Lower Back and Lower Limb Neuromuscular Structure and Function in Chronic Low Back Pain Patients with Associated Radiculopathy

by

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ABSTRACT

LOWER BACK AND LOWER LIMB NEUROMUSCULAR STRUCTURE AND FUNCTION IN CHRONIC LOW BACK PAIN PATIENTS WITH ASSOCIATED RADICULOPATHY

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Chronic low back pain patients with associated radiculopathy (LBP-R) experience neuromuscular symptoms in the lower back and down the leg; however research to date is limited to the lower back and trunk. This thesis aims to expand previous research into the lower limb. LBP-R patients with unilateral radiculopathy and healthy matched controls were recruited. Structure of the sciatic nerve and associated musculature was investigated using ultrasound imaging, and functional capacity was analyzed through surface electromyography and force plate recordings during balance perturbations. Results showed that LBP-R patients had swollen sciatic nerves, but that this was not associated with altered muscle quality or the ability of the lower back and leg muscles to activate sub-maximally, with the exception of soleus. Additionally, LBP-R patients’ lower back and leg muscle activation timing during balance perturbations was not delayed; however there were some differences in the kinetic response following perturbation in LBP-R patients.
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LIST OF ABBREVIATIONS

AP – Anterior posterior
BB – Biceps Brachii
BF – Biceps Femoris
COP – Centre of Pressure
CSA - Cross sectional area
EMG – Electromyography
ES – Erector Spinae
L2-S1 – Vertebral levels
LBP – Chronic low back pain
LBP-R – Chronic low back pain with associated radiculopathy
MG – Medial Gastrocnemius
ML – Medial lateral
ODI – Oswestry Disability Index
Sol – Soleus
TA – Tibialis Anterior
VAS – Visual Analog Score
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CHAPTER 1: INTRODUCTION

Chronic low back pain (LBP) is a highly debilitating musculoskeletal disorder that affects nearly 80% of the Canadian population at some point in their lifetime (Cassidy et al., 1998; Andersson, 1999). The direct medical expenses from LBP are estimated at 6 to 12 billion dollars per year in Canada, which does not include the indirect costs of lost time at work and lost productivity of workers with LBP (Church et al, 2004). Specifically within the province of Ontario, the Workplace Safety & Insurance Board (WSIB) stated in their 2012 statistical report that the area of the body most frequently injured in the workplace was the lower back, accounting for 18-20% of all insurance claims. Lower back claims comprised most of the high impact claims, which are defined as having a significant impact on the worker and employer with higher lifetime cost and longer recovery time than lower-impact claims.

Chronic non-specific LBP is a heterogeneous condition with many variations in cause and symptoms. Most LBP research uses a non-specific LBP patient population, which limits the potential for research and clinical applications to specific patient populations. There is a distinct need in LBP research to conduct studies focusing on more homogenous groups of LBP patients. Of the many conditions associated with LBP, one of the most common is lumbar radiculopathy, or sciatica, with lifetime prevalence reports ranging from 1.2% to 43% (Konstantinou and Dunn, 2008). Lumbar radiculopathy is often the result of a lumbar intervertebral disc bulge or herniation compressing spinal
nerve roots. Patients with LBP and associated radiculopathy (LBP-R) suffer from pain in the lower back region as well as pain, tingling and / or numbness down the legs and into the feet.

In LBP patients, there is evidence of altered neuromuscular structure and function at the lower back. Further, muscular changes are more pronounced in a LBP-R population than individuals with only LBP (Hyun et al, 2007). Ultrasound imaging of the multifidus muscle by Wallwork et al (2009) reported a reduced ability to contract multifidus in LBP patients as compared to matched healthy control participants; muscle contraction was quantified as the change in muscle thickness from a relaxed to contracted state. In addition to reduced contractibility, a reduction in the muscle quality of multifidus was found in LBP patients by Chan et al (2012), quantified through the identification of increased fat area within the muscle from the ultrasound image. Similar research using magnetic resonance imaging and computed tomography imaging has found atrophy and / or increased fat infiltration in lower back musculature in individuals with LBP (Ploumis et al, 2011; Hyun et al, 2007; Min et al, 2013; Campbell et al, 1998; Kader et al, 2000; Danneels et al, 2000). As a result of changes in the nerve and muscle structure, there will be alterations in how they function. Functional changes in neuromuscular control can be investigated during balance perturbations, by analyzing local muscle activation with electromyography (EMG). LBP patients have demonstrated delays in lower back and trunk muscle activation in response to perturbations of balance, relative to controls (Hodges et al, 1999b; Hodges et al, 2003; Jacobs et al, 2009; Mochizuki et al, 2004; Leinonen et al, 2001; Magnusson et al, 1996). The quality of the whole body balance
response strategies can be assessed through force plate analysis of centre of pressure (COP) excursions (Mok et al, 2011a; Mok et al, 2011b).

The scope of current research on neuromuscular structure and function in LBP patients has been isolated to the lower back and trunk region. However, when looking specifically at a LBP-R population, the pathology is not limited to the lower back region. Compressive and inflammatory injury to the sciatic nerve at the level of the nerve roots results in sciatic nerve damage distal to the site of injury, causing symptoms of pain, tingling and numbness in the lower limb. Sciatic nerve damage could result in delayed or impaired neuromuscular signals to the musculature controlling movement around the hip, knee and ankle joints. Appropriate magnitude and timing of lower limb muscle activation during balance perturbations is essential for proper recovery of balance, and to minimize transmission of the perturbation to the lower back region in a LBP-R population.

In summary, neuromuscular structure and function has demonstrated impairments in the lower back region of LBP-R patients. Given that (a) the symptoms and pathology of LBP-R extend beyond the lower back to follow the anatomical course of the sciatic nerve into the lower limb, and (b) adequate and efficient activation of the lower limb musculature is essential for maintenance of balance, it is imperative that current research is extended to investigate not only the lower back, but also the lower limb, of LBP-R patients.
Purpose:
To investigate nerve and muscle structure and function in the lower back and lower limb in a chronic LBP-R population.

Hypotheses:

1) LBP-R patients will demonstrate alterations in sciatic nerve and associated lower back and lower limb muscle structure, as evidenced by ultrasound imaging. Specifically, compressive injury to the sciatic nerve leading to inflammation and edema will result in (i) an increase in sciatic nerve cross sectional area, and (ii) a decrease in sciatic nerve echo intensity, specifically on the radiculopathy-affected side. Muscles in the lower back and lower limb innervated by the lumbar nerve roots and the sciatic nerve (erector spinae (ES), biceps femoris (BF), medial gastrocnemius (MG), soleus (Sol)) will show structural evidence of denervation and fat infiltration on the radiculopathy-affected side, specifically (i) increased mean echo intensity, (ii) increased muscle-fascia ratio, (iii) increased percentage of tissue above the echo intensity threshold for fat/fascia tissue, as well as structural evidence of decreased motor control, specifically decreased contraction index (thickening of the muscle upon contraction).

2) LBP-R patients will demonstrate delays in muscle activation (measured through surface EMG) during balance perturbations as compared to control participants. This is hypothesized to occur in the lower back musculature (ES), as well as distally in the BF, MG and tibilais anterior (TA) muscles. Differences between
LBP-R patients and controls are hypothesized to be greater in anticipated conditions, relative to unanticipated conditions, due to impairments in central processing guiding anticipatory feed-forward control in LBP patients (Leinonen et al, 2001).

3) LBP-R patients will demonstrate altered whole-body balance control during balance perturbations, as evidenced by force plate analyses. Specifically, LBP-R patients will have greater COP excursions and velocities in the anterior-posterior (AP) and medial-lateral (ML) planes of motion, relative to controls. Further, it is hypothesized that LBP-R patients will require more time and direction changes to stabilize their AP COP velocity back to baseline levels following perturbations in the AP plane.
2.1 Chronic low back pain and radiculopathy

Chronic LBP is a heterogeneous pathology, with a variety of associated pathophysiological conditions. One of the most common is associated radiculopathy, also known as sciatica. The lifetime prevalence of sciatica reports range from 1.2 to 43% (Konstantinou and Dunn, 2008). In patients under the age of 50, LBP-R is most frequently the result of an intervertebral disc herniation or bulge in the lumbar spine that compresses on the nerve root; in later years lumbar spinal stenosis is the most likely cause (Tarulli et al, 2007). Overall, approximately 90% of sciatica cases are the result of a disc herniation or bulge (Valat et al, 2010). Posterior disc herniation is often the result of repetitive or prolonged spine flexion and loading, causing strain and breakdown of the posterior annulus fibrosis, and bulging of the nucleus pulposus beyond the annulus fibrosis. Additionally, genetic predisposition to lumbar disc herniation can place an individual at heightened risk (Ala-Kokko, 2002). Lumbar discs herniate most frequently in the posterior-lateral direction due to the constraint of the posterior longitudinal ligament, therefore the bulge or herniation will often compress one nerve root and result in unilateral radiculopathy symptoms. However, patients can also present with bilateral symptoms. The compression of the nerve, and the associated inflammatory process, contributes to symptoms of radiating pain, tingling or numbness down the course of the sciatic nerve and its branches. Symptoms are reported in the gluteal, hamstring, posterior leg, lower limb, and foot regions. Depending on which nerve root(s) is (are) affected, the
sensory and motor implications of lumbosacral radiculopathy will be noted in the respective dermatome(s) (the area of skin with sensory innervation by a spinal nerve) and myotome(s) (the musculature with motor innervation by a spinal nerve), although there is a large variation in radiation pattern, specifically for pain (Van Boxem et al, 2010). Testing within myotomes has higher repeatability than dermatome pinprick testing (Krisa et al, 2012). Myotomes are generally tested using needle EMG to detect fibrillations, or spontaneous firing of muscle fibres. Clinical myotome testing is performed in adductor magnus and quadratus femoris (L2-4), tibialis anterior and extensor hallus longus (L4-L5), peroneus longus, extensor digitorum brevis, gluteus medius and tensor fasciae latae (L5), gastrocnemius medialis/lateralis, abductor hallus (S1), biceps femoris and gluteus maximus (S1-S2) (Wilbourn and Aminoff, 1998).

2.2 Nerve and muscle structure and function in LBP-R

2.2.1 Formation of the sciatic nerve
Spinal nerves, which contribute to form the sciatic nerve, are formed from the combination of the posterior (dorsal) nerve root (carries afferent sensory information to the brain) and anterior (ventral) spinal nerve root (carries efferent motor information from the brain). The spinal nerve exits the spinal column through the intervertebral foramen between adjacent vertebrae, and is named based on the vertebra above. The spinal nerve branches into anterior and posterior rami. The sciatic nerve is formed from spinal nerves L4 through to S3, and travels deep to piriformis, exits the pelvis through the greater sciatic foramen, down the posterior thigh travelling deep to adductor magnus along
biceps femoris. The sciatic nerve branches into the tibial and common fibular nerve at some point in the posterior thigh before the popliteal fossa. The tibial nerve continues to the posterior compartment of the leg and the foot, and the common fibular to the anterior and lateral leg.

2.2.2 Anatomy of healthy nerves

Spinal nerves and peripheral nerves have distinct structural features. In peripheral nerves, a perineurial membrane surrounds the nerve bundles, termed fascicles (Rempel et al, 1999). Between the fascicles is the endoneurial connective tissue, and within the fascicles, the groups of nerve fibres are held together by epineurium (Rempel et al, 1999). Spinal nerve roots, which contribute to the peripheral nerve, do not have a perineurium and the epineurial connective tissue is poorly developed (Rydevik et al, 1984). While most peripheral nerves are well vascularized and myelenated, characterized by Schwann cells arranged along the length of the axon, spinal nerves are relatively avascular and composed of both myelinated and unmyelinated nerve fibres (Rydevik et al, 1984).

2.2.3 Nerve compression pathology

Nerve compression in LBP-R results in a cascade of responses affecting the structure and function of the nerve root.

2.2.3.1 Structural changes of the nerve

The lumbar nerve root is particularly susceptible to compression due to the lack of perineurium (provides mechanical protection) and the relative hypovascularity of the cauda equina (Rydevik et al, 1984). Experimental studies in animal models have
demonstrated that in response to peripheral nerve compression, endoneurial edema is the first response, followed by demyelination, inflammation, distal axonal degeneration, and fibrosis (Rempel et al, 1999). Intraneural blood vessels respond to compression by increasing permeability, which contributes to the edema response (Rydevik et al, 1984). Inflammation results in larger cross sectional area (CSA) of the nerve (Kara et al, 2012), and edema will result in the loss of the regular fascicular pattern, due to a breakdown of organized nerve fibre bundles (Martinoli et al, 2007; Koenig et al, 2009). Acute nerve compression results in reversible changes in permeability and blood flow; however, chronic compression is required for persistent structural changes and deterioration in nerve function (Rydevik et al, 1984).

2.2.3.2 Functional changes of the nerve

In addition to structural changes associated with nerve compression in LBP-R, there are also alterations in nerve function. This is commonly measured through electrodiagnostic testing, using needle EMG within the muscle innervated by the nerve of interest. Detection of nerve fibrillations, characterized by spontaneous firing of individual muscle fibres (Boon et al, 2012), and nerve conduction velocity tests can be used to detect and quantify nerve dysfunction. A compressed nerve will have fibrillations and decreased conduction velocity. Fibrillations are most commonly detected using needle EMG; however, preliminary work has shown that high-resolution imaging ultrasound can detect muscle fibrillations non-invasively (Pillen et al, 2009). In a porcine model, unilateral nerve compression or exposure to nucleus pulposus both independently resulted in decreased conduction velocity, and in response to nucleus pulposus application there was
also contralateral decrease in nerve conduction velocity due to diffusion of nucleus pulposus components (Cornefjord et al, 1996). This provides evidence that functional deficits in nerve function, such as reduced conduction velocity, are multi-factorial and not solely related to axonal degeneration as a result of chronic nerve compression. Nerve damage in LBP-R did not indicate de-myelination, according to results of nerve conduction velocity tests using a figure eight motor coil stimulation (Maccabee et al, 2011).

2.2.4 Sensory changes in LBP-R

Functional sensory nerve changes can also be assessed through quantitative sensory testing in the dermatomes of the affected nerve root. Quantitative sensory testing assesses sensation thresholds for touch, vibration, heat, cold, and pain at the skin; each test is targeted to assess the function of a different type of nerve fibre. Touch and vibration sensations are transmitted by myelinated nerve fibres, and in nerve compression pathologies the integrity of the myelin sheath surrounding the nerve can be compromised (Nygaard and Mellgren, 1998). Vibration and touch sensation thresholds in the foot of chronic LBP-R patients have been tested under the hypothesis that LBP individuals will have higher thresholds (lower sensitivity) due to compressive nerve damage of the sensory nerves innervating the foot (Frost et al, submitted). Sensory deficits on the foot sole were proposed to be a main mechanism behind reduced balance control in this population. LBP-R patients demonstrated deficits in vibratory sensitivity, specifically at high frequencies (stimulating the pacinian corpuscle skin receptors), but no clear
indication of balance deficits in COP measures during quiet standing balance and voluntary arm raise balance perturbations.

2.2.5 Motor changes in LBP-R

Further to sensory alterations, it is important to examine the effects of LBP-R on motor innervation. The nerve roots that contribute to the sciatic nerve (L4 to S3) innervate the paraspinal muscles (musculature parallel to the vertebral column, lateral to medial: iliocostalis lumborum, longissimus lumborum, multifidus), then form the sciatic nerve to innervate muscles of the lower limb (among others: BF, semitendinosus, semimembranosus, hamstring portion of adductor magnus, gastrocnemius, soleus, TA) and the foot. Innervation of the multifidus muscle is unique, as each muscle bundle is mono-segmentally innervated by the nerve root exiting below the spinous process where the muscle originates (Hyun et al, 2007; Yoshihara et al, 2003). Innervation of other paraspinal and lower limb muscles by the sciatic nerve is multi-segmental, meaning that multiple nerve roots converge to innervate the muscle. In LBP-R, damage to the sciatic nerve can result in denervation of the muscles it innervates. Human nerve denervation is commonly identified through electrodiagnostic testing, involving invasive needle electromyography, but can also be identified non-invasively through ultrasound imaging, detected as decreased muscle thickness and impaired muscle quality, specifically increased echo intensity and altered homogeneity (Maurits et al, 2003; Gunreben et al, 1991; Kullmer et al, 1998). Yarjanian et al (2013), however, did not find that atrophy was related to the degree of denervation, as measured by electrodiagnostic testing. In a rat model, complete transection of the sciatic nerve resulted in severe decreases in muscle
mass (atrophy) of the soleus and tibialis anterior muscle (Higashino et al, 2013). In addition to atrophy, animal model studies have shown further physiological and biochemical changes in response to denervation, such as a shift from slow to fast twitch muscle fibre type and decreased resistance to fatigue (Higashino et al, 2013).

2.2.6 Muscular atrophy

Atrophy of the paraspinal and hip musculature in chronic LBP patients has been investigated with magnetic resonance imaging, computed tomography and ultrasound imaging. Asymmetric atrophy is often reported as pathological; however substantial asymmetry in paraspinal muscle CSA of healthy control individuals has also been reported (Niemelainen et al, 2011). Therefore comparison of patients to a healthy control group is imperative in this area of research. Focal multifidus atrophy at the level of the affected nerve root in LBP-R has been documented (Campbell et al, 1998). Ploumis et al (2011) investigated localized muscle atrophy in individuals with unilateral LBP, with or without radiculopathy, using MRI imaging to trace muscle cross sectional area (CSA). They found significant muscle atrophy on the affected side of the multifidus, ES, quadratus lumborum and psoas, but degree of atrophy was not correlated with symptom duration, pain rating, or disability rating. In contrast, Barker et al (2004) found significant positive correlations between unilateral atrophy of multifidus and psoas muscles of the affected side with pain rating, duration of symptoms, and reported degree of nerve compression. The LBP patients in this study were severely affected, with average visual analog score (VAS) score of 7.4 (0 – 10 scale), and Oswestry Disability Index (ODI) of 38.4%, which are more severely affected than those included in the study by Ploumis et al (2011), with an average VAS of 5.3 and ODI of 25.2%. A similar magnetic resonance
imaging study by Hyun et al (2007) examined multifidus CSA in LBP patients with radiculopathy and those with intervertebral disc herniation but no radiculopathy, and compared fat-free CSA of multifidus between unaffected and affected sides (or between the right and left side in the control group). They determined that multifidus atrophy, defined as a statistically significant difference between sides, was apparent in 78.6% of radiculopathy patients, but only 24% of the disc herniation without radiculopathy group and 10% in the control group. Similar results were found by Min et al (2013), where the LBP individuals afflicted with radiculopathy had more extensive multifidus atrophy than non-radiculopathy LBP individuals, as measured through magnetic resonance imaging.

Multifidus atrophy, measured with magnetic resonance imaging in 90 chronic non-specific LBP patients, was correlated with leg pain rating, but not with the presence of disc herniation, radiculopathy symptoms, or number of herniated discs (Kader et al, 2000). Atrophy in the multifidus, but not in ES or psoas was found in chronic low back pain patients using computed tomography imaging by Danneels et al (2000).

2.3 Musculoskeletal and nerve ultrasound imaging

2.3.1 Scope and reliability of ultrasound imaging

The use of high-resolution ultrasound imaging of nerve and muscle in clinical and research applications is a rapidly growing field. Ultrasound imaging provides real-time high-resolution images of internal body structures in static or dynamic scenarios, and is non-invasive. Many ultrasound systems are portable, relatively inexpensive, and much easier to access than other common medical imaging techniques, such as magnetic
resonance imaging or computed tomography scanning. Although not as high resolution as magnetic resonance imaging, nerve and muscle ultrasound imaging accurately reflects actual anatomical measurements, as demonstrated by Cartwright et al (2013) where ultrasound measurements of median, ulnar, radial, sciatic, tibial and fibular nerve CSA and biceps brachii (BB) and TA muscle thickness on cadavers were compared to dissected measurements on the same cadavers, and by Kellis et al (2009) comparing human semitendinosis and BF muscle ultrasound thickness measurements in cadavers with dissected measures. Brightness mode (B-mode) imaging is most common for nerve and musculoskeletal ultrasound, but motion mode (M-mode) and Doppler imaging can also be used to measure muscle contraction timing, vascularization, and movement tracking.

2.3.2 Formation of the ultrasound image

The principle of ultrasound imaging is based on the reflection and transmission of sound waves. The transducer sends sound wave pulses into biological tissue, that will either reflect or transmit the sound waves depending on its properties, and the returning echo is used to reconstruct an image. A low frequency sound wave will penetrate deeper into the tissue, but produce a lower resolution image than a higher frequency sound wave that provides a more superficial, higher detail image (Derchi et al, 2007; Walker et al, 2004). A broadband frequency transducer will optimize the frequency depending on the desired depth (Derchi et al, 2007). Tissue that transmits sound waves (such as muscle tissue) will appear as darker, or less echogenic, and tissue that reflects sound waves (such as fibrous connective tissue surrounding muscle fascicles or fat tissue) will appear brighter, or more
echogenic. Bone will reflect all sound waves and therefore show up as a very bright edge (echogenic) with no structures discernable deep to the bone. A more echogenic image (brighter) is termed hyperechoic, and a less echogenic image (darker) is hypoechoic.

2.3.3. Peripheral nerve imaging

Peripheral nerve imaging with ultrasound is a novel but rapidly advancing field. Nerve tissue appears as more echogenic (brighter) than muscle tissue, with hypoechoic rounded areas (nerve fibre bundle, consisting of nerve fibres embedded in endoneurium) embedded in a hyperechoic background (epineurium, consisting of loose connective tissue), giving the nerve a characteristic ‘stippled’ or ‘honeycomb’ appearance in cross section (Walker et al, 2004; Boon et al, 2012; Rempel et al, 1999) (Figure 1). The epineurial rim will appear as a bright (hyperechoic) rim surrounding the nerve (Hobson-Webb et al, 2012). The honeycomb appearance is more apparent in smaller, more superficial nerves, such as the median nerve (Figure 1a), than larger, deeper nerves, such as the sciatic nerve (Figure 1b).
Figure 2.1: Cross sectional view of the median nerve in the mid-forearm [A] (Tagliafico et al, 2010), and the sciatic nerve [B], indicated by the black arrow, in a healthy control participant (from this thesis). The hypoechoic nerve fibre bundles embedded in hyperechoic epineurium that gives the honeycomb appearance is more apparent in the median nerve.

2.3.3.1. Analysis software and measures

A growing trend in nerve and muscle ultrasound imaging is to assess the image quantitatively to facilitate more direct comparisons between pathological and healthy states. Dimensional measures are very commonly reported, such as CSA (cm$^2$ or mm$^2$), and thickness (cm or mm) of a nerve or muscle. These can be measured online with the ultrasound system, or offline using image analysis software. The echo spectrum of the ultrasound image can also be analyzed to provide information about muscle fat and connective tissue infiltration, inflammation, edema, and homogeneity. Given that any tissue superficial to the one of interest can absorb the sound waves emitted by the
ultrasound transducer, caution must be taken to account for between-participant differences in subcutaneous fat (Nijboer-Oosterveld et al, 2011). Increased amounts of subcutaneous fat tissue was hypothesized by Nijboer-Oostervel et al (2011) to decrease echo intensity, as fat tissue absorbs sound waves, however the opposite was found; thicker fat thickness was correlated with increased echo intensity, which was attributed to over-compensation of the ultrasound device’s built-in correction for sound wave attenuation. Subcutaneous fat thickness should be recorded to account for any possible alterations in echo intensity. Further, each ultrasound device influences the displayed echo intensity, therefore if comparing between devices a conversion must be applied (Pillen et al, 2009). In order to facilitate analysis of ultrasound images, image analysis software, such as ImageJ (Boom et al, 2012; Koppenhaven et al, 2009) or OsiriX, can be used. Last, the longitudinal excursion of nerves during mobilization exercises can be analyzed either through cross-correlation analysis of regions of interest of the nerve or through Doppler imaging, as the joint is brought through its range of motion (Hough et al, 2000; Dilley et al, 2001).

There are a number of measurement techniques used while imaging peripheral nerves. The field of nerve ultrasonography primarily began by imaging compression neuropathies such as carpal tunnel syndrome and ulnar neuropathy, where the very superficial peripheral nerves are easy to image. Nerve echogenicity was reported to be capable of discriminating between healthy and pathological nerves, as intraneural edema results in increased hypoechoic areas (Boom et al, 2012; Tagliafico et al, 2010). Image analysis software (e.g. ImageJ) can be used to generate histogram-based thresholds to differentiate
between hypoechoic and hyperechoic areas; a larger proportion of hypoechoic area is indicative of edema (Boom et al, 2012). Tagliafico et al (2010) quantified nerve density as the ratio between nerve fascicles (hypoechoic pixels) and perifascicular tissue (hyperechoic pixels) in carpal tunnel syndrome patients, based on both manual visually-determined thresholds, and also with automatic threshold methods based on analysis of the histogram in ImageJ. They concluded that nerve density is a sensitive outcome measure that is able to differentiate between mild and severe carpal tunnel syndrome. However, the distinction between hyperechoic and hyperechoic areas is not as apparent in the sciatic nerve, therefore this may not be an appropriate measure for detecting echogenic alterations in LBP-R.

2.3.4 Imaging the sciatic nerve

Recent research has started to investigate the sciatic nerve using ultrasound imaging in both healthy and pathologic states. CSA measurements of the sciatic nerve taken at the mid-thigh region are reliable, with a minimum detectable difference of 13% of the mean (Tagliafico et al, 2012); reference healthy ranges and variation for CSA have been previously reported (Cartwright et al, 2008). Further, Cartwright et al (2013) reported a significant correlation (correlation coefficient 0.917, p = 0.001) between ultrasound measures of a cadaver sciatic nerve CSA, with the same cadaveric nerve dissected and physically measured. In the proximal thigh region, location and capture of a good quality image was attained in all 15 participants tested in a study by Chan et al (2006) while using a 2-5 MHz transducer. Imaging of the sciatic nerve in patients with lumbar disc herniation-induced nerve compression has been investigated in a few recent publications.
Kara et al (2012) found increased sciatic nerve dimensions and CSA, presumably as a result of inflammation or edema.

In addition to dimensional measurements of the sciatic nerve, the longitudinal mobility of the nerve during nerve mobilization exercises has been measured. Methods to measure longitudinal nerve mobility were first established in the median nerve using Doppler ultrasonography (Hough et al, 2000) and cross correlation analysis (Dilley et al, 2001). Sciatic nerve longitudinal movements have been measured using cross correlation analysis of regions of interest of the nerve during ankle dorsiflexion and neck flexion (Ridehalgh et al, 2012; Ellis et al, 2008; Ellis et al, 2012), and has been found to be a reliable measure. Transverse movement of the sciatic nerve in the anterior-posterior and medial-lateral planes during ankle dorsiflexion and neck flexion mobilizations has also been recorded in a healthy population, by measuring the positional difference in digital markers on the borders of the sciatic nerve between the beginning and end of the mobilization (Ellis et al, 2008); however, this has yet to be investigated in a patient population.

2.3.5 Imaging musculature associated with the sciatic nerve

Ultrasound imaging of muscle can be performed in the axial plane (transverse) to get a cross sectional view of the muscle, or in the longitudinal plane, to examine the muscle thickness. Longitudinal imaging of trunk muscles in LBP patients using ultrasound has primarily focussed on quantifying the percent change in thickness of muscles in a relaxed versus a submaximal contraction. Measurements of the transversus abdominus, internal
oblique, and lumbar multifidus thickness were reported to have high inter-rater reliability (Teyhen et al, 2011). Further, Koppenhaver et al (2009) found high inter- and intra-reliability using ultrasound to image multifidus and transversus abdominus muscle activation, as percent change in thickness. In 2012, Teyhen et al generated a reference database of abdominal and lower back muscle thickness in rested and submaximally contracted states in healthy adults, and reported good symmetry for the multifidus muscle, a finding also supported by Pressler et al (2006). In a study by Kiesel et al (2007), ultrasound measure of muscle thickness prior to and during a submaximal activation of multifidus was used to quantify the change in muscle thickness upon activation; this was highly correlated to activation levels measured by indwelling EMG, the gold standard for measuring muscle activation. Ultrasound investigation of multifidus in chronic LBP patients demonstrated that localized multifidus had a smaller CSA and a smaller change in thickness during a submaximal contraction as compared to a control group (Wallwork et al, 2009). Further, a comprehensive investigation into spinal imaging with ultrasound by Darrieutort-Laffite et al (2014) details the technique to image the ES muscles in both longitudinal and axial planes. Collectively this prior work demonstrates that ultrasound recording of muscle thickness change allows for non-invasive quantification of deep muscle contraction.

In the axial plane, quantitative analysis of muscle ultrasound echo intensity can be used to detect increases in intramuscular fat and fibrosis to measure muscle quality. Fat area was quantified by Chan et al (2012) through echo intensity histogram that defines a ‘fat threshold’, and the percentage of pixels within this area over this threshold were
considered to be fat or fibrotic tissue. They investigated lumbar multifidus ultrasound images of a group of chronic LBP patients, and found that the LBP patients had reduced CSA and larger fat area within the multifidus muscle, as compared to controls. In a population of older adults, mean echo intensity was analysed within a region of interest of the quadriceps femoris muscle (Fukumoto et al, 2011). A higher mean echo intensity was interpreted as containing more fat and fibrosis, and less contractile tissue, within the muscle, as fat and fibrotic tissue are more echogenic (hyperechoic) than muscle tissue. Fukumoto et al (2011) found a significant correlation between higher mean echo intensity and decreased muscle strength, independent of muscle thickness.

2.4 Whole body balance control
In addition to examining structural properties of nerve and muscle, it is important to gain insight into the functional capacity of the neuromuscular system. This insight can be provided by analyzing responses following perturbations that challenge whole body balance.

2.4.1 Balance perturbations
Perturbations of balance can originate from self-generated motions of the lower limb (bottom-up), such as a rise up to toe (Frank et al, 2000) and voluntary hip flexion (Arab et al, 2011), or upper limb movements (top-down), such as unilateral or bilateral arm raise (Mok et al, 2011; Leinonen et al, 2003; Mochizuki et al, 2004). Unexpected balance perturbations could involve motion of the support surface (e.g. Maki et al, 2003) or releasing or dropping a weight into a hand-held apparatus (Mok et al, 2011; Aruin 2006;
Brown et al, 2003). A voluntary perturbation, generated by internal body movement such as an arm raise or rise up onto toes, will involve a preparatory phase prior to movement onset, characterized by muscle activity onset and COP movement in the form of an anticipatory postural adjustment. This requires feed-forward control prior to perturbation onset, as well as reactive feedback control following the postural perturbation. In contrast, an involuntary or external perturbation involves only reactive balance control, whereby muscle activation and COP oscillation occur following movement onset.

2.4.1.2 Muscle activation strategies

The timing of lower limb muscle activation in response to a balance perturbation is important to appropriately respond to the perturbation, and in the case of a bottom-up perturbation, to minimize transmission of the perturbation to the lower back and trunk. In response to anterior-posterior balance perturbations originating at the trunk, individuals can adopt either an ankle strategy (plantarflexion and dorsiflexion about the ankle joint) or a hip strategy (flexion and extension about the hip joint) in order to return to balance equilibrium (Winter et al, 1990). The ankle strategy requires proper activation of the ankle dorsiflexors (TA) and plantarflexors (soleus, lateral and medial gastrocnemius), and the hip strategy will require proper activation of the hip flexors (iliacus and psoas) and hip extensors (gluteal muscles, hamstring muscles). Individuals with LBP have demonstrated deficits using the hip strategy for balance in quiet stance; this was attributed potentially to reduced lumbopelvic motion due to increased activity of trunk muscles resulting in a stiffer system (Mok et al, 2004). The subsequent increased dependence on the ankle strategy to respond to perturbations of balance requires that
control of ankle dorsiflexion and plantarflexion is appropriate in both timing and magnitude; however there is potential for compromised neuromuscular control of this musculature due to its innervation origin at the lumbar nerve roots, directly affected in LBP-R.

2.4.2 Electromyography during balance perturbations

2.4.2.1 Recording surface electromyography

EMG is a technique that involves placing electrodes on the skin surface over the muscle belly (surface EMG) or wire electrodes within the muscle (indwelling EMG), and recording and differentially amplifying the electrical activity associated with muscle activation. Investigation into the magnitude of activation requires that the EMG signal, originally in units of voltage, be normalized to either a maximum voluntary contraction or a reference voluntary submaximal contraction to control for confounders such as subcutaneous tissue filtering effects, slight variation in electrode placement, and variation in skin impedance (Lehmen and McGill, 1999). However, similar normalization is not required to examine muscle activation timing. Muscle activation timing can be determined based on the latency of the EMG signal increase in relation to the perturbation stimulus, and relative activations of a series of muscles can provide insight into muscular coordination.

2.4.2.2 Altered muscle activation timing
Using EMG to investigate trunk muscle activation timing, LBP patients have demonstrated altered motor control of many trunk muscles. van Dieen et al (2003) published a review covering trunk muscle activation in LBP patients; within studies investigating muscle activation timing, LBP patients demonstrated delays in muscle activation.

Previous research has investigated internal and external perturbations, originating from both the upper and lower limbs. A rapid arm raise is a voluntary, feed-forward control, perturbation that activates lower back as well as lower limb musculature. Mochizuki et al (2004) investigated muscle activation patterns during bilateral and unilateral arm raises at different speeds, and characterized the muscle activation patterns in healthy normal individuals. Additionally, Hodges and colleagues investigated activation of trunk musculature prior to rapid upper limb movements in healthy individuals (Hodges et al, 1999a; Hodges et al, 1997). In LBP patients, muscle activation of transversus abdominus (Hodges et al, 2003; Hodges et al, 1999b) and external oblique (Hodges et al, 1999b) were delayed during rapid arm movements. Further, LBP patients have demonstrated decreased variability in the timing of the internal oblique, but not ES muscles, during rapid arm movements (Jacobs et al, 2009).

As mentioned earlier, external perturbations of balance are used to assess reactive balance control. Leinonen et al (2001) tested participants with disc herniation-related LBP in unexpected and expected upper limb perturbations that involved dropping a weight into a hand-held box, and found that feed-forward activation of ES and multifidus...
muscles was slower as compared to controls in expected perturbations, but not in unexpected perturbations. In contrast, Magnusson et al (1996) found delayed ES muscle activation in unilaterally-affected LBP patients as compared to controls in response to an unexpected trunk load, as well as a further delay in activation on the painful side relative to the contralateral side. In trials with the same perturbation elicited in both an unexpected and expected scenario, an expected perturbation has resulted in decreased latency and magnitude of postural responses (Leinonen et al, 2002). Altered muscle activation timing is specific to chronic LBP, as acute induced LBP (via injection of saline solution) did not alter the relative timing of trunk muscle (ES and external oblique) activation in response to platform perturbations of standing balance (Boudreau et al, 2011).

In the lower limb, Bruno et al (2007) investigated the alterations in hamstring, gluteal and ES muscle activation order during a prone hip extension, but found a variable activation order for these muscles, even in healthy control participants, and slightly more consistent activation order in chronic LBP patients; there did not appear to be one ‘normal’ activation order. A similar study by Arab et al (2011) investigated the magnitude of ES, gluteal and hamstring musculature activation during a prone hip extension, and found higher normalized EMG signals in the ES muscles in the LBP individuals as compared to controls. These studies did not specify the presence or absence of radiculopathy in the LBP patients, or confirmation of disc herniation or bulge in the lumbar spine.

2.4.3 Force plate for balance analysis
Following a balance perturbation, the goal of neuromuscular balance control strategy is to effectively regain balance equilibrium. One widely accepted and commonly used way to assess the effectiveness of the whole body balance control is to record and analyze force plate data acquired during experimentally induced perturbations.

2.4.3.1 Recording and analyzing force plate data

Force plates contain sensors (piezoelectric or strain gauge) that record three-dimensional forces (Fx, Fy, Fz) and moments (Mx, My, Mz), from which the COP can be calculated. The COP, defined as the point of application of the ground reaction force beneath the feet, is located within the base of support and oscillates during standing balance and perturbations of balance. Measures of the COP, such as mean or maximum excursions, mean or maximum velocity, or variability, are frequently used to detect differences in balance capacity in patient groups relative to control individuals (e.g. Ruhe et al, 2011). When examining COP excursions (in the AP and ML planes), measuring the maximum excursion will capture the magnitude of the range of postural sway. In contrast, recording the mean excursion or root mean square of the excursion will de-emphasize any possible outliers that may skew these magnitude measures, but risks losing important information that these postural outliers may provide. The velocity of COP movements provides further information about balance control strategies; for example AP COP velocity is very highly correlated with clinical balance tests in stroke patients (Frykberg and Karlsson, 2000) and older adults (Berg et al, 1992).

2.4.3.2 Kinetic response to perturbations
Research in whole-body balance control of LBP patients from a kinetic perspective is limited, as much of the research to date has focused on muscle activation measures, and not on force plate analyses. Mok et al conducted two critical studies in 2011 that investigated balance control strategies in voluntary arm raise trials (Mok et al, 2011a) and weight drop trials (Mok et al, 2011b). In both studies, there were no differences in COP excursion in the AP plane between LBP patients and controls, but the COP stabilization was further examined by calculating the time required for AP COP velocity to return within two standard deviations of baseline velocity, as well as the number of postural adjustments during this stabilization period. The time required for stabilization represents the quality of the postural recovery, and the number of postural adjustments provides information about the fine-tuning of postural control following perturbation (Mok et al, 2011a). LBP patients were found to take longer to stabilize following a perturbation, and required more fine-tuning adjustments during the stabilization; this was true for both types of perturbations. In contrast to this, Frost et al (submitted) found no difference between healthy controls and LBP-R patients in balance stabilization measures, and similarly found no difference in COP excursion measures.

There has been no prior research investigating lower-limb generated balance perturbation in LBP patients. The voluntary rise to toe perturbation requires initial postural adjustments to prepare the body for an anterior shift in the COM, and the magnitude and timing of the MG and TA muscles is critical to task success (Frank et al, 2000). This rise to toe task has been investigated in healthy individuals (Nardone and Schieppati, 1988) as well as individuals with Parkinson’s disease to assess full body balance control (Frank et
al, 2000), but has never been investigated in LBP patients. Investigation of the rise to toe perturbation in LBP patients may provide insight into voluntary lower limb muscle control.
CHAPTER 3
METHODS

3.1 Participant characteristics

Individuals with LBP-R and matched control participants were recruited to the study. All LBP-R participants had unilateral (n = 17) or bilateral (n = 6) radiculopathy (sciatica) for a minimum of 3 consecutive months as a result of a clinically diagnosed lumbar intervertebral disc bulge or herniation. The LBP-R patients experienced lower back pain as well as symptoms of pain, tingling, or numbness radiating down the leg and/or into the foot. A subset of LBP-R patients had a history of spine surgery (n = 4). Full clinical detail on all LBP-R patients can be found in Appendix A. Control participants (n = 17) with no history of chronic LBP, musculoskeletal disorder, or neurological deficit were matched to unilateral LBP-R patients for age, sex, mass, height, foot dominance, and physical activity status (Table 3.1). All participants completed a medical questionnaire pertaining to musculoskeletal and neurological disorders, an ODI score, a VAS of pain for the lower back region and legs, a Waterloo Footedness Questionnaire, and a Baecke score of physical activity (Appendix B). LBP-R patients ODI scores ranged from minimal (n = 7) to moderate (n = 9) to severe (n = 1) disability (Vianin, 2008). VAS scores at the lower back ranged from no pain (n = 3) to mild (n = 10) to moderate (n = 3) to severe (n = 1), and at the affected leg ranged from no pain (n = 1) to mild (n = 16) (Hawker et al, 2011). Baecke scores of physical activity level for both the LBP-R and control groups indicated moderate levels of physical activity (Baecke et al, 1982). All participants were right foot
dominant, according to the Waterloo Footedness Questionnaire. Ethics approval from University of Guelph Research Ethics Board was obtained prior to data collection.

Table 3.1: Participant characteristics (mean ± SD) of matched unilateral LBP-R patients (n = 17) and controls (n = 17).

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Sex (M:F)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Baecke score</th>
<th>ODI (%)</th>
<th>VAS back</th>
<th>VAS leg</th>
<th>Duration (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBP-R</td>
<td>44.2 ± 14.9</td>
<td>6:11</td>
<td>1.69 ± 7.7</td>
<td>69.5 ± 9.2</td>
<td>8.18 ± 1.4</td>
<td>19.9 ± 12.8</td>
<td>2.59 ± 2.3</td>
<td>1.81 ± 1.2</td>
<td>126 ± 143</td>
</tr>
<tr>
<td>Control</td>
<td>44.2 ± 15.7</td>
<td>6:11</td>
<td>1.72 ± 7.9</td>
<td>69.1 ± 10.8</td>
<td>8.35 ± 1.4</td>
<td>0.69 ± 1.3</td>
<td>0.34 ± 0.4</td>
<td>0.29 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>

1 Baecke score of physical activity for work, sport and leisure activity
2 Oswestry Disability Index, on a percentage scale; scores from 0-20% indicate minimal disability, 20-40% indicate moderate disability, 40-60% severe disability
3 Visual Analog Scale of pain recorded at the back and the affected leg on separate scales, on a scale of 0-10. A score of 0-0.4 indicates no pain, 0.5-4.4 indicates mild pain, 4.5-7.4 indicates moderate pain, 7.5-10 indicates severe pain

3.2 Experimental protocol overview

The experimental protocol involved ultrasound imaging, followed by balance perturbations (Figure 3.1). Specifically, ultrasound imaging was first completed in a rested state, followed by outfitting with surface EMG and ultrasound imaging in a contracted state. Following this, participants stood on a force plate and performed balance perturbations while surface EMG was recorded.

Figure 3.1: Experimental protocol flowchart.
3.3 Ultrasound imaging

Ultrasound imaging was conducted in both relaxed and contracted states. This was done to assess the muscle thickening during contraction.

3.3.1 Imaging at rest

High-resolution ultrasound images were obtained using a 6-15 MHz linear transducer (Sonosite M-Turbo, Markham, ON) manually held over the skin. Ultrasound imaging was completed in brightness mode and set to the standard Auto Gain setting to ensure consistent baseline brightness between trials and participants. The same experimenter conducted all ultrasound imaging and analyses. Hypoallergenic water-soluble ultrasound transmission gel (Aquasonic 100) was applied to the skin to enable acoustic coupling between the transducer and the skin surface. First, bilateral ultrasound imaging was conducted while the participant lay prone on a chiropractic bench in a relaxed state with his/her ankles in a neutral position. Selected muscles of the lower limb innervated by the sciatic nerve and branches were imaged. The experimenter alternated between imaging right and left sides until three images had been taken from each side; measures were later averaged across the three images for each side. In order to ensure consistency in imaging location between recordings, the location of the transducer was marked on the skin surface in reference to anatomical landmarks. Imaging in both the axial (view cross-section) and longitudinal (view thickness) planes was completed.

The BF muscle and the sciatic nerve were imaged at the level of the posterior midthigh, standardized as the point 25% along a line measured from the popliteal crease to the
ipsilateral iliac crest (Figure 3.2). Axial images provided a cross sectional view of the sciatic nerve and the BF muscle (Figure 3.3), and longitudinal images allowed for determination of muscle thickness, measured as the linear distance between the superficial and deep fascial planes of the muscle (Figure 3.4).

**Figure 3.2:** Representation of location of ultrasound imaging locations for [A] ES muscle, located 2 cm lateral to L2 spinous process (black circle), [B] BF muscle, located 25% along a line between the popliteal crease and the ipsilateral iliac crest, and [C] MG muscle, located 30% along a line from the popliteal crease to the medial malleolus. Ultrasound imaging locations are depicted as open rectangles.
**Figure 3.3:** Representative axial ultrasound images of the sciatic nerve (black arrow) and BF muscle (region of interest outlined in dashed green line). Note the brighter (more hyperechoic) sciatic nerve in the control participant [A] relative to the LBP-R participant [B, C], as well as the increased sciatic nerve CSA on the affected side [C] relative to unaffected side [B].

**Figure 3.4:** Representative longitudinal images of the BF muscle in relaxed [A] and contracted [B] states. The muscle thickness is shown by the green line, measured between the superficial and deep aponeurosis, with the intermediate aponeurosis also visible in the image. The top of the image is superficial, and the bottom is deep.
The MG muscle was imaged at a location measured as 30% of the tibial length from the popliteal crease to the midpoint of the medial malleolus. This imaging site has previously been shown to give reliable images, with an interclass correlation coefficient of 0.97 for measuring thickness of MG (Cho et al, 2013; Raj et al, 2012). The MG and soleus muscle thickness was recorded from the longitudinal image, quantified as the linear distance between the superficial and deep fascial planes of the respective muscle (Figure 3.5). Further, axial images provided a cross sectional view of the muscle (Figure 3.6).

**Figure 3.5**: Representative longitudinal images of MG and soleus muscles in relaxed [A] and contracted [B] states. The muscle thickness is shown by the green line, measured between inferior and the superior fascial planes of the muscles. The top of the image is superficial, and the bottom is deep.
Figure 3.6: Representative axial (cross-sectional view) images of MG muscle, indicated by the dashed green line around the muscle region of interest, showing a healthy control participant [A] and a LBP-R patient with a fat infiltrated muscle [B].

The ES muscle group was imaged bilaterally at the L2 to L3 vertebral level of the lower back. Longitudinal images were taken with the transducer approximately 2 cm lateral to the midline (spinous process), so that the facet joints of the spine could be clearly identified in the ultrasound image. ES muscle thickness was measured as the linear distance between the facet joint and the superficial fascial plane of the muscle (Figure 3.7). Axial (transverse) images were recorded by spanning the transducer across the spinous processes so that bilateral cross-sectional views of the ES and multifidus muscles could be recorded (Figure 3.8).
Figure 3.7: Representative longitudinal images of the ES muscle in relaxed [A] and contracted [B] states. The muscle thickness is shown by the green line, measured between facet joint and the superior fascial planes of the muscle.

Figure 3.8: Representative axial ultrasound images of the ES and multifidus muscles, indicated by the dashed green line surrounding the muscle region of interest, showing control participant [A] and LBP-R patient with fat infiltration [B]. SP indicates where the spinous process is located, and the right and left sides are represented as R and L.
Last, the BB muscle was imaged bilaterally, as an area of the body not directly affected by sciatica. This measurement was performed to ensure that the patient and control groups had no baseline differences in muscle activation or quality. BB was imaged at a point 50% along a line between the acromion and the elbow crease. Both axial and longitudinal images were recorded.

3.3.2 Imaging in contracted state

Participants were instrumented with 8 pairs of disposable Ag/AgCl surface EMG electrodes (Ambu Blue Sensor, Medicotest Inc., Olstykke, Denmark), placed bilaterally on the muscle belly of ES at L4, BF, MG, and TA, with a ground electrode on the iliac crest. Prior to electrode application, skin sites were shaved and cleaned with rubbing alcohol; this was done to ensure adequate adherence of the electrodes to the skin surface and to minimize electrical impedance. All of the EMG channels were checked to adjust the gain and to ensure that good quality signals of muscle activation were being obtained. Raw EMG signals were band-pass filtered at 10-1000 Hz, amplified (AMT-16, Bortec, Calgary AB, Canada), and sampled at 2048 Hz.

A 5-second trial of baseline EMG activity was collected during relaxed prone lying. In order to assess the transverse mobility of the sciatic nerve, a 6-second ultrasound video of the sciatic nerve was recorded while the participants’ ankle was passively moved from full plantarflexion to full dorsiflexion by an experimenter, therefore requiring no active contraction. From the ultrasound video, the AP and ML excursions of the sciatic nerve relative to the femur were recorded during the ankle dorsiflexion movement. Concurrent
EMG recording from the MG and BF muscles were examined to ensure that the movement was passive. These data will not be further presented or discussed, as we were unable to clearly view the sciatic nerve relative to the femur in over 50% of the participants.

Next, participants performed standardized submaximal isometric muscle activations of ES, BB, MG and BB. Prior to each muscular effort, the experimenters fully described the procedure to ensure that the participants would be comfortable performing the activation. Three repetitions of each submaximal activation were performed on each side of the body, alternating between the right and left sides of the body to minimize fatigue. During the isometric hold of each of these manoeuvres, a longitudinal ultrasound image of the muscle of interest (in the same location as the relaxed ultrasound imaging) was taken concurrent to a 2-second EMG recording.

For the ES muscles submaximal activation, participants lay prone on the chiropractic bench with both arms extended above their head. They were instructed to raise one arm 5 cm (measured by an experimenter) off of the bench while holding a 1 kg weight in their hand, which activates the contralateral multifidus and ES muscles (Figure 3.9a). This was repeated on the opposite side of the body. This procedure has previously been reported to activate the lumbar multifidus to approximately 30% of maximum (Kiesel et al, 2007). In the event that participants were uncomfortable holding the 1 kg weight in their hand, they performed the exercise without any hand weights (6 LBP-R occurrences, 1 control occurrence).
The BF muscle was activated using an isometric prone hip extension, and ultrasound images were acquired in this position. Participants lay prone on the chiropractic bench, then extended one leg at the hip until their ankle was 15 cm off of the bench (measured and verbally guided by an experimenter) while keeping their knee in the fully extended position (Figure 3.9b). All participants were able to perform this task without modifications.

**Figure 3.9:** Representation of the submaximal activation tasks for ES [A] and BF [B] muscles. The ES activation required the participants to lift their extended arm off of the table so that the wrist was 5 cm above the table, while holding a 1 kg weight in their hand. The BF activation required the participants to extended their leg at the hip so that their ankle was 15 cm above the table.
The submaximal activation of the MG and soleus muscles required the participants to begin in a relaxed standing position, then slowly rise to their toes until their heels were 5 cm off of the ground (measured and verbally guided by an experimenter), maintain this position for 3 to 5 seconds while EMG and ultrasound were recorded, then return to neutral stance. Participants were encouraged to gently rest their hands on the chiropractic bench to maintain balance during this procedure.

For the BB submaximal activation, participants stood while holding a weight in their hand with their elbow at a 90-degree angle. Participants were given the option of using a 6.8 kg weight or 4.5 kg weight, depending on strength capacity. In all cases, participants used the same weight on both sides of the body. A 10 kg weight held in this position has previously been shown to activate the BB muscle to approximately 25% of maximum in a healthy young male population (Frost et al, 2012). Note that females on average have approximately 40% less upper body muscle mass than males (Janssen et al, 2000).

3.4 Balance perturbations

In order to assess whole body standing balance, four different balance perturbations were conducted. Three successful trials of each balance perturbation were recorded, and analyzed data were averaged across the three trials. Participants stood in a self-selected neutral stance on an AMTI force plate. During all trials, one kinematic infrared marker (Optotrak 3D Investigator, Northern Digital, Waterloo ON, Canada) was adhered to a body landmark (wrist or ankle) using double sided tape, to allow for detection of onset and velocity of movement. Kinematic data were sampled at 512 Hz. Additionally, EMG
data were recorded during all balance perturbation trials, and sampled at 2048 Hz. In order to determine EMG onset time relative to kinematic movement, the kinematic movement onset frame number was multiplied by 4 in order to determine the EMG frame number.

Participants first completed the voluntary rise to toe perturbation. For these trials, the kinematic infrared marker was adhered to the lateral malleolus of the right heel. Participants began the trial standing on the force plate in a normal width stance with eyes open, then on a countdown verbal cue, were instructed to rise up onto their toes as rapidly as possible, maintain this position for a count of 3 seconds, then slowly lower back down to neutral stance. A successful trial required that the participants did not take a step to recover balance during the trial, and maintained the position up on their toes for a full 3 seconds.

The second balance perturbation was the rapid bilateral arm raise perturbation. The kinematic infrared marker was placed on the lateral condyle of the right wrist. Participants began by standing in a normal width stance with their eyes open and arms at their sides, then on a verbal countdown flexed their arms at the shoulder to 90 degrees as rapidly as possible, held that position for a count of 3 seconds, then slowly lowered their arms to the starting position.

The final two balance perturbations were external perturbations, involving a weight drop. Participants held a box while maintaining a 90-degree elbow angle, and the kinematic
marker was adhered to the wrist. A 2.27 kg weight was dropped into the box by an experimenter, from a height of 5 cm (Leinonen et al, 2001; Mok et al, 2011). The participant was instructed to respond to the perturbation by returning his/her elbow and the box to its original position as soon as possible. The participant’s view of the box was obscured so that he/she could not see when the weight was dropped. The weight was removed from the box at the completion of the trial. This procedure was conducted under two conditions: unanticipated (10 second window of time when the weight could be dropped) and anticipated (experimenter count down to weight drop). This procedure was repeated three times consecutively for each condition. All participants were given one practice trial using a 1 kg weight, and some participants chose to use this lighter weight for the experimental trials (3 occurrences, all LBP-R participants).

3.5 Data Analyses

3.5.1 Ultrasound

Analysis was completed offline using OsiriX (version 5.6 32 bit) and ImageJ (32-bit, version 1.47t) software. The axial view of each muscle was analyzed with OsiriX to record the mean and standard deviation echo intensity of the muscle (taken from a standard size region of interest of the muscle), the mean echo intensity of a region of interest of the fascia, and the thickness (cm) of the subcutaneous fat tissue. Given that there may be small image-to-image differences in image brightness that would shift the mean echo intensity, the mean echo intensity of the surrounding fascia was measured, and the muscle-fascia ratio of echo intensity was computed as [muscle mean echo
intensity / fascia mean echo intensity] (Equation 1). This facilitated the comparison of the relative amount of fascia/fat in the muscle region of interest between sides and participants. The muscle-fascia ratio assumes that there is no difference in fascia brightness between unaffected and affected legs, and between LBP-R patients and controls. We were able to verify this by statistically comparing the fascia brightness between groups, and found no significant differences. The final assessment of muscle quality, the percent over threshold, used ImageJ histogram analysis to threshold between more echogenic areas of the muscle (an echo intensity of 69 and over, presumed to be comprised of fat and fascia) and less echogenic areas (echo intensity of 68 and under, presumed to be muscle tissue) (Chan et al, 2012). The percentage of pixels within the region of interest over the fascia/fat threshold was calculated and considered to represent the relative amount of fascia/fat present within the muscle region of interest.

From the axial (transverse) images at the posterior midthigh, the sciatic nerve was analyzed using OsiriX to determine the cross sectional area (cm²), by tracing outside the hyperechoic ring of the sciatic nerve and recording the area of pixels within this tracing. The mean echo intensity of the sciatic nerve cross sectional area were recorded.

Longitudinal ultrasound images of ES, BF, MG, and BB in relaxed and contracted conditions were used to calculate the contraction index for each muscle, bilaterally. The contraction index was calculated as [muscle thickness contracted / muscle thickness relaxed] (Equation 2). A higher contraction index value indicates that the muscle is thickening more during contraction, and a contraction index of 1.0 means that the muscle
does not change thickness when contracted compared to its relaxed state. Greater thickening during contraction is indicative of proper muscle function.

3.5.2 Electromyography

EMG was processed in Labview (Version 10.0) as a linear envelope by rectification followed by a dual pass 4th order Butterworth filter with a low pass cutoff frequency of 50 Hz. Bilateral EMG activation timing of ES, BF, MG and TA was computed during the balance perturbation trials relative to the onset of movement, as determined by the initial movement of the kinematic marker (Figure 3.9). A custom-made Labview program was used to determine muscle activation within 100 ms before and 1000 ms after kinematic marker movement. The threshold for onset was defined as the processed EMG exceeding 3 standard deviations above baseline for at least 20 ms; baseline activation was averaged from 250 ms to 150 ms before kinematic movement onset. All muscle activation onsets were visually inspected and confirmed.
Figure 3.10: Representative trial of kinematic marker position over time [A], with the vertical line indicating onset of movement; muscle activation onset (vertical line) of left and right ES [B]; and raw EMG tracings for left and right ES [C].

3.5.3 Force plate data

Force plate data were processed in Labview (Version 10.0). First, data were filtered using a dual pass 4th order Butterworth filter with a lowpass cutoff frequency of 6 Hz. COP in the AP and ML directions were calculated from the recorded forces and moments using equation 3a \[ \text{COP}_x = -(M_y + cF_x) / F_z \] and equation 3b \[ \text{COP}_y = (M_x - cF_y) / F_z \], where \( c \) is the force plate z-offset value of 1.35 cm. For all trials, the following parameters were computed in both AP and ML planes of motion: maximum anterior-posterior and medial-lateral COP excursion (cm), maximum anterior-posterior and medial-lateral COP velocity (cm/s), mean absolute value of the COP AP and ML velocity (cm/s). Excursions in the ML plane were quantified in terms of going towards the unaffected leg, or towards the affected leg; control participants were assigned unaffected
and affected legs to mimic their LBP-R match. COP parameters were analyzed for the balance recovery phase, defined as the two seconds following movement initiation (as measured by the kinematic marker), as well as during the perturbation preparation phase, defined as the one second prior to movement initiation. Additionally, the time to recover stability and number of corrections were computed during the balance recovery phase of the arm raise and weight drop trials, similar to the work of Mok et al (2011). Time to recover stability was defined as the time until the rectified COP AP velocity (cm/s) returned back to a baseline value (average of 1000 ms to 500 ms prior to the perturbation) and remained there for 50 ms. The number of corrections was the number of times that non-rectified COP AP velocity (cm/s) crossed the zero-point from the time of perturbation until the previously defined return to baseline stability.

3.6 Statistical analyses

All statistical analyses were completed using SAS 9.2. Normality of data was verified using the Shaprio-Wilk W statistic (minimum value of 0.80 to be defined as normally distributed data), and outliers were detected using Lunds test. For the ultrasound data, 1-way mixed model analyses of variance were completed to compare between group (control, LBP-R unaffected leg, and LBP-R affected leg) for each outcome measure. Control participants’ data were averaged between their right and left leg, as there were no statistically significant differences between legs for any parameter, verified using 1-way analysis of variance to compare between right and left leg for each parameter. For force plate outcome measures, 1-way analyses of variance were completed to compare between group (LBP-R and control) for each outcome measure; there was no distinction between
affected or unaffected side due to the use of only one force plate. For EMG muscle activation timing, 2-way analyses of variance were completed for each type of balance perturbation, to compare between group (control, LBP-R unaffected, LBP-R affected) and muscle (ES, BF, MG, TA). Further, a 2-way analysis of variance was completed to compare between weight drop trial type (unanticipated vs anticipated) and muscle (ES, BF, MG, TA). Main effects and interactions were examined. For all, tukey-adjusted post-hoc tests of significant main effects were used. Additionally, Pearson correlations were computed between measures of LBP-R severity (ODI, VAS at the back, VAS at the affected leg, duration of symptoms), with each outcome measure. All statistical analyses were completed at a significance level of \( \alpha = 0.05 \).

The presented results include all unilateral LBP-R patients, including those with a history of spine surgery, and matched controls. Bilaterally affected patients were not included. Full statistical analyses were additionally completed on a data set that excluded patients with a history of spine surgery, but as there were no notable differences in the results, it was determined that patients with surgery should be included. Likewise, statistical analyses of force plate measures were additionally completed including bilaterally-affected LBP-R patients, and no notable differences were apparent. Therefore, only unilaterally-affected patients were included in the final analysis to ensure that the same data set was reported throughout.
CHAPTER 4:
RESULTS

4.1 Ultrasound imaging
The sciatic nerve was imaged bilaterally in the cross-sectional plane. LBP-R patients had significantly greater sciatic nerve CSA on their radiculopathy-affected side (0.66 cm\(^2\)), as compared to the unaffected side (0.55 cm\(^2\)) (p = 0.0001) (Figure 4.1). Further, the sciatic nerve of control participants (0.57 cm\(^2\)) was not significantly different in CSA than either the affected or unaffected side of LBP-R patients (Figure 4.1). Analysis of the echo intensity of the sciatic nerve demonstrated a non-significant decrease in echo intensity mean (more hypoechoic) on the affected side of LBP-R patients (69.7) as compared to the unaffected side (72.6), and again as compared to control participants (77.5) (p = 0.56) (Figure 4.2). There was no alteration of this trend when the nerve echo intensity mean was normalized to the fascia mean echo intensity, to account for between-image changes in brightness.
Figure 4.1: Mean (± SE) sciatic nerve cross sectional area (cm$^2$) for control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg. * p < 0.05

Figure 4.2: Mean (± SE) sciatic nerve echo intensity mean for control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg.
Longitudinal imaging of the lower back and lower leg muscles in relaxed and contracted states allowed for calculation of the contraction index (Figure 4.3). With the exception of the MG on the unaffected leg of LBP-R patients, all muscles increased in thickness during contraction, demonstrated by a contraction index above one. In the ES and BF muscles, the contraction index was non-significantly lower on the LBP-R affected side as compared to unaffected. Further down the leg, the soleus muscle was not significantly different between group (p = 0.2924), however a significant post-hoc difference between the unaffected and affected side of LBP-R patients (p = 0.05), backed up by a significant t-test (p = 0.04047), indicates that there is a clear trend here. The MG muscle did not follow this trend, and similarly there was no difference between groups in the BB muscle, which acted as a control region of the body.

**Figure 4.3**: Mean (± SE) ultrasound muscle contraction index of the ES, BF, MG, soleus (Sol) and biceps brachii (BB) muscles. Contraction index represents [thickness contracted / thickness relaxed]. * p = 0.05
Analysis of the muscle ultrasound images in the axial plane provides insight into the muscle quality within a region of interest of the muscle. Mean echo intensity of the muscle did not differ significantly between-group for any of the measured muscles (ES, BF, MG or BB) (Figure 4.4). When the mean muscle EI was related to the echo intensity of the fascia (muscle-fascia ratio), to adjust for differences in image brightness, there was again no significant between-group difference for any muscle (Table 4.1). Further assessment of muscle quality involved calculating the percentage of pixels above an echo intensity threshold designed to separate muscle tissue from fat and fascia (Chan et al, 2012). This thresholding technique again did not demonstrate any significant between-group differences for any muscle; however, there was a statistically insignificant trend ($p = 0.4$) for LBP-R patients to have higher percentage of pixels above this threshold than controls (Figure 4.5).

![Figure 4.4: Muscle (± SE) mean ultrasound echo intensity for control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg.](image-url)
Table 4.1: Mean (± SE) ultrasound muscle-fascia echo intensity ratio of muscle region of interest, of control participants, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg.

<table>
<thead>
<tr>
<th></th>
<th>ES</th>
<th>BF</th>
<th>MG</th>
<th>BB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.27 ± 0.03</td>
<td>0.41 ± 0.02</td>
<td>0.32 ± 0.02</td>
<td>0.28 ± 0.02</td>
</tr>
<tr>
<td>LBP-R unaffected</td>
<td>0.24 ± 0.02</td>
<td>0.43 ± 0.02</td>
<td>0.30 ± 0.03</td>
<td>0.24 ± 0.02</td>
</tr>
<tr>
<td>LBP-R affected</td>
<td>0.25 ± 0.02</td>
<td>0.43 ± 0.02</td>
<td>0.32 ± 0.03</td>
<td>0.25 ± 0.02</td>
</tr>
</tbody>
</table>

Figure 4.5: Mean (± SE) percent of muscle region of interest that is over threshold (echo intensity of 69, representing fat or fascia tissue), represented for control, LBP-R patients on their unaffected leg and LBP-R patients on their affected leg. Data was log transformed to ensure normality.
4.2 Electromyography

Muscle activation timing of bilateral ES, BF, MG and TA was computed during the balance perturbation trials (Table 4.2). Weight drop trials, in both unanticipated and anticipated conditions, represent an external perturbation - muscles are activated following the weight drop in response to the perturbation, and to work to recover balance. Comparison of muscle activation timing between LBP-R patients on their unaffected and affected sides, with control participants, did not reveal any statistically significant differences (Figure 4.6). However, when muscle activation sequencing was compared between LBP-R patients and control participants, we saw some interesting relationships. Activation onset of the ES muscle was faster in the anticipated condition (42-48 ms), as compared to the unanticipated weight drop (62-73 ms), across all groups ($p < 0.0001$). In the anticipated condition, all participants were able to adopt a more sequenced activation pattern, by activating first the ES (42-48 ms), then moving from top to bottom to next activate the BF (56-61 ms), then MG (58-65 ms). ES activation was significantly faster than BF ($p = 0.0006$) and MG activation ($p = 0.0002$). Interestingly, BF and MG activation was significantly later ($p < 0.05$) than ES activation in control participants and the unaffected side of LBP-R patients, but on the affected side of LBP-R patients these two muscles were not activated at significantly different times ($p > 0.1$). This pattern was not apparent in the unanticipated trials, where all participants activated all three muscles at similar times. In both conditions, the TA muscle was activated significantly later than other muscles ($p < 0.0001$; unanticipated 88-99 ms, anticipated 83-93 ms), and was not presented in Figure 4.6 to allow for direct comparison of posterior chain muscle response to perturbation.
Table 4.2: Mean (± SE) EMG muscle activation timing (ms) of the control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg. A negative value indicates muscle activation prior to onset of movement. Data from all four balance perturbations is presented.

<table>
<thead>
<tr>
<th></th>
<th>ES</th>
<th>BF</th>
<th>MG</th>
<th>TA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rise to Toe</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>23.8 ± 11.3</td>
<td>2.9 ± 10.1</td>
<td>-82.1 ± 6.1</td>
<td>12.7 ± 14.9</td>
</tr>
<tr>
<td>LBP-R unaffected</td>
<td>57.5 ± 16.3</td>
<td>-13.5 ± 12.3</td>
<td>-80.4 ± 8.3</td>
<td>49.7 ± 20.0</td>
</tr>
<tr>
<td>LBP-R affected</td>
<td>36.2 ± 15.6</td>
<td>8.2 ± 12.0</td>
<td>-92.5 ± 8.4</td>
<td>71.4 ± 20.7</td>
</tr>
<tr>
<td><strong>Arm raise</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>-96.4 ± 10.1</td>
<td>-86.9 ± 9.7</td>
<td>-56.3 ± 6.8</td>
<td>-4.1 ± 25.9</td>
</tr>
<tr>
<td>LBP-R unaffected</td>
<td>-90.9 ± 13.3</td>
<td>-96.1 ± 11.5</td>
<td>-36.8 ± 9.2</td>
<td>-7.8 ± 44.5</td>
</tr>
<tr>
<td>LBP-R affected</td>
<td>-89.3 ± 13.2</td>
<td>-85.6 ± 12.0</td>
<td>-13.4 ± 9.6</td>
<td>49.8 ± 29.2</td>
</tr>
<tr>
<td><strong>Weight drop</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unanticipated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>62.4 ± 9.7</td>
<td>66.2 ± 9.2</td>
<td>67.0 ± 6.0</td>
<td>88.9 ± 13.5</td>
</tr>
<tr>
<td>LBP-R unaffected</td>
<td>64.9 ± 13.2</td>
<td>68.1 ± 12.0</td>
<td>59.3 ± 8.4</td>
<td>93.2 ± 18.8</td>
</tr>
<tr>
<td>LBP-R affected</td>
<td>73.3 ± 13.4</td>
<td>71.3 ± 12.2</td>
<td>60.9 ± 8.5</td>
<td>99.8 ± 18.7</td>
</tr>
<tr>
<td>anticipated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>42.4 ± 10.4</td>
<td>56.6 ± 9.4</td>
<td>58.6 ± 6.2</td>
<td>83.5 ± 13.5</td>
</tr>
<tr>
<td>LBP-R unaffected</td>
<td>43.8 ± 13.3</td>
<td>61.5 ± 12.0</td>
<td>65.8 ± 8.3</td>
<td>90.1 ± 19.3</td>
</tr>
<tr>
<td>LBP-R affected</td>
<td>48.3 ± 13.6</td>
<td>57.8 ± 12.4</td>
<td>60.0 ± 9.0</td>
<td>93.8 ± 21.4</td>
</tr>
</tbody>
</table>
Figure 4.6: Mean (± SE) EMG muscle activation timing (mean ± SE) for ES, BF and MG during the weight drop balance perturbations in unanticipated [A] and anticipated [B] conditions. The weight was dropped in the bucket at 0 ms, as indicated by the black arrow. Data is represented for control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg.

Bilateral arm raise trials represent an internally generated perturbation, and therefore involve voluntary activation of muscles prior to onset of movement. Average angular velocity (degrees / second) of the arm raise was not significantly different between LBP-R participants (mean ± SE of 256.2 ± 13.2 °/s) and control participants (mean ± SE of 250.0 ± 10.9 °/s). MG muscle activation was significantly delayed on the affected side of
LBP-R patients (-13.4 ms) as compared to controls (-56.3 ms) (p < 0.01); however, there were no between-group significant differences in activation timing of the ES or BF muscles (Figure 4.7). In order to perform the voluntary arm raise, both patients and controls used a similar sequence strategy of activating the ES and BF muscles 85 to 96 ms prior to arm movement, followed by significantly later activation of the MG muscle (p < 0.01), then arm movement. Activation of the TA muscle was significantly later than all other muscles (p < 0.01), and used as stabilization either before or after the initiation of arm movement (Table 4.2). TA activation was significantly delayed on the affected-side of LBP-R patients, as compared to controls (p < 0.01).

**Figure 4.7:** Mean (± SE) EMG muscle activation timing (mean ± SE) for ES, BF and MG during the arm raise perturbation. The initiation of arm raise movement was at 0 ms, as indicated by the black arrow. Data is represented for control, LBP-R patients on their unaffected leg, and LBP-R patients on their affected leg. * p < 0.05
Muscle activation during the rise to toe perturbation was less consistent, reflecting the varied ability of participants to complete this task (Table 4.2). Average rise to toe velocity (mm/s) was not significantly different between LBP-R participants (mean ± SE of 165.4 ± 14.6 mm/s) and control participants (mean ± SE of 156.7 ± 10.4 mm/s). The MG muscle was activated 80 to 92 ms prior to onset of ankle movement, which was significantly earlier than all other muscles activation (p < 0.01), and was not significantly different between groups. Similarly, the BF muscle did not show between-group differences, and was activated slightly before (-13 ms) or after (2 ms) onset of movement. In order to stabilize during the perturbation, the ES and TA muscles turn on following movement onset; ES at 23 to 56 ms, TA at 12 to 71 ms. Activation of the TA muscle was slightly delayed on the affected leg of the LBP-R patients (71 ms) as compared to controls (12 ms) (p = 0.08).

4.3 Force Plate

During balance perturbation trials, the quality of the balance response can be quantified through COP analysis from force plate data. In both weight drop perturbations (unanticipated and anticipated), LBP-R patients had some significantly lower COP measures as compared to controls (Table 4.3). Specifically, in the unanticipated condition, LBP-R patients had lower maximum anterior COP excursion (p = 0.05) and velocity (p = 0.05), and lower maximum posterior COP velocity (p < 0.01). In the anticipated condition, LBP-R patients had smaller maximum anterior (p = 0.01) and posterior (p < 0.01) COP velocity than controls. Across all outcome measures, COP measures were of larger magnitude in the unanticipated condition, as compared to
anticipated. The rise to toe trials demonstrated some significant between-group differences; however, the LBP-R patients had increased COP movement as compared to controls. Specifically, LBP-R patients had larger maximum COP excursions in the anterior direction (p < 0.01) and towards the unaffected side (p < 0.05), larger maximum COP velocity towards both the unaffected (p < 0.05) and affected sides (p < 0.01), and greater mean absolute ML velocity (p < 0.05), as compared to controls (Table 4.3). COP measures during the arm raise trials did not demonstrate any significant differences between LBP-R patients and controls (Table 4.3). Further, there were no between-group differences in COP stabilization latency and number of crossings during arm raise and weight drop trials (Figure 4.8).
Table 4.3: Mean (± SE) Anterior-Posterior [A] and Medial-Lateral [B] force plate COP parameters for LBP-R and control participants in each of the balance perturbations. Measures that are significantly different (p < 0.05) between LBP-R and control groups are shown in bold.

### A

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Group</th>
<th>Maximum anterior excursion (cm)</th>
<th>Maximum posterior excursion (cm)</th>
<th>Maximum anterior velocity (cm/s)</th>
<th>Maximum posterior velocity (cm/s)</th>
<th>Mean absolute AP velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise to Toe</td>
<td>LBP-R</td>
<td>12.1 ± 0.31</td>
<td>-1.2 ± 0.11</td>
<td>78.1 ± 4.1</td>
<td>-17.9 ± 1.8</td>
<td>8.8 ± 0.33</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>10.7 ± 0.34</td>
<td>-1.5 ± .012</td>
<td>74.6 ± 4.5</td>
<td>-17.3 ± 2.0</td>
<td>8.7 ± 0.36</td>
</tr>
<tr>
<td>Arm raise</td>
<td>LBP-R</td>
<td>1.9 ± 0.29</td>
<td>-0.29 ± 0.12</td>
<td>12.4 ± 4.0</td>
<td>-6.1 ± 1.8</td>
<td>2.3 ± 0.32</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.9 ± 0.31</td>
<td>-0.39 ± 0.11</td>
<td>12.9 ± 4.4</td>
<td>-6.8 ± 1.8</td>
<td>2.6 ± 0.36</td>
</tr>
<tr>
<td>Weight drop</td>
<td>LBP-R</td>
<td>3.9 ± 0.30</td>
<td>-0.61 ± 0.09</td>
<td>36.9 ± 3.9</td>
<td>-18.2 ± 1.8</td>
<td>5.5 ± 0.37</td>
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<tr>
<td>unanticipated</td>
<td>Control</td>
<td>4.9 ± 0.33</td>
<td>-0.82 ± 0.12</td>
<td>49.9 ± 4.4</td>
<td>-34.3 ± 1.9</td>
<td>7.2 ± 0.35</td>
</tr>
<tr>
<td>Weight drop</td>
<td>LBP-R</td>
<td>3.2 ± 0.29</td>
<td>-0.36 ± 0.17</td>
<td>25.0 ± 3.6</td>
<td>-9.6 ± 1.6</td>
<td>3.9 ± 0.32</td>
</tr>
<tr>
<td>anticipated</td>
<td>Control</td>
<td>3.8 ± 0.33</td>
<td>-0.49 ± 0.11</td>
<td>36.1 ± 4.4</td>
<td>-19.3 ± 1.5</td>
<td>5.3 ± 0.36</td>
</tr>
</tbody>
</table>

### B

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Group</th>
<th>Maximum excursion to unaffected side (cm)</th>
<th>Maximum excursion to affected side (cm)</th>
<th>Maximum velocity on unaffected side (cm/s)</th>
<th>Maximum velocity on affected side (cm/s)</th>
<th>Mean absolute ML velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise to Toe</td>
<td>LBP-R</td>
<td>1.7 ± 0.10</td>
<td>1.4 ± 0.12</td>
<td>16.9 ± 1.0</td>
<td>18.9 ± 1.2</td>
<td>4.7 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.3 ± 0.11</td>
<td>1.5 ± 0.13</td>
<td>13.5 ± 1.1</td>
<td>14.3 ± 1.3</td>
<td>3.9 ± 0.20</td>
</tr>
<tr>
<td>Arm raise</td>
<td>LBP-R</td>
<td>0.65 ± 0.10</td>
<td>0.46 ± 0.10</td>
<td>6.6 ± 0.94</td>
<td>5.8 ± 1.0</td>
<td>1.5 ± 0.18</td>
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<tr>
<td></td>
<td>Control</td>
<td>0.50 ± 0.09</td>
<td>0.53 ± 0.11</td>
<td>4.5 ± 1.0</td>
<td>5.2 ± 1.1</td>
<td>1.4 ± 0.20</td>
</tr>
<tr>
<td>Weight drop</td>
<td>LBP-R</td>
<td>0.63 ± 0.09</td>
<td>0.61 ± 0.11</td>
<td>7.1 ± 0.93</td>
<td>7.9 ± 1.0</td>
<td>1.7 ± 0.18</td>
</tr>
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<td>unanticipated</td>
<td>Control</td>
<td>0.78 ± 0.10</td>
<td>0.68 ± 0.12</td>
<td>8.0 ± 1.0</td>
<td>8.7 ± 1.2</td>
<td>1.9 ± 0.19</td>
</tr>
<tr>
<td>Weight drop</td>
<td>LBP-R</td>
<td>0.63 ± 0.10</td>
<td>0.38 ± 0.12</td>
<td>5.3 ± 0.97</td>
<td>4.5 ± 1.0</td>
<td>1.3 ± 0.18</td>
</tr>
<tr>
<td>anticipated</td>
<td>Control</td>
<td>0.63 ± 0.08</td>
<td>0.55 ± 0.13</td>
<td>5.3 ± 1.1</td>
<td>5.3 ± 1.2</td>
<td>1.4 ± 0.20</td>
</tr>
</tbody>
</table>
Figure 4.8: Mean (± SE) stabilization latency [A] and number of crossings [B] of the AP COP velocity in the 2 seconds following movement initiation for control and LBP-R participants.
4.4 Correlations with LBP-R severity

Across all outcome measures from ultrasound, EMG and force plate data, there were no statistically significant Pearson correlations (p-value < 0.05 and |r| < ± 0.20) with ODI, VAS at the lower back, VAS at the affected leg, or symptom duration.

4.5 Summary of statistical results

Following are summaries of ANOVA results for ultrasound (Table 4.4), EMG (Table 4.5), and force plate (Table 4.6, Table 4.7) data.

Table 4.4: Summary of statistical results for ultrasound outcome measures, with 1-way ANOVA results for group (control, LBP-R unaffected, LBP-R affected), as well as post-hoc comparisons.

<table>
<thead>
<tr>
<th>Ultrasound outcome measure</th>
<th>Group p-value</th>
<th>Post-hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sciatic nerve CSA</td>
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</tr>
<tr>
<td>Sciatic nerve echo intensity mean</td>
<td>0.5649</td>
<td></td>
</tr>
<tr>
<td>ES contraction index</td>
<td>0.2942</td>
<td></td>
</tr>
<tr>
<td>BF contraction index</td>
<td>0.5742</td>
<td></td>
</tr>
<tr>
<td>MG contraction index</td>
<td>0.336</td>
<td></td>
</tr>
<tr>
<td>Soleus contraction index</td>
<td>0.2924</td>
<td></td>
</tr>
<tr>
<td>ES echo intensity mean</td>
<td>0.5932</td>
<td></td>
</tr>
<tr>
<td>BF echo intensity mean</td>
<td>0.7542</td>
<td></td>
</tr>
<tr>
<td>MG echo intensity mean</td>
<td>0.882</td>
<td></td>
</tr>
<tr>
<td>ES muscle-fascia echo intensity ratio</td>
<td>0.439</td>
<td></td>
</tr>
<tr>
<td>BF muscle-fascia echo intensity ratio</td>
<td>0.9749</td>
<td></td>
</tr>
<tr>
<td>MG muscle-fascia echo intensity ratio</td>
<td>0.0709</td>
<td></td>
</tr>
<tr>
<td>ES percent over fat/fascia threshold</td>
<td>0.4199</td>
<td></td>
</tr>
<tr>
<td>BF percent over fat/fascia threshold</td>
<td>0.4535</td>
<td></td>
</tr>
<tr>
<td>MG percent over fat/fascia threshold</td>
<td>0.3495</td>
<td></td>
</tr>
</tbody>
</table>
**Table 4.5:** Summary of statistical results for EMG muscle activation timing, with 2-way ANOVA results for group (control, LBP-R unaffected, LBP-R affected) by muscle (ES, BF, MG, TA), as well as significant post-hoc comparisons.

<table>
<thead>
<tr>
<th>EMG outcome measure</th>
<th>Group</th>
<th>Muscle</th>
<th>Group*muscle</th>
<th>Post hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise to toe</td>
<td>0.6987</td>
<td>&lt;0.0001</td>
<td>0.807</td>
<td>Muscle: MG prior to all other muscles (p &lt; 0.01); TA after BF &amp; MG (p &lt; 0.01)</td>
</tr>
<tr>
<td>Arm raise</td>
<td>0.047</td>
<td>&lt;0.0001</td>
<td>0.0497</td>
<td>Group*muscle: MG LBP-R affected delayed vs control p = 0.0239; TA LBP-R affected delayed vs control p = 0.0055</td>
</tr>
<tr>
<td>Weight drop unanticipated</td>
<td>0.4728</td>
<td>&lt;0.0001</td>
<td>0.4027</td>
<td>Muscle: TA after all other muscles (p &lt; 0.01)</td>
</tr>
<tr>
<td>Weight drop anticipated</td>
<td>0.562</td>
<td>&lt;0.0001</td>
<td>0.9542</td>
<td>Muscle: ES before all other muscles; TA after all other muscles (p &lt; 0.05)</td>
</tr>
</tbody>
</table>

**Table 4.6:** Summary of statistical results for force plate outcome measures in the AP direction of motion, with 1-way ANOVA results for group (LBP-R, control).

<table>
<thead>
<tr>
<th>Force plate outcome measure</th>
<th>Group p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise to toe: maximum anterior excursion</td>
<td>0.0069 (LBP-R 🔺)</td>
</tr>
<tr>
<td>Rise to toe: maximum posterior excursion</td>
<td>0.3605</td>
</tr>
<tr>
<td>Rise to toe: maximum anterior velocity</td>
<td>0.9509</td>
</tr>
<tr>
<td>Rise to toe: maximum posterior velocity</td>
<td>0.9128</td>
</tr>
<tr>
<td>Rise to toe: mean absolute AP velocity</td>
<td>0.942</td>
</tr>
<tr>
<td>Arm raise: maximum anterior excursion</td>
<td>0.8496</td>
</tr>
<tr>
<td>Arm raise: maximum posterior excursion</td>
<td>0.3138</td>
</tr>
<tr>
<td>Arm raise: maximum anterior velocity</td>
<td>0.7206</td>
</tr>
<tr>
<td>Arm raise: maximum posterior velocity</td>
<td>0.3695</td>
</tr>
<tr>
<td>Arm raise: mean absolute AP velocity</td>
<td>0.1835</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum anterior excursion</td>
<td>0.0009 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum posterior excursion</td>
<td>0.083</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum anterior velocity</td>
<td>0.0037 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum posterior velocity</td>
<td>0.0003 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop unanticipated: mean absolute AP velocity</td>
<td>0.0015 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum anterior excursion</td>
<td>0.0547</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum posterior excursion</td>
<td>0.2551</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum anterior velocity</td>
<td>0.0106 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum posterior velocity</td>
<td>0.0013 (LBP-R 🔻)</td>
</tr>
<tr>
<td>Weight drop anticipated: mean absolute AP velocity</td>
<td>0.0107 (LBP-R 🔻)</td>
</tr>
</tbody>
</table>
Table 4.7: Summary of statistical results for force plate COP outcome measures in the ML direction of motion, with 1-way ANOVA results for group (LBP-R, control).

<table>
<thead>
<tr>
<th>Force plate outcome measure</th>
<th>Group p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise to toe: maximum unaffected excursion</td>
<td>0.0161 (LBP-R ↑)</td>
</tr>
<tr>
<td>Rise to toe: maximum affected excursion</td>
<td>0.8342</td>
</tr>
<tr>
<td>Rise to toe: maximum unaffected velocity</td>
<td><strong>0.0236</strong> (LBP-R ↑)</td>
</tr>
<tr>
<td>Rise to toe: maximum affected velocity</td>
<td><strong>0.0033</strong> (LBP-R ↑)</td>
</tr>
<tr>
<td>Rise to toe: mean absolute ML velocity</td>
<td><strong>0.023</strong> (LBP-R ↑)</td>
</tr>
<tr>
<td>Arm raise: maximum unaffected excursion</td>
<td>0.183</td>
</tr>
<tr>
<td>Arm raise: maximum affected excursion</td>
<td>0.5079</td>
</tr>
<tr>
<td>Arm raise: maximum unaffected velocity</td>
<td>0.0927</td>
</tr>
<tr>
<td>Arm raise: maximum affected velocity</td>
<td>0.5935</td>
</tr>
<tr>
<td>Arm raise: mean absolute ML velocity</td>
<td>0.7408</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum unaffected excursion</td>
<td>0.0962</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum affected excursion</td>
<td>0.5053</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum unaffected velocity</td>
<td>0.3444</td>
</tr>
<tr>
<td>Weight drop unanticipated: maximum affected velocity</td>
<td>0.5808</td>
</tr>
<tr>
<td>Weight drop unanticipated: mean absolute ML velocity</td>
<td>0.2755</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum unaffected excursion</td>
<td>0.4393</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum affected excursion</td>
<td>0.0539</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum unaffected velocity</td>
<td>0.9839</td>
</tr>
<tr>
<td>Weight drop anticipated: maximum affected velocity</td>
<td>0.2244</td>
</tr>
<tr>
<td>Weight drop anticipated: mean absolute ML velocity</td>
<td>0.3886</td>
</tr>
</tbody>
</table>
CHAPTER 5
DISCUSSION

5.1 Hypotheses revisited

Ultrasound imaging of the sciatic nerve in LBP-R patients and controls revealed that LBP-R patients had significantly larger sciatic nerve CSA on their radiculopathy-affected side as compared to their unaffected side; therefore we accept our hypothesis that there would be evidence of sciatic nerve swelling in the affected leg of LBP-R patients. However, we do not accept our hypothesis that the affected leg of LBP-R patients would have a larger sciatic nerve CSA than controls, as this difference was not statistically significant. Further, we reject our hypothesis that the sciatic nerve echo intensity would be lower in LBP-R patients, specifically on their affected leg, relative to controls; echo intensity was lower, but not significantly so.

Musculature associated with the sciatic nerve in the lower back and lower limb was imaged in both longitudinal and axial planes. Longitudinal imaging in rested and contracted states allowed for calculation of the contraction index, or thickening of the muscle during contraction. We reject our hypothesis that the ES muscle contraction index would be lower in LBP-R patients relative to controls, specifically on their affected side. We also did not accept this hypothesis in the lower limb for the BF muscle or MG muscle; however, there is some evidence to accept the hypothesis that LBP-R patients would have lower contraction index in their affected leg compared to controls in the soleus muscle. From axial imaging of each muscle of interest, we were able to quantify
muscle quality. We reject our hypotheses that LBP-R patients’ muscles would have increased echo intensity mean, increased muscle-fascia ratio, and increased % pixels above fat/fascia threshold; these would all demonstrate increased fat infiltration and/or fibrosis within the muscle region of interest.

Activation timing of the lower back and lower limb musculature was quantified using surface EMG during four types of balance perturbations. Across all balance perturbations, we reject our hypothesis that LBP-R patients would have delayed muscle activation relative to controls at the ES and BF muscles. In the MG and TA muscles, we can accept our hypothesis in two instances: MG and TA activation, on the affected side, were delayed in LBP-R patients in the rapid bilateral arm raise. For the weight drop balance perturbation, we reject our hypothesis that the difference between LBP-R patients and controls would be greater in anticipated trials, compared to unanticipated trials.

COP excursions and velocities during each balance perturbation were computed from force plate data. In the rise to toe perturbation, we accept our hypothesis that LBP-R patients would have greater COP oscillations in the medial-lateral plane of motion; however, there was no group difference in the anterior-posterior plane. Further, in the rapid bilateral arm raise and weight drop trials, we reject our hypothesis that LBP-R patients would have greater COP oscillations than controls. In fact, the weight drop trials demonstrated significant reductions in some COP excursion and velocity parameters in the LBP-R group as compared to controls, which opposes our hypothesis. In the arm raise and weight drop balance perturbations, we reject our hypothesis that LBP-R patients
would require more time and adjustments to stabilize their anterior-posterior COP velocity compared to controls.

5.2 Ultrasound

5.2.1 Sciatic nerve

5.2.1.1 Cross sectional area

Our results demonstrate a significantly larger sciatic nerve CSA on the radiculopathy-affected side of LBP-R patients, as compared to their unaffected side, but not when compared to control participants. To our knowledge, only one previously published study has reported ultrasound measurements of sciatic nerve CSA in LBP-R patients (Kara et al, 2012). Kara et al (2012) used ultrasound imaging to compare sciatic nerve CSA at the midthigh level of the unaffected to affected side in a group of unilateral LBP-R patients; they did not include a control group. In support of our findings, Kara et al (2012) found a significantly greater sciatic nerve CSA on the affected side relative to the unaffected side. The sciatic nerve CSA measurements we report (unaffected 55 mm$^2$, affected 65 mm$^2$) are slightly larger than those in Kara et al (2012) (unaffected 39 mm$^2$, affected 52 mm$^2$); however the magnitude of difference between the unaffected and affected side is quite similar (10 cm$^2$ compared to 13 cm$^2$). We believe that the inclusion of a healthy control group strengthens our findings relative to those of Kara et al (2012), due to the potential confounding presence of inflammation. In the event of a complete disc herniation, components from the nucleus pulposus escape the annulus fibrosis and induce an inflammatory response that can result in nerve injury independent of mechanical
compression (Cornefjord et al, 1996). Even if the mechanical compression is unilateral, the inflammatory state could have bilateral impact. Therefore, it is important to compare not only to the unaffected side of the LBP-R patient, but also to a healthy control group to verify that the unaffected leg can be used as a within-subject comparator. In this case, sciatic nerve CSA is comparable between healthy controls and the unaffected leg of LBP-R patients, therefore a within-patient comparison is appropriate.

5.2.1.1.1 Inflammation and edema

The increased sciatic nerve CSA, or nerve swelling, that is commonly observed in LBP-R patients is due to inflammation and edema as a result of chronic nerve compression (Walker et al, 2004). Compressive injury to the nerve increases the vascular permeability of the endoneurial membrane, and the compression-induced reduction in blood flow may result in ischemic changes to the membrane as well (Rempel et al, 1999). The endoneurium consists of connective tissue surrounding nerve fascicles, therefore higher permeability of the endoneurial membrane results in an influx of fluid to the endoneurium, causing edema. Edema, defined as abnormal accumulation of fluid into the interstitium of a tissue, has been demonstrated in animal models of nerve compression, such as rat sciatic nerve compression (Lundborg et al, 1983).

In addition to edema, there in a concurrent inflammatory state associated with chronic nerve compression that also contributes to nerve swelling. In a healthy spine, the nucleus pulposus remains within the annulus fibrosis; however in a complete disc herniation the nucleus pulposus escapes the annulus fibrosis, resulting in an inflammatory reaction. In a
porcine model, Cornefjord et al (1996) demonstrated that nerve exposure to nucleus pulposus, with or without mechanical compression, resulted in decreased conduction velocity of the sciatic nerve. Further, human case study reports show that nerve root related LBP symptoms can change without any alteration in the degree of mechanical compression on the nerve root, therefore suggesting that inflammation can drive symptoms (Garfin et al, 1991).

Although there was a difference in sciatic nerve CSA between LBP-R patients on their affected and unaffected legs, there was no significant correlation between nerve swelling with measures of LBP-R severity (ODI, VAS) or duration of symptoms. Kara et al (2012) similarly did not find correlations with VAS scales; however they found negative correlations between sciatic nerve swelling and duration of symptoms, as well as LANSS neuropathic pain score. They attributed this to distal fibre degeneration occurring later in the course of chronic nerve compression, whereas edema occurs earlier. Kara et al (2012) included LBP-R patients with both acute symptoms (1 month) and chronic symptoms (3 to 36 months); the presence of patients with acute edema and no degeneration may have driven the correlations in their data, whereas our study included only chronic patients. Overall, it appears that sciatic nerve swelling (CSA) is an excellent tool to measure and monitor the degree of edema and inflammation present in the nerve, but may not fully reflect the severity or level of disability of the patient.
5.2.1.1.2 Healthy reference values

It is important to relate our sciatic nerve CSA values to previously published results to verify that the imaging and measuring techniques were accurate. Reference values in healthy control participants of peripheral nerve CSA have been reported by Cartwright et al (2008). Cartwright et al (2008) measured the CSA of the sciatic nerve in 60 healthy control participants at the distal thigh, and found a mean CSA of 52.6 mm$^2$, with an upper limit of side-to-side difference of 18.9 mm$^2$. Compared to Cartwright et al (2008), our healthy control population had a similar sciatic nerve CSA of 57 mm$^2$; the slightly larger CSA can be attributed to the more distal measuring location used by Cartwright et al (2008) relative to our midthigh location.

5.2.1.1.3 Reliability

We did not perform a full reliability analysis on our data, but previous studies have investigated the feasibility and reliability of imaging the sciatic nerve CSA with ultrasound. One of the first studies to comprehensively investigate the feasibility and best location for imaging the sciatic nerve with ultrasound was Chan et al (2006). They used a curvilinear ultrasound probe, and were able to clearly identify the sciatic nerve in all 15 participants within 10 seconds when imaging at the thigh. Similarly, we were able to identify and trace the CSA of the sciatic nerve in all of our unilateral LBP-R and control participants; there was one bilateral LBP-R participant in whom we could not confidently trace the CSA of the sciatic nerve. In order to verify that the measure of CSA recorded from an ultrasound image is reflective of the actual anatomical dimensions of the structure, Cartwright et al (2013) published a comparison of ultrasound-recorded sciatic
nerve CSA in cadavers, and the actual dissected measures of CSA from the same cadavers. The correlation coefficient between ultrasound and dissected measurements was 0.917, therefore very significantly correlated (p = 0.001). One further study that verifies the reliability of measuring sciatic nerve CSA with ultrasound was conducted by Tagliafico et al (2012), who measured the sciatic nerve CSA at the midthigh and found good inter and intra-rater reliability, good reproducibility between two testing sessions, and no significant side-to-side differences in healthy controls. The mean side-to-side difference was 5.1 mm², which is considerably smaller than the upper limit found by Cartwright et al (2008).

5.2.1.2 Echo intensity mean
The sciatic nerve mean echo intensity decreased, but not significantly, from control, to LBP-R patients on their unaffected side, to LBP-R patients on their affected side. A lower mean echo intensity of the nerve would be expected when compressive injury results in nerve inflammation and edema, however no previous research has investigated this in the sciatic nerve. The expectation that nerve echo intensity would decrease was based on research in carpal tunnel syndrome and ulnar neuropathy, where nerve compression results in the loss of the regular fascicular pattern. Specifically, endoneurial edema is characterized by excess fluid crossing the endoneurial membrane into the endoneurium surrounding the nerve fascicle bundles. Therefore, swelling is primarily localized to the hypoechoic fascicular region of the nerve, and not in the hyperechoic non-fascicular portion, and a swollen nerve will have increased hypoechoic area and therefore lower ultrasound echo intensity. Using this principle, Tagliafico et al (2010) were able to
compare the ratio of hypoechoic to hyperechoic fractions (termed nerve density) of the median nerve cross section in individuals with carpal tunnel syndrome, and found that their nerve density measure was sensitive to the presence of both mild and severe carpal tunnel syndrome. Tagliafico et al (2010) visually selected the threshold echo intensity to separate the hypoechoic fascicular area of the nerve from the hyperechoic non-fascicular surroundings. A similar principle of thresholding between hypoechoic and hyperechoic regions of the nerve was investigated by Boom et al (2012) in patients with ulnar neuropathy. However, they found that using a manual threshold to differentiate was not effective in detecting a difference between patient and control groups, but the use of automated thresholding software available in ImageJ was able to detect abnormal echogeneity in the ulnar nerve in patients.

The median and ulnar nerves have much more clear distinctions between hypoechoic and hyperechoic regions than the sciatic nerve (Walker et al, 2004), therefore measuring nerve density or thresholding techniques would not be feasible to quantify shifts in sciatic nerve echo intensity. For this reason, we chose to look simply at the shift in echo intensity mean between LBP-R patients and controls. We saw some non-significant differences between groups; this could either mean that looking at echo intensity mean is not as sensitive as the more sophisticated thresholding methods, or that in our specific LBP-R population there were less apparent changes in the nerve fascicular structure than in the previously published work in upper arm neuropathies. Future work should investigate additional methods of detecting alterations in sciatic nerve quality.
5.2.2 Muscle contraction

Ultrasound imaging of muscles in a relaxed state and during standardized submaximal contractions allowed for the calculation of the contraction index, which represents the thickening of the muscle during contraction. This was analyzed at the ES, BF, MG and soleus muscles.

5.2.2.1 Erector spinae

We found no statistically significant difference in ES contraction index between control and LBP-R patients on both unaffected and affected legs, although the LBP-R patients on their affected side had slightly lower contraction index than their unaffected side, and likewise relative to controls. For all groups, the contraction index was greater than 1.0, therefore indicating that, as expected, the muscle did thicken during the contraction. We hypothesized to see a smaller ES contraction index in LBP-R patients, specifically on their affected side, based on the findings of Wallwork et al (2009). In a population of chronic LBP patients (minimum VAS score of 3 out of 10), Wallwork et al (2009) used ultrasound imaging at vertebral levels L2 through L5 to image bilateral multifidus thickness, therefore imaging a few centimetres more medial than the location of the ES. By measuring muscle thickness in relaxed and contracted states (voluntary muscle swelling), they found a significantly lower contraction index in LBP patients relative to controls, but only at the L5 vertebral level and not at L2, L3 or L4. The LBP patients were categorized as having chronic, non-specific LBP, and therefore did not have specific disc level diagnoses.
There are therefore a few explanations for why we did not find differences between LBP-R patients and controls, in contrast to the findings of Wallwork et al (2009). Most prominently, we imaged the ES at the L3 vertebral level only, and did not look at the L5 level; we recorded surface EMG at the L4-L5 vertebral level concurrently during this study, and therefore could not image at this location. Multifidus atrophy with disc-related LBP is quite localized (Barker et al, 2004; Campbell et al, 1998), so it is possible that by only imaging the ES at a L3, we missed detecting differences that existed in only the lower lumbar region. Six of our LBP-R patients did have confirmed disc level of injury from magnetic resonance (n = 5) or x-ray imaging (n = 1), and all six had lower lumbar involvement (L4/L5, L5/S1). Although we did not have MRI-confirmed disc level for the rest of our LBP-R patients, disc herniation or bulge occurs more frequently at L4-L5 and L5-S1 than at higher lumbar levels. Second, Wallwork et al (2009) imaged the multifidus musculature, whereas our contraction index investigation focused on the ES, to allow for comparison with muscle function as recorded by surface EMG at the ES. There is evidence that nerve-related LBP will affect both ES and multifidus similarly, demonstrated by magnetic resonance imaging-detected atrophy in both muscle groups (Ploumis et al, 2011), but one computed tomography imaging study in LBP patients found atrophy in multifidus but not ES (Danneels et al, 2000). Therefore, imaging at the multifidus may be a more locally sensitive muscle to detect changes in LBP-R.

Assessing muscle contraction by comparing muscle thickness in relaxed and contracted states relies on the assumption that the muscle is able to completely relax in prone lying. If LBP-R patients had higher tonic activity in a relaxed state, there would be less increase
in thickness during a standardized contraction. This could be misinterpreted as less thickening upon contraction; however it would merely be a reflection of an inability to relax the muscle. Previous research, however, has indicated that there is likely no increase in resting paraspinal muscle activity in LBP patients as compared to controls (Kravitz et al, 1981; Nouwen et al, 1984).

5.2.2.1.1 Reliability
The location and manner in which we conducted the ES ultrasound imaging in the longitudinal plane is in line with the spinal ultrasound imaging guidelines set forth by Darrietort-Laffite et al (2014). This group recommends imaging the ES muscles 3 to 4 cm lateral to the midline, and measuring the muscle thickness between the facet joint to the superficial fascia. The submaximal contraction for ES, raising the contralateral arm up 5 cm while holding a 1 kg weight in prone lying, was based on research by Kiesel et al (2007), who found excellent reliability for within day (ICC 0.99) and between day (ICC 0.98) measure of multifidus muscle thickness in both relaxed and contracted states in healthy controls. Further, Kiesel et al (2007) determined that these measurements were reliable when averaging two images, but the variability decreased when three images were averaged (as done here) to give the greatest measurement precision.

5.2.2.1.2 Healthy reference values
It is important to compare our results to published reference data. In healthy control participants, contralateral arm raise to 5 cm while holding a 1 kg hand weight has been shown to activate the multifidus to approximately 30% of MVC, which corresponded to a
thickening of 9% in contraction (Kiesel et al, 2007). In the same contraction protocol, Teyhen et al (2012) reported multifidus muscle thickening of 23%. Our investigation of the ES muscle contraction index (thickening) during the same contraction resulted in a 15% increase in thickness in the healthy control participants. This value is intermediate between the two published results; therefore it appears that the contralateral arm raise contraction activates ES musculature similarly to the multifidus muscle.

It is also important to compare the asymmetry present in measuring ES and/or multifidus muscle thickness in rested and contracted states in healthy controls, to be able to determine if the asymmetry we saw in our comparison of affected versus unaffected sides of LBP-R patients is clinically meaningful, even if not statistically significant. Teyhen et al (2012) found a 5% difference between sides in healthy adults, in both rested and contracted state; our results show a 1% difference between sides in healthy controls, and a 3% difference between unaffected and affected sides of LBP-R. Therefore, the difference in contraction index between sides for LBP-R patients was more than control participants, but within normal variation previously published in healthy control participants.

5.2.2.2 Biceps femoris

The contraction index results for the BF muscle were similar to those for the ES muscle, with no significant difference between groups, but a slight but non-significant decrease in contraction index from the unaffected to affected side of the LBP-R patients. Unexpectedly, the control participants have a slightly lower contraction index than the
LBP-R patients. However, these are not statistically significant results therefore it should be concluded that there is no effect of LBP-R on the contraction index of the BF muscle. There has been no prior research investigating activation of the BF, or any hamstring muscle, in LBP-R patients.

5.2.2.2.1 Reliability

It is important to demonstrate that recording ultrasound thickness at the BF muscle is a reliable measure. Kellis et al (2009) conducted a study to verify that thickness measurements of hamstring musculature accurately reflected actual dimensions; cadaver BF muscle thickness, as measured by ultrasound, was highly correlated with the actual measure of muscle thickness after dissection (ICC 0.992). Notably, Kellis et al (2009) discussed the presence of superficial, intermediate and deep aponeuroses that are visible within the ultrasound image of BF, which were noted in our ultrasound imaging along with a change in pennation angle in the deeper portion of the BF muscle (see Figure 3.2). However, as pennation angle was not a component of the research question, this was not analyzed.

5.2.2.3 Medial gastrocnemius

The contraction index results for the MG were not as expected. First, the LBP-R patients on their unaffected side had a contraction index that was below a value of one, indicating that the muscle became thinner upon contraction, rather than thicker. However, the MG muscle was successfully being activated, as the EMG magnitude was 16 times that of the baseline prone trial. The control participants and LBP-R patients on their affected sides
both had similar, but small, magnitudes of thickening upon contraction, with 4 to 5% thickening relative to relaxed. Again, this corresponded to EMG magnitude of 16 times baseline for both control and LBP-R patients on their affected leg. None of these measures were significantly different from one another. Further, one case study LBP-R patient with notable unilateral calf atrophy had a nearly identical MG contraction index on unaffected and affected sides, demonstrating a potential lack of sensitivity of this measure for detecting differences.

A possible explanation for these unexpected findings could lie in the nature of how the images were taken in the rested relative to contracted states. The rested images were taken while participants lay prone on the chiropractic bench, with their ankle in a neutral position, whereas the contracted images were taken while participants were in a standing position, raised up on their toes so that their heel was 5 cm above the floor. In the MG, standing up and rising up onto the toes results in movement of the muscle belly relative to the skin surface. The anatomical location of the ultrasound image was standardized between the relaxed and contracted images through skin surface markings, therefore if the muscle belly moves relative to the skin surface then the image would, in fact, be taken from a different region of the muscle. Further, the MG muscle is bi-articular, therefore changes in knee and ankle angle in prone vs standing may impact the muscle architecture. This may be why we do not see the expected thickening of the muscle, in any group. However, the procedure was completed in the same manner for LBP-R and control participants, therefore the finding still remains that there were no between-group differences in the activation of the MG muscle.
5.2.2.3.1 Reliability

Ultrasound imaging of the MG muscle thickness in a relaxed state has been shown to be acceptable for both intra- and inter-rater reliability, with ICC over 0.9 (Cho et al, 2013). This is specific to an ultrasound imaging location measured as 30% of tibial length between the medial condyle of the knee and the medial malleolus of the ankle, which are the anatomical landmarks that were used in the present study.

5.2.2.4 Soleus

Post-hoc statistical tests revealed that soleus contraction index was lower in the LBP-R patients on their affected side, relative to control participants, but not relative to their unaffected side, however this trend is present without a main effect of group. This means that in response to the same submaximal contraction, LBP-R patients may not increase the thickness of their radiculopathy-affected soleus muscle as much as healthy control participants. No prior research has investigated soleus muscle activation or contraction in LBP-R patients; this is the first evidence of impaired lower limb muscular contraction in LBP-R patients. Reduced contraction index has been previously interpreted as impaired neuromotor control (Wallwork et al, 2009), and reflects an inability or unwillingness to voluntarily activate the muscle under a motor command.

5.2.2.4.1 Reliability

Previous ultrasound investigations in the soleus muscle have imaged in one of two ways: measuring muscle thickness of the soleus deep to MG (Fujiwara et al, 2010a; Fujiwara et al, 2010b), or imaging the soleus more distally where it is the most superficial muscle
Fujiwara et al. (2010b) measured soleus thickness in older adults, and found high inter and intra-rater reliability (ICC 0.99) for thickness measures of MG and soleus. Additionally, they measured muscle thickness of both of these muscles at adjacent locations to their imaging site and found only small differences in muscle thickness; therefore, they concluded that their imaging site (at the point of maximum calf girth, lined up with the centre of the MG) was the most reliable. The measurement location of soleus and MG thickness in the present study is very similar to that used by Fujiwara et al. (2010b).

5.2.2.5 Comparing MG and soleus

Within the calf region we see differing ultrasound muscle contraction index results from the MG and soleus muscle. LBP-R related differences were detected in the soleus muscle, but not in the MG. This could either be due to flawed measurement of either muscle contraction index (more likely in MG, as discussed above), or a result of physiological and biomechanical differences in these muscles that result in different responses to LBP-R.

Soleus is a postural muscle composed of mostly slow twitch oxidative muscle fibres, with estimates ranging from 68% (Tirrell et al., 2012) and 70% (Edgerton et al., 1975), to 80% (Gollnick et al., 1974). In contrast, MG has a lower proportion of slow twitch oxidative muscle fibres, with estimates of 50% (Edgerton et al., 1975), 57% (Gollnick et al., 1974), and 58% (Tirrell et al., 2012). The gastrocnemius muscle functions in more ballistic movements, such as recovering from a postural perturbation. There are differences in
susceptibility of muscle fibre types to muscle atrophy and dysfunction following nerve compression injury, however not in a manner that helps explain this discrepancy of results. Fast-twitch muscle fibres are more susceptible to atrophy than slow-twitch (Wang et al, 2013). Further, rat soleus muscle, composed mostly slow-twitch fibres, recovered almost full function following experimental sciatic nerve compression, whereas fast-twitch TA muscle recovered only 50% of function within the same recovery period (Lowrie et al, 1982). Both of these forms of evidence would indicate that we should see nerve-pathology related changes in in the MG muscle more so than the soleus; however, we found the opposite. It is therefore likely that our measure of MG was not fully representative of muscle contraction.

5.2.3 Muscle quality

From axial ultrasound images of the ES, BF, MG and BB muscles, we analyzed a region of interest of the muscle for three measures: mean muscle echo intensity, ratio of mean muscle echo intensity to mean fascia echo intensity (muscle-fascia ratio), and percentage of pixels within the region of interest that were over a threshold echo intensity aiming to separate muscle tissue from fat and fascia tissue (percent above threshold).

5.2.3.1 Echo intensity mean

There were no significant differences between control and LBP-R patients on their unaffected or affected side for mean echo intensity of any of the muscles measured. It was expected that there would be a greater mean echo intensity of the muscles of the affected leg; this was hypothesized based on the fact that a denervated muscle
experiences fat infiltration and fibrosis (Salonen et al, 1985), and both fat and fibrotic tissue are more hyperechoic (higher echo intensity) than muscle tissue. Evidence of increased fat infiltration into the lower back musculature in patients in remission of LBP has been detected using magnetic resonance imaging to calculate the muscle-fat index (D’Hooge et al, 2012). This was detected in the multifidus and ES at vertebral levels of L4 and L5, but not L3 (D’Hooge et al, 2012). Further, Hyun et al (2007) compared the ratio of pure muscle area to total muscle area of multifidus in LBP-R patients using magnetic resonance imaging, and found differences between patients and controls at L3/L4 and L4/L5, but not L5/S1. Our ultrasound imaging of the ES muscles was completed at the L3 level, therefore we may have not detected differences because (a) the alterations in muscle quality only occurred in the lower lumbar levels and not at L3, (b) ultrasound imaging mean echo intensity is not sensitive enough to detect changes in muscle fat content in LBP, or (c) our LBP-R patients did not have any muscle quality changes relative to controls.

Muscle ultrasound echo intensity mean has been able to detect muscle quality changes with aging. In the quadriceps muscle, older adults have higher mean echo intensity relative to young controls, which was attributed to an increase in fat and fibrotic tissue relative to contractile tissue within the muscle (Fukumoto et al, 2011; Strasser et al, 2013). Fukomoto et al (2011) also found significant correlations between increased muscle echo intensity mean and decreased quadriceps strength in older adults, whereas Strasser et al (2013) only found significant correlations to maximum voluntary contraction in younger adults but not older adults. Together, this research indicates that
mean ultrasound echo intensity can be used to detect changes in muscle quality, but it may only be sensitive enough to detect severe changes.

5.2.3.2 Muscle fascia ratio

Analyzing muscle quality through mean muscle echo intensity does not correct for potential small changes in brightness of the image, or gain of the ultrasound system, that may be present. It is therefore useful to normalize the brightness of the image; this can be achieved by calculating the muscle-fascia ratio. When comparing the muscle-fascia ratio between LBP-R patients and controls or affected and unaffected legs of LBP-R patients, there were no significant differences for any of the measured muscles. In fact, the trends look nearly identical to the results seen with the mean muscle echo intensity. This indicates that there were no notable alterations in baseline brightness of the images. It should be noted that by using fascia to normalize the brightness of each ultrasound image, we rely on the assumption that fascia brightness is not affected by LBP-R nor by any associated conditions.

5.2.3.3 Percent above threshold

There were no significant differences in percent of muscle above the fat and fascia threshold between LBP-R patients and controls or between affected and unaffected legs of LBP-R patients. In contrast to the muscle quality measures of echo intensity mean and muscle-fascia ratio, LBP-R patients appear to have slightly higher percent above threshold within the ES muscle on their affected side relative to the unaffected side and controls. However, this non-significant trend is mirrored in the BB muscle, which is
imaged as a control region of the body to account for any baseline differences between the groups not related to LBP-R. Therefore, caution should be taken in interpreting this as related to LBP-R.

The lack of difference in this measure between LBP-R patients and controls at the ES muscle is in contrast to findings by Chan et al (2012), who examined muscle quality of the multifidus muscle at L4 in a group of moderately-affected LBP patients (ODI of at least 20%). Chan et al (2012) quantified muscle quality using the threshold technique, to calculate the ‘fat area’ within the muscle (area with echo intensity over threshold of 68). LBP patients were found to have increased fat area, within the multifidus, compared to controls, and additionally LBP patients had smaller multifidus CSA relative to the control group. Two factors may contribute to the discrepancy between our findings and those of Chan et al (2012). First, the control group used by Chan et al (2012) was not age matched to their LBP patients; control participants were 25 years old on average, whereas LBP patients were 37 years old. Others have presented evidence of altered muscle quality with increased age (Fukumoto et al, 2011; Strasser et al, 2013), and although the age differential in the Chan et al (2012) paper is not as marked, it should be noted. Second, the LBP patients in the study by Chan et al (2012) had a minimum ODI disability rating of 20%, therefore all are moderately affected or higher; our LBP-R population had an average ODI of 20%, therefore almost half of them were less severely affected than those in the Chan et al (2012) study. It is plausible that alterations in muscle quality can only be detected in more severely affected patients.
Analyzing muscle quality as percent above threshold assumes that the brightness is constant in each image, and that all tissue above threshold (echo intensity of 68) is fat and fibrotic, and all tissue below threshold is muscle contractile tissue. Chan et al (2012) assumed that all tissue above threshold was fat; however in response to muscle denervation there are increases in muscle fibrosis as well (Salonen et al, 1985), therefore we have defined it as percent above fat and fibrotic tissue threshold. The echo intensity threshold of 68 was selected by Chan et al (2012) to best differentiate between muscle tissue and fat tissue, however this value may vary between ultrasound devices. Chan et al (2012) used a 5-12 MHz linear transducer, whereas the present study used a 6-15 MHz linear transducer.

5.2.3.4 Case study
One LBP-R patient with unilateral symptoms demonstrated notable calf atrophy on his radiculopathy-affected side. All three measures of muscle quality showed large differences between this patient’s affected and unaffected sides. In the affected side relative to the unaffected side, mean echo intensity was 42% greater, muscle-fascia ratio was 60% greater, and percent above threshold was 92% greater. Therefore, an individual with LBP-R symptoms that resulted in notable atrophy of the muscle due to denervation, does demonstrate alterations in muscle quality using any of these measures. It seems that percent above threshold may be the most sensitive, and mean echo intensity the least sensitive ultrasound measure of muscle quality.
5.3 Electromyography muscle activation timing

Muscle activation timing was computed bilaterally using surface EMG for the ES, BF, MG and TA muscles during the four types of balance perturbation trials.

5.3.1 Weight drop trials

There was no difference between LBP-R patients, on either their affected or unaffected sides, and control participants for muscle activation timing of any muscle. This is contrary to findings in the literature that have investigated muscle activation timing at the lower back musculature, which demonstrated delayed ES activation in LBP patients in a weight drop perturbation. Specifically, Leinonen et al (2001) looked at multifidus and ES muscle activation timing in a group of disc-herniation related LBP patients during perturbations where a weight was dropped into a box, in both unanticipated and anticipated scenarios. ES and multifidus were both recorded with surface EMG at T12-L1 and L5-S1, respectively, although surface EMG recording of multifidus reflects mostly ES activation. LBP patients had delayed paraspinal (ES and multifidus) muscle activation (at both vertebral levels) relative to controls in the trials where they expected the weight drop, but not in unanticipated trials (Leinonen et al, 2001). Similarly, Magnusson et al (1996) found delayed ES muscle activation at L3 in LBP patients as compared to controls in response to a sudden load release from the trunk (load applied at T4); however they found significant between-group differences in both unanticipated and anticipated scenarios. Our results may not correspond to the findings of Leinonen et al (2001) due to a difference in severity of LBP; Leinonen et al (2001) were working with a more severely affected LBP group, with an average ODI of 38.4% and VAS of 6.8 (on a scale of 0-10).
Magnusson et al (1996) did not specify LBP patient severity. It could be that only more severely affected LBP patients have delays in paraspinal muscle activation timing.

No previous researchers have investigated muscle activation timing in the lower limb musculature in weight drop perturbations. We did not see any significant differences in LBP-R patients in the timing of lower limb muscles during this perturbation; however, this may be due to the relatively low level of pain and disability in our LBP-R population. In a LBP-R population that does demonstrate delays in paraspinal muscle activation, there may be delays in lower limb muscle activation, therefore further investigation is warranted.

5.3.1.1 Effect of anticipation

When comparing anticipated to unanticipated weight drop trials, we hypothesized more between-group differences in the anticipated trial due to deficits in feed-forward planning in the LBP group (Leinonen et al, 2001). However, we did not observe this relationship. LBP-R patients were not significantly different from control participants in both unanticipated and anticipated trials. Overall, all participants had faster activation of ES in the anticipated trial relative to unanticipated, which is in agreement with Leinonen et al (2002). Additionally, it was observed that control participants and the unaffected side of LBP-R patients had a more clear top-down sequence of muscle activation in response to the weight drop in the anticipated trial, by activating first ES, then significantly later BF and MG. LBP-R patients on their affected side co-activated all muscles at the same time, and therefore did not demonstrate this specific muscle sequencing. This pattern was
similar to all participants in the unanticipated weight drop trials, where all muscles co-activated with similar timing in response to the perturbation. These strategies were the same for both control and LBP-R patients.

5.3.2 Arm raise trials

In preparation for a rapid bilateral arm raise, LBP-R patients had slower MG activation on their affected side than control participants, but not compared to their unaffected side, and delayed TA activation on their affected side relative to control participants. The other muscles recorded during this perturbation, ES and BF, did not have any differences in muscle activation timing between LBP-R patients and controls or between unaffected and affected sides of LBP-R patients. We had expected to see delays in ES activation, and potentially in lower limb muscle activation as well, based on previous research that demonstrated trunk muscle activation delays in LBP patients during voluntary arm movement perturbations. Mehta et al (2010) used surface EMG of the multifidus to compare muscle activation latency in rapid arm flexion trials between a group of non-specific chronic LBP patients and controls. Activation latency was determined relative to the onset of deltoid muscle activity, and LBP patients had a significant delay (94 ms) in multifidus activation as compared to controls (Mehta et al, 2010). The LBP patients studied by Mehta et al (2010) were slightly more severely affected than our cohort, which might explain why their results showed differences and our LBP-R population did not. There have been a number of investigations led by the Hodges et al group that examined trunk musculature, namely transversus abdominus and external oblique, and in general found that LBP patients have delays in activation prior to voluntary arm movements.
(Hodges et al, 2003; Hodges et al, 1999b). This research, however, does not highlight the paraspinal or lower limb musculature, so will not be discussed in detail.

No studies have looked at muscle activation of lower limb muscles in LBP-R patients in response to an arm raise perturbation; therefore we are the first to report delays in MG and TA activation. During a rapid bilateral arm raise, MG activates in a feed-forward manner, following ES and BF activation, to assist with pulling the centre of mass of the body posteriorly to prepare for the anterior shift in centre of mass that occurs during an arm raise. A later activation of MG may impair the feed-forward preparation for this movement; however, there are no between-group differences in the kinetic balance outcome measures for the arm raise trials so it appears that the effect of this MG activation delay in LBP-R patients is minimal. It is also interesting that we see a significant delay in activation of the MG muscle, but no alteration in the ultrasound contraction index measure; this may be due to previously discussed limitations in the MG ultrasound imaging in relaxed relative to contracted states. TA activates slightly prior to the arm raise movement onset, in control and LBP-R patients on their unaffected side, however activation is delayed on the affected side of LBP-R patients. Activation of TA functions to stabilize the lower limb by providing counter balanced response to the feed-forward activation of posterior chain muscles. We did not find any difference in the timing of the BF muscle activation between LBP-R and control participants, which is again a novel finding. The timing of BF activation was 87 ms prior to the onset of arm raise movement, which is comparable but slightly delayed relative to BF activation
timing results reported by Mochizuki et al (2004) in rapid arm raise trials in healthy control participants (112 to 146 ms prior to arm raise movement).

5.3.3 Rise to toe trials

In the rise to toe trials, activation of TA was slightly, but not significantly, delayed on the affected side of LBP-R patients as compared to controls, but not compared to the unaffected side. Further, in the posterior muscles (ES, BF and MG) there were no between-group differences in muscle activation timing. During this perturbation of balance, MG is activated first to prepare for the rise up onto the toes, followed by BF activation at the approximate time when the movement of the heel is initiated, followed by ES and TA muscles activating after movement initiation. TA is an antagonist to MG, therefore activation of the TA functions to balance the MG activation that propels the body up onto the toes. However, due to the self-timed nature of the task, activation timing of TA was quite variable in all participants, both LBP-R and control. The clinical and functional relevance of non-statistically significant delay in TA activation in LBP-R patients may be questionable.

Rise to toe perturbations were investigated in order to target a bottom-up perturbation that requires a major contribution of lower limb musculature to control the movement and maintain the COP within the reduced base of support while up on the toes. It has been investigated previously in patients with Parkinson’s disease and showed prolonged activation of TA and delayed activation of MG musculature (Frank et al, 2000).
5.3.4 Mechanisms of delay

Across all investigations, we hypothesized that LBP-R patients would have delayed muscle activation timing relative to controls. This was hypothesized for two reasons. First, in chronic nerve compression pathologies, nerve conduction velocity decreases. Kim et al (2013) found a positive correlation between swelling (increased CSA) of the median nerve and decreased median nerve conduction velocity in carpal tunnel syndrome. We found increased sciatic nerve CSA, which would therefore correspond to decreased nerve conduction velocity if we assume similar correlations exist as demonstrated by Kim et al (2013). Directly relating nerve conduction velocity to muscle activation timing, however, does not account for any changes in central command to the muscle. This is considered in the pain-adaptation model, which states that in a pain state, such as LBP-R, motor neuron excitability of agonist muscles reduced, therefore the response to a neuromotor command will be reduced in magnitude and have an increased latency of response (van Dieen et al, 2003; Lund et al, 1991). Muscle activation timing was not delayed for most muscles, therefore it appears that this population of LBP-R patients is likely not experiencing decreased sciatic nerve conduction velocity or significant motor system adaptations to pain. Given the long duration of LBP-R symptoms in the patient group (average 126 months), it is unlikely that there will be further motor system adaptations to pain if they remain at the same level of disability.

5.4 Force plate

5.4.1 Weight drop trials
When a small weight was unexpectedly dropped into a hand-held box, generating a top-down external AP perturbation, LBP-R patients had smaller maximum COP excursion (anterior) and velocity (anterior and posterior) as compared to control participants. In anticipated trials, LBP-R patients had smaller maximum COP velocity in the posterior direction, but no difference in anterior COP velocity or in excursion of COP. There were no differences in AP COP velocity stabilization parameters. It had been hypothesized, based on previous research that demonstrated poorer balance control in LBP-R patients, that LBP-R patients would require more COP movement to stabilize following this perturbation. However, the demonstrated decrease in COP excursion and velocity in LBP-R patients indicates a stiffer balance control strategy. This could be a result of muscle co-contraction in anticipation of the perturbation, which would result in less COP movement following perturbation. This seemingly occurs without any detectable alteration in muscle activation timing in response to the perturbation. Increased co-contraction of muscles would be in agreement with the pain-adaption model reviewed by van Dieen et al (2003), where, in response to a pain state, movement velocity and excursion are reduced to prevent provocation of pain. This is accomplished through increased activation of antagonist muscles and decreased activation of agonist muscles, to facilitate co-contraction. Unfortunately, we are unable to assess the active stiffening of the body as we do not have muscle activation magnitude data due to the inability of LBP-R patients to complete a reliable maximum voluntary contraction. Therefore, we are unable to provide direct evidence to confirm this proposal.
Our results are not in complete agreement with previous unanticipated weight drop balance perturbations completed in LBP patients by Mok et al (2011), who studied a very similar patient group using a similar weight drop protocol and instructions to participants. Mok et al (2011) found no difference in AP COP excursion, whereas we found significantly less anterior excursion, and Mok et al found that LBP-R patients required a longer time and more corrections to stabilize their AP COP velocity, a finding that was not replicated in our study. COP stabilization was calculated in the same manner as Mok et al (2011), therefore there is no clear explanation for the difference in the findings between these two studies.

It appears that there are more differences in LBP-R patients’ kinetic response to this perturbation relative to controls in the unanticipated loading scenario, as compared to the anticipated loading scenario. This parallels the findings by Leinonen et al (2001) in lower back muscle activation timing of LBP patients in response to unanticipated versus anticipated loading. When the weight drop is unanticipated, the muscle activation strategy adopted by both LBP-R patients and control participants is to co-contract the ES, BF and MG muscles prior to the load onset. This co-contraction strategy may be contributing to the tighter COP control that LBP-R patients have during the unanticipated weight drop trials, as compared to controls, however we do not have direct evidence of muscle activation magnitude during this co-contraction sequence. A higher level of active stiffening of the trunk and lower limbs could contribute to tighter control over the COP in LBP-R patients. When the load is anticipated, muscle activation sequencing is more
apparent, with activation of the ES muscle prior to the BF and MG muscles, which is seen alongside less between-group differences in force plate parameters.

5.4.2 Rise to toe trials

Compared to weight drop trials, LBP-R patients had the opposite kinetic results in the rise to toe trials. The between-group differences were mainly seen in the ML plane; LBP-R patients had larger maximum COP excursion (towards their unaffected leg) and velocities (medial/lateral) than controls. Rise to toe perturbations have never been investigated before in LBP or LBP-R patients, therefore these are all novel findings. Larger COP excursion towards the unaffected side indicates that LBP-R patients were favouring their radiculopathy-unaffected side when rising up onto their toes and stabilizing in that position. Further, the increased ML COP velocity (both mean and maximum) provides insight into the control capability; larger COP velocity can be interpreted as reduced balance control in the LBP-R patients. LBP-R patients also had larger anterior COP excursion than controls; however, this parameter mainly reflects how far forwards onto their feet participants moved and would be partly dependent on foot size. Therefore, it could either be interpreted as LBP-R patients going further up onto their toes than controls, or could simply be due to a larger foot size; foot size was not recorded although patients and controls were matched for height.

5.4.3 Arm raise trials

There were no significant differences between LBP-R patients and control participants in any of the measured COP balance parameters in the bilateral arm raise perturbation. LBP-
R patients execute their arm raise at the same angular velocity as controls, therefore they are capable of kinetically preparing and responding to this voluntary perturbation of balance as well as controls. This lack of difference between groups is in agreement with submitted work (Frost et al) in LBP-R patients during the same protocol of rapid bilateral arm raise, where no differences in AP COP excursion, velocity, or stabilization were found. Further, this finding corresponds to the findings of Mok et al (2011) in a group of LBP patients of similar disability and pain rating for AP COP excursion and velocity; however, Mok et al (2011) reported that LBP patients required more time and more corrections to stabilize their AP COP velocity.

5.5 Insight into neuromuscular control

This research project was designed to gain insight into the neuromuscular system of LBP-R patients from both a structural and functional level. To understand any local structural changes, we completed axial ultrasound imaging of the sciatic nerve and associated musculature in the lower back (ES) and lower limb (BF, MG). Structural changes in the sciatic nerve were detected; however there were no changes in muscle quality. This indicates that this level of compressive/inflammatory damage to the sciatic nerve does not result in notable fat infiltration or fibrosis in the muscle, therefore these changes may only occur in more severely-affected cases (such as the case study with notable calf atrophy) or in complete transection of the nerve. We did not detect changes in the lower back or the lower limb, therefore in a LBP-R population with detectable reduction in muscle quality at the lower back, there could still be parallel changes in the lower limb.
However, we must still consider that changes at the lower back may have occurred but only at an inferior vertebral level.

Following local structural changes, we wanted to investigate how local muscular function may be impacted, given any evidence of local structural change. For this, we examined the ultrasound muscle contraction index of ES and lower limb muscles during submaximal contractions. It is difficult to tease out the neuromuscular implications of the ES contraction index results, as we may have missed detecting differences at the L4 and L5 vertebral levels. Further, we identified some potential flaws in the contraction index of the MG muscle. These factors, combined with the evidence of a decrease in the radiculopathy-affected soleus contraction index, indicates that sciatic nerve structural damage may contribute to impaired submaximal activation of musculature down the leg, but this perhaps was not adequately detected.

Local functional changes may also lead to whole body alterations in neuromuscular function, which were investigated through perturbations of balance. LBP-R patients were able to complete the perturbations with similar muscle activation timing and sequencing as control participants, with the exception of delayed MG and TA activation in arm raise trials, and less muscle activation sequencing in anticipated weight drop trials. However, the overall control strategy was different than healthy controls, as evidenced by differences in the kinetic outcome measures in weight drop and rise to toe perturbations. It appears that sciatic nerve structural changes only impact the activation timing of the innervated musculature in isolated cases; however, the magnitude of the muscle
activation is unknown, and is likely contributing to these differences in balance control. Additionally, alterations in balance control could be a result of chronic adaptations to LBP-R in other muscles or segments not measured in the current study.

5.6 Limitations

5.6.1 Severity of LBP-R patients

Of the unilateral LBP-R patients included in this study, most had minimal (ODI 0 - 20%, n = 7) and moderate (ODI 20 - 40%, n = 9) levels of disability according to the ODI questionnaire, and VAS scores of pain were mostly mild (0.5 – 4.4; lower back n = 10, affected leg n = 16), with the rest classified as no (0 – 0.4), moderate (4.5 – 7.4) or severe (7.5 – 10) pain. Much of the reviewed research that demonstrated differences in LBP patients relative to controls had examined more severely affected LBP patients; many set a cut-off score, such as ODI of 20% or VAS of 3/10, for inclusion in the study. These cut-off scores are very close to our average ODI and low back VAS scores for the LBP-R patients. There were (n = 9) LBP-R patients with an ODI of 20% or higher, and (n = 7) LBP-R patients with a VAS score of 3.0 or higher. It is possible that our LBP-R patient population was not severely enough affected to be able to detect differences in some measures. However, there were no significant correlations between ultrasound, EMG, or FP outcome measures with markers of LBP-R disability. This leads us to believe that it might not be the level of severity of the LBP-R patients that determines whether differences may be present or not. Rather, there could be a more complex relationship between level of severity, duration of symptoms, and functional physical activity status.
that contributes to the presence or absence of symptoms. A lack of correlation also brings into question the clinical relevance of the outcome measures investigated in this research for detecting presence or changes of LBP-R in patients, especially with lower levels of disability. Alternatively, clinical assessment scores (ODI, VAS) could be poorly reflecting the current physical state of the LBP-R patients.

5.6.2 Ultrasound muscle CSA

The ultrasound transducer that was used in this study, a 6-15 MHz linear transducer, has a maximum imaging area of 5 cm breadth and 6 cm depth. Due to this limited imaging area, we were unable to image and measure complete muscle CSA. In some participants, ES and multifidus muscles in the lower back could be fully captured within the ultrasound image. However, the distinction of the borders of the ES and multifidus was not determined to be clear enough to facilitate confident tracing; therefore, we did not record multifidus CSA as has been previously done in ultrasound research in LBP with a curvilinear probe (Wallwork et al, 2009). Muscle atrophy, quantified as decreased CSA, is one of the most commonly reported measures in magnetic resonance imaging, computed tomography, and ultrasound investigation of LBP. It would have been valuable to be able to look for unilateral atrophy in the lower back and lower limb of the LBP-R patients relative to controls.

5.6.3 Muscle activation magnitude

LBP-R patients, in current states of pain, are not capable of safely producing a true maximum voluntary contraction of muscles. In order to reliably normalize EMG signals
for analysis of activation magnitude, they should be normalized to a maximum voluntary contraction. Normalization to submaximal activation or to baseline activation while lying prone does not allow for comparison to the maximal potential of the muscle. To ensure that all participants were able to safely and comfortably complete data collection, we chose to only examine the muscle activation timing from the EMG data during balance perturbations, which does not require normalization to a maximum voluntary contraction. However, this limited our ability to interpret muscle activation levels during the balance perturbations. If we had access to measures of muscle activation magnitude, we could examine the magnitude of muscle co-contraction in anticipation of balance perturbations, and during the balance recovery phase, in order to interpret the active stiffening of the system.

5.7 Conclusion
The purpose of this research was to expand previous LBP neuromuscular research that focussed on the lower back and trunk, into the lower limb in LBP-R patients to determine the neuromuscular effect of radiculopathy. We were able to see clear evidence of sciatic nerve structural changes, markedly increased CSA, which confirmed previous findings of edema and inflammation at the nerve. However, even with these structural changes to the nerve, paraspinal and lower limb musculature contracted (thickened) comparably to controls in submaximal conditions, with some evidence of dysfunction in the soleus muscle. Overall, there was no structural evidence of impaired muscle quality. Musculature in the lower back and lower limb of LBP-R patients also activated with similar latency and sequence as control participants during most balance perturbations.
with a few exceptions, but there was evidence of differing balance control strategies when kinetic data were analyzed. LBP-R patients had less AP COP movement during unexpected upper body loading, potentially due to a stiffer control strategy, and more ML COP movement in voluntary rise to toe perturbations, demonstrating poorer balance control. Overall, neuromuscular changes were not consistently present in the lower limb; however, as they were not present in the lower back region either, it is possible that the mildly-affected LBP-R patient group was functioning at a neuromuscular level comparable to controls, and a more severely affected group is needed to detect differences.

5.8 Recommendations for future research
As a result of the completion of this research, there logically follows many further areas to explore, the most pertinent of which will be highlighted here. First, it would be very interesting to investigate the fatigability of the lower limb muscles in a LBP-R population. There has been extensive research in the paraspinal musculature of LBP patients demonstrating deficits in muscle endurance, and a shift from slow to fast twitch muscle fibre type (Mannion, 1999). Mannion (1999) attributed the fibre type shift to reflex inhibition or pain-induced inactivity of the muscle. This shift in muscle fibre type from slow twitch to fast twitch has also been demonstrated experimentally in a rat model with sciatic nerve transection (Higashino et al, 2013). Therefore, nerve-damage related increases in muscle fatigability present in the paraspinal musculature could also be present in the radiculopathy-affected lower limb of LBP-R patients. The second area of research that would be intriguing to investigate is a more comprehensive analysis of
lower limb balance control in LBP-R patients; the present study only examined the rise to toe perturbation, but it would be valuable to examine controlled lower limb perturbations in expected and unexpected scenarios. This could be accomplished through platform perturbations of balance, which would allow for the same perturbation magnitude to be applied to each participant, for more directly comparable results. Mok et al (2013) utilized platform perturbations to tease out differences in balance control with and without restricting lumbar movement with a trunk brace in healthy control participants. Third, it would be valuable to perform sciatic nerve conduction velocity testing in conjunction with lower limb muscle activation timing in LBP-R patients. This would allow for the connection between local nerve function (nerve conduction velocity) and neuromuscular function (activation of the muscle) to be established in this patient population.
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APPENDIX A

Table A.1: Individual patient characteristics of unilateral LBP-R patients. Patients who have a history of spinal surgery are in italic font. For patients with confirmed disc level, n = 5 of them had recent MRI imaging, and one patient had x-ray imaging confirm the level of disc herniation.

<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>BMI</th>
<th>Side</th>
<th>Duration (months)</th>
<th>ODI (%)</th>
<th>VAS back</th>
<th>VAS leg</th>
<th>Baeke</th>
<th>Disc level</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>21</td>
<td>L</td>
<td>30</td>
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<td>2.9</td>
<td>3.3</td>
<td>7.5</td>
<td></td>
<td>Pain, tingling, numbness</td>
</tr>
<tr>
<td>62</td>
<td>M</td>
<td>27</td>
<td>R</td>
<td>120</td>
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<td>2</td>
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<td></td>
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<td>F</td>
<td>28</td>
<td>R</td>
<td>18</td>
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<td>7.8</td>
<td>0.5</td>
<td>6.625</td>
<td></td>
<td>Pain, numbness</td>
</tr>
<tr>
<td>56</td>
<td>M</td>
<td>25</td>
<td>R</td>
<td>360</td>
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<td>0.7</td>
<td>0.1</td>
<td>11</td>
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<td>R</td>
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<td>0.36</td>
<td>0.54</td>
<td>7</td>
<td></td>
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<td>F</td>
<td>20</td>
<td>R</td>
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<td>8.25</td>
<td></td>
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</tr>
<tr>
<td>45</td>
<td>F</td>
<td>22</td>
<td>R</td>
<td>18</td>
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<td>2.5</td>
<td>1.1</td>
<td>8</td>
<td>L4/L5, L5/S1</td>
<td>Pain</td>
</tr>
<tr>
<td>25</td>
<td>M</td>
<td>22</td>
<td>L</td>
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</tr>
<tr>
<td>57</td>
<td>F</td>
<td>24</td>
<td>R</td>
<td>3</td>
<td>20</td>
<td>4.6</td>
<td>1.4</td>
<td>6.125</td>
<td>L3/L4, L4/L5</td>
<td>Pain</td>
</tr>
<tr>
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<td>F</td>
<td>26</td>
<td>L</td>
<td>4</td>
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<td>1.8</td>
<td>1.4</td>
<td>9.625</td>
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<td>F</td>
<td>25</td>
<td>R</td>
<td>18</td>
<td>17.8</td>
<td>5.5</td>
<td>1.3</td>
<td>7.625</td>
<td></td>
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<tr>
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<td>L</td>
<td>432</td>
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</tr>
<tr>
<td>56</td>
<td>M</td>
<td>27</td>
<td>L</td>
<td>120</td>
<td>20</td>
<td>1.8</td>
<td>3.5</td>
<td>9.75</td>
<td>L3/4, L4/5, L5/S1</td>
<td>Pain, atrophy</td>
</tr>
<tr>
<td>55</td>
<td>F</td>
<td>22</td>
<td>L</td>
<td>8</td>
<td>20</td>
<td>0.3</td>
<td>2.4</td>
<td>8.125</td>
<td>L4/L5</td>
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<td>F</td>
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<td>0.8</td>
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<td>Pain, tingling, numbness</td>
</tr>
<tr>
<td>48</td>
<td>F</td>
<td>21</td>
<td>L</td>
<td>192</td>
<td>22.2</td>
<td>0.1</td>
<td>2.8</td>
<td>8.25</td>
<td>L4/L5, L5/S1</td>
<td>Numbness, pain</td>
</tr>
<tr>
<td>62</td>
<td>M</td>
<td>23</td>
<td>L</td>
<td>360</td>
<td>20</td>
<td>1.3</td>
<td>1.6</td>
<td>11.125</td>
<td>L4/L5, L5/S1</td>
<td>Tingling, coldness</td>
</tr>
</tbody>
</table>
Table A.2: Individual participant characteristics of LBP-R patients not included in data analysis. Patients had bilateral symptoms, or had radiculopathy due to scoliosis (grey highlight) rather than a disc herniation. One patient had a previous spine surgery, and is in italic font.

<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>BMI</th>
<th>Side</th>
<th>Duration (months)</th>
<th>ODI (%)</th>
<th>VAS back</th>
<th>VAS leg</th>
<th>Baeke</th>
<th>Disc level</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>M</td>
<td>33</td>
<td>R, L</td>
<td>36</td>
<td>28.9</td>
<td>4.7</td>
<td>7</td>
<td>8.75</td>
<td>L4/L5</td>
<td>Numbness, foot drop, atrophy, pain</td>
</tr>
<tr>
<td>59</td>
<td>F</td>
<td>26</td>
<td>R, L</td>
<td>63</td>
<td>8.9</td>
<td>.</td>
<td>2.8</td>
<td>8.875</td>
<td></td>
<td>Pain, numbness</td>
</tr>
<tr>
<td>24</td>
<td>M</td>
<td>24</td>
<td>L, R</td>
<td>12</td>
<td>20</td>
<td>0.5</td>
<td>1.7</td>
<td>8.375</td>
<td></td>
<td>Pain</td>
</tr>
<tr>
<td>24</td>
<td>F</td>
<td>25</td>
<td>L, R</td>
<td>18</td>
<td>22.2</td>
<td>1</td>
<td>0.8</td>
<td>8.125</td>
<td>L4/L5</td>
<td>Pain</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>24</td>
<td>Both</td>
<td>24</td>
<td>46.7</td>
<td>1.8</td>
<td>1.8</td>
<td>7.875</td>
<td></td>
<td>Pain</td>
</tr>
<tr>
<td>56</td>
<td>F</td>
<td>33</td>
<td>R, L</td>
<td>240</td>
<td>37.8</td>
<td>1.6</td>
<td>5.4</td>
<td>5.5</td>
<td>L1/L2, L2/L3, L3/L4</td>
<td>Pain, tingling</td>
</tr>
<tr>
<td>53</td>
<td>F</td>
<td>23</td>
<td>L</td>
<td>408</td>
<td>20</td>
<td>1.6</td>
<td>0</td>
<td>9.75</td>
<td></td>
<td>Scoliosis, Pain</td>
</tr>
</tbody>
</table>

111
APPENDIX B

Medical screening questionnaires for potential participants:

Health questionnaire:

1. Do you currently have pain in the low back region?

   (YES) or (NO)

   If NO, please skip to question 5

2. Do you experience clinical symptoms of lower limb radiculopathy (aka. sciatica), such as pain, tingling or numbness radiating down one or both legs?

   Answer (yes or no; if yes please describe):

3. What is the duration that you have been experiencing low back pain and associated radiculopathy?

4. Have you ever undergone spine surgery?

   Answer (yes or no; if yes please describe):

5. Do you currently have, or have a history of, any chronic musculoskeletal disorders other than low back pain?

   Answer (yes or no; if yes please describe):
6. Do you currently have, or have a history of, any neurological or nerve-related disorders other than radiculopathy or sciatica?

   Answer (yes or no; if yes please describe):

7. Are you currently on any medications to treat chronic low back pain and associated radiculopathy?

   Answer (yes or no; if yes please describe):

8. Do you regularly engage in any type of physical activity?

   Answer (yes or no; if yes please describe the type and frequency of training/exercise):

9. Do you have a history of skin irritation in response to surface electromyography electrodes, or to hypoallergenic ultrasound transmission gel?

   Answer (yes or no; if yes please describe):
Waterloo Footedness Questionnaire

Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle Ra or Lu (for right always or left always). If you usually use one foot circle Ru or Eq, as appropriate. If you use both feet equally often, circle Eq.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

1. Which foot would you use to kick a stationary ball at a target straight in front of you? La Lu Eq Ru Ra
2. If you had to stand on one foot, which foot would it be? La Lu Eq Ru Ra
3. Which foot would you use to smooth sand at the beach? La Lu Eq Ru Ra
4. If you had to step up onto a chair, which foot would you place on the chair first? La Lu Eq Ru Ra
5. Which foot would you use to stomp on a fast-moving bug? La Lu Eq Ru Ra
6. If you were to balance on one foot on a railway track, which foot would you use? La Lu Eq Ru Ra
7. If you wanted to pick up a marble with your toes, which foot would you use? La Lu Eq Ru Ra
8. If you had to hop on one foot, which foot would you use? La Lu Eq Ru Ra
9. Which foot would you use to help push a shovel into the ground? La Lu Eq Ru Ra
10. During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first? La Lu Eq Ru Ra
11. Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities? YES NO (circle one)
12. Have you ever been given special training or encouragement to use a particular foot for certain activities? YES NO (circle one)
13. If you have answered YES for either question 11 or 12, please explain:

Scoring:

Ra = +2
Ru = +1
Eq = 0
Lu = -1
La = -2

Positive score = right foot dominant
Negative score = left foot dominant
Oswestry Disability Index

Could you please complete this questionnaire? It is designed to give us information about how your back (or leg) trouble affects your ability to manage in everyday life. Please answer every section. Fill in the one bubble only in each section that most closely describes you today.

Section 1 - Pain intensity
○ I have no pain at the moment.
○ The pain is very mild at the moment.
○ The pain is moderate at the moment.
○ The pain is fairly severe at the moment.
○ The pain is very severe at the moment.
○ The pain is the worst imaginable at the moment.

Section 2 - Personal care (washing, dressing, etc.)
○ I can look after myself normally without causing extra pain.
○ I can look after myself normally but it is very painful.
○ It is painful to look after myself and I am slow and careful.
○ I need some help but manage most of my personal care.
○ I need help every day in most aspects of self care.
○ I do not get dressed, wash with difficulty and stay in bed.

Section 3 - Lifting
○ I can lift heavy weights without extra pain.
○ I can lift heavy weights but it gives extra pain.
  Pain prevents me from lifting heavy weights off the floor but I can manage if they are conveniently positioned, e.g. on a table.
  Pain prevents me from lifting heavy weights but I can manage light to medium weights if they are conveniently positioned.
○ I can lift only very light weights.
○ I cannot lift or carry anything at all.

Section 4 - Walking
○ Pain does not prevent me walking any distance.
○ I can travel anywhere without pain.
  Pain prevents me from walking more than one mile.
  Pain prevents me from walking more than a quarter of a mile.
  Pain prevents me from walking more than 100 yards.
  Pain prevents me from walking more than half an hour.
○ I can only walk using a stick or crutches.
○ I am in bed most of the time and have to crawl to the toilet.

Section 5 - Sitting
○ I can sit in any chair as long as I like.
  Pain prevents me from sitting for more than 1 hour.
  Pain prevents me from sitting for more than half an hour.
  Pain prevents me from sitting for more than 10 minutes.
  Pain prevents me from sitting at all.

Section 6 - Standing
○ I can stand as long as I want without extra pain.
  Pain prevents me from standing for more than half an hour.
  Pain prevents me from standing for more than 10 minutes.
○ Pain prevents me from standing at all.

Section 7 - Sleeping
○ My sleep is never disturbed by pain.
○ My sleep is occasionally disturbed by pain.
○ My sleep is frequently disturbed by pain.
○ My sleep is severely disturbed by pain.
○ Pain prevents me from sleeping at all.

Section 8 - Social life
○ My social life is normal and causes me no extra pain.
○ My social life is normal but increases the degree of pain.
  Pain has no significant effect on my social life apart from limiting my more energetic interests, etc.
  Pain has restricted my social life and I do not go out as often.
  Pain has restricted social life to my home.
○ I have no social life because of pain.

Section 9 - Travelling
○ I can travel anywhere without pain.
  Pain prevents me to journeys of less than one hour.
  Pain prevents me from journeys of less than two hours.
  Pain restricts me to short necessary journeys under 30 minutes.
  Pain prevents me from travelling except to receive treatment.

Fairbank JC, Couper J, Davies JB. “The Oswestry Low Back Pain Questionnaire” Physiotherapy 1980: 66: 2
ODI Scoring:

For each section, assign score (0, 1, 2, 3, 4 or 5) based on their selected answer, with 0 being the first option (least severely affected), and 5 being the last option (most severely affected).

Sum total score for all sections (maximum score of 45).

ODI % score = \( \frac{\text{sum total score}}{45} \times 100 \)
Visual Analog Scale

Please mark a point along this horizontal line to indicate your current level of pain:

Lower back:

________________________________

No pain                            Worst pain imaginable

Affected leg:

________________________________

No pain                            Worst pain imaginable

VAS scoring:

Measure with ruler from left anchor of line, in cm.
The Questionnaire of Baecke et al (1982) for Measurement of a Person’s Habitual Physical Activity:

Score = sum (work index + sport index + leisure index)
Higher score = more physically active; lower score = less physically active

Work Index

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is your main occupation?</td>
<td>low activity</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>moderate activity</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>high activity</td>
<td>5</td>
</tr>
<tr>
<td>At work I sit</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>always</td>
<td>5</td>
</tr>
<tr>
<td>At work I stand</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>always</td>
<td>5</td>
</tr>
<tr>
<td>At work I walk</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
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<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>always</td>
<td>5</td>
</tr>
</tbody>
</table>
At work I lift heavy loads

<table>
<thead>
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<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>seldom</td>
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</tr>
<tr>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td>always</td>
<td>5</td>
</tr>
</tbody>
</table>

After working I am tired

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td>never</td>
<td>1</td>
</tr>
</tbody>
</table>

At work I sweat

<table>
<thead>
<tr>
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<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td>never</td>
<td>1</td>
</tr>
</tbody>
</table>

In comparison of others of my own age I think my work is physically

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>much heavier</td>
<td>5</td>
</tr>
<tr>
<td>heavier</td>
<td>4</td>
</tr>
<tr>
<td>as heavy</td>
<td>3</td>
</tr>
<tr>
<td>lighter</td>
<td>2</td>
</tr>
<tr>
<td>much lighter</td>
<td>1</td>
</tr>
</tbody>
</table>

where: • The work activity is according to the Netherlands Nutrition Council with (1) low activity including clerical work driving shopkeeping teaching studying housework medical practice and occupations requiring a university education; (2) middle activity including factory work plumbing carpentry and farming; (3) high activity includes dock work construction work and professional sport.

work index = \(((6 – \text{points for sitting})) + \text{SUM(points for the other 7 parameters)}) / 8
<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you play sports?</td>
<td>yes then calculate sport score</td>
<td>(see below)</td>
</tr>
<tr>
<td></td>
<td>• sport score &gt;= 12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>• sport score 8 to &lt; 12</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>• sport score 4 to &lt; 8</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>• sport score 0.01 to &lt; 4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>• sport score = 0</td>
<td>1</td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>In comparison with others of my own age I think my physical activity during leisure time is</td>
<td>much more</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>More</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>the same</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Less</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>much less</td>
<td>1</td>
</tr>
<tr>
<td>During leisure time I sweat</td>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>1</td>
</tr>
<tr>
<td>During leisure time I play sport</td>
<td>Never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>Data on Most Frequently Played Sport</td>
<td>Finding</td>
<td>Value</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>--------------</td>
<td>--------</td>
</tr>
<tr>
<td>What sport do you play most frequently</td>
<td>low intensity</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>medium intensity</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>high intensity</td>
<td>1.76</td>
</tr>
<tr>
<td>How many hours do you play a week?</td>
<td>&lt; 1 hour</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1-2 hours</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2-3 hours</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3-4 hours</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>&gt; 4 hours</td>
<td>4.5</td>
</tr>
<tr>
<td>How many months do you play in a year?</td>
<td>&lt; 1 month</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>1-3 months</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>4-6 months</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>7-9 months</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>&gt; 9 months</td>
<td>0.92</td>
</tr>
</tbody>
</table>

where: • The sport intensity is divided into 3 levels: (1) low level (billiards sailing bowling golf etc) with an average energy expenditure of 0.76 MK/h; (2) middle level (badminton cycling dancing swimming tennis) with an average energy expenditure of 1.26 MJ/h; (3) high level (boxing basketball football rugby rowing) with an average energy expenditure of 1.76 MJ/h
<table>
<thead>
<tr>
<th>Data on Second Most Frequently Played Sport</th>
<th>Finding</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>What sport do you play most frequently</td>
<td>low intensity</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>medium intensity</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>high intensity</td>
<td>1.76</td>
</tr>
<tr>
<td>How many hours do you play a week?</td>
<td>&lt; 1 hour</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1-2 hours</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2-3 hours</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3-4 hours</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>&gt; 4 hours</td>
<td>4.5</td>
</tr>
<tr>
<td>How many months do you play in a year?</td>
<td>&lt; 1 month</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>1-3 months</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>4-6 months</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>7-9 months</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>&gt; 9 months</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The simple sports score is calculated as:

$$\text{simple sports score} = ((\text{value for intensity of most frequent sport}) \times (\text{value for weekly time of most frequent sport}) \times (\text{value for yearly proportion of most frequent sport})) \times ((\text{value for intensity of second sport}) \times (\text{value for weekly time of second sport}) \times (\text{value for yearly proportion of second sport}))$$

The sport index is calculated as:

$$\text{sport index} = \frac{\text{SUM(points for all 4 parameters))}}{4}$$
Leisure Index

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>During leisure time I watch television</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>During leisure time I walk</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>During leisure time I cycle</td>
<td>never</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>seldom</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>sometimes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>often</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>very often</td>
<td>5</td>
</tr>
<tr>
<td>How many minutes do you walk and/or cycle per day to and from work school and shopping?</td>
<td>&lt; 5 minutes</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5-15 minutes</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>15-30 minutes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>30-45 minutes</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>&gt; 45 minutes</td>
<td>5</td>
</tr>
</tbody>
</table>

leisure index = ((6 – (points for television watching)) + SUM(points for remaining 3 items)) / 4
APPENDIX C

Presented here are case study reports highlighting individual patient clinical conditions and notable results for LBP-R patients with (a) bilateral radiculopathy symptoms, (b) history of spinal surgery, or (c) outstanding condition other than lumbar disc herniation or bulge resulting in radiculopathy. Patients with unilateral LBP-R and spinal surgery were included in the primary data set; however, patients with bilateral LBP-R symptoms and those without disc herniation or bulge were not included.

Case #1: Bilateral LBP-R

This patient was a 59 year old female with a history of LBP-R for 63 months and moderate physical activity (Baecke score of 8.9). She had an ODI score of 8.9% and a VAS score of leg pain of 2.8. Her sciatic pain was originally in her right leg only, but in the past 12 months she began experiencing left leg sciatica as well, although not as severe as on the right side. She experiences sciatic pain in her leg, and numbness in her toes and feet.

Ultrasound analysis of her less-affected sciatic nerve CSA was very similar to the group mean data for LBP-R patients on their unaffected side, demonstrating that the low level sciatica in her left leg has not resulted in any nerve swelling symptoms, and her more-affected side sciatic nerve CSA was similar to the LBP-R patient group mean on their affected side. Her right sciatic nerve echo intensity was 11% lower than her left, which is a greater margin of difference than the LBP-R group mean for unaffected versus affected.
(4% difference). Her radiculopathy symptoms have resulted in a decreased muscle contraction index, measured by ultrasound, on her more affected right leg relative to the left, in the ES muscle (13% lower contraction index on the right side) and in the BF muscle (22% lower contraction index on the right side). There was further clear evidence of reduced muscle quality on her more-affected right side relative to her left, with increase in percent above the fat-fascia threshold in both the ES and BF muscles. In contrast to the ultrasound differences between her more and less severely affected sides, she did not have any notable side-to-side differences in EMG muscle activation timing during balance perturbations.

**Case # 2: Bilateral LBP-R**

This patient was a 24 year old male, moderately active (Baecke 8.4) and a history of LBP-R for 12 months. He had an ODI score of 20% and a VAS score of 0.5 at the lower back and 1.7 at the legs. He primarily experienced shooting pain in his hamstrings, more in the left leg than the right leg.

Interestingly, this patient demonstrated clear differences between his left and right sciatic nerves; his left sciatic nerve was 18% larger than his right side, which is a similar degree of side-to-side difference of the group mean for all unilateral LBP-R patients (19% difference). Further, his left sciatic nerve had 25% lower mean echo intensity than the right side, which is a much greater difference than the group mean difference of 4%. Potentially related to these unilateral sciatic nerve structural changes, there was evidence of local muscle structural and functional deficits in the left MG. All three indices of
muscle quality showed evidence of increased fat and fibrosis in the left MG relative to the right (30% increase in mean echo intensity and muscle-fat ratio, and 65% increase in percent above threshold). Further, left MG activation was delayed in the arm raise balance perturbation relative to the right MG. However, the muscle contraction index was 35% greater on the left, or more affected, side, which does not follow the expected trend.

Case #3: Bilateral LBP-R

This patient was a 24 year old female, moderately active (Baecke 8.1), with a history of LBP-R for 18 months. She had an ODI score of 22.2%, and a VAS score of 1.0 at the lower back and 0.8 in the legs. Her LBP-R pain began when she introduced running into her exercise routine, and she experiences shooting pain through her gluteal region and legs. Pain symptoms alternate legs, although are more frequent in her left leg than her right leg. She was clinically diagnosed with a disc bulge at the L4-L5 vertebral level.

The results for this patient are somewhat conflicting. Her sciatic nerve is 20% larger on her less affected side (right), which is unexpected, yet on her more affected side (left) she has a 20% lower mean echo intensity, which would be expected to occur along with swelling. There are no notable side-to-side differences in muscle quality, although in her MG and soleus muscles we see decreases in muscle contraction index on her more affected side, by 16% and 32%, respectively. Further, we see a delay in her MG muscle activation during the arm raise perturbation, such that her MG is activated following movement initiation, rather than in a feed-forward manner. Therefore, it appears that her symptoms are localized predominantly within her calf region.
Case #4: Bilateral LBP-R

This patient was a 20 year old male, moderately active (Baecke 7.9), with a history of LBP-R for 24 months. He had an ODI score of 46.7%, and a VAS score of 1.8 at both the lower back and legs. He experienced radiculopathy symptoms in both his left and right legs equally.

As would be expected, this patient did not have side-to-side difference in sciatic nerve CSA; however, the CSA on both sides (0.62 cm², 0.66 cm²) was within range of the group mean for the affected side of unilateral LBP-R patients. Further, there were no side-to-side differences in muscle quality or muscle contraction index. The only side-to-side difference was a delay in MG activation on the right side, such that MG activated following movement initiation rather than in a feed-forward manner. Muscle activation timings during the weight drop perturbations were very close side-to-side, and not delayed compared to control participants.

Case #5: Bilateral LBP-R

This patient was a 62 year old male, moderately active (Baecke 8.8), with a history of LBP-R for 36 months, although he had experienced on and off LBP without radiculopathy for 25 years. He had an ODI score of 29% and a VAS of 4.7 at the lower back and 7 at the legs. His LBP-R symptoms were left side dominant 25 years ago, diagnosed as L5 level nerve pinching, and resulted in notable calf atrophy, loss of dorsiflexion motor control and symptoms of foot drop. Three years ago, he began
experiencing right-side dominant radiculopathy and numbness. Two weeks prior to participating in this research study, he experienced complete loss of sensation in his right foot and loss of motor control, resulting in an inability to plantarflex. He currently experiences pain in both of posterior legs and into his feet. He was unable to complete the rise to toe perturbation of balance due to plantarflexion weakness in his left leg.

When examining the results for this patient, there is some evidence of the current right-side dominant symptoms. On the right side, the sciatic nerve CSA was 25% larger, BF muscle contraction index was 45% lower, and ES echo intensity mean and muscle-fascia ratio were 45% greater. In addition to noted difficulty in plantarflexion on the right side, there was a large delay in MG activation during the arm raise, such that the right MG was activated following arm movement initiation rather than in a feed-forward manner. However, there is also some evidence of reduced muscle quality in the left MG muscle, which was notably atrophied; all three measures of muscle quality were 13-15% higher on the right side, indicating increased fat and fibrosis infiltration.

**Case #6: Bilateral LBP-R with surgery**

This patient was a 56 year old female, BMI of 31, low activity level (Baecke 5.5), with a history of LBP-R for 240 months. She had an ODI score of 37.8%, and VAS scores of 1.6 at the lower back and 5.4 at the legs. MRI imaging confirmed disc herniation at L1/L2, disc bulge at L2/L3 and L3/L4, and spinal stenosis from L1 to L4. She experienced burning, pain and tingling in her right and left posterior leg, as well as referred right leg pain in the anterior, outer and inner thigh. She had spinal surgery,
specifically a laminectomy at L1 to L3. Additionally, she was diagnosed with fibromyalgia, essential tremors in both arms, carpal tunnel syndrome, as well as Hallux Rigidus in her right foot, for which she had surgery one month prior to participation in this research study. She was unable to complete the rise to toe trials due to ongoing recovery from her foot surgery.

We were not able to trace the CSA of the sciatic nerve in this patient, due to unclear nerve boundaries. This patient experienced right-side dominant leg pain, and this was apparent in increased percent above fat-fascia threshold in the right ES, BF and MG muscles, by approximately 60%. However, the other metrics of muscle quality, mean echo intensity and muscle-fascia ratio, did not have a notable difference between sides. There were no side-to-side differences in muscle ultrasound contraction index, and further, delays in muscle activation timing were seen in both the left and right sides, compared to control participants.

**Case #7: Unilateral LBP-R with surgery**

This patient was a 22 year old female, moderately active (Baecke 8.3), with a history of LBP-R for 84 months. She had an ODI score of 13.3%, and VAS scores of 0.8 at both her lower back and legs. She experienced radiculopathy on her right side only, and had pain in her leg and tingling and numbness in her feet. She had spinal surgery, discectomy, three years ago but still experiences symptoms.
There was clear evidence of ride-side radiculopathy that was in line with the group mean LBP-R data. Affected side sciatic nerve CSA was 14% larger and mean echo intensity was decreased by 8%, relative to the unaffected side. There was evidence of reduced muscle quality in the BF muscle, but no notable side-to-side changes in the ES or MG muscles. When looking at muscle contraction with ultrasound imaging, this patient demonstrated a 17% decrease in ES contraction index on the right side. Further, the muscle activation of ES and MG were delayed during the weight drop perturbation trials. There were no results from this patient that indicated that her history of spinal surgery altered her results from the group mean of unilateral LBP-R patients.

**Case #8: Unilateral LBP-R with surgery**

This patient was a 48 year old female, moderately active (Baecke 8.3), with a history of LBP-R for 192 months. She had an ODI score of 22.2%, and VAS scores of 0.1 at the lower back, and 2.8 in her leg. She had MRI-confirmed disc herniations at L4/L5 and L5/L6, and one year prior to participation in this research study had a discectomy at L4/L5 and L5/L6. Prior to surgery, she experienced complete numbness and foot drop symptoms in her left foot as well as pain down her leg. Following surgery, she still experiences lingering foot numbness as well as rare shooting pain down her leg and into her foot.

Ultrasound imaging of this patient’s sciatic nerve shows a dramatic increase in CSA on the affected side (54% larger), and a similar decrease in mean echo intensity (45% decrease), both demonstrating severe sciatic nerve pathology. There was a corresponding
decrease in ES muscle quality, in all three measures, but not in the BF or MG. Similarly, only the ES demonstrated any notable muscle activation timing delay on the affected side during the weight drop perturbations, and both BF and MG timing did not have large side-to-side differences. Therefore it seems that in this patient, sciatic nerve pathology is primarily having an impact in the ES muscles, and not in the leg.

Case #9: Unilateral LBP-R with surgery

This patient was a 62 year old male, very physically active (Baecke 11.1), with a history of LBP-R for 360 months. He had an ODI score of 20%, and VAS scores of 1.3 in the lower back and 1.6 in the leg. He had MRI-confirmed disc herniation at L4/L5 and L5/S1. He had a laminectomy and discectomy at L4/L5 and L5/S1 in 1985, and in 1984 had a surgery to inject Chymopapain into the disc herniation to reduce its size. He experiences radiating pain down the left leg and into the foot, as well as coldness and tingling in the foot. He has also been diagnosed with a possible case of ankylosing spondylitis (spine inflammation).

Similar to the previous case, there is clear evidence of sciatic nerve pathology, with the affected (left) side having a 56% increase in CSA and a 9% decrease in echo intensity mean. Muscle quality changes are only seen at the ES, with increases in all three measures indicating increased fat and fibrosis infiltration on the left side relative to the unaffected right side. The muscle ultrasound index was not calculated for the ES muscle (unable to measure thickness in the contracted state), but there was a 20% decrease on the affected side in the BF muscle, although in contrast there was a 15% increase on the
affected side in MG. Finally, ES muscle activation was delayed on the affected side during the unanticipated weight drop trials, but not when the weight was anticipated. These results do not provide any indication that this patient’s previous surgeries confounded the results.

Case #10: Unilateral LBP-R with surgery

This patient was a 55 year old female, moderately physically active (Baecke 8.1), with a history of LBP-R and current pain symptoms for 8 months. She had an ODI score of 20%, and VAS scores of 0.3 in the lower back and 2.4 in the leg. She had an MRI-confirmed disc protrusion at L4-L5 resulting in left leg radiating pain. She first experienced pain while gardening, and pain was worst while sleeping. She had a left microdiscectomy at L4/L5 8 years prior to participating in this study due to previous episodes of lower back pain.

There was not as much evidence of sciatic nerve swelling in this patient, an only 4% increase in CSA on the affected side. However, there were delays in muscle activation timing at the ES and BF muscles on the affected side in the weight drop perturbations. Further, the ES and soleus muscles had decreased contraction indices on the affected side, however MG showed the opposite trend. When muscle quality was assessed, there was some indication of increased fat and fibrosis infiltration at the ES and MG, but the opposite trend was seen in BF, showing more fat and fibrosis on the unaffected side than the affected side. The most notable result for this patient was the delays in activation
timing of ES and BF unilaterally in the weight drop trial; this demonstrates that delayed muscle activation at the lower back continues into the lower limb.

**Case #11: Unilateral LBP-R resulting from scoliosis**

This patient was a 53 year old female, quite physically active (Baecke 9.8), with a history of LBP-R for 408 months. She had an ODI score of 20%, and VAS scores of 1.6 in the lower back and 0 in the leg. She had scoliosis that resulted in consistent low-level LBP with flare-ups of left leg radiculopathy that occurred previously during pregnancy, and currently due to lifting or prolonged physical activity.

Most notably, this patient had a sciatic nerve CSA almost double the size on her affected (left) leg, with a slight decrease in echo intensity mean. In line with this, there were large increases in all three measures of muscle quality for ES and BF, indicating increased fat and fibrosis infiltration into the muscles on the affected side. This finding is in agreement with an investigation into muscle fat infiltration in patients with degenerative lumbar scoliosis causing unilateral radiculopathy by Shafaq et al (2012). Using magnetic resonance imaging, Shafaq et al (2012) found increased multifidus fat infiltration area on the affected side of patients relative to the unaffected side, and relative to control participants. However, the ultrasound contraction index results were somewhat unexpected; we were unable to measure ES thickness during the contracted state, but both BF and MG had higher contraction indices on the affected side, and only soleus showed a decreased contraction index on the affected side, as would have been expected for all of the muscles. It appears that this patient presented with principally structural changes
(sciatic nerve and muscle quality) and did not have as pronounced functional changes in muscle activation or contraction. This may be attributed to her high level of physical activity.