 59 patients with chronic LBP, randomly assigned to either lumbar stabilization exercises, or 2 different types of resistance exercises. They found significant increases in CSA only for the 2 resistance exercise groups. Hebert et al\textsuperscript{94} found no significant difference in ODI and pain scale scores in experimental and control participants with LBP who performed a general exercise program, and those performing general exercises plus additional exercises targeting MF. However, the general exercises in standing, supine and quadruped also have been shown to target the MF muscle, so there was not a substantial difference between treatments for the 2 groups in this study.

**Resistance Exercise** Recent research has begun to document the effectiveness of resistance exercises in treating LBP. Choi et al\textsuperscript{112} reported on 75 men and women undergoing single level microdiscectomy for disc herniation. All participants were given “basic lumbar conditioning exercises”, and the experimental group were also given 12 weeks of graded isometric and dynamic lumbar extension exercises. The experimental group showed significantly more improvement in extensor muscle strength, pain scale score, and MF and ES CSAs, than the control group. Kell et al\textsuperscript{15} sought to demonstrate the impact of 13 full-body resistance exercises on LBP severity and upper and lower extremity strength in 240 individuals with LBP. After 13 weeks of exercises at the 2 to 4-day a week levels, all 3 training groups had a significant decrease in pain and increase in strength compared with the control group. The 4 day/week group had the most
improvement and no adverse effects. Aasa et al\textsuperscript{113} assessed the effects of 2 treatment plans on LBP outcomes in 70 adult male and female participants. The low load group performed 6 sessions of gentle, graded, lumbar stabilization exercises in various positions, as well as some jumping and functional trunk rotation activities. The second group performed barbell deadlifts at weights deemed safe by the supervising physical therapist, with increases in loads and reps over an 11-session treatment period. Both groups showed significant improvement in functional test and pain scores compared with baseline values. The low load group, however, had significantly higher post intervention functional test scores than did the deadlift group. Daneels et al\textsuperscript{16} studied paravertebral muscle CSA at 3 levels in 59 patients with chronic LBP, randomly assigned to either lumbar stabilization exercises, or 2 different types of resistance exercises. They found significant increases in CSA only for the 2 resistance exercise groups.

ES strengthening has not been consistently included in treatment plans for LBP patients. Exercises which target MF will also always elicit some activation of the ES muscles as well; however, exercises which would preferentially target the ES are often avoided in conservative treatment plans. In their study of 24 healthy adult males and females, Arokoski et al\textsuperscript{114} found that while bridging exercises, a common component in LBP treatment plans, activated both MF and ES, the normalized EMG amplitude during this exercise was more than twice as high in MF as in ES. However, when they assessed EMG during standing upper extremity resisted flexion, amplitudes increased for both muscle groups, but were almost twice as high in the ES as in the MF. This latter exercise currently would not be included in many LBP treatment plans which take a more conservative approach.
**Cardiovascular Exercise** There are few studies which examine the impact of purely cardiovascular exercises on LBP. In general, cardiovascular exercise has been shown to be effective in temporarily reducing PPT in both human and animal studies.\textsuperscript{115,116} Meeus et al\textsuperscript{117} found significantly increased PPT in multiple locations in participants with LBP after one bicycle ergometer exercise intervention.

**Aquatic Therapy/Yoga/Pilates** Aquatic Therapy is widely prescribed as an intervention for LBP patients and has been shown to be an effective treatment for LBP in those patients that tolerate it.\textsuperscript{118,119} Yoga,\textsuperscript{120} and Pilates\textsuperscript{121} have been shown to be an effective intervention in LBP patients in a small number of studies. Their effectiveness, which has been only minimally studied, may be attributed at least in part to the lumbar stabilization aspects of these exercise modalities.

**The Role of Exercise Induced Analgesia in LBP Treatment** It must be recognized that positive exercise effects on LBP may be partially or largely due to the mechanism of exercise-induced analgesia. It has long been known that the human body has inherent pain suppression abilities contained within the CNS, and the PAG in the midbrain is the source of this endogenous analgesia. The PAG works to suppress pain through the integration of inputs from several brain areas involved in affective, endocrine and behavioral responses. After integration of these inputs, the PAG sends efferent responses to the medullary reticular formation and ultimately to the dorsal horn of the spinal cord. In the spinal cord, these neurons synapse on cell bodies of second order pain-sensing neurons in the substantia gelatinosa and inhibit the pain transmissions of ascending LSTT neurons through release of serotonin, an inhibitory neurotransmitter. Total analgesia has been produced in animal studies through electrical stimulation of the PAG. Opioid
receptors found in the PAG and in the dorsal horn are also activated endogenously by neurotransmitters which include enkephalins, dynorphins and endorphins. These same receptors are activated exogenously by narcotics and explain the mechanism of action for that class of drugs.\textsuperscript{122,123,124}

In a review of more than a dozen studies assessing the effect of exercise on endogenous analgesia, Koltyn\textsuperscript{125} described studies involving the effects of cycling, running, step exercises, arm and leg exercises, various team sports, resistance and isometric exercises on: dental pain thresholds, PPT, thermal sensitivity, and skin sensitivity. These effects lasted from 5 to 60 minutes. More intense exercise was correlated with increased analgesia, and cardiovascular exercise produced, in general, more analgesic effects than resisted or isometric exercise. Naloxone, used clinically to counteract opioid overdose, has been shown to block exercise induced analgesia when administered both locally and systemically, thus supporting the claim of involvement of the endogenous opioid system.\textsuperscript{116,126,127}

**Pharmacological, Thermal, Electrotherapeutic and Manual Interventions**

**Pharmacological Treatment** Pain medications are widely prescribed to treat LBP and include NSAIDS, acetaminophen, muscle relaxants, selective serotonin uptake inhibitors, opioids, and corticosteroids.\textsuperscript{128,129}

**Pain Relieving Modalities** It has been reported that 65% of physical therapists use electrotherapeutic and thermal modalities (such as electrical stimulation, ultrasound and moist heat) as an adjunct to exercises, education and manual techniques in treating LBP patients.\textsuperscript{106} It is through the mechanism described in Melzack and Wall’s\textsuperscript{79} gate control theory of pain that these modalities are believed to work. This theory holds that
ascending pain signals from C fibers can be stopped in the substantia gelatinosa of the
dorsal horn by incoming signals from larger, myelinated A beta fibers, with the latter
sensations overriding the pain signal. This theory of pain control has been refined over
the years but still stands as the primary mechanism to explain the success of tactile,
thermal and electric sensations in overriding pain signals.\textsuperscript{123}

\textbf{Manual Therapy} Manual therapy includes spinal manipulation, mobilization,
massage, and other less common techniques. In their survey of LBP treatment practices
among physical therapists in Ontario, Li and Bombardier\textsuperscript{106} found that 83\% of therapists
used spinal mobilization and 7\% used spinal manipulation to treat subacute LBP patients.

\textbf{Surgery}

Various surgeries are performed by either orthopedic surgeons or neurosurgeons
to address a variety of spinal conditions related to LBP. Below are descriptions of the
surgeries most relevant to the present research.

\textbf{Laminectomy and Decompression} Unilateral or bilateral laminectomy and
decompression are commonly used to treat spinal stenosis, and also as a part of lumbar
fusion or discectomy surgeries. This surgery involves removing one or both laminae, and
carefully clearing away IVD, ligament or bone tissue which may be compressing neural
structures. Laminectomy is the first step in many back surgeries.\textsuperscript{130}

\textbf{Microdiscectomy} Microdiscectomy involves performing a hemi-laminectomy and
removing small pieces of IVD tissue that are compressing neural structures. This
 technique is minimally invasive and patients have a high rate of return to work and
improvement in pain scores.\textsuperscript{112} This good recovery rate may be due to the fact that
microdiscectomy patients have lower pre-surgical LBP severity. Unpublished data from
Ferguson and Marras\textsuperscript{131} shows pre-surgical LMM probability of normal scores for microdiscectomy patients, as well as non-normalized component scores for lumbar range of motion, flexion velocity and extension velocity, are significantly higher than the scores of pre-surgical lumbar fusion patients. However, because overall scores are quite low for both groups, there is some question as to clinical relevance.

**Fusion** Spinal fusion involves performing a laminectomy and decompression, and then either: placing bone graft tissue in the disc space which will fuse the spinal segment after it heals; and/or using metal cages and pedicle screws to stabilize the fusion. Anterior or posterior spinal fusions are commonly performed due to diagnoses of multilevel disc herniation, spinal stenosis, degenerative disc disease with instability, or grade II or III spondylolisthesis.\textsuperscript{132}

**Evidence of the Role of Selected Trunk and Hip Muscles in Low Back Pain**

**Multifidus**

**Morphology/Innervation/Actions** The MF runs the entire length of the spine and has a distinctly different morphology in the different regions of the spine. It is named by region based on the rostral insertion of its fascicles. The lumbar MF originates in the sacral region from the posterior sacrum, posterior superior iliac spine and posterior sacroiliac ligaments; and inserts on the lumbar spinous processes. The lumbar MF is much thicker and more superficial than MF in other regions. Origins in the lumbar region are from the mammillary processes of the transverse processes; in the thoracic region from the transverse processes themselves; and in the cervical region from the articular processes. Insertions for all regions are one to 4 vertebral segments superior, on the entire
length of the spinous process; with superficial fascicles inserting up to 4 segments superior; and deep fascicles one to 2 segments superior. The MF is innervated by the dorsal primary rami of adjacent spinal nerves. Its actions are to extend, laterally bend and rotate the spine to the opposite side. However, it is its role as a spinal stabilizer that is thought to be its most significant function.

**Multifidus as Stabilizer** Evidence exists showing that MF plays a segmental stabilizing role throughout the spine. EMG studies have shown MF to be active during neutral postures and with loading, along with other agonist extensors and antagonist flexors, to maintain neutral posture. The deep fibers of MF are believed to most affect vertebral stability and thus be implicated in LBP, although this relationship remains unclear. Ward et al[137] in a study of MF mass, sarcomere length, fiber length, and CSA, found a high CSA and high fiber-length to muscle-length ratio which supports the notion of MF as a strong spinal stabilizer. There is evidence of altered supraspinal control of MF’s stabilizing abilities in individuals with LBP. Masse-Alarie et al[138] used transcranial magnetic imaging to show evidence of cortical reorganization in the M1 area of the motor cortex representing the MF muscle, during isometric MF contraction.

**Multifidus Cross-Sectional Area and Low Back Pain** MF CSA has been found to be smaller in persons with LBP in numerous studies. Hides et al[139] found significantly decreased ipsilateral MF CSA in adults with their first episode of acute, unilateral LBP. Barker et al[14] and Ploumis et al[93] found significantly decreased ipsilateral MF CSA in adults with chronic LBP. Kang et al[140] found significantly decreased MF CSA in adults with lumbar degenerative kyphosis, compared with a control group of adults with a diagnosis of chronic LBP. Thakar et al[141] found significantly decreased MF CSA among
adults with a diagnosis of isthmic spondylolisthesis compared with a healthy control group. Hyun et al\textsuperscript{142} found significantly decreased MF CSA in patients with lumbar IVD herniation with and without radiculopathy, compared with a healthy control group. Bouche et al\textsuperscript{143} found significantly decreased MF CSA among participants who had previously undergone discectomy surgery at L5-S1.

There have been a small number of studies which show a lack of MF atrophy with LBP. Battie et al\textsuperscript{144} found no significant asymmetries in CSA of MF in adults with acute LBP with verified lumbar disc herniation on imaging, and unilateral leg symptoms. However, significant increases in adipose tissue content were found in the ipsilateral MF muscles, particularly just below the level of the lesion. Mattila et al\textsuperscript{145} used intraoperative biopsy to analyze differences in muscle fibers of adults undergoing surgery for herniated disks at L4-5 and L5-S1 levels. Controls were samples from 12 post-mortem human subjects with no known LBP pathology, taken within 48 hours of death. They did not find significant differences in either type I or type II fiber size between the control and experimental groups. However, lack of medical history in the control group calls these results into question.

**Gluteus Maximus**

**Morphology/Innervation/Actions** GM is a large quadrilateral shaped muscle arising from the gluteus medius fascia, the posterior ilium, the thoracolumbar fascia, the erector spinae aponeurosis, the dorsal sacroiliac ligaments, the sacrum, the sacrotuberous ligament and the coccyx. It runs obliquely and inserts on the iliotibial band over the greater trochanter, and inferiorly onto the gluteal tuberosity of the femur.\textsuperscript{146} Its primary
action is hip extension, and it also functions as an external rotator of the hip. It is innervated by the inferior gluteal nerve.\textsuperscript{135}

Because it crosses the sacroiliac joint (SIJ), and exerts much of its force perpendicular to the SIJ, GM is thought to be important in stabilizing this joint. It also functions as a couple with the latissimus dorsi muscle to generate a sling mechanism that may be important in normal gait.\textsuperscript{147}

**Gluteus Maximus’ Role in Lifting** GM’s role as a prime mover in the first part of trunk extension from full flexion has been previously discussed. Intervertebral discs are known to be most at risk for herniation in full flexion;\textsuperscript{50,74} thus, because GM is so important at the start of lumbar extension, weak GM may lead to improper lifting technique just when the discs are most vulnerable to herniation. This GM weakness may also increase the time when most stress is placed on the passive elements that stabilize the spine such as ligaments and discs, and which are known sources of pain in the lumbar region. GM may have an even larger role in trunk extension when muscles are fatigued. Clark et al\textsuperscript{148} found that, in healthy young adults performing trunk extension exercises to exhaustion, ES muscles begin to de-recruit at 55% of maximal fatigue; at this point GM and the hamstring muscles increase their activation, seemingly to compensate for this loss of ES activity.

GM has been found to fatigue more quickly in adults with LBP during trunk extension, and to be active for shorter duration.\textsuperscript{50,89} Leinonen et al\textsuperscript{50} found such alterations in both GM and ES muscle activation during extension in LBP participants. Interestingly, these deficits were corrected after 5 weeks of physical therapy in the ES,
but remained unchanged in the GM. This difference may be due to the fact that most therapy protocols for LBP do not address GM weakness.

GM is considered important in the development of bipedalism in humans, as it allowed the use of upper extremities in functional activities unavailable to quadrupeds, such as lifting, clubbing and gathering.\textsuperscript{149,150} Marzke et al\textsuperscript{150} used EMG in 6 participants to measure the activation of gluteus maximus during several tasks important to early hunter-gatherers. They found maximal activation of GM with lifting and dragging of loads across the floor. The strong EMG signal was maintained throughout the dragging of the load, with variation in right and left GM activation among participants.

**Gluteus Maximus Cross-Sectional Area and Low Back Pain** The possible role of GM in the genesis of LBP has been virtually unstudied. In the sole study identified that assessed GM CSA and LBP, Kamaz et al\textsuperscript{96} found no significant differences in CSA measurements in the GM muscles of 36 sedentary women with chronic LBP, compared with 34 control participants. However the study’s authors appear to not have normalized CSA to body size, which may have skewed the results.

**Psoas Major**

**Morphology/Innervation/Actions** Psoas major arises from the transverse processes, vertebral bodies and intervertebral discs of the L1-L5 vertebrae; and it inserts with the tendon of iliacus onto the lesser trochanter of the femur. It is innervated by branches from the ventral primary rami of L1-L3 and its actions are to flex the hip, and laterally flex the trunk.\textsuperscript{135,151}

**Stabilization of the Lumbar Lordosis** A likely explanation of PM’s role in LBP is via its mechanism of stabilization of the lumbar lordosis. This stabilization takes place
through the angles of pull of its muscle fascicles, which, in healthy individuals, result in extension of the upper lumbar spine and flexion of the lower lumbar spine in certain postures.\textsuperscript{151,152} The lordotic posture achieved partially through this mechanism, has been associated with lower incidence of LBP in patients with a McKenzie posterior derangement type of clinical presentation.\textsuperscript{61}

**Psoas Major Cross-Sectional Area and Low Back Pain** A number of studies have assessed PM CSA and LBP. Kamaz et al\textsuperscript{96}, Barker et al\textsuperscript{14}, Kang et al\textsuperscript{140} Dangaria and Naesh\textsuperscript{153} and Thakar et al\textsuperscript{141} all found significantly lower CSA measurements in PM in adults with chronic LBP with and without other lumbar comorbidities.

**Erector Spinae**

**Morphology/Innervation/Actions** The ES muscles are powerful extensors of the spine running from the sacrum to the occiput. From medial to lateral they consist of 3 muscles: spinalis, longissimus and iliocostalis. The regions of the ES are named based on the vertebral levels of their rostral attachments. The present research is concerned only with the ES muscles in the lumbar region: iliocostalis lumbarum and longissimus thoracis pars lumbarum. Iliocostalis lumbarum has caudal attachments on the ES aponeurosis, and the posterior iliac crest; and rostral attachments to the inferior borders of the angles of the lower 6 ribs. Longissimus thoracis has caudal attachments to the ES aponeurosis, posterior iliac crest and posterior superior iliac spine; and rostral attachments to the accessory process of the transverse processes of the lumbar vertebrae. The erector spinae aponeurosis is itself attached to the median crest of the sacrum and the spinous processes of the lumbar vertebrae. The ES is innervated by the dorsal primary rami of adjacent spinal nerves. Its actions are to extend, and laterally bend the spine.\textsuperscript{133,134,154,155}
Erector Spinae and Lifting  ES has been shown to be an important muscle group when arising from full trunk flexion into extension, particularly during the last 50% of extension.\textsuperscript{48,49,50} During lifting of asymmetric loads, the contralateral ES is most active, and it has been shown to be more active bilaterally when base of support is increased during a lift.\textsuperscript{51,52} ES has been shown to be active during agonist/antagonist co-contraction required to maintain erect posture in both unloaded and loaded participants.\textsuperscript{43} In individuals with LBP, different studies show contradictory ES responses. ES activation has been found to be diminished overall, and to occur later in the extension cycle with LBP;\textsuperscript{50} and conversely to be activated earlier and for a longer period.\textsuperscript{54}

Erector Spinae Cross-Sectional Area and Low Back Pain Results of studies assessing CSA changes in ES with LBP have been conflicting. Kang et al\textsuperscript{140} found significantly more atrophy in ES CSA measured at the L4-5 disc of patients with a more severe variant of chronic LBP, than in participants with generalized chronic LBP. Ploumis et al\textsuperscript{93} also found significantly smaller ES CSA in participants with LBP. But Lee et al\textsuperscript{156} and Bouche et al\textsuperscript{143} had mixed results when they assessed ES CSA in LBP participants. At some levels, they found atrophy correlated with LBP, but at other levels, this was not the case. For example Lee et al\textsuperscript{156} found no significant difference in ESA CSA at the L3 level, but Bouche et al\textsuperscript{143} found significance in ES CSA only at the L3 level. Thakar et al\textsuperscript{141} found significantly decreased MF CSA but increased ES CSA in adults with isthmic spondylolisthesis.
Measuring Muscle Strength

Electromyography

EMG is widely used to measure the strength of skeletal muscles.\textsuperscript{36,89,157,158,159} EMG values are typically normalized to maximum voluntary contraction, to control for differences in body habitus which can independently affect EMG amplitudes. However, study participants experiencing pain often are unwilling to perform a maximal contraction, and thus some studies do not normalize EMG for these participants, making comparison across studies challenging.\textsuperscript{8}

Manual Muscle Testing

Traditional manual muscle testing (MMT) techniques as described by Kendall\textsuperscript{160} are widely used by physicians and physical therapists. Testing positions for back extensor muscles as a group are prone and involve sustained isometric extension;\textsuperscript{31,160} however, for comfort and safety reasons, the formal testing position is rarely used on patients with LBP. Because of anatomical issues, isolated MF strength cannot be measured using MMT. MMT, while an inherently subjective procedure, has been found to be reliable for testing upper and lower extremity muscle strength when practitioners are well-trained in the grading system and testing positions.\textsuperscript{161}

Muscle Morphometry

Muscle CSA has been measured using MRI,\textsuperscript{140,144,153,162,163,164} CT,\textsuperscript{96,164} and ultrasound.\textsuperscript{163,165} Measurements of muscle CSA and volume have been correlated with strength in a number of studies on upper and lower extremity muscles in healthy adults. Ninimaki et al\textsuperscript{149} measured GM CSA in female young adult athletes and sedentary women. They found CSA was correlated with dynamic and isometric muscle strength.
Mersmann et al\textsuperscript{166} found that triceps surae volume was significantly greater in resistance trained athletes than in endurance trained athletes and untrained adults. Maugan et al\textsuperscript{167} compared isometric strength and CSA of the quadriceps muscles of 36 untrained males and 8 weight-trained males. They found that strength was correlated with CSA in both groups. Akagi et al\textsuperscript{168} found that the CSA and muscle volume of elbow flexors was correlated with increased force and torque of young and older males and females.

\textbf{Cross-Sectional Area} CSA measurements are easily performed using a region of interest (ROI) tool within many imaging software programs. CSA measurements can be either anatomical or physiological. Anatomical CSA is the area of a muscle measured perpendicular to the longitudinal axis of a muscle, at its widest point.\textsuperscript{169} Physiological CSA is the sum of the area of a cross-section of a muscle perpendicular to all of its fibers, at its widest point.\textsuperscript{170} Physiological CSA is a more complicated measurement and appropriate for use with multipennate muscles.

\textbf{Right/Left Symmetry of Muscle Cross-Sectional Area} It is often assumed that muscle CSA is symmetrical in healthy individuals, and this has been shown in some studies.\textsuperscript{163,171} However a number of studies have found that paired muscles are not always symmetrical in a normal population, which raises the question of whether it is valid to use the unaffected side as a control, as is done in several of the previously described unilateral LBP studies. Valentin et al\textsuperscript{172} found asymmetry in muscle volume in ES, MF, and PM, in healthy young and mature adults. Marras et al\textsuperscript{173} found significant differences in CSA from right to left in latissimus dorsi, quadratus lumborum, and PM among healthy adults. Teyhen et al\textsuperscript{174} found 5 to 20 percent asymmetry in muscle thickness from
right to left in MF, transverse abdominus, rectus abdominus, and the obliques of healthy adults.

Choosing Vertebral Levels for Trunk Muscle Cross-Sectional Area Measurements

Locations of CSA measurements for trunk muscle CSA are chosen by researchers either due to perceived lesion level, area of greatest muscle thickness, or convenience. Definitions of anatomical and physiological CSA require measurement at the muscle’s widest point; however, this is not always feasible due to imaging availability and quality. Furthermore, there is a belief, borne out somewhat by the literature, that muscles adjacent to a lesion may be selectively atrophied due to the segmental nature of innervation of paraspinal muscles. Barker et al.\textsuperscript{14} found that MF and PM CSA in LBP participants showed a maximal decrease at the symptomatic level, but also significant decreases at one level above and below the lesion level. Dangaria and Naesh\textsuperscript{153} found that asymmetry was greatest at the levels of the individual disc herniations, although 21\% of the CSAs were smallest one level above or below the lesion level. Ploumis et al.\textsuperscript{93} found that the smallest MF, ES and quadratus lumborum CSAs were found at the level below the lesion, followed by the lesion level.

The above examples show that it is not predictable where maximum CSA changes will be seen with LBP, but it tends to be at lesion level or one vertebral level below. It is important to note that unless documented nerve or nerve root compression has been found on imaging or in surgery, there will be no true lesion level, as no denervation atrophy can be assumed. In cases where radiologist or other physician imaging reports are not available, which is often the case when using de-identified patient data, it is reasonable to take measurements at the most likely lesion level if possible. The most
common site for lesion level in the lumbar spine is the L4-5 disc space, followed by the L5-S1 disk space.

**Effect of Histological Changes on Cross-Sectional Area**  Histological changes seen consistently in paraspinal muscles of LBP patients include increased fat content, moth eaten and targetoid fibers, and smaller muscle fiber diameter. Because of limitations in software analysis capabilities for the present research, we did not attempt to exclude the above histological changes from our CSA analysis. However, in component 3, where MRI scans were used for CSA measurement, we were able to identify percentages of fatty infiltration (FI) for use in statistical analysis. MRI scans are able to clearly delineate fat from muscle tissue, and this visual inspection method has been used by other researchers in muscle CSA studies.

**Muscle Volume**  Muscle volume measurements are becoming more common as imaging and software analysis capabilities become more sophisticated. The advantage of morphometry using muscle volume is that, when performed correctly, it provides more precise muscle morphometry than does CSA. However, because muscle volume measurements require the use of multiple CSA measurements for each muscle, this method is extremely time-consuming. This raises the question of whether the benefit of this extra time investment is worth the cost, as some recent studies have shown that muscle volume correlates quite well to CSA.

**Scaling Muscle Morphometry to Stature**  Muscle CSA and volume measurements must be scaled to stature in order to compare measurements among individuals with different heights. It has long been known that the size of various body tissues correlates with stature, with much of the earlier research performed by anthropologists seeking to
estimate living stature from bony human remains.\textsuperscript{180,181,182} Bone has been the more commonly studied tissue vis a vis correlation with stature,\textsuperscript{183,184} but recent studies have shown correlations of muscle and other soft tissue thickness, CSA, and volume with height and/or weight.\textsuperscript{173,172,174,185} Vertebral body CSA has been used by several LBP researchers as a proxy for stature, and thus a ratio of CSA to vertebral body CSA has also been used to normalize their data.\textsuperscript{16,140,141,143,186}

To address the problem of inconsistent use of anthropometric variables to normalize morphometry to stature, Heymsfield et al\textsuperscript{184} measured different tissue masses in 759 adult males and 998 females, and derived regression equations for adipose tissue, skeletal muscle, bone, brain and liver tissue. They demonstrated that skeletal muscle mass scaled best to the square of stature. Therefore in components 2 and 3 of the present study, we normalized muscle CSA to the square of participant height.

**Effect of Age and Sex on Muscle Morphometry** Muscle size in adults has been shown to decrease with age.\textsuperscript{35,102,141,155,186,187} Sexual dimorphism is seen in muscle size with females consistently showing decreased gross muscle and individual muscle fiber size compared to males,\textsuperscript{33,102,155,173,174} except for the transverse abdominus.\textsuperscript{174} Therefore, all components of the present research will control for age and sex through sampling or statistical analysis.

**Theories of Muscle Atrophy with Low Back Pain**

The following are possible theories to explain the muscle atrophy seen with LBP. Although the documented sedentary lifestyle of many individuals with LBP will, over time, lead to some sort of disuse atrophy, the possible contributions of other mechanisms are debated but unknown.
**Disuse Atrophy** Disuse atrophy results from low mechanical load placed on muscle fibers. This can be the result of sedentary lifestyle, bedrest or, in its most extreme form, space flight. It is important to note that disuse atrophy reflects decreased CSA of muscle fibers but not an actual decrease in numbers of muscle fibers. Another important aspect of disuse atrophy is a switching of fiber types from slow-twitch to fast-twitch fibers. Numbers of myonuclei also decrease with disuse atrophy. This atrophy is rapid when compared with skeletal muscle hypertrophy, which is more gradual. Satellite cells, important in hypertrophy, have uncertain behavior with disuse atrophy.  

**Denervation Atrophy** Denervation atrophy happens after a complete lesion to a neuron, and is much more rapid than age, disuse or disease-related atrophy. There is decreased myofibril diameter as well as actual apoptosis of muscle fibers. This atrophy has been found to occur through neurotrophic changes resulting in decreased protein synthesis and increased protein turnover within the neuron, and at the neuromuscular junction. It can be partially modulated by the application of functional electrical stimulation in intact lower motor neurons, through mechanisms affecting gene expression of acetylcholine.  

Yarjanian et al. proposed that spinal stenosis can lead to nerve root or dorsal rami impingement or stretching, which can lead to denervation atrophy; however, their results, while showing decreased paraspinal cross sectional area with stenosis, had inconclusive EMG evidence of actual denervation. Partial neural lesions do not consistently show denervation atrophy.  

**Age Related Atrophy/Sarcopenia** Age related atrophy, also known as sarcopenia, happens as a natural process of aging in humans, and can be partially arrested by performance of resistance exercises. This type of atrophy reflects decreases in both CSA
of muscle fibers, and in the actual number of muscle fibers. Type I fibers decrease and type II fibers increase with age. In a mouse model, sarcopenic changes in muscle fibers have been shown to occur not just in older but in middle aged mice, before gross changes in muscle atrophy are visible.

Disease-Related Atrophy Disease-related atrophy, secondary to, for example, AIDS or cancer, causes a characteristic inflammatory response which is not seen with other types of atrophy. Additionally, in disease-related atrophy, fast-twitch fibers are more affected than slow-twitch fibers.

Compensatory Hypertrophy/Muscle Substitution Compensatory hypertrophy will only be seen in those studies which compare the affected side in unilateral LBP, with the unaffected side as a control. For example, Dangaria and Nash postulated that the asymmetries found in psoas CSA in their study may also be caused by compensatory hypertrophy on the unaffected side. Agonist substitution in which the ES hypertrophies to compensate for the atrophied MF seen with LBP, has been hypothesized by Danneels et al.

Reflex Inhibition Normal spinal reflexes maintain motor control and allow the automatic postural adjustments that happen secondary to perturbation in order to maintain the spine in its steady state. Franklin and Granata developed a model to show the importance of reflexes in stabilization of the spine, through their potentiation of the intrinsic stiffness of the spine provided by agonist and antagonist co-contraction. This results in lower metabolic cost, increased stability in the spine and lower risk of injury. Stokes and Young postulated, based on theirs and others’ research, that disuse atrophy is partially caused by a cycle of immobility initiated by reflex inhibition. Their work is
based mostly on the study of inhibition post meniscectomy and arthrotomy. Effusion and pain clearly cause reflex inhibition of the quadriceps; but this inhibition can happen in the absence of effusion, and also in the absence of pain. Because of the difficulties inherent in attempting to isolate and measure individual paraspinal muscle actions, it is unknown if a similar mechanism exists in the lumbar spine.

**Conclusion**

This literature review has sought to investigate all of the facets of LBP that are relevant to the present research, and that support the experimental methods used in the execution of this research. These include LBP diagnostic, causation, measurement, and treatment issues. Relevant anatomical, biomechanical and morphometric topics were also explored in detail. Previous research studies which have inspired the present research were also reviewed, and used in the design of the 3 components of this study.

Background on diagnosis and causation of LBP highlighted important factors to be considered during sampling for Aim 2 and Aim 3. A review of anatomical and biomechanical factors implicated in LBP provided a rationale for possible LBP causation related to the muscle CSAs of interest in Aims 1 through 3. Finally, prior research on MF CSA and LBP provided an overall framework and rationale for the CSA studies involving MF, PM, ES, and GM outlined in Aims 1 through 3.
CHAPTER 3: CORRELATION OF GLUTEUS MAXIMUS AND PSOAS MAJOR CROSS-SECTIONAL AREAS WITH MULTIFIDUS CROSS-SECTIONAL AREA IN A CADAVER SAMPLE.
Introduction

Decreased trunk muscle strength and endurance has been identified in persons with low back pain (LBP), yet it is unknown if these deficits are a cause or an effect of LBP.\textsuperscript{29,31,36} Successful interventions to address muscular deficits in individuals with LBP range from core strengthening and motor control exercises designed to explicitly target the multifidus (MF) muscle, to full-body resistance exercises. Positive outcomes in terms of increased function and decreased pain have been demonstrated.\textsuperscript{107,111}

The MF has been extensively studied vis-à-vis LBP. MF is believed to be an important intersegmental spinal stabilizer, and it is through this role as a stabilizer that LBP causality has been proposed.\textsuperscript{137} Individuals with LBP have shown significantly decreased electromyographic activity in the MF compared with healthy controls,\textsuperscript{58} and MF atrophy, measured by cross-sectional area (CSA), has been demonstrated in numerous studies to be correlated with LBP.\textsuperscript{14,139,140} Muscle strength has been positively correlated with CSA, which is therefore used as one indicator of muscle strength in clinical research.\textsuperscript{194} However, because there are a greater proportion of type I muscle fibers in MF, reflecting its tonic function, MF muscle atrophy is considered by some to be a manifestation of decreased endurance rather than decreased strength.\textsuperscript{32,36} The trend toward transition of slow to fast twitch fibers with disuse atrophy provides one rationale for this decreased endurance seen in individuals with LBP.\textsuperscript{34,35}

It is important to recognize that changes in MF in LBP patients are not solely a function of actual strength/endurance deficits, but also may result from altered motor control. MF’s role in motor control is made possible by nociceptors and mechanoreceptors present in ligaments, capsules and discs, which then project to the
alpha and gamma motor efferents of the MF, resulting in stabilization of vertebral segments.\textsuperscript{39} It is has been shown that both pain and loading will alter this mechanism in both human and animal studies.\textsuperscript{40,42}

While important, the focus on MF-related research, and on designing interventions to address MF deficits, has to some degree prevented the research community from assessing the role that strength and/or motor control deficits in other muscles may play in LBP. A causative role for gluteus maximus (GM) in LBP has not been shown in the literature; however, GM’s role in returning the trunk to an upright position after full flexion, and thus in lifting loads, is well established.\textsuperscript{150} GM biomechanics become relevant when we consider that improper lifting practices have emerged as perhaps the most important and preventable cause of LBP.\textsuperscript{23}

Similarly, the possible role of decreased psoas major (PM) strength in LBP genesis has been only minimally studied, although it has received more attention than GM. A likely explanation of PM’s impact on LBP is via interruption to its mechanism of stabilization of the lumbar lordosis. This stabilization takes place through the angles of pull of its muscle fascicles, which, in healthy individuals, result in extension of the upper lumbar spine and flexion of the lower lumbar spine in certain postures.\textsuperscript{151} This is relevant because an increased lordosis has been associated with lower incidence of LBP in patients with a posterior derangement type of clinical presentation.\textsuperscript{61}

The purpose of this study was to determine whether there is an association between MF’s CSA and the CSA of GM and PM in a sample of adult cadavers. As decreased MF CSA has been correlated with LBP, our hypothesis was that both PM and
GM CSA in our cadavers would show an atrophy pattern that is significantly correlated with that of MF.

**Methods**

**Participant Description**

A convenience sample of 28 male and 7 female, unembalmed cadavers, between the ages of 42 and 94 years of age, from The Ohio State University (OSU) Injury Biomechanics Research Center (IBRC) were used for this study (Table 3.1). The Body Donor Program Advisory Committee of the OSU Division of Anatomy approved the use of cadavers for this study. Exclusion criteria were: 1) presence of lumbar or sacral surgical metal implants, if these devices impeded accurate measurement; 2) history of medical diagnoses with the potential to alter muscle morphology asymmetrically, including cerebrovascular accident (CVA) or other acute or chronic neurological conditions; and 3) cadavers whose computed tomography (CT) imaging quality was poor, making accurate measurement of CSA not feasible.

A total of 73 cadavers for which CT imaging was available for the body regions in question were found in the IBRC collection, and were thus initially considered for the study. Eighteen were excluded due to a history of CVA or other neurological impairment; 5 were excluded because of the presence of lumbar/sacral surgical implants; and 15 were excluded because of poor imaging quality. Thirty-five cadavers were thus selected for inclusion in the study.
Measurements and Procedures

All cadavers underwent CT scanning using either a Lightspeed VCT (General Electric) or Somatom (Siemens) CT scanner at 120kV and 200mA. Slice thickness was 0.6 mm. Anatomical CSA measurement requires that a muscle be measured perpendicular to the longitudinal axis of a muscle, at its widest point.\(^\text{169}\) Thus our muscle CSA was measured perpendicular to the muscle’s line of action, in axial sections, for MF, PM and GM. MF and PM were measured at the L4 mid-vertebral body, and GM was measured at the level of the second sacral foramen (Figure 3.1). These measurement locations were chosen based on the availability of easily identifiable anatomical landmarks on participant CT scans, closest to the thickest available portion of the muscles. Because the quality of CT scans varied, and some medial attachments were hard to discern, the medial attachment of GM was defined as the sacroiliac joint for all GM measurements.

Data were analyzed using OsiriX (version 5.8.5, Pixmeo, Geneva) software on an Apple i-Mac computer. Each muscle CSA was determined by using the OsiriX region of interest pencil tool and was manually traced by the study’s principal author using an Apple Magic Trackpad. Use of a single measurer for muscle CSA has been seen in prior studies by Barker et al\(^\text{14}\) and Kang et al.\(^\text{140}\) Each CSA was measured 3 times in one session, and then an average of these measurements was taken, based on the protocol used by McGill et al\(^\text{162}\) to maximize measurement reliability.
Table 3.1 Participant Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Males (n=28)</th>
<th>Females (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>42.0</td>
<td>94.0</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>162.56</td>
<td>187.96</td>
</tr>
</tbody>
</table>

Figure 3.1 Measurement of Gluteus Maximus Cross-Sectional Area

**Statistical Analysis**

Statistical analysis was performed using SPSS Version 22. Intraclass correlation coefficients (ICC) were obtained to assess intra-rater reliability of the CSA measurements. Spearman’s correlation coefficient was used to assess correlation between the muscle CSAs. Paired sample t-tests were used to assess differences between the mean CSAs of the right and left sides of individual participants. Statistical significance was defined as p<0.05.
Results

Table 3.2 shows muscle CSA measurements. Paired sample t-tests indicated that right and left CSAs were not significantly different for all 3 muscles \( (p=0.750\) for MF; \( p=0.258\) for PM; \( p=0.433\) for GM). Therefore CSA measurements for both right and left sides were combined for further analysis. Although many studies\(^{14,93,139,141}\) of unilateral LBP have shown asymmetries in muscle CSA for study participants, data on sidedness of symptoms was not available for the present sample. Furthermore, a number of studies\(^{172,173,174}\) have found that paired muscles are not always symmetrical in a normal population, which argues for using a combined CSA in order to capture changes that may occur due to LBP.

Measurements for the combined MF and PM CSAs were found to be normally distributed, but GM combined CSA results were not normally distributed. Thus non-parametric tests were used for all analyses involving the GM. ICCs of 0.875, 0.931, and 0.973 were obtained for MF, PM, and GM, respectively, indicating good intra-rater reliability.
### Table 3.2 Muscle Cross-Sectional Areas

<table>
<thead>
<tr>
<th>Muscle Type</th>
<th>Males (n=28)</th>
<th>Females (n=7)</th>
<th>Males and Females (n=35)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Multifidus CSA - Right</td>
<td>5.49</td>
<td>11.06</td>
<td>7.59±1.44</td>
</tr>
<tr>
<td>Multifidus CSA - Left</td>
<td>4.94</td>
<td>10.29</td>
<td>7.66±1.47</td>
</tr>
<tr>
<td>Psoas Major CSA - Right</td>
<td>4.92</td>
<td>12.91</td>
<td>8.95±2.07</td>
</tr>
<tr>
<td>Psoas Major CSA - Left</td>
<td>5.68</td>
<td>13.09</td>
<td>8.57±2.04</td>
</tr>
<tr>
<td>Gluteus Maximus CSA - Right</td>
<td>10.00</td>
<td>31.09</td>
<td>19.53±5.01</td>
</tr>
<tr>
<td>Gluteus Maximus CSA - Left</td>
<td>11.83</td>
<td>35.50</td>
<td>19.65±5.85</td>
</tr>
<tr>
<td>Multifidus CSA - Bilateral</td>
<td>10.93</td>
<td>21.35</td>
<td>15.24±2.75</td>
</tr>
<tr>
<td>Psoas Major CSA - Bilateral</td>
<td>10.60</td>
<td>25.39</td>
<td>17.53±3.87</td>
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<tr>
<td>Gluteus Maximus CSA - Bilateral</td>
<td>21.93</td>
<td>64.04</td>
<td>39.18±10.41</td>
</tr>
</tbody>
</table>

**Abbreviations:** CSA, cross-sectional area in cm$^2$; Statistical Significance is $p<0.05$
Table 3.3 and Figures 3.2 and 3.3 show Pearson’s r for MF and PM, and Spearman’s rho values for MF and GM. Both GM and PM CSA showed a statistically significant, positive correlation with MF CSA \((p<0.01)\). Spearman’s test values for male and female participants analyzed separately are also provided, showing a statistically significant correlation between MF and PM in both male \((p=0.004)\) and female \((p=0.019)\) participants, and a significant correlation between MF and GM in male \((p=0.002)\) participants only. Spearman’s correlation coefficient was used to assess correlation between CSA for all 3 muscles with height and age; no significant correlation was found.

![Figure 3.2 Correlation of Multifidus and Psoas Major Cross-Sectional Areas for all Participants](image)
Table 3.3 Correlations of Cross-Sectional Area Measurements

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Males (n=28)</th>
<th>Females (n=7)</th>
<th>Males and Females (n=35)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>p-value</td>
<td>Correlation Coefficient</td>
</tr>
<tr>
<td>Multifidus &amp; Psoas Major*</td>
<td>0.521</td>
<td>0.004</td>
<td>0.837</td>
</tr>
<tr>
<td>Multifidus &amp; Gluteus Maximus**</td>
<td>0.563</td>
<td>0.002</td>
<td>0.071</td>
</tr>
</tbody>
</table>

*Pearsons Correlation Coefficient; **Spearmann's Correlation Coefficient. Statistical Significance is p<0.05

Figure 3.3 Correlation of Multifidus and Gluteus Maximus Cross-Sectional Areas for all Participants
Discussion

The results of this study show that the CSA of MF correlates positively with the CSA of both GM and PM, in a non-random sample of male cadavers. Both PM and GM CSAs showed what can be considered a moderate correlation with MF CSA.\textsuperscript{195} In addition, PM CSA was shown to vary significantly with MF CSA in a small sample of female cadavers. Muscle CSA was not shown to correlate with either height or age, in spite of the fact that muscle size is known to vary with both height\textsuperscript{173,184} and age.\textsuperscript{35,102,155,141,186,187} This implies that other, unidentified covariates, including but not limited to LBP, may contribute to the correlation.

This study indicates that GM and PM atrophy varies with MF atrophy, and many studies have already shown that individuals with LBP have decreased MF size. For example, Hides et al\textsuperscript{139} found a significantly decreased CSA in the ipsilateral MF of patients with acute LBP, compared with the unaffected side. Barker et al,\textsuperscript{14} Kang et al,\textsuperscript{140} and Ploumis et al\textsuperscript{93} all found significant decreases in MF CSA in adults with chronic LBP. This plethora of MF research has led to the development of therapeutic interventions to address putative MF weakness and motor control deficits.\textsuperscript{107,111,196}

Although less well-studied, PM atrophy has also been linked with LBP. Studies by Barker et al,\textsuperscript{14} Kang et al,\textsuperscript{140} and Ploumis et al\textsuperscript{93} all found significantly decreased ipsilateral PM CSA in patients with LBP. In spite of growing research showing a connection between LBP and PM atrophy, exercises targeting PM, are rarely integrated into treatment plans for LBP patients. This is perhaps due to a lack of awareness on the part of clinicians of the possible connection between PM and LBP.
As stated above, a direct link between GM and LBP has yet to be made. The possible role of GM in the genesis of LBP has been virtually unstudied. In the sole study identified that assessed GM CSA and LBP, Kamaz et al\textsuperscript{96} found no significant differences in CSA measurements in the GM muscles of 36 sedenary women with chronic LBP, compared with 34 control participants. However the study’s authors appear to not have normalized CSA to body size, which would have skewed the results.

Although GM clearly plays a major part in the lifting of loads, clinical literature rarely mentions it. In fact, GM is such an important factor in lifting that it is believed to have played a crucial role in the development of bipedalism in humans, allowing the use of the upper extremities in functional activities unavailable to quadrupeds, such as lifting, clubbing, and gathering.\textsuperscript{150} When arising from full trunk flexion into extension, most movement happens at the hip joint and is accomplished by GM and the hamstrings during the first 50\% of the movement cycle. By 75\% of extension, contributions from hip extensors and spinal extensors are equal. In the last 25\% of extension to neutral, lumbar extension predominates.\textsuperscript{48} Importantly, altered trunk and hip kinematics have been noted in individuals with LBP, although cause and effect have not been completely elucidated.\textsuperscript{48,50,103} Intervertebral discs are also known to be most at risk for herniation in full flexion;\textsuperscript{74} thus, because GM is so important at the start of lumbar extension, weak GM may lead to improper lifting technique just when the discs are most vulnerable to herniation.

**Limitations:** Causation of atrophy by LBP has not been demonstrated, and is beyond the scope of this study. Correlations between 2 variables, such as MF and GM
CSAs, are not guaranteed to be transitive to a third variable, such as LBP. Only the most basic medical information was available for the cadavers used in this study. In most cases, only cause of death was available and it is likely that multiple, unknown, confounding medical diagnoses were present in our sample. It is impossible to know the impact that these diagnoses had on our data. Participants were not randomized, and CSA measurements were performed by one researcher who was not blinded, which limits our ability to interpret a relationship between PM, GM and MF. Because the CT imaging was taken post mortem, soft tissue deformation, especially in the GM region, may have affected the accuracy of some of the GM CSA measurements. In addition, the presence of fatty infiltration (FI) and other pathological changes often accompany muscle atrophy. Several of the participants’ muscles demonstrated the presence of FI, which would ideally not be included in the muscle CSA measurements. However, because of limitations in the quality of the CT scans for some participants, and limitations in our software analysis abilities, these fibers could not be removed from our CSA measurements. Separate analysis of female participants indicated no significant correlation between MF and GM CSA. However, the small number of female participants in the study greatly limited the potential to find significance in this subpopulation. Further research including adequate numbers of female participants is indicated.

**Conclusion:** Our hypothesis that GM and PM CSA will vary with MF CSA was confirmed. Further research is indicated to determine whether the CSA of GM and PM has a relationship to LBP similar to MF and LBP.
CHAPTER 4: CORRELATION OF GLUTEUS MAXIMUS CROSS-SECTIONAL AREA WITH INCIDENCE AND SEVERITY OF LOW BACK PAIN IN ADULT FEMALES
Introduction

The possible role of gluteus maximus (GM) in the genesis of low back pain (LBP) has been virtually unstudied. GM has a well-established role in the lifting of loads from a fully flexed position,\textsuperscript{48,49,50} and lifting has been identified as an important cause of LBP.\textsuperscript{25,30,43} GM is most important during the first 50\% of trunk extension from full flexion, which is the point where intervertebral discs are known to be most at risk for herniation.\textsuperscript{50,74} Thus weak GM may lead to an improper lifting technique just when the discs are most vulnerable to herniation, and also when most stress is placed on other passive elements that stabilize the spine such as ligaments. There is also evidence that GM compensates for the erector spinae (ES) muscles by becoming more active when the ES are fatigued.\textsuperscript{148}

Decreased trunk and hip muscle strength has been identified in persons with LBP, yet it is unknown if these strength deficits are a cause or an effect of LBP. Muscle cross-sectional area (CSA) has been correlated with strength in a number of studies on upper and lower extremity muscles in healthy adults.\textsuperscript{149,166,167,168} Multifidus (MF) has been the most well-studied of trunk muscles vis-a-vis LBP, and has been found in numerous studies to atrophy in the presence of LBP.\textsuperscript{14,93,140,141,142,143} In a previous, unpublished study,\textsuperscript{198} we found that GM CSA correlated significantly with MF CSA in a cadaver sample of adult males, motivating us to further investigate the direct relationship of GM size to LBP.

The purpose of the present study was to compare GM CSA in individuals with chronic low back pain (CLBP) with GM CSA in a control group of individuals without
CLBP. Our hypothesis was that participants with CLBP will have greater atrophy in their GM muscles than control participants.

Methods

Participant Description Participants were 36 adult females with CLBP, aged 40-69, and 32 adult females in the same age range and without any known history of back pain. Female participants were chosen to control for known variance of muscle CSA between males and females; and because pelvic CT scans of adult females are widely available. Participants and controls had all received a minimum of one year of medical care as inpatients or outpatients within the OSU (OSU) Wexner Medical Center care system. Each experimental participant had at least 2 back pain-related medical visits, with a history of back pain lasting at least 3 months, in order to comply with the most commonly used definition of CLBP.\textsuperscript{14,15,16,88,89}

Exclusion criteria included any history of diagnoses that can cause back pain or muscle atrophy, including: benign or malignant neoplasm, central nervous system disorders, chronic pain syndromes, connective tissue or rheumatoid disorders, upper urinary tract or reproductive organ dysfunction, and HIV/AIDS. Control participants were subject to the same exclusion criteria as experimental participants, with the additional exclusion criteria of an absence of documented history of back pain.

Participants were identified through the OSU Center for Clinical and Translational Science, Honest Broker Protocol. This allows access to de-identified patient data from the OSU Wexner Medical Center electronic medical record (EMR) system, and as such is exempt from Institutional Review Board (IRB) approval. In order to obtain a
set of participants for whom imaging was available for the GM muscle, participants were selected from a master list of all female patients at OSU, aged 40-69, who underwent a pelvic computed tomography (CT) scan in 2013 or 2014. This age range represents the cohort with most cases of CLBP in the United States, and was chosen in order to limit the effects of age on our outcomes, as age is known to vary with CLBP. Participant height was also obtained from the participant’s EMR to use for normalization of CSA measurements. History of CLBP was assessed based on the presence of a “reason for visit” of “back pain” or “lower back pain” in the patient’s electronic medical record. Because over 60 different International Classification of Diseases (ICD-9) codes have been identified that pertain to back pain, we chose to base our definition of CLBP on the participant’s reported visit reason. Table 4.1 lists mean participant characteristics for the two groups. ICD-9 codes for our CLBP sample are listed in Table 4.2.

Out of the 10,586 women who underwent scans in this time period, after the above medical exclusionary criteria were applied, and records were eliminated from participants with missing data fields, a pool of 1,604 participants remained. After removing participants who had less than one year of care at OSU, a pool of 610 participants remained, of whom 118 had a history of back pain. Of these, 39 had greater than one visit for back pain with episodes lasting greater than 3 months. Thirty-nine age-matched controls were selected randomly, using a random number generator function in Excel 2013. After elimination due to poor scan quality, 36 experimental and 32 control participants remained (Table 4.1).
Table 4.1 Participant Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Back Pain (n=36)</th>
<th>Controls (n=32)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>40.0</td>
<td>67.0</td>
<td>51.6 +/-8.7</td>
</tr>
<tr>
<td>Number of Back Pain Visits</td>
<td>2.0</td>
<td>14.0</td>
<td>4.5 +/-3.0</td>
</tr>
</tbody>
</table>

Statistical Significance is p<0.05

Table 4.2 ICD-9 Codes for Chronic Back Pain Sample

<table>
<thead>
<tr>
<th>ICD-9 Codes</th>
<th>Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbago (724.2)</td>
<td>18</td>
</tr>
<tr>
<td>Backache Unspecified (724.5)</td>
<td>7</td>
</tr>
<tr>
<td>Sciatica (724.3)</td>
<td>4</td>
</tr>
<tr>
<td>Thoracic or Lumboscaral Neuritis or Radiculitus (724.4)</td>
<td>3</td>
</tr>
<tr>
<td>Non Allopathic Lesions of Lumbar Region (739.3)</td>
<td>2</td>
</tr>
<tr>
<td>Post Laminectomy Syndrome of Lumbar Region (722.83)</td>
<td>1</td>
</tr>
<tr>
<td>Lumbar Disc Displacement without Myelopathy (722.1)</td>
<td>1</td>
</tr>
</tbody>
</table>

Abbreviations: ICD-9, International Classification of Diseases

Measurements and Procedures

Participants underwent CT scanning using either a Somatom (Siemens), Emotion (Siemens), Lightspeed VCT (General Electric) or Brightspeed (General Electric) CT scanner at 100 to 130kV. Slice thickness was 5.0 millimeters. The CSA of GM was measured in axial sections at the apex of the coccyx, based on preliminary analysis of participant scans which showed the coccygeal apex to be the thickest part of the GM in this sample. This methodology was used to meet the requirements for anatomical CSA measurement.169

Data were analyzed using OsiriX MD (version 7.0.2, Pixmeo, Geneva) software on an Apple i-Mac computer. Each muscle CSA was determined by using the OsiriX
region of interest pencil tool and was manually traced by the study’s principal author using an Apple Magic Trackpad. Use of a single measurer for muscle CSA has been seen in prior studies by Barker et al.\textsuperscript{14} and Kang et al.\textsuperscript{140} Each CSA was measured 3 times in one session, and then an average of these measurements was taken, based on the protocol used by McGill et al.\textsuperscript{162} to maximize measurement reliability.

**Statistical Analysis**

Data were analyzed using SPSS version 22 (Armonk, NY) for Windows. CSA was measured in centimeters squared, and was normalized to stature by taking the ratio of CSA to the square of patient height in centimeters, based on Heymsfield et al.’s\textsuperscript{184} findings vis-a-vis the scaling of lean muscle to stature. Intraclass correlation coefficients were performed to test the reliability of the CSA measurements. Normality tests showed CSA data were not normally distributed, and thus non-parametric testing was performed to compare means. Logarithmic transformation was also performed, as noted, on the data to achieve a normal distribution and allow data analysis of covariance (ANCOVA) using parametric tests. Statistical significance was defined as $p<0.05$.

**Results**

Table 4.1 shows the characteristics of the control and CLBP participants, showing no significant differences in age or height between the groups. Intraclass correlation coefficients were 0.99 for both right and left-sided CSA measurements, showing excellent reliability of the 3 measurements taken for each muscle. Kolmogorov-Smirnov and Shapiro Wilk tests showed both raw and normalized CSA data were not normally distributed ($p<0.01$). Spearman’s correlation test was performed comparing right and left
sides of both raw and normalized CSA, and they were found to be highly correlated with a Spearman’s rho of 0.935 and 0.937 respectively (\(p<0.001\)). Thus, CSA for both sides was combined for continued data analysis. Muscle CSA from both left and right sides were combined in the present research in order to capture any CSA differences that may manifest bilaterally. Although many studies\(^{14,93,139,141}\) of unilateral LBP have shown asymmetries in muscle CSA for study participants, data on sidedness of symptoms was not available for the present sample. Furthermore, a number of studies\(^{172,173,174}\) have found that paired muscles are not always symmetrical in a normal population, which argues for using a combined CSA in order to capture changes that may occur due to LBP.

Mean normalized CSA was compared using the Mann-Whitney U test, showing a significantly smaller CSA for the CLBP group than for the control group, with \(U=383, z=-2.371\), at the \(p<0.05\) level (Table 4.3). The number of back pain-related visits was correlated with normalized CSA using Spearman’s Test and were found to be significantly correlated with a Spearman’s rho of \(-0.339\) (\(p<0.005\)) (Figure 4.1).

### Table 4.3 Gluteus Maximus Cross-Sectional Areas in Chronic Back Pain and Control Participants

<table>
<thead>
<tr>
<th></th>
<th>Back Pain (n=36)</th>
<th>Controls (n=32)</th>
<th>(p)-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus Maximus CSA- Right (cm(^2))</td>
<td>Min 75.07 Max 45.12</td>
<td>Mean 29.00</td>
<td>Min 51.89 Mean 28.29</td>
</tr>
<tr>
<td>Gluteus Maximus CSA- Left (cm(^2))</td>
<td>Min 71.07 Max 44.67</td>
<td>Mean 28.29</td>
<td>Min 51.51 Mean 28.29</td>
</tr>
<tr>
<td>Gluteus Maximus CSA- Combined (cm(^2))</td>
<td>Min 89.79 Max 89.79</td>
<td>Mean 57.29</td>
<td>Min 103.39 Mean 74.19</td>
</tr>
<tr>
<td>Normalized Combined Gluteus Maximus CSA (CSA/Ht(cm(^2)))</td>
<td>Min 0.00328 Mean 0.00377</td>
<td>Max 7.11E-4 Mean 9.25E-4</td>
<td>=9.25E-4 0.018</td>
</tr>
</tbody>
</table>

*Abbreviations: CSA, cross-sectional area; Ht, height;* Mann-Whitney U Test; Statistical Significance is \(p<0.05\)
Logarithmic transformations were performed on the normalized combined CSA scores in order to achieve a normal distribution. An independent samples t-test was then performed comparing means between the CLBP and control groups. Statistically significant differences in the group means were found with \( t(66)=2.448 \) at the \( p<0.05 \) level. One-way ANCOVA testing to control for the effect of age on the relationship between CLBP and CSA showed that, in this sample, age had no effect as a covariate with \( F(1,65)=5.957 \) at the \( p<0.05 \) level.

**Discussion**

The results of this study show that the CSA of GM does vary significantly with CLBP incidence in this sample of adult women between the ages of 40 and 69. CSA is also correlated with the number of medical visits related to CLBP with what can be considered a moderate correlation in normalized CSA scores.\(^{195}\)

CSA scores were not affected by age, which contradicts previous findings that CLBP varies with age.\(^{23,27,29}\) This lack of covariance can be explained by the narrow age range chosen for this study in order to limit the effects of age on our outcome variables.
Our results are in conflict with the only other identified study that assessed the relationship of GM CSA and CLBP. Kamaz et al.\textsuperscript{96} found no significant differences in CSA measurements in the GM muscles of 36 sedentary women with CLBP, compared with 34 control participants, with absolutely no trending towards significance ($p=0.503$). The study’s authors appear to not have normalized CSA to body size, which may have skewed the results. However, they did find significantly decreased CSAs of MF, PM and

\textbf{Figure 4.1} Correlation of Normalized Gluteus Maximus Cross-Sectional Area (CSA) with \# of Back Pain-Related Visits
quadratus lumborum in their CLBP cohort, which measurements should also have been affected by the lack of normalization.

This previously unrecognized association between GM’s CSA with LBP provides a rationale for further research into GM’s role in LBP, the nature of its atrophy, and whether GM atrophy is pre-morbid or a result of LBP. It also supports the use of physical therapy interventions targeting GM for LBP patients.

*Limitations:* CSA measurements were performed by one reviewer who was not blinded to the medical histories of the participants, allowing potential introduction of bias into measurements. Because we had limited access to participant medical history, other than reasons for visits and ICD-9 codes, it is possible that unknown, confounding medical diagnoses were present in both our control and CLBP sample.

*Conclusion:* Our hypothesis that GM atrophy will be greater in individuals with CLBP was confirmed. Further research is indicated on GM CSA in individuals with varying age, sex and LBP diagnoses. Research on the potential impact of exercise interventions targeting GM in individuals with CLBP is also indicated.
CHAPTER 5: CORRELATION OF PRE-SURGICAL MUSCLE MORPHOMETRY AND VARIOUS MEASURES OF LOW BACK PAIN SEVERITY WITH TREATMENT RECOMMENDATIONS AND SURGICAL OUTCOMES IN ADULT FEMALES AND MALES
Introduction

Low back pain (LBP) is a major cause of disability, absenteeism, and expense in the United States and worldwide. Treatment for LBP includes conservative care such as physical therapy, pain-relieving modalities, manual therapy, and prescription pain medication. When conservative interventions have failed, surgery may be recommended. The most common surgeries performed to address LBP include laminectomy and decompression, microdiscectomy, and lumbar fusion.

Causes of LBP are diverse and multifactorial. There is typically not one exclusive factor, but rather an interaction of multiple causal factors, which leads to LBP. Age, sex, muscle weakness, motor control deficits, faulty lifting techniques, sedentary lifestyle, psychosocial factors, and underlying medical conditions have all been implicated in the genesis of LBP. Many episodes of LBP are of unknown etiology, and are considered “non-specific” back pain. Decreased trunk muscle strength in persons with LBP has been identified, yet it is unknown if these strength deficits are a cause or an effect of LBP.

Certain morphometric and histological changes are associated with LBP, including muscle atrophy and fatty infiltration (FI). Muscle cross-sectional area (CSA) has been positively correlated with muscle strength, and is thus a frequently used morphometric measure in clinical research. Anatomical CSA, measured with the aid of imaging software programs, is the area of a muscle measured perpendicular to its longitudinal axis, at its widest point. FI is a common histological change seen in paraspinal muscles of LBP patients. Fat content of a muscle is considered non-
contractile and is estimated visually,\textsuperscript{140} via software analysis,\textsuperscript{172} or traced manually and subtracted from CSA measurements.\textsuperscript{189}

Multifidus (MF) has been by far the most well-studied muscle vis-à-vis LBP, and MF CSA has been found to be smaller in persons with LBP in numerous studies.\textsuperscript{14,93,139,140,141} It is MF’s role as an intersegmental stabilizer that is thought to be critical in its connection to LBP.\textsuperscript{39,43} A number of studies have also assessed psoas major (PM) CSA and LBP, and have found significantly lower CSA measurements in PM in adults with chronic LBP.\textsuperscript{14,96,140} A likely explanation of PM’s role in LBP is via its mechanism of stabilization of the lumbar lordosis, due to the varying angles of pull of its muscle fascicles.\textsuperscript{151,152} Results of studies assessing CSA changes in erector spinae (ES) with LBP have, however, been conflicting. Some have found decreased ES CSA,\textsuperscript{93,140} while others have found no significant differences in ES CSA in LBP participants, or had mixed results with atrophy found at some levels, and not at others.\textsuperscript{143,156} ES is implicated in LBP through its role as a key muscle group when arising from full trunk flexion into extension, particularly during the last 50% of extension.\textsuperscript{48,49,50}

Measurement of LBP severity has taken a number of forms over the years and multiple methods have been validated experimentally. Common methods of measuring LBP severity relevant to the present research include: numeric pain scales,\textsuperscript{84} chronicity,\textsuperscript{14,15} peripheralization of pain,\textsuperscript{19} and scores on functional disability scales such as the Oswestry Disability Index (ODI).\textsuperscript{22,91} The ODI measures a patient’s perceived disability related to LBP, based on 10 functional categories; total scores range from zero to 50 with higher scores representing greater disability. Other factors thought relevant to
LBP severity include number of comorbidities\textsuperscript{199,200} and number of identified levels of vertebral pathology on imaging.\textsuperscript{132}

The goal of the present research was to evaluate differences in values of various morphometric and LBP-related variables between patients with LBP referred for lumbar surgery, and those referred for conservative care. In addition, the relationship of these variables to post-surgical outcomes was assessed. Differences in values for the above variables were also compared between sides in participants with unilateral LBP. Our hypothesis was that muscle CSA for MF, PM and ES would be significantly lower in the surgery group, and positively correlated with favorable surgical outcomes; and that numeric pain score, chronicity, number of affected vertebral levels, percent of peripheralization of LBP, number of comorbidities, ODI scores and percent of FI would all be significantly higher in the surgery group, and would be negatively correlated with favorable surgical outcomes. Muscle CSA will be smaller on the affected side of participants with unilateral LBP.

**Methods**

**Participant Description**

This study was approved by the Ohio State University (OSU) Institutional Review Board. Participants were 70 adult females and males (34 females, 36 males) from 30-69 years of age, with a physician diagnosis of LBP, who had been referred for surgical consultation at the OSU Comprehensive Spine Center. Participants were divided into 2 groups based on the treatment recommendations of the consulting orthopedic spine surgeon: surgery (SURG) patients for whom either lumbar fusion, laminectomy or
microdiscectomy surgeries were recommended; and conservative care (CONS) patients for whom non-surgical conservative care such as physical therapy was recommended. Patients referred to conservative care solely because of high surgical risk were not included in the CONS group. The SURG group represented participants with greater severity of LBP, and the CONS group represented participants with less severe LBP, and thus served as the control group for the present study. This stratification of participants into SURG and CONS was partly based on prior research by Ferguson and Marras\textsuperscript{131} which demonstrated that low back function, as measured by the lumbar motion monitor, can accurately differentiate more severely affected LBP patients (referred for lumbar fusion) from less severely affected (referred for microdiscectomy) patients.

Both SURG and CONS participants were subject to the same exclusion criteria. Exclusion criteria included any history of diagnoses that can cause back pain or muscle atrophy, including: benign or malignant neoplasm, except for non-invasive skin cancers; central nervous system disorders; chronic pain syndromes; connective tissue or rheumatoid disorders; upper urinary tract or reproductive organ dysfunction; and HIV/AIDS. Individuals with scoliosis, greater than grade one spondylolisthesis, and prior low back surgery were also excluded. Additional exclusion criteria included: missing data in participant medical records required for this study; absence of a lumbar MRI scan within 12 months of surgical evaluation; and those participants found to have poor scan quality that interfered with muscle CSA measurement.

All patients with LBP seen by 2 orthopedic spine surgeons in a 12-month period from 10/15/14 to 10/14/15 were initially considered for the study. Individual patient medical records were accessed through the OSU Wexner Medical Center electronic
medical records (EMR) system, and study information for anthropometric, LBP severity, and morphometric dependent and independent variables was obtained through analysis of physician initial surgical evaluations, follow-up progress notes, operative reports, imaging reports, and MRI scans. After applying inclusionary and exclusionary criteria, 40 SURG and 30 CONS participants were identified. Table 5.1 contains participant characteristics.

**Measurements and Procedures**

Participant MRI scans were obtained for analysis from the OSU Wexner Medical Center EMR system. Scans were originally performed at either OSU (68%), or at external institutions (32%). OSU MRI scans were performed on either an Avanto, Skyra or Verlo (Siemens, Erlangen, Germany) 1.5 Tesla scanner. Slice thickness varied from 3.0 to 4.0 mm, with varying repetition and echo times. Images were stored in DICOM format for processing. T1 axial scans were used primarily for analysis, although because of image quality, T2 axial scans were used for analysis in 15% of scans. Most participants had multi-level vertebral involvement based on imaging reports and physician evaluation; therefore anatomical CSA (Figure 5.1) of all 3 muscles was measured at the L4-L5 intervertebral disc (IVD), as this level has been shown to correspond to the majority of lumbar spine lesions.\textsuperscript{14,68,93} Fatty infiltration (Figures 5.2 and 5.3) was estimated visually in percentages, based on the method used by Kader et al\textsuperscript{102} and Kang et al.\textsuperscript{140} Fatty infiltration estimate is for total, bilateral muscle CSA, unless otherwise stated.

Data were analyzed using OsiriX MD (version 7.0.2, Pixmeo, Geneva) software on an Apple i-Mac computer. Each muscle CSA was determined by using the OsiriX region of interest pencil tool and was manually traced by the study’s author using an
Apple Magic Trackpad. Use of a single measurer for muscle CSA has been seen in prior studies by Barker et al\textsuperscript{14} and Kang et al.\textsuperscript{140} Each CSA was measured 3 times in one session, and then an average of these measurements was taken, based on the protocol used by McGill et al\textsuperscript{162} to maximize measurement reliability.

Participant demographic and anthropometric information, as well as LBP severity-related variables, were obtained from participant EMRs. These included: pain measured on a numeric pain scale from one to 10; time since onset of LBP measured in months; amount of back versus lower extremity pain, measured in percentages; number of involved vertebral levels based on participant’s imaging report; and unweighted disease and surgery count based on participant’s past medical history, excluding childhood illnesses, elective surgeries, obesity, cataracts, and caesarean section, as these were unlikely to affect participant’s overall morbidity. ODI values, obtained from the EMR, were based on participant pre-surgical ODI scores (Version 2.1a Appendix A). For missing ODI values the mean values of that participant’s answers to the other ODI questions was substituted.

Surgical outcomes were measured at 6 months and 12 months after surgery for all participants for whom this data was available in their medical record. A Likert scale\textsuperscript{18,98,201} was devised based on patient reported outcomes, as reflected in physician progress notes at approximately 6 month and 12 months after surgery, and included the following scores: 1 = surgery failed, revision required; 2 = patient reports pain is worse than before surgery; 3 = patient reports pain is the same as before surgery; 4 = patient reports pain is better than before surgery; and 5 = patient reports pain is much better than before surgery.
Table 5.1 Participant Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Females SURG (n=19)</th>
<th>Males SURG (n=21)</th>
<th>Total SURG (n=40)</th>
<th>Females CONS (n=15)</th>
<th>Males CONS (n=15)</th>
<th>Total CONS (n=30)</th>
<th>p-value SURG/CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>56.2+/-9.2</td>
<td>49.1+/-11.0</td>
<td>52.5+/-10.7</td>
<td>51.6+/-11.0</td>
<td>48.2+/-10.3</td>
<td>49.9+/-10.6</td>
<td>*0.313</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162.96+/-7.19</td>
<td>180.44+/-8.25</td>
<td>172.14+/-11.70</td>
<td>165.37+/-7.78</td>
<td>179.66+/-5.71</td>
<td>172.51+/-9.89</td>
<td>*0.888</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>79.32+/-16.50</td>
<td>102.79+/-23.03</td>
<td>91.64+/-23.21</td>
<td>89.79+/-17.08</td>
<td>101.06+/-23.73</td>
<td>95.42+/-21.11</td>
<td>**0.200</td>
</tr>
<tr>
<td>Body Mass Index</td>
<td>48.57+/-9.19</td>
<td>56.79+/-11.66</td>
<td>52.88+/-11.23</td>
<td>54.23+/-9.42</td>
<td>56.24+/-12.91</td>
<td>55.23+/-11.15</td>
<td>**0.184</td>
</tr>
<tr>
<td>Number of Comorbidities</td>
<td>4.58+/-1.92</td>
<td>3.71+/-2.94</td>
<td>4.13+/-2.51</td>
<td>5.93+/-3.67</td>
<td>2.87+/-2.07</td>
<td>4.40+/-3.32</td>
<td>**0.914</td>
</tr>
<tr>
<td>Pain Score</td>
<td>6.63+/-1.74</td>
<td>5.76+/-2.23</td>
<td>6.18+/-2.04</td>
<td>5.53+/-2.17</td>
<td>5.80+/-2.04</td>
<td>5.67+/-2.07</td>
<td>**0.290</td>
</tr>
<tr>
<td>Time Since Onset of LBP (mos)***</td>
<td>43.84+/-41.39</td>
<td>27.74+/-29.05</td>
<td>35.79+/-36.20</td>
<td>29.08+/-30.64</td>
<td>22.96+/-25.60</td>
<td>26.14+/-27.92</td>
<td>**0.220</td>
</tr>
<tr>
<td>Percent Back Pain</td>
<td>42.63+/-22.45</td>
<td>43.10+/-28.61</td>
<td>42.88+/-25.54</td>
<td>67.00+/-30.42</td>
<td>74.27+/-23.82</td>
<td>70.63+/-27.09</td>
<td>**0.000</td>
</tr>
<tr>
<td>Percent Lower Extremity Pain</td>
<td>57.37+/-22.45</td>
<td>56.90+/-28.61</td>
<td>57.13+/-25.54</td>
<td>33.00+/-30.40</td>
<td>25.73+/-23.82</td>
<td>29.37+/-27.09</td>
<td>**0.000</td>
</tr>
<tr>
<td>ODI Score</td>
<td>26.25+/-9.70</td>
<td>22.35+/-9.57</td>
<td>24.20+/-9.71</td>
<td>20.29+/-8.91</td>
<td>22.47+/-8.84</td>
<td>21.38+/-8.80</td>
<td>*0.215</td>
</tr>
</tbody>
</table>

Abbreviations: mos, months; ODI, Oswestry Disability Index; *Student’s t-test; **Mann-Whitney U-test; ***Seven records removed due to outliers; Statistical Significance is p<0.05
**Statistical Analysis** Data were analyzed using SPSS version 22 (Armonk, NY) for Windows. CSA was measured in centimeters squared (cm$^2$), and was normalized to stature by taking the ratio of CSA to the square of patient height in centimeters, based on Heymsfield et al.’s findings related to the scaling of muscle morphometry to stature. Intraclass correlation coefficients (ICC) were performed to test the reliability of the CSA measurements. Both parametric and non-parametric testing was performed and so noted.

**Figure 5.1** Psoas Major and Erector Spinae Cross-Sectional Area Measurement
depending on normality testing of the subsets of the sample, to compare means and for correlations. Statistical significance was defined as p<0.05.

**Figure 5.2** Example of 0% Fatty Infiltration in All Three Muscles

**Results**

Distribution of variables was found to be mixed; thus either parametric or non-parametric tests were used for analysis, and are so noted. Table 5.1 lists the characteristics of all of the participants. The SURG and CONS groups had no significant
differences in characteristics, except for percent back and lower extremity pain (p<0.001). When analyzed further by sex, also in Table 5.1, no additional differences between groups were found in either females or males.

**Figure 5.3** Example of Fatty Infiltration of: 25% Multifidus; 10% Psoas; 40% Erector Spinae

**SURG vs. CONS Results**

Bilateral Muscle Cross-Sectional Areas Intraclass correlation coefficients ranged from 0.945 to 0.993 for both right and left-sided CSA measurements for all muscles,
showing excellent reliability of the 3 measurements taken for each muscle. Only the CSA of MF, less FI, and normalized to height squared, was found to be significantly different between the SURG and CONS groups, with a Mann-Whitney U=429, z=-2.029, at the p<0.05 level (Table 5.2). When males and females were analyzed separately (Table 5.3), normalized MF CSA less FI in females became even more significant (p<0.01); however, normalized MF CSA less FI in males became insignificant when analyzed separately.

Time since onset of LBP, number of involved vertebral levels, and number of comorbidities showed no correlation with any normalized muscle CSA less FI in our sample. Numeric pain score was also uncorrelated to MF and PM, but showed a significant, moderate, negative correlation with normalized ES CSA less FI, with Spearman’s rho=-0.300 at the p<0.05 level.

**Unilateral Muscle Cross-Sectional Areas** Tests were performed separately on participants with reported unilateral LBP. Out of a total of 70 participants, 22 reported bilateral LBP with 48 reporting unilateral LBP (26 right sided and 22 left sided). Thirty-one participants were in the SURG group and 17 were in the CONS group. Again, normality varied greatly among the sample variables; thus parametric or non-parametric tests were performed when indicated, and are noted. Paired t-tests for ES for the CONS group showed a significantly smaller normalized CSA less FI on the affected side compared with the unaffected side, with t(16)=-3.040 at the p<0.01 level. No other CSAs were found to be significantly different for either the SURG or CONS group. In addition, there was no statistically significant difference between groups in the overall percentage of affected side FI for either SURG or CONS groups.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Females SURG (n=19)</th>
<th>Males SURG (n=21)</th>
<th>Total SURG (n=40)</th>
<th>Females CONS (n=15)</th>
<th>Males CONS (n=15)</th>
<th>Total CONS (n=30)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF - Right CSA</td>
<td>9.29+/-1.61</td>
<td>11.41+/-1.98</td>
<td>10.40+/-2.08</td>
<td>9.65+/-1.37</td>
<td>11.37+/-1.52</td>
<td>10.51+/-1.67</td>
<td>*0.817</td>
</tr>
<tr>
<td>MF - Left CSA</td>
<td>9.01+/-1.79</td>
<td>11.21+/-1.92</td>
<td>10.16+/-2.15</td>
<td>9.99+/-1.66</td>
<td>10.91+/-1.94</td>
<td>10.45+/-1.83</td>
<td>*0.558</td>
</tr>
<tr>
<td>PM - Right CSA</td>
<td>10.97+/-2.44</td>
<td>19.91+/-4.21</td>
<td>15.67+/-5.68</td>
<td>12.17+/-1.73</td>
<td>19.81+/-3.20</td>
<td>15.99+/-4.63</td>
<td>**0.043</td>
</tr>
<tr>
<td>PM - Left CSA</td>
<td>10.88+/-2.49</td>
<td>20.35+/-4.29</td>
<td>15.85+/-5.93</td>
<td>12.29+/-2.07</td>
<td>20.42+/-3.03</td>
<td>16.35+/-4.86</td>
<td>**0.593</td>
</tr>
<tr>
<td>ES - Right CSA</td>
<td>13.76+/-2.76</td>
<td>15.79+/-4.39</td>
<td>14.83+/-3.80</td>
<td>14.61+/-3.38</td>
<td>17.10+/-3.97</td>
<td>15.86+/-3.84</td>
<td>**0.222</td>
</tr>
<tr>
<td>ES - Left CSA</td>
<td>14.94+/-2.54</td>
<td>16.44+/-4.32</td>
<td>15.73+/-3.62</td>
<td>15.02+/-3.19</td>
<td>17.26+/-4.26</td>
<td>16.14+/-3.87</td>
<td>**0.722</td>
</tr>
<tr>
<td>MF - Right/Left Sum CSA</td>
<td>18.30+/-3.21</td>
<td>22.62+/-3.76</td>
<td>20.57+/-4.10</td>
<td>19.64+/-2.78</td>
<td>22.28+/-3.22</td>
<td>20.96+/-3.25</td>
<td>*0.665</td>
</tr>
<tr>
<td>PM - Right/Left Sum CSA</td>
<td>21.85+/-4.71</td>
<td>40.26+/-8.19</td>
<td>31.52+/-11.50</td>
<td>24.46+/-3.73</td>
<td>40.23+/-5.94</td>
<td>32.35+/-9.38</td>
<td>**0.643</td>
</tr>
<tr>
<td>ES - Right/Left Sum CSA</td>
<td>28.70+/-5.00</td>
<td>32.24+/-8.46</td>
<td>30.56+/-7.17</td>
<td>29.63+/-6.51</td>
<td>34.36+/-8.05</td>
<td>32.00+/-7.59</td>
<td>**0.484</td>
</tr>
<tr>
<td>MF - Right/Left Sum CSA less fat infiltration</td>
<td>12.39+/-3.28</td>
<td>18.26+/-3.71</td>
<td>15.48+/-4.56</td>
<td>14.88+/-2.70</td>
<td>18.93+/-3.24</td>
<td>16.90+/-3.57</td>
<td>*0.160</td>
</tr>
<tr>
<td>PM - Right/Left Sum CSA less fat infiltration</td>
<td>20.46+/-4.56</td>
<td>38.58+/-7.75</td>
<td>29.97+/-11.15</td>
<td>23.35+/-4.10</td>
<td>38.84+/-6.48</td>
<td>31.09+/-9.51</td>
<td>**0.625</td>
</tr>
<tr>
<td>ES - Right/Left Sum CSA less fat infiltration</td>
<td>20.97+/-6.03</td>
<td>27.64+/-8.27</td>
<td>24.47+/-7.95</td>
<td>23.11+/-6.97</td>
<td>29.18+/-7.12</td>
<td>26.64+/-7.80</td>
<td>*0.259</td>
</tr>
<tr>
<td>MF - Right/Left Sum CSA less fat infiltration/Ht</td>
<td>0.000463+/-5.42E-4</td>
<td>0.000696+/-1.22E-4</td>
<td>0.000514+/-1.15E-4</td>
<td>0.000542+/-7.19E-5</td>
<td>0.000692+/-1.05E-4</td>
<td>0.000565+/-8.96E-5</td>
<td>**0.042</td>
</tr>
<tr>
<td>PM - Right/Left Sum CSA less fat infiltration/Ht</td>
<td>0.000769+/-1.59E-4</td>
<td>0.001234+/-2.26E-4</td>
<td>0.000996+/-2.80E-4</td>
<td>0.000854+/-1.36E-4</td>
<td>0.001250+/-2.06E-4</td>
<td>0.001031+/-2.56E-4</td>
<td>*0.497</td>
</tr>
<tr>
<td>ES - Right/Left Sum CSA less fat infiltration/Ht</td>
<td>0.000790+/-2.17E-4</td>
<td>0.000988+/-2.52E-4</td>
<td>0.000819+/-2.31E-4</td>
<td>0.000856+/-2.87E-4</td>
<td>0.001073+/-3.00E-4</td>
<td>0.000899+/-2.73E-4</td>
<td>**0.250</td>
</tr>
</tbody>
</table>

Abbreviations: CSA, cross-sectional area in cm$^2$; MF, multifidus; PM, psoas major; ES, erector spinae; Ht, height in cm; *Student's t-test; ** Mann-Whitney U-test; Statistical Significance is p<0.05

Table 5.2 Muscle Cross-Sectional Area Measurements
Table 5.3 Significant Muscle Cross-Sectional Area Measurements by Sex

<table>
<thead>
<tr>
<th>Variable</th>
<th>p-value SURG/CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF - Right/Left Sum less fat infiltration - Females</td>
<td>*0.023</td>
</tr>
<tr>
<td>MF - Right/Left Sum less fat infiltration/Ht(cm)^2 - Females</td>
<td>**0.008</td>
</tr>
</tbody>
</table>

Abbreviations: MF, multifidus; Ht, height; *Student's t-test;** Mann-Whitney U-test; Statistical Significance is p<0.05

Fatty Infiltration Table 5.4 shows the bilateral FI percentage for the SURG and CONS groups. Although, as previously mentioned, normalized MF CSA less FI was found to be significantly smaller in the SURG group, FI percentage alone was not significantly different. When analyzed separately by sex, there was still no significant difference between the 2 groups when muscle FI percentage was analyzed both bilaterally, and on the affected side in unilateral LBP participants.

Percent of Back Versus Lower Extremity Pain Table 5.1 shows a significantly lower percentage of back pain (Mann-Whitney U=268, z=-3.963, at the p<0.001 level), and a significantly higher percentage of lower extremity pain (Mann-Whitney U=268, z=-3.963, at the p<0.001 level), in the SURG group compared with the CONS group. When analyzed separately by sex, the relationship of the variables remained significant for both females (p<0.01) and for males (p<0.005). Logistic regression was performed with SURG and CONS as the dependent variable. All relevant demographic, LBP severity and CSA variables were entered into the equation using the forward “conditional
<table>
<thead>
<tr>
<th>Variable</th>
<th>Females SURG (n=19)</th>
<th>Males SURG (n=21)</th>
<th>Total SURG (n=40)</th>
<th>Females CONS (n=15)</th>
<th>Males CONS (n=15)</th>
<th>Total CONS (n=30)</th>
<th>*p-value I SURG/CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF - Bilateral Fatty Infiltration %</td>
<td>31.84+/15.29</td>
<td>18.90+/12.30</td>
<td>25.05+/15.11</td>
<td>23.67+/11.57</td>
<td>15.00+/8.24</td>
<td>19.33+/10.81</td>
<td>0.158</td>
</tr>
<tr>
<td>PM - Bilateral Fatty Infiltration %</td>
<td>6.42+/3.50</td>
<td>4.10+/2.34</td>
<td>5.20+/3.14</td>
<td>4.80+/3.86</td>
<td>3.73+/3.31</td>
<td>4.27+/3.57</td>
<td>0.205</td>
</tr>
<tr>
<td>ES - Bilateral Fatty Infiltration %</td>
<td>26.58+/17.72</td>
<td>14.76+/10.55</td>
<td>20.38+/15.42</td>
<td>22.33+/15.57</td>
<td>12.00+/7.02</td>
<td>17.17+/12.98</td>
<td>0.415</td>
</tr>
</tbody>
</table>

**Abbreviations:** MF, multifidus; Ht, height; *Mann-Whitney U-test

**Table 5.4** Bilateral Fatty Infiltration Percentage by Muscle
method of variable entry. Only percent of back pain and lower extremity pain was found to add significantly (p<0.001) to the model with increased lower extremity pain being associated with presence in the SURG group.

**Oswestry Disability Index Scores in SURG Versus CONS Groups** Table 5.5 lists Mann-Whitney and Student’s t-test p-values for mean ODI scores in the SURG and CONS groups. The mean overall raw ODI score was greater in the SURG group (24.20) than in the CONS group (21.38), but not significantly so. However, ODI questions 4 (walking), 6 (standing), and 10 (travelling) were all significantly different (p<0.05) for the 2 groups for females, with higher ODI scores on these questions associated with the SURG group. For males, only ODI question 2 (personal care) was significantly higher (p<0.05) for the SURG group.

**Surgical Outcomes**

**Bilateral Surgical Outcomes** Of the 40 participants who were referred for surgery after physician evaluation, 6-month outcomes data were available for 25 participants, and 12-month outcomes data were available for 11 participants. One Way ANOVA tests were performed, and Spearman’s Correlation Coefficients were derived, to compare 6-month and 12-month post-surgical outcomes with muscle CSA, FI percentage, and all LBP severity variables.
Pre-surgical normalized MF CSA less FI showed a significant moderate positive correlation with 6-month post-surgical outcomes with Spearman’s rho=0.407 at the $p<0.05$ level. At 6 months, percent of back pain showed a moderate negative correlation with surgical outcomes (Spearman’s rho=−0.440 at the $p<0.05$ level), and percent lower extremity pain showed a moderate positive correlation with surgical outcomes (Spearman’s rho=0.440 at the $p<0.05$ level). There were no other statistically significant relationships between 6-month or 12-month outcomes and any variables except for ODI scores (Table 5.6).

Total ODI scores were negatively correlated with favorable surgical outcomes, with a moderate correlation present for 6-month outcomes (Pearson’s $r(23)=-0.448$ at the $p<0.05$ level), and a strong correlation present for 12-month outcomes (Pearson’s $r(9)=-0.744$ at the $p<0.01$ level). Furthermore, questions 3 (lifting), 5 (sitting) and 8 (sex life)
were significantly, negatively correlated with both 6 and 12-month favorable surgical outcomes (Figure 5.4).

**Unilateral Surgical Outcomes** Six-month outcomes data were available for eighteen participants with unilateral LBP. Normality varied among the variables, and non-parametric tests were chosen for analysis to avoid type one error with this small sample size. Normalized affected side MF CSA less FI was found to have a significant, strong, positive correlation with surgical outcomes Spearman’s rho of 0.682 \( (p<0.01) \). Questions 3 and 5 on the ODI maintained a moderate, significant, \( (p<0.05) \) negative correlation with 6-month outcomes in this smaller, unilateral sample. No other variables were significantly correlated. Twelve month outcomes were not analyzed due to the small sample size in the unilateral cohort.

<table>
<thead>
<tr>
<th>ODI Score</th>
<th>6 Months (n=25)</th>
<th>12 Months (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Correlation Coefficient</strong></td>
<td><em>p</em>-value</td>
</tr>
<tr>
<td>Question 1</td>
<td>-0.283</td>
<td>0.170</td>
</tr>
<tr>
<td>Question 2</td>
<td>-0.153</td>
<td>0.467</td>
</tr>
<tr>
<td>Question 3</td>
<td>-0.505</td>
<td>0.010</td>
</tr>
<tr>
<td>Question 4</td>
<td>-0.239</td>
<td>0.250</td>
</tr>
<tr>
<td>Question 5</td>
<td>-0.422</td>
<td>0.035</td>
</tr>
<tr>
<td>Question 6</td>
<td>-0.237</td>
<td>0.255</td>
</tr>
<tr>
<td>Question 7</td>
<td>-0.226</td>
<td>0.276</td>
</tr>
<tr>
<td>Question 8</td>
<td>-0.419</td>
<td>0.037</td>
</tr>
<tr>
<td>Question 9</td>
<td>-0.311</td>
<td>0.131</td>
</tr>
<tr>
<td>Question 10</td>
<td>-0.341</td>
<td>0.095</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-0.428</td>
<td>0.033</td>
</tr>
</tbody>
</table>

**Table 5.6** Correlation of Oswestry Disability Index Scores with Post-Surgical Outcomes

Abbreviations: ODI, Oswestry Disability Index; *Spearmann’s rho; Statistical Significance is \( p<0.05 \)
Low Back Pain Diagnosis

One way ANOVA tests were performed to investigate the relationship of demographic, LBP-severity and morphometric variables to diagnosis. Participants were stratified into 3 diagnostic categories based on their primary diagnosis given by the physician at initial evaluation: 1) stenosis (n=27), 2) discogenic disease (n=27), and 3) generalized spondylosis (n=16). Age (F(92,67)=11.521, p<0.001), weight (F(92,67)=4.255, p<0.05), percent of FI of MF (F(92,67)=3.980, p<0.05), and percent of FI of ES (F(92,67)=3.785, p<0.05), were all found to be significantly different among the 3 categories. Tukey post-hoc comparisons were made for these 4 variables and showed the following: age was significantly (p<0.001) greater in the stenosis than the discogenic group; weight was significantly (p<0.05) greater in the spondylosis group than in both the stenosis and the discogenic group; and the percent of FI of both MF and ES was significantly (p<0.05) greater in the stenosis group than in the discogenic group.

When analyzed separately by sex, only age remained significantly (p<0.05) different, with older participants found in the stenosis group than the discogenic group for both females and males. When the covariant of age was controlled through ANCOVA testing, all significance for both FI variables was lost.

Type of Surgery

Among the 40 participants who were referred for surgical intervention, lumbar fusion was recommended for 19, and microdiscectomy, or laminectomy with decompression, was recommended for 21 of the participants. All 19 of the lumbar fusion participants had a diagnosis of spinal stenosis; 12 of these had multiple LBP diagnoses including disc herniation and spondylosis. All 21 of the microdiscectomy participants had
a diagnosis of disc herniation; with 8 of these participants having multiple LBP diagnoses including stenosis and spondylosis. Mann Whitney tests were performed to assess the relationship of the demographic, LBP-severity and morphometric variables to type of surgery. Age (Mann-Whitney U=61, z=-3.772, p<0.001), number of comorbidities (U=100, z=-2.752, p<0.01), number of involved disc levels (U=121, z=-2.353, p<0.05), percent of FI of MF (U=109, z=-2.484, p<0.05), and normalized CSA less FI for both MF (U=116, z=-2.397, p<0.05) and PM (U=111, z=-2.397, p<0.05) were all found to be significantly different in the fusion versus the microdiscectomy group. However, when the covariate of age was controlled through ANCOVA testing, all significance for each variable was lost.
Cross-Sectional Area

Multifidus Only normalized MF CSA less FI for females differentiated between the SURG and CONS groups when CSA was measured bilaterally. This suggests that MF CSA is a good measure of LBP severity and is in agreement with the many studies\textsuperscript{93,96,139,140} showing that decreased MF is correlated with LBP. Furthermore, normalized pre-surgical MF CSA less FI, measured both bilaterally and in unilateral LBP.
participants, was the only muscle to show significant correlations with post-surgical outcomes at 6 months. This suggests that physicians may want to consider a patient’s MF CSA during the pre-surgical decision-making process. Although some studies have assessed MF CSA in surgical patients\textsuperscript{132,143} none have been identified that show larger pre-surgical MF CSA is correlated with favorable surgical outcomes.

**Psoas Major** Normalized PM CSA less FI was not found to be significantly different in our SURG and CONS groups; or on the affected side of unilateral LBP participants. It was also not related to post-surgical outcomes in any way. This contradicts the findings of several studies\textsuperscript{14,96,140,153} which show that PM CSA decreases with both unilateral and bilateral LBP.

**Erector Spinae** Normalized ES CSA less FI was found to be significantly smaller on the affected side in the unilateral LBP CONS participants; however not for the SURG participants. Additionally, only normalized ES CSA less FI was correlated, moderately and negatively, with numeric pain score, a commonly used method for assessing LBP severity.\textsuperscript{85} This is in line with previous research studies\textsuperscript{93,140} showing that ES atrophy is correlated with LBP.

**Fatty Infiltration**

The FI percentage of MF and ES were found to be significantly correlated with age, and thus also with the stenosis surgery group which also varied with age. Although percentage of FI was used to achieve the final normalized muscle CSA, raw FI percentages were not significantly different when CSA was measured bilaterally, or for unilateral LBP. Nor were there any significant differences in FI when analyzed separately by sex. FI was not related to surgical outcomes in this cohort. These results contradict
other studies\textsuperscript{140,177} which show increased MF and ES FI in chronic LBP participants. The results from the present study do not support the use of FI as a diagnostic criteria or in the surgical decision-making process.

**Type of Surgery**

Normalized CSA less FI for both MF and PM, number of comorbidities, and number of involved disc levels, were all found to be significantly different in the fusion versus the microdiscectomy group in the present research. After adjustment for age, however, this difference became insignificant. Ferguson and Marras\textsuperscript{131} also found that LMM scores, a quantitative measurement of low back function, were able to differentiate between fusion and microdiscectomy patients (Table 5.7). These differences, however, also lost significance when results were controlled for the covariate of age.

There are fundamental diagnostic differences between patients undergoing fusion and those undergoing microdiscectomy surgery. In the present study, all 19 fusion participants had a diagnosis of lumbar spinal stenosis; and all 21 microdiscectomy participants had a diagnosis of disc herniation. However, the fusion participants arguably had a more complicated overall presentation, with 63% presenting with multiple LBP diagnoses, compared with only 38% of microdiscectomy participants presenting with multiple LBP diagnoses. Although both muscle CSA\textsuperscript{34,187} and LMM\textsuperscript{57} scores are known to vary with age, the overall higher complexity of the fusion surgery participants could be expected to result in differences in CSA and LMM values independent of age; however, both our sample and the Ferguson and Marras results do not support this conclusion at this time.
Oswestry Disability Index scores showed themselves to be relevant in several different ways. Firstly, among females, significantly higher walking, standing and travelling scores were seen in the SURG group; and for males significantly higher personal care scores were seen in the SURG groups. This shows that some ODI measures are able to accurately differentiate higher-severity surgical patients from lower-severity conservative care patients. Perhaps the most surprising result of this study was the strong correlation of lower overall ODI scores with favorable surgical outcomes at both 6 and 12 months after surgery. Furthermore, when individual ODI items were analyzed, those participants reporting better pre-surgical sex life, and greater lifting and sitting tolerance, had markedly better post-surgical outcomes at both 6 and 12 months. This suggests that pre-surgical ODI scores could be valuable to physicians in the surgical decision-making process. Two prior studies have been identified which assess the effect of pre-surgical ODI scores on post-surgical outcomes. Little and MacDonald\textsuperscript{202} found that a greater percent change in overall ODI scores, from before and after surgery, was correlated with more favorable surgical outcomes, with a stronger correlation among lumbar stenosis...
patients than in patients with IVD herniation. Cook et al\textsuperscript{100} found that higher pre-surgical ODI scores predicted lower post-surgical pain reports in patients undergoing lumbar discectomy, which is in conflict with the results of the present study.

No studies were found which analyzed individual ODI items. However, such a sub-item analysis has been performed in at least one study related to balance and falls risk in individuals with Parkinson Disease. Schlenstedt et al\textsuperscript{203} argue that assessing individual sub-items on assessment tools allows for greater accuracy in identifying individual factors contributing, in this case, to increased incidence of falls. Individual analysis of ODI items may offer similar benefits in identifying those factor most contributing to patient-perceptions of LBP-related functional disability.

**Percent of Back versus Lower Extremity Pain**

Lower percent of back pain and higher percent of lower extremity pain were strongly correlated with presence in the SURG group. This is not surprising, as this percentage was a major criterion used by the 2 physicians participating in this research to recommend surgical intervention. At 6-month follow-up a higher percentage of pre-surgical lower extremity pain was moderately positively correlated with favorable surgical outcomes. This agrees with prior research showing that LBP surgeries tend to be more successful in decreasing lower extremity pain than in decreasing back pain.\textsuperscript{100}

*Limitations:* CSA measurements were performed by one reviewer who was not blinded to the medical histories of the participants, allowing potential introduction of bias into measurements. The fact that we used a cohort that had significant LBP for our control (CONS) group, as opposed to using a cohort that had no history of LBP, likely affected the limited strength of our CSA differences between our groups. The CONS
group participants were not a true control group in that they had a history of LBP significant enough to result in a surgical referral, if not actual surgery. Because of the recent time frame of our sample selection, we had only limited availability of 6 and, especially, 12-month post-surgical outcomes data for our sample, and this limited the conclusions we were able to make about surgical outcomes.

Conclusions: Our hypothesis that muscle CSA for MF, PM and ES would be significantly lower in the surgery group, and positively correlated with favorable post-surgical outcomes was confirmed for MF only. Only normalized MF CSA less FI was able to significantly differentiate SURG from CONS participants. This same pre-surgical, normalized MF CSA was also the only muscle variable to correlate significantly and positively with post-surgical outcomes. Therefore, some physicians may want to consider MF CSA in surgical decision-making. Furthermore, efforts to increase patient MF CSA before surgery through physical therapy referrals may be of value.

Our hypothesis that numeric pain score, chronicity, number of affected vertebral levels, percent of peripheralization of LBP, number of comorbidities, ODI scores and percent of FI would be significantly higher in the SURG group was not confirmed, except for peripheralization of LBP.

Our hypothesis that LBP severity outcomes would be correlated with surgical outcomes was upheld for percent of back and lower extremity pain at 6 months after surgery; and for total ODI score both 6 and 12 months post-surgery. This supports prior research showing that individuals with increased percent of pre-surgical lower extremity pain have better surgical outcomes.\textsuperscript{100} It also supports the possible use of ODI scores by physicians in pre-surgical decision-making.
Our hypothesis that muscle CSA would be smaller on the affected side of participants with unilateral LBP was confirmed for only normalized ES less FI. Of the measured LBP-related variables, only numeric pain score was significantly correlated with muscle CSA, and this with only normalized ES less FI CSA.
CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH
Conclusions

The results of the present research reaffirm what many prior studies\textsuperscript{93,96,139,140,141} have shown: that multifidus (MF) size has an important association with low back pain (LBP). Even within a cohort of individuals with severe LBP and contemplating surgical intervention, MF atrophy is able to differentiate surgical from non-surgical patients. And larger MF pre-surgical cross-sectional area (CSA) was shown to be positively correlated with favorable outcomes at 6 months after spine surgery. These results in no way support the use of MF CSA as a criterion in the pre-surgical decision-making process. They do, however, lend support to the practice of referring certain patients to physical therapy before surgery, as conservative exercises targeting MF have shown the ability to increase MF CSA in relatively short periods of time.

Gluteus maximus (GM) showed a previously unrecognized association with LBP in this study. Shown in component one of the present research to vary with MF CSA, GM was found in component 2 to be significantly atrophied among adult women with a history of chronic LBP. Furthermore, the number of LBP-related medical visits was also shown to correlate negatively with GM CSA. This provides a rationale for further research into GM’s role in LBP, the nature of its atrophy, and whether GM atrophy is pre-morbid or a result of LBP. It also supports the use of physical therapy interventions targeting GM for LBP patients.

Erector spinae (ES) was found to be significantly smaller only with a subset of unilateral, chronic LBP participants. Psoas major (PM) while shown to vary with MF CSA in the first component of the present research, did not show significant atrophy among surgical LBP participants in component 3 of the study. The weak and absent roles
for ES and PM, respectively, in the present research may be due to the lack of a
significant difference in severity of LBP among participants in component 3 of this study.
A similar study using a control group of individuals with no history of LBP would
perhaps have been able to show the significant differences in ES and PM muscle size
seen in other studies.\textsuperscript{14,96,140,153,93}

Surprisingly, fatty infiltration (FI) of MF, ES and PM was not found to be
significantly different in the surgical and non-surgical groups in our study. Furthermore,
there was no association between FI and surgical outcomes at 6 or 12 months. These
results contradict other studies\textsuperscript{140,177} which show increased MF and ES FI in chronic LBP
participants. The results from the present study do not support the use of FI as a
diagnostic criteria or in the surgical decision-making process.

Oswestry Disability Index (ODI) scores showed themselves to be relevant to LBP
in a number of different ways. Individual items on the index related to personal care,
walking, standing, and travelling, were able to differentiate between surgical and non-
surgical participants. And lower overall ODI scores, as well as lower individual items
related to sitting, lifting and sex life, showed significant correlations with post-surgical
outcomes at both 6 and 12 months. This suggests physicians may want to consider pre-
surgical ODI scores in the surgical decision-making process.

**Future Research**

Important further studies on muscle CSA and LBP can be conducted using
cadaver samples. A medical history questionnaire is currently being developed which
could be included in the forms completed by donors to the Ohio State University Body
Donor Program. The form takes 5 to 10 minutes to complete and is designed to be completed by next of kin without medical training. If this or a similar questionnaire is adopted by the Body Donor Program, cadaver studies that assess muscle CSA for all 4 of the above muscles of interest could be conducted, while taking participant medical history into account. This would allow researchers to control for important confounding medical exclusionary criteria, and would greatly increase the internal validity of this cadaver-based research.

Future research assessing the role of GM in LBP is planned in collaboration with an outpatient orthopedic physical therapy clinic. Participants will be individuals with LBP with a McKenzie\textsuperscript{20} posterior derangement classification, and will receive a standardized physical therapy treatment including extension-based and lumbar stabilization exercises, and electrotherapeutic modalities. Experimental participants will also perform exercises in the clinic and in their home program which target the GM. Physical therapy outcomes, including numeric pain scale and ODI scores, will be compared between the control and GM groups. If significance is found with this study, then a further study targeting individuals with a diagnosis of spinal stenosis will be planned.
References


APPENDIX A: OWSESTRY DISABILITY INDEX VERSION 2.1A
This questionnaire is designed to provide information about how your back (or leg) affects your daily life. Choose the ONE BEST ANSWER to each question.

<table>
<thead>
<tr>
<th>SECTION 1 - Pain intensity</th>
<th>SECTION 6 - Standing</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ I have no pain at the moment.</td>
<td>□ I can stand as long as I want without extra pain.</td>
</tr>
<tr>
<td>□ The pain is very mild at the moment.</td>
<td>□ I can stand as long as I want but it gives me extra pain.</td>
</tr>
<tr>
<td>□ The pain is moderate at the moment.</td>
<td>□ Pain prevents me from standing for more than 1 hour.</td>
</tr>
<tr>
<td>□ The pain is fairly severe at the moment.</td>
<td>□ Pain prevents me from standing for more than half an hour.</td>
</tr>
<tr>
<td>□ The pain is very severe at the moment.</td>
<td>□ Pain prevents me from standing for more than 10 minutes.</td>
</tr>
<tr>
<td>□ The pain is the worst imaginable at the moment.</td>
<td>□ Pain prevents me from standing at all.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION 2 - Personal care (Washing, Dressing, etc.)</th>
<th>SECTION 7 - Sleeping</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ I can look after myself normally without causing extra pain.</td>
<td>□ My sleep is never disturbed by pain.</td>
</tr>
<tr>
<td>□ I can look after myself normally but it is very painful.</td>
<td>□ My sleep is occasionally disturbed by pain.</td>
</tr>
<tr>
<td>□ It is painful to look after myself and I am slow and careful.</td>
<td>□ Because of pain I have less than 6 hours sleep.</td>
</tr>
<tr>
<td>□ I need some help but manage most of my personal care.</td>
<td>□ Because of pain I have less than 4 hours sleep.</td>
</tr>
<tr>
<td>□ I need help everyday in most aspects of self care.</td>
<td>□ Because of pain I have less than 2 hours sleep.</td>
</tr>
<tr>
<td>□ I do not get dressed, wash with difficulty and stay in bed</td>
<td>□ Pain prevents me from sleeping at all.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION 3 - Lifting</th>
<th>SECTION 8 - Sex life (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ I can lift heavy weights without extra pain.</td>
<td>□ My sex life is normal and causes no extra pain.</td>
</tr>
<tr>
<td>□ I can lift heavy weights but it gives extra pain.</td>
<td>□ My sex life is normal but causes some extra pain.</td>
</tr>
<tr>
<td>□ Pain prevents me from lifting heavy weights off the floor but I can manage if they are conveniently positioned, e.g. on a table.</td>
<td>□ My sex life is severely restricted by pain.</td>
</tr>
<tr>
<td>□ Pain prevents me from lifting heavy weights but I can manage light to medium weights if they are conveniently positioned.</td>
<td>□ My sex life is nearly absent because of pain.</td>
</tr>
<tr>
<td>□ I can lift only very light weights.</td>
<td>□ Pain prevents any sex life at all.</td>
</tr>
<tr>
<td>□ I cannot lift or carry anything at all.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION 4 - Walking</th>
<th>SECTION 9 - Social life</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Pain does not prevent me walking any distance.</td>
<td>□ My social life is normal and causes me no extra pain.</td>
</tr>
<tr>
<td>□ Pain prevents me walking more than a mile.</td>
<td>□ My social life is normal but increases the degree of pain.</td>
</tr>
<tr>
<td>□ Pain prevents me walking more than a quarter mile.</td>
<td>□ Pain has no significant effect on my social life apart from limiting my more energetic interests, e.g. sport, etc.</td>
</tr>
<tr>
<td>□ Pain prevents me walking more than 100 yards.</td>
<td>□ Pain has restricted my social life and I do not go out as often.</td>
</tr>
<tr>
<td>□ I can only walk using a stick or crutches.</td>
<td>□ Pain has restricted my social life to my home.</td>
</tr>
<tr>
<td>□ I am in bed most of the time and have to crawl to the toilet.</td>
<td>□ I have no social life because of pain.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION 5 - Sitting</th>
<th>SECTION 10 - Traveling</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ I can sit in any chair as long as I like.</td>
<td>□ I can travel anywhere without pain.</td>
</tr>
<tr>
<td>□ I can sit in my favorite chair as long as I like.</td>
<td>□ I can travel anywhere but it gives extra pain.</td>
</tr>
<tr>
<td>□ Pain prevents me from sitting for more than 1 hour.</td>
<td>□ Pain is bad but I manage journeys over two hours.</td>
</tr>
<tr>
<td>□ Pain prevents me from sitting for more than half an hour.</td>
<td>□ Pain restricts me to journeys of less than one hour.</td>
</tr>
<tr>
<td>□ Pain prevents me from sitting for more than 10 minutes.</td>
<td>□ Pain restricts me to short necessary journeys under 30 minutes.</td>
</tr>
<tr>
<td>□ Pain prevents me from sitting at all.</td>
<td>□ Pain prevents me from travelling except to receive treatment.</td>
</tr>
</tbody>
</table>