Correlation Between Self-Report Measures of Function and Lower Limb Motor Performance in Patients With and Without Imaging Evidence of Unilateral Lumbar Nerve Root Compression

by

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Abstract

Lumbar radiculopathy is defined as compression of a lumbar nerve root, resulting in motor, sensory and, or reflex changes, correlating with the effected segment. Magnetic resonance imaging (MRI) investigations remain the gold standard for diagnosis of this condition. However, research studies provide evidence for the limitations of imaging to define the functional impact of various spinal conditions. The present study considered the impact of lumbar nerve compression on motor performance during a Fitts' lower limb reaching task. Participants were stratified into three groups based on lumbar imaging and clinical presentation. Group 1 included subjects with imaging indicating lumbar nerve root compression, who presented with neurological deficit. Group 2 subjects demonstrated imaging evidence of nerve compression, without motor, sensory or reflex change. Group 3 were neurologically intact, and possessed degenerative changes on lumbar imaging films.

Movement time (MT), reaction time (RT), peak acceleration (PA), peak velocity (PV), time to peak acceleration (ttPA), time to peak velocity (ttPV), constant error (CE), absolute error (AE) and variable error (VE) were analyzed using 3 Group (1,2,3) by 4 ID (3,4a,4b,5) ANOVA models. The sole main effect for group was AE, where subjects in group 1 tended to land further from the target, compared to those in group 3.

A 2 Group (effected, non-effected limb) by 4 ID (3,4a,4b,5) ANOVA model revealed longer MTs and lower PVs for the effected limb in group 2. Between limb comparisons determined lower PAs and longer ttPAs for the non-dominant limb in group 3. There were no main effects for group, or group by ID interactions found between limbs for group 1. However, a tendency to undershoot the target at larger amplitudes of movement was a characteristic shared by group 1 and 2 participants.

Sub-analysis of between limb differences, using limb dominance to stratify subjects yielded main effects for PA and PV for group 2, when the dominant leg was the effected leg. The effected, dominant limb exhibited lower values for PA and PV, compared to the non-dominant, non-effected limb. Alterations in accuracy were noted for groups 1 and 2 when the non-dominant limb was impacted. The results align with the serial hybrid control theory regarding lateralization.

Pearson's Correlation analysis revealed many significant correlations for groups 2 and 3 between self-report measures and motor performance variables. There was a lack of association between subjective and objective measures in group 1, which suggests that the presence of neurological deficit may impede evaluation of functional capability.

Overall, imaging did not predict most aspects of functional performance, when legs were collapsed for analysis. However, the Fitts' task was able to differentiate groups, by way of accuracy evaluation and within group, between limb comparisons.

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Dedication

This work is dedicated to my parents, for igniting my passion for learning and to my husband and children, for their enduring support and limitless sacrifice. You are my foundation and my motivation.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Incidence and Impact of Lumbar Conditions

The management of low back pain is becoming increasingly onerous, globally (Clark & Horton, 2018). Between 1990 and 2015, years lived with low back disability increased by 54% worldwide (Hartvigsen et al., 2018). In 2015, the point prevalence of low back pain was estimated to be 540 million people. Low back pain has been labelled as the most significant factor related to disability, globally (Hartvigsen et al., 2018). The prevalence of low back pain rises to around 40% between the ages of 9-18 (Calvo-Munoz, Gomez-Conesa, & Sanchez-Meca, 2013). It peaks in middle age, with a greater impact on activity tolerance as age advances (Hoy et al., 2012). Nearly all individuals over the age of 18 will experience back-related symptoms at some point in their lifetime (Hartvigsen et al., 2018; Lemeunier, Leboeuf-Yde, & Gagey, 2012). Those who experience radicular pain, related to lumbar radiculopathy tend to describe more intensified pain, and disability, compared to individuals with back pain complaints only (Kongsted, Kent, Jensen, Albert, & Manniche, 2013).

The cause of back-pain related dysfunction is thought to be the result of an interplay between biophysical, psychosocial, cultural, comorbidity and central processing factors (Hartvigsen et al., 2018). Fear avoidance and maladaptive pain cognitions may contribute to disability in chronic conditions, such as back pain (Crombez, Eccleston, Van Damme, Vlaeyen, & Karoly, 2012).

The financial burden of managing back-related pain has been compared to the cost of shouldering other major pathologies, such as cardiovascular disease. (Maniadakis & Gray, 2000). The expected costs and associated dysfunction related to low back pain is expected to rise in the upcoming decade, according to a recent article in the Lancet (Clark & Horton, 2018). This

may in part, be due to a lack of understanding of the mechanisms that are associated with low back pain by healthcare providers and inappropriate selection of assessment and treatment options (Foster et al., 2018).

LITTERATURE REVIEW

Lumbar Radiculopathy

Lumbar radiculopathy (LR) is defined as compression, or irritation of one, or more lumbar nerve roots. It is often associated with motor, sensory, reflex changes, and, or pain referral into the distribution of the effected nerve root (Govind, 2004). Common causes of LR include intervertebral disc herniation (most common), and degenerative changes, such as facet arthropathy, ligament hypertrophy, bulging discs and endplate spurring, resulting in narrowing of the lateral recess, foraminal space, or central spinal canal (Tarulli & Raynor, 2007). Less common documented causes of LR include nerve root compression due to tumours, infections, synovial cysts and vascular anomalies (Govind, 2004).

The prevalence of lumbar radiculopathy, associated with disc herniation has variable estimates in the literature. The results of Schoenfeld's work (2012) include a reported incidence of lumbar radiculopathy between 4-86 per 1000 persons (Schoenfeld, Laughlin, Bader, & Bono, 2012). Rhee et al (2006) report a 10% population estimate of low back pain associated with sciatica symptoms (Rhee, Schaufele, & Abdu, 2006). Van Boxem et al (2010) estimate a point prevalence of disc herniation with lumbar radiculopathy between 4.6-13.4%, with a lifetime prevalence of 1.2-43% (Van Boxem et al., 2010). Data on questionnaires administered to 5000 individuals revealed an annual prevalence of 2.2%, and an incidence of 1.44% for disc related sciatica, in this sampled population (Younes et al., 2006). Konstantinou argues that the discrepancy in epidemiological data may relate to variability in sampling techniques, conflicting

definitions of radiculopathy, and sciatica symptoms (Konstantinou & Dunn, 2008). Lumbar radiculopathy is often interchangeable with the term sciatica. However, the classic definition of sciatica is pathology of the sciatic nerve, which by definition, is a peripheral neuralgia.

Pathophysiology

Disc herniation is characterized by sequestration of discal material beyond the normal constraints of the disc annulus (Kreiner et al., 2014). Mechanical stress was proposed as a plausible explanation for the signs / symptoms associated with disc herniation in the 1940's (Rhee et al., 2006). Due to its' fragile structure (Rhee et al., 2006) the lumbar nerve root may be inherently susceptible to compressive forces. It is encompassed by a thin endoneurium, cerebrospinal fluid and dural lining (Rhee et al., 2006) and is distinct, in terms of its vascular vulnerability (Weber, 1994). These vulnerable structures are not designed to withstand mechanical deformation (Rhee et al., 2006). Mechanical stress results in intraneural edema, ischemia and fibrosis of the effected nerve root (Rhee et al., 2006).

However, there is an argument that other mechanisms are involved in the evolution of symptoms, as not all imaging findings of nerve root compression correlate with subjective pain complaints (Rhee et al., 2006). In the 1970's it was proposed that repeated compression, related to disc herniation results in a chemical/inflammatory reaction, and subsequent mechanical sensitivity of the nerve root (Rhee et al., 2006). Kuslich et al. (1991) reported a discrepancy in subjective pain complaints during mechanical stimulation of compressed nerve roots and normal nerve roots within non-sedated subjects during lumbar discectomy. Mechanical stimulation of a nerve root exposed to disc herniation reproduced pain 90% of the time, where compression of roots not exposed to disc herniation resulted in admitted pain in only 9% of trials (Kuslich, Ulstrom, & Michael, 1991).

When the disc annulus is compromised, sequestration of the nucleus pulposus into the spinal canal ensues (Shahbandar, & Press, 2005). The nucleus pulposus contains proteoglycans and collagen. There are a number of bioactive molecules in the nucleus puplosus that have been suggested as chemical mediators, including phospholipase A2, tumor necrosis factor-alpha, interleukin 23 and nitric oxide (Brisby et al., 2000). Although, their exact roles have been debated, it is believed that exposure to these mediators results in inflammation of the nerve root (Laroche & Perrot, 2013; Rhee et al., 2006). It is postulated that a combination of mechanical stress, inflammation and subsequent sensitization results in the clinical manifestations of radiculopathy.

Symptomatic nerve root compromise due to degenerative stenosis may be primarily due to ongoing mechanical pressure (Lipetz, 2002). It is theorized that sustained compression of nerve roots results in sensitization of neural tissue, and subsequent symptoms of radicular pain, or radiculopathy (Govind, 2004). However, there may be an associated biochemical component if disc material is breached through an annular tear, or if the nerve root is exposed to synovial fluid from a degenerative facet joint (Lipetz, 2002).

The Natural History of Lumbar Radiculopathy

The North American Spine Society (NASS) published evidence based clinical practice guidelines, regarding the natural history of lumbar disc herniation (Kreiner et al., 2014). Sixty-five articles were included in their analysis. The group was unable to epitomize the typical course of disc herniation, as most studies reported outcomes of disc-related pathology for subjects who obtained interventional therapies. However, it is the opinion of the group that the natural course of lumbar disc herniation likely has a favourable clinical outcome, as most studies

report improvement in symptoms and regression in the size of herniation, regardless of treatment pursued (Kreiner et al., 2014).

One of the earliest studies on the natural history of disc herniation was performed by Hakelius, and associates in 1970. Their work included 38 patients with confirmed lumbosacral radiculopathy, of which, 58% were symptom-free in thirty days, and 88% were symptom-free in six months (Hakelius, 1970). In another study by Saal and Saal, (1989) 90% of patients with confirmed lumbar radiculopathy obtained either excellent, or good self-reported outcomes after 31 months of back education and lumbar stabilization programming (Saal & Saal, 1989). In 1983, a cohort study by Weber was published, which followed 280 patients with confirmed lumbar radiculopathy for 10 years. Subjects were categorized into two groups. One group received surgical intervention, and the other group was managed conservatively. The group that received surgical interventions demonstrated improved ratings (good, fair, poor, bad) on a follow-up examination (neurological assessment, psychological assessment, pain intensity, tenderness, work status, use of analgesics, participation in leisure, spinal range of motion and straight leg raise) compared to those treated conservatively at one year. However, at the 4-year follow-up, the differences between groups were no longer statistically significant. Observation/examination findings (listed above) changed very minimally within both groups in the last 6 years of the study. Again, these differences were not statistically significant (Weber, 1983). Short term outcomes of surgery were superior then conservative treatment for management of lumbar radiculopathy. However, no significant differences were found between groups after 4 years of follow-up evaluations.

Unfavorable outcomes of the sequela of disc herniation are evident in the literature. Employees at the National Electricity and Gas Company in 1991 participated in an investigation

of sciatica, involving a total of 3164 workers. Of those studied, 622 had symptoms consistent with sciatica (confirmation of back pain with leg pain referral on questionnaire). It was concluded that 55% had ongoing symptoms in 1993, and that 53% remained symptomatic in 1995 (Tubach, Beaute, & Leclerc, 2004). However, the definition of sciatica in this study is not consistent with the accepted definition of lumbar radiculopathy, which is objective evidence of motor, sensory, or reflex changes correlating to compression of a lumbar nerve root. Literature review of reported natural history of lumbar radiculopathy by Hooten and colleagues concluded that between 15-40% of individuals will report symptom recurrence or ongoing symptoms beyond a year after initial onset (Hooten & Cohen, 2015).

There is suggestion that larger disc herniations demonstrate greater regression in subsequent imaging. In a study by Cribb et al, fifteen patients with disc herniation classified as massive (greater then 50% of spinal canal occupied by disc material), demonstrated an average reduction in size of the sequestrated disc by 80% in repeat MRI films, (completed 24 months post-initial exam), (Cribb, Jaffray, & Cassar-Pullicino, 2007). It has been proposed that larger disc herniations regress further due to high water content (Rhee et al., 2006).

The natural history of nerve root compression due to degenerative changes, is not as propitious as compression, due to disc herniation (Hooten & Cohen, 2015). Spinal stenosis is narrowing of the spaces occupied by nerve roots, or the spinal cord. The cause of this condition is usually multifactorial (Hooten & Cohen, 2015). The degenerative changes that contribute to lateral recess or foraminal narrowing, such as disc protrusion, osteophyte formation and hypertrophy of the facet joints/ligamentum flavum do not tend to resolve overtime (Hooten & Cohen, 2015). A review of available literature on the natural course of lumbar spinal stenosis by Benoit and associates reports a consensus that surgical interventions are associated with

improved pain and function, in comparison to conservative strategies. However, a significant number of patients with confirmed lumbar spinal stenosis (LSS) remain stable, in fact, even improve over time, up to 10 years (Benoist, 2002). For example, in a cohort study that followed 56 conservatively managed patients with LSS, 60.7% did not change clinically, or improved by the 88 month follow-up (Micankova Adamova, Vohanka, Dusek, Jarkovsky, & Bednarik, 2012). However, these studies did not clearly define LSS. It is unclear whether spinal stenosis relates to foraminal, lateral, or central canal narrowing, or any combination. Therefore, it is uncertain if the natural history of unilateral, single segmental nerve root compression, due to degenerative changes has a similar prognosis to central lumbar stenosis, or multi-segmental nerve root compression.

Clinical Impact

The pathological mechanisms of nerve root compression can result in reduced neuronal firings, or nerve conduction block, resulting in motor, and, or sensory deficit (Govind, 2004; Lipetz, 2002). However, it is estimated that only 30-35% of patients with disc-related lumbar radiculopathy develop motor loss (Sharma, Lee, & Cole, 2012). Diminished reflexes are also associated with nerve compression. When a muscle tendon is struck by a reflex hammer, the stretch of the muscle spindle causes a signal to travel to the alpha motor neuron at the appropriate segmental level in the spinal cord. An efferent signal is then sent to the muscle, inducing contraction (Ginanneschi, Mondelli, Piu, & Rossi, 2015). Pathology of the nerve root may interrupt reflex action. Sensory, motor and reflex changes may occur concurrently in cases of nerve compression, may exist independently, or not at all (Govind, 2004). Webber argues that the clinical manifestation of disc related radiculopathy may depend on the size, localization and advancement of disc herniation (Weber, Holme, & Amlie, 1993).

The term radicular pain is not synonymous with radiculopathy, which implies objective motor, and, or sensory deficit (Govind, 2004). Radicular pain is often associated with lumbar radiculopathy. However, radicular pain is the result of stimulation of nerve, or nerve root nociceptive afferent fibres, which can evolve into ectopic nerve impulse generation (Govind, 2004). Radicular pain does not imply injury, or insult to neurological tissue (Laroche & Perrot, 2013). In radiculopathy, objective motor, sensory, or reflexes changes may be evident, as mechanical/chemical deformation of the nerve results in a pathological state (Laroche & Perrot, 2013).

The North American Spine Society published evidence based clinical practice guidelines for the management of lumbar disc herniation with radiculopathy in 2014. Grade A evidence represents agreement between reviewed studies for, or against an intervention. Clinical application of myotomal and sensory testing is recommended, as are the use of the straight leg test, or the Lasegue sign/ crossed Lasegue sign as diagnostic tools for identifying disc- related, lumbar radiculopathy. The Lasegue sign is synonymous with the straight leg test. A positive test is signified by reproduction of pain in the distribution of a lumbosacral nerve root, while the subject's leg is elevated above the treatment surface, with the knee extended. The crossed Lasegue, or crossed straight leg test is positive when elevation of the contralateral lower limb evokes symptoms into a nerve root pattern in the effected lower limb. Reproduction of leg pain during testing implicates lumbosacral nerve root irritation. The assigned grade of recommendation for use of these clinical tests is grade A evidence (Kreiner et al., 2014).

Imaging Definition of Nerve Root Compression

An MRI of the lumbar spine typically consists of sagittal T1-weighted sequences, sagittal T2-weighted sequences and axial T2-weighted imaging films. Sagittal T1-weighted images can

assist in determining abnormalities in spinal alignment. They identify the presence of neural foraminal narrowing, by the distinction between fat and nerve roots (Buller, 2018). Sagittal T2-weighted images are advantageous for determining variance between fluid (ie: cerebrospinal fluid) and outlying structures (ie: spinal cord, etc.). Like T1-weighted films, they provide information on spinal alignment. The T2 images are preferred for evaluation of the intervertebral disc (Buller, 2018). Axial cut images reveal relationships between the central canal, foraminal and lateral recess space, the disc, articular structures and ligaments (Buller, 2018). Axial cuts are excellent for assessment of the descending and traversing nerve roots (van Rijn et al., 2005).

Studies comparing computed topography and magnetic resonance imaging for evaluation of disc herniation and lumbar nerve root compression were found in a literature search. Van Rijn et al (2005) employed two experienced radiologists to grade disc herniation and lumbar nerve root compression for 456 nerve roots using both MRI and CT imaging films. There was no significant advantage of CT over MRI for evaluation of lumbar discs, however there was superior interrater agreement of lumbar nerve root compression using MR imaging. Evaluators debated nerve compression grades for 40/456 nerve roots using CT scan images, versus 22/456 nerve roots, using MRI films. This difference was found to be statistically significant (van Rijn et al., 2005).

In a study by Bartynski et al (2003), MR imaging, conventional myelography and CT scans of the lumbar spine were performed for 26 patients who underwent surgery for radiculopathy, due to nerve root compromise in the lateral recess. Nerve root compression was graded using MRI, CT and myelopathy investigation. Grading designations were then compared to intra-operative evaluation of the effected descending nerve root. MR imaging underestimated

nerve root compression in 28-29% of cases and CT underestimated nerve root compression in 38% of the surgical population (Bartynski & Lin, 2003).

The NASS suggests that magnetic resonance imaging is a gold standard for diagnosing lumbar radiculopathy (Kreiner et al., 2014). However, there is a lack of consistency among radiologists, in terms of language used to describe the impact on neurological tissue by disc material, or other degenerative changes (Li, Fredrickson, & Resnick, 2015). This has led to perplexity in determining the clinical impact of imaging findings.

Classic descriptions of nerve root compression may include some of the following terminology: amputation of the nerve root sleeve, widening of the nerve root above this level (indication of swelling), flattening of the dural sac, and displacement of the epidural fat. There is literature support to establish common language when evaluating the impact of neurological tissue (Li et al., 2015).

A systematic review by Li et al (2015) searched multiple databases for grading systems of nerve root compression. Ten papers that evaluated disc herniation and nerve root compression were found. Two commonly cited grading systems were identified as having proven reliability. The grading systems were proposed by Pfirrmann et al (2004) and Van Rijn et al (2005). Pfirmman describes a four-point grading system to distinguish lumbar nerve root compromise by disc material. Grade 0 (normal) describes preservation of epidural fat between the nerve root and the lumbar disc. Grade 0 implies no evidence of nerve contact. In grade 1 (contact), one can visualize contact of the nerve root by the disc, without deviation of the nerve root. The epidural fat layer is not visualized here. Grade 2 (deviation) is defined as nerve root contact with evidence of dorsal deviation. Grade 3 (compression) characterizes a nerve root wedged between the spinal canal and the descending or traversing lumbar nerve root. It often appears flattened,

compared to the contralateral nerve root. In this case, the nerve root cannot be distinguished from discal material (Pfirrmann et al., 2004). According to Pfirrmann, the axial cut MRI film is better for visualizing the nerve root (Bartynski & Lin, 2003). Statistical evaluation demonstrates a strong correlation between Pfirrmann's proposed imaging grading system and surgical evaluation of 94 nerve roots (r=0.86) (Pfirrmann et al., 2004). A separate evaluation revealed significant intra-observer accord (k= 0.72-0.77) and inter-observer accord (k= 0.62-0.67) for three different evaluators (Pfirrmann et al., 2004).

Pfirrmann's classification system was re-evaluated in 2018 by Kaliya-Perumal et al. Five orthopedic residents independently evaluated fifty axial lumbar images, using Pfirrmann's system. Statistical analysis suggests 100% agreement for 14 images, 80% agreement for 22 images and 60% agreement for 14 images. Kaliya-Perumal's paper (2018) reports an overall agreement of 80% +/- 15.1%. There was moderate interrater reliability (0.521), and more significant intrarater reliability (0.696). Disagreement between evaluators was most evident between grade 0 and grade 1 designation. There was less dispute in allocation of grade 2 and grade 3, the more clinically significant grades (Kaliya-Perumal et al., 2018). Pfirrmann's classification is one of the most widely used and widely cited classification system reported in the literature (van Rijn et al., 2005).

In 2005, Van Rijn proposed a 5- point scale for classification of nerve root compression. This scale contains the following categories: "definitely no root compression", "possibly no root compression", "indeterminate", "possibly root compression" and "definitely root compression". This nomenclature is sometimes regarded as root compression (last two categories) and no nerve root compression (first 3 categories). A systematic review of lumbar nerve root assessment reported superior interrater agreement using Van Rijn's grading, compared to Pfirrmann's

system for determination of lumbar nerve root compression (Li et al., 2015). In consideration of the strong interrater agreement, this system was deemed to be the most reliable system to delineate lumbar nerve root compromise. However, both systems are widely used because of their lucidity and proven reliability (Li et al., 2015).

Reliability of Imaging

Previous studies challenge the diagnostic value of MRI or CT scans for disc herniation (Boos et al., 1995; Govind, 2004). The MRI investigations on asymptomatic individuals commonly reveal disc herniation (Truumees, 2015). Work by Jensen et al (1994) revealed disc bulging at one or more levels in 52% , disc protrusion in 27% and disc extrusion in 1% of 98 asymptomatic individuals who underwent MRI investigations for the lumbar spine. Boos et al (1995) argue that minor disc herniations identified on MRI films may not explain the prevalence of pain and dysfunction, as up to 63% of asymptomatic individuals imaged in this study demonstrate disc herniation, or disc prolapse.

The prognostic value of imaging is also questioned. Repeat MRI on 31 subjects, who were asymptomatic in 1989, were performed seven years after the original MRI investigations. There was no association between the degree of lumbar symptoms developed in this group and the degree of lumbar pathology suggested by the initial studies. Imaging was not predictive of the onset, or duration of symptoms (Borenstein et al., 2001).

It is debated whether a reduction in the size, or degree of disc herniation translates into a relative abatement in subjective pain. In a study by Bush et al (1992), 23 of 165 subjects with sciatica due to lumbar nerve root compromise required surgery. All subjects managed by conservative therapies reported significant improvement in symptoms. The average reduction in reported pain intensity was 94%. Repeat imaging confirmed resolution, or significant reduction

of disc herniation in 76% of cases, and resolution, or improvement in disc bulging in 26% of subjects. In this study, improved symptoms correlated with imaging changes, suggestive of regression of discal material (Bush, Cowan, Katz, & Gishen, 1992). Correlations between improved imaging and symptoms were also reported in others studies (Benoist, 2002; Saal, 1996).

In a study by Ellenburg et al in 1993, subjects with confirmed disc herniation and associated radiculopathy were imaged using CT scans, and followed for repeat imaging between 6-18 months. The authors reported improvement in the size of herniation in 78% of this patient population. Fourteen out of eighteen patients completed the study. Several subjects (43%) demonstrated complete resolution of disc extrusion; 36% demonstrated a reduction in size of disc fragments and 21% did not demonstrate segmental changes at follow-up. Only one of the 14 subjects had a recurrence of symptoms, and underwent subsequent surgical interventions. Unlike findings by Benoist, Saal and Bush, there was no difference in reported symptoms at follow-up, regardless of repeat CT scan findings (Ellenberg et al., 1993). However, the small sample size used in the Ellenberg study (1993) may not be sufficiently large to make inferences.

Many studies have explored the relationship between imaging findings and subjective pain complaints, concluding that a weak relationship exists between the two (Haig, Tong, Yamakawa, Quint, et al., 2006). Fewer studies evaluated the ability of imaging to predict functional impact of various lumbar conditions. In a study by Chapman et al (2016), 286 adult subjects with symptomatic lumbar scoliosis, were evaluated in terms of radiographic parameters (Cobb angle, pelvic tilt, pelvic incidence-lumbar lordosis) and self-report questionnaires regarding pain and disability (Oswestry Disability Index, Scoliosis Research Scociety-23). The results provide evidence of a weak correlation between the severity of anatomic

deformity/variation and subjective evaluation of pain and dysfunction (Chapman et al., 2016). A cohort study attempted to determine if pain and function can be predicted by MRI scans, confirming or precluding a diagnosis of central spinal stenosis. This study included 23 asymptomatic subjects, 28 subjects with back pain (no imaging evidence of central stenosis), and 32 with signs/symptoms of central stenosis, confirmed on MRI. They were all evaluated by initial and 18-month follow-up screening questionnaires, physical examination for neurological deficits, MRI, EMG studies and objective gait analysis. Interpretation of results provided evidence that anatomic findings and measured neurological deficits associated with central stenosis were not predictive of pain, or dysfunction on follow-up examination. Current presence of pain did not predict future pain, or evaluations of function in the population studied. However, function determined on initial inspection predicted future functional status (Haig, Tong, Yamakawa, Parres, et al., 2006).

In summary, despite the fact that MRI investigation for lumbar radiculopathy remains the gold standard for diagnosis, prior studies expose limitations of imaging to define, or predict differences in the impact of this condition among those with suspected pathology. It has been suggested that there is a role for clinicians to establish a correlation between symptoms and imaging to improve diagnostic accuracy (Iversen et al., 2013).

Subjective Versus Objective Measurements of Function

If subjective reports of function are predictive of future functional status for certain lumbar populations, (Haig, Tong, Yamakawa, Parres, et al., 2006), researchers have also questioned whether a significant correlation exists between self-reported function and objective measures of performance. In a study by Lee et al (2001), 83 participants with non-specific low back pain completed the Roland Morris questionnaire, a self-evaluation of activities commonly

impaired by those with reported lumbar pain complaints. Pearson's correlation analyses were performed to determine the strength of the association between questionnaire scores and the results of physical performance tests (lumbar range of motion, standing transfers and reaching tasks- while holding a weighted object). Correlation coefficients ranged from 0.29 to 0.41, suggesting that a mild-moderate correlation between measures of function exist (Lee, Simmonds, Novy, & Jones, 2001). A modest association between the two suggests that a comprehensive evaluation of physical capability should involve both subjective and objective analysis (Lee et al., 2001).

Patients with low back pain may inaccurately report their functional capabilities, due to the influence of pain catastrophization, fear avoidance beliefs and other psychological factors (Heymans et al., 2007; Shaw et al., 2007). Chronic pain suffers may be more at risk for developing maladaptive pain cognitions (Turk & Okifuji, 2002). Evaluations of trunk range of motion, gait analysis and self-report questionnaires regarding function (Oswestry Disability Index, EQ-5D questionnaire) were conducted on 26 patients requiring lumbosacral surgical fusion pre and post-operatively. A poor association was found between subjective and objective measures of function pre-operatively, but a stronger correlation was revealed with post-operative assessment (Stief, Meurer, Wienand, Rauschmann, & Rickert, 2018). Psychological influences were suggested as a plausible inference for pre-operative findings. A stronger correlation post-operatively, may be due to a reduction in pain. As pain dissipates, psychological factors have less effect on subjective evaluations (Stief et al., 2018).

There is support for evaluating lumbar related disability using objective measures (Stief et al., 2018). There is an argument that function, rather than imaging findings should be considered when defining the impact of lumbar pathology (Lehman, 2004). A systematic review

by Lehman et al (2004) investigated strategies used in research to evaluate spinal kinematics of asymptomatic and low back pain populations. This study identified 3 common methods of evaluation: end-range spinal motion analysis, higher order spinal kinematics (displacement, velocity, acceleration), and spinal proprioception. It was concluded that higher order kinematic analysis is the most widely cited/researched technique regarding lumbar biomechanics, and the most sensitize in revealing differences in functional capability between groups (Lehman, 2004). It is known that patients with confirmed lumbar nerve root compression often demonstrate alterations in vibration sense, measures of dynamic balance (center of pressure in static positioning and during forward reaching) and leg strength then healthy controls (Lin & Lin, 2002). Given literature reported shortcomings of MRI and self-report questionnaires to define the impact of lumbar conditions, there may exist a role for objective performance evaluation.

Self-Report Questionnaires

Despite suggestion by Lee (2001) and Steif (2018), (self-report questionnaires may not accurately reflect a back pain subject's functional capability), these instruments are often used in the research and clinical worlds to describe the severity of lumbar conditions, and to evaluate change. Clinical practice guidelines exist in support of self-report outcome measurements for lumbar pathology. There is agreement that instruments should possess five important domains, including back related function, self-reported health status, work disability and patient satisfaction (Bombardier, 2000; Marin, Furlan, Bombardier, van Tulder, & Editorial Board of the Cochrane Back Review, 2013). In a systematic review of articles for outcome evaluation from January 2001 to December 2010, the most commonly reported instruments included the Oswestry Disability Index (ODI), the Roland Morris (RMDQ) and spinal range of motion (ROM) analysis (J. R. Chapman et al., 2011). There is endorsement for use of both the ODI

and RMDQ for self-evaluation of functional status for persons impacted by a number of lumbar conditions (J. R. Chapman et al., 2011; Marin et al., 2013).

Despite previously cited research questioning the validity of self-report questionnaires, there is corroboration of ODI scores with objective measures of function, including spinal range of motion (ROM) assessment in a study of individuals who were about to receive spinal injections, or surgical procedures for lumbar pathology. The ODI demonstrated an inverse correlation relationship with ROM into all motion parameters and with functional ROM into 10/15 common activities of daily living in this investigation (Ruiz, Bohl, Webb, Russo, & Grauer, 2014). In this same study, it was concluded that the ODI demonstrates a stronger association then the visual analogue scale (VAS) to objective measures of function (spinal ROM) (Ruiz et al., 2014). However, a correlation between scores on the ODI and the results of a lower limb motor control task for subjects with radiographic evidence of unilateral lumbar nerve root compression was not found in a literature search.

Fitts' Law

Fitts' law is a mathematical equation, used to define movement time relative to movement accuracy. It is a theory of human motor behavior that estimates the amount of time it takes to complete rapid motion towards designated targets (Fitts & Peterson, 1964). It has been used in various research settings, such as upper/lower limb pointing tasks, head/eye tracking for various populations, (old vs young, pathological vs asymptomatic) (Hoffmann, 1991; M. Kim, Chae, & Jo, 2013; Passmore, Burke, & Lyons, 2007; Passmore et al., 2014; So & Griffin, 2000). In a paper proposed by Fitts in 1954, "the performance capacity of human motor systems and associated visual and proprioceptive feedback mechanisms, when measured in information units, is relatively constant over a considerable range of task conditions" (Fitts, 1954). The

relationship between movement time, amplitude of movement and target width is defined as: MT= a + b (ID); where ID= log(2A/W). Movement time (MT) is the total time to complete a rapid moving task, ID is the index of difficulty of the task, A is the amplitude of movement, W is the width of the target, and a/b are constants, (determined empirically by linear regression) (Fitts, 1954). This equation implies that there is a linear relationship between movement time and the index of difficulty (Fitts, 1954). As the amplitude "A" of movement increases, or the size of the target width "W" decreases, movement time is lengthened. This relationship describes the speed accuracy trade-off for rapid aiming movements (Fitts, 1954). When the size of the designated target decreases, one will trade speed for accuracy, thus increasing time travelled to the target. By using Fitts' law, researchers have been able to predict movement time, for rapid aiming performance tasks, across a range of target widths and movement amplitudes (Butzler, Vetter, Jochems, & Schlick, 2012). However, further investigations have found evidence that movement time and reaction time for a given task are in fact independent of each other (Fitts & Peterson, 1964). The amplitude of movement and the target width have predictable impact on movement time, but smaller impact on reaction time (Fitts & Peterson, 1964).

A Fitts' task, involving rapid aiming motions towards targets of various widths, at various heights was conducted by Poletti, et al in 2016 (Poletti, Sleimen-Malkoun, Lemaire, & Temprado, 2016). Measurements of reaction time, movement time, acceleration, velocity, time to peak acceleration, and time to peak velocity may be estimated using computerized and optical measurement equipment. This information can be used to define differences between individuals, or groups in terms of planning and execution of movement (Poletti et al., 2016). Fitts' task analysis has been used to describe the impact of spinal conditions on sensorimotor control (Passmore et al., 2014). In a study involving patients with confirmed lumbar spinal

stenosis and healthy age-matched controls, subjects were asked to point their foot towards targets on the floor. Data analysis determined that the spinal pathology group had a decrement in performance, compared to controls for most kinematic measures. Performance in the pathology group declined further as task difficulty increased. Stenotic subjects also exhibited more variability in time to peak velocity post-strain (ambulation on a treadmill). It was concluded that a foot pointing task could be used to convey variance in aspects of motor control between groups (Passmore et al., 2014).

A foot pointing task may mimic activities of daily living, such as weight-bearing, weight shifting, and stepping, as in functional ambulation. This experimentation may be preferred over standard gait analysis (step count, time to complete task, cadence, etc), as detailed kinematic variables can be applied. Subjects with low back pain may have alterations in movement, or function that can only be revealed with kinematic assessment (Lehman, 2004). This conjecture supports spinal kinematic motion evaluation for patients with nonspecific low back pain (Lehman, 2004). Subjects with conditions such as lumbar radiculopathy due to disc herniation, or degenerative stenosis often describe lower extremity involvement (Govind, 2004). Consequently, a more appropriate functional task for subjects with this condition may involve weight-bearing, and, or lower limb motion.

Another proposed benefit of Fitts' task analysis is to assist in devising an appropriate treatment plan for rehabilitation clients. If a patient demonstrates significant inaccuracy when defining target location, or significant delay in reaction time, prolonging overall movement time, treatment can be aimed at improving these aspects of performance (Lehman, 2004). Patients may respond better to well defined goals, and may increase compliance to programs that can

demonstrate improvement in specific measurable parameters with re-testing post-interventions (Lehman, 2004).

It is unknown whether subjects with confirmed unilateral lumbar radiculopathy will demonstrate enhanced or inferior performance with their effected limb on a foot pointing Fitts' task, when compared to their non-effected side. Conversely, these subjects may encounter challenge aiming with their non-effected limb, due to the need to weight shift, and support the body weight on the impacted side. It is therefore pertinent to test both limbs within subjects.

It is crucial for a performance-based outcome to be resistant to learning effects, as it will be repeated multiple times on two separate limbs, for serial aiming motion. In a study by Boyle, et al (2012), researchers attempted to determine whether performance of a Fitts' task improved with practice for wrist and elbow motions. Participants performed rapid wrist and elbow movements in the horizontal plane towards two defined targets, with four associated indices of difficulty. Data analysis after 480 trials (12 trials for the wrist, 12 trials for the arm x 20 sessions), resulted in minimal change in movement time, and the movement time- ID relationship. Although variability in movement end point and wrist movement time at ID=6 decreased slightly with repeat trials, the overall impression post-analysis is that a Fitts' task is resistant to enhanced performance, due to practice. Because of the randomization process of target presentation, subjects cannot predict which targets will appear in sequence. (Boyle, Panzer, Wright, & Shea, 2012).

Interpretation of Kinematic and Behavioural Variables

Prior to initiation of movement, an individual prepares to reach a specific goal, or target. Alterations in reaction time may suggest impairments in the preparatory phase of motor planning, or neuromuscular recruitment (Delmas, Casamento Moran, Park, Yacoubi, & Christou,

2018). Difficulties in planning of motor control can lead to issues with initiation of movement, force production and preservation of speed of movement (Sheridan, Flowers, & Hurrell, 1987) . Online motor control refers to modifications in motor planning during execution of movement. This is accomplished through feedback loops that compare limb position to target destination, resulting in subsequent adjustments in limb position (Desmurget & Grafton, 2000; Grea, Desmurget, & Prablanc, 2000) Online motor control depends on visual perception, effective feedback loops, proprioception and vestibular factors (Prablanc & Martin, 1992; Todorov & Jordan, 2002) A debate between motor planning and online mechanisms as an explanation for a violation of Fitts' law was explored by Glazebrook et al in 2015. In this study, participants moved randomly to one of three illuminated placeholders from the home position "as quickly and accurately as possible". Post-hoc analysis revealed no statistically significant difference in peak velocity (PV) between middle, and furthest targets. No significant differences across PVs suggests that motor planning cannot be the only explanation for findings. (ie: Higher level planning predicts greater PVs, associated with target 3, when it was in the farthest position). There was no statistical difference in average displacement between trials. If planning was a significant factor, one might expect greater average displacement early in the movement pattern, when subjects reached towards the furthest target. Variability in movement early in the trajectory, and less variability in end point position was observed for target 3, when it was in the last position. This supports online, rather than motor planning mechanisms of control (Glazebrook, Kiernan, Welsh, & Tremblay, 2015). Therefore, lower peak velocity and increased time to peak velocity suggests impaired online control of movement (Grierson & Elliott, 2009).

Alternatively, lower peak velocity may be evidence of a design to reduce the speed of the movement task (Passmore et al., 2015). In a study by Passmore et al, subjects with known

lumbar spinal stenosis were evaluated by a lower limb Fitts' task. Stenotic subjects demonstrated equivocal reaction times and endpoint variability on a lower limb reaching task to 2 different targets, at 3 different widths. However, their overall movement time increased significantly in the stenosis group, most evident when moving to targets requiring longer amplitudes of movement. It has been proposed that this strategy may be an attempt by the lumbar pathology group to improve accuracy of motion (Passmore et al., 2015).

Serial Hybrid Control Theory

The present study's task design and analysis also considered the serial hybrid control theory (Yadav & Sainburg, 2014). Similar to upper arm movement, the serial hybrid control theory proposes that the dominant and non-dominant limbs are characterized by different control processes. The brain hemisphere contralateral to the non-dominant limb is designed for maintenance of stability, where the hemisphere contralateral to the dominant limb is concerned with predictive control. The hybrid control theory describes predictive strategies at the initiation of movement, and use of impedance control to achieve stability at the movement end point. Further research supports the notion of both predictive and impedance control operating in both limbs. The difference between the dominant and non-dominant limb is when this control converts from one to another (Sainburg, 2005).

Studies of individuals post-stroke determined specific deficits in impedance or predictive control of each upper extremity, depending on the hemisphere impacted (Schaefer, Haaland, & Sainburg, 2009). When the hemisphere contralateral to the dominant arm was impacted, there was impact on limb trajectory (related to inter-joint coordination), but accuracy was spared. Conversely, impact on the hemisphere contralateral to the non-dominant limb resulted in less accuracy at movement endpoint (Schaefer et al., 2009). In a study by Haaland et al (2009),

subjects with left hemispheric damage (contralateral to dominant limb) secondary to stroke, demonstrated lower values for PV, MT, increased duration of acceleration and less increase in PA as amplitude increases. Literature by Schaefer (2009) and Haaland (2009), provide evidence that stroke motor control impairments relate to a specific brain hemisphere. The serial hybrid control model attributes predictive control of movement dynamics to the dominant limb, and impedance control, or ability to stabilize in unpredictable conditions to the non-dominant limb (Yadav & Sainburg, 2014).

Predictions

Comparisons Between Groups

It is hypothesized that MRI findings of unilateral nerve root compression will not predict performance on a Fitts' motor control task for all groups. Despite imaging evidence of nerve root compression, subjects without measurable neurological deficit will likely perform better then groups where there are objective motor, or sensory changes. These results would be consistent with proposed theories regarding the pathophysiology of radiculopathy. The presence of pain, without neurological change suggests that there is ectopic impulse generation, due to an irritated nerve root (Govind, 2004). If the function of the nerve root changes, due to conduction block, there should be positive motor and sensory findings (Govind, 2004). It is thought that such deficits in sensorimotor control of a lower limb could be revealed with a Fitts' motor control task (Passmore et al., 2014). The same theory supports the notion of superior performance for groups whose imaging lacks evidence of neurological compromise. Hypothesis related to differences between groups will be explored using a 3 group x 4 ID (3,4a,4b,5) ANOVA, collapsed by leg.

Comparisons Between Limbs

It is unknown if differences will exist between limbs on a lower limb Fitts' task for three groups of spine pathology subjects, as no comparisons were found in the literature. Inter-limb differences will be examined using a 2 group (effected, non-effected limb) x 4 ID (3,4a,4b,5) ANOVA.

Comparisons Between Limbs (Stratified by Limb Dominance)

Interpretation of the serial hybrid control theory, as it relates to lumbar radiculopathy, may include alterations in motor performance, specifically PV, PA, or MT if the dominant limb is the effected limb. Conversely, similar alterations in accuracy, CE, AE, or VE may be observed if the non-dominant limb is impacted (Schaefer et al., 2009). The hypothesis related to the serial hybrid control theory will be evaluated using a 2 group (effected, non-effected limb) x 4 ID (3,4a,4b,5) ANOVA, using limb dominance to define groups. In this analysis, subjects in groups 1 and 2 will be stratified into dominant effected and non-dominant effected categories, for between limb comparisons.

Correlation Analysis

It is hypothesized that a poor correlation will exist between results of self-report scales, pertaining to disability, function and results of the Fitts' task for groups that report a high average level of pain intensity, or maladaptive pain cognitions on pain questionnaires. Patients with back/radicular pain may inaccurately report their functional capabilities, due to the influence of pain catastrophization, fear avoidance beliefs and other psychological factors (Heymans et al., 2007; Stief et al., 2018). The association may improve in groups where there are no reports of pain, or mechanical back pain, without radicular symptoms, as psychological factors may have less of an impact on subjective evaluation. Correlation analyses will be performed between motor performance variables and self-report questionnaires. Scores on the

Pain Catastrophizing Scale will be examined, to determine if high levels of maladaptive pain cognitions co-exist with low correlation coefficient values.

Objectives

The primary objective of the proposed study is to determine if imaging findings of nerve root compression can predict performance on a coordinated motor performance task. The specific objectives are as follows:

1. To compare motor performance on a lower limb reaching task between 3 groups. Groups will be defined as follows:

   Group 1 (Positive-Positive): Positive imaging for unilateral nerve root compression, and at least one objective neurological deficit (motor, sensory, or reflex change).

   Group 2 (Positive-Negative): Positive imaging for unilateral nerve root compression, no objective neurological deficits.

   Group 3 (Negative-Negative): Negative imaging for unilateral nerve root compression, no objective neurological deficits.

2. To determine if differences exist in aspects of motor performance [reaction time (RT), movement time (MT), peak acceleration (PA), peak velocity (PV), time to peak acceleration (ttPA), time to peak velocity (ttPV), constant error (CE), absolute error (AE) and variable error (VE)] for groups 1, 2 and 3, between the effected and non-effected limbs. For Group 1, the lower limb that demonstrates objective neurological deficits, (correlating with imaging findings of unilateral nerve root compression) will be labelled as the "effected" limb. For Group 2, imaging findings of unilateral nerve root compression will be used to predict the "effected limb". For group 3, a comparison will be made between motor

performance of the dominant and non-dominant limb. This will serve as a control group for the analysis.

3. To determine if results of motor performance (ie: RT, MT, PA, PV, ttPA, ttPV, CE, AE and VE) correlate with self- report questionnaires regarding disability [Oswestry Disability Index (ODI) and the Roland Morris Questionnaire (RMDQ)], and function [Patient Specific Functional Scale (PSFS)] for each group listed above, using Pearson's correlation analysis. The calculated r values will then be compared between all three groups described in objective number 1. This will assist in determining if subjective evaluations of function and disability reflect objective motor performance of persons with and without unilateral lumbar nerve root compression. The Pain Catastrophizing Scale (PCS) will be used to assist in interpretation of the results.
4. To determine if results of motor performance (RT, MT, PA, PV, ttPA, ttPV, AE, CE and VE) correlate with self-report questionnaires regarding pain [Quadruple Numeric Rating Scale (QNRS) (effected/non-effected, or dominant/non-dominant leg, and low back)], for each group listed above, using Pearson's correlation analysis. The calculated r values will then be compared between all four groups described in objective number 1. This will assist in determining if a relationship exists between aspects of objective motor performance and pain intensity.

METHOD

Participants

To determine a minimal sample size, an a priori power calculation was performed using G*Power for F-tests, repeat measures ANOVA. The power calculation considered a published formula for partial eta squared, for determining effect size in the model (Lakens, 2013). The

value of partial eta squared was determined by knowledge of the F value for movement time in a similar lower limb reaching study (Passmore et al., 2015). The formula for calculating partial eta squared from F value is as follows: N_p^2= F x df(effect)/ F x df(effect) + df(error), where F= F statistic value, and df= degrees of freedom. The 2015 Passmore study employed a Fitts' task analysis to examine lower limb motor performance of individuals with confirmed lumbar stenosis. A desired statistical power level of 0.8, and an alpha set to 0.05 was used in the computation. The suggested sample size was determined to be 10 participants per group, with a total sample size of 30. However, 15 participants per group were recruited, as most Fitts' tasks involve 10-20 participants.

Participants with radiographic evidence of nerve root compression were recruited from the Winnipeg Spine Assessment Clinic. All participants received a clinical exam, including a subjective history to determine if complaints correlate with imaging findings, and an objective exam for evaluation of the presence/absence of neurological deficits. This examination was performed by a clinician deemed competent in performing surgical screening, confirming the presence of unilateral nerve root compression on imaging. The neurological exam was performed prior to the subjective exam, and prior to review of imaging films, or radiology report. The goal was objectivity, as the evaluator was not biased by knowledge of symptoms, or imaging confirmation of nerve compression. Group allocation was as follows:

1. **Group 1 (Positive-Positive):** Evidence of unilateral nerve root compression on imaging, and objective evidence of motor, sensory, and/ or reflex change, that correlates with segmental findings.
2. **Group 2 (Positive-Negative):** Evidence of unilateral nerve root compression on imaging, but no objective evidence of neurological deficits.

3. Group 3 (Negative-Negative): No evidence of nerve root compression on imaging (degenerative changes, not associated with nerve compromise acceptable), and no objective evidence of neurological deficits. These patients were recruited from a spine surgical screening clinic. Therefore, they all possessed degenerative segmental changes on imaging, and or back pain. Otherwise, they would not have been referred for consultation. Healthy, aged matched individuals without imaging were not considered for inclusion, as asymptomatic populations often possess positive imaging findings, such as nerve root compression (Boos et al., 1995)

Inclusion Criteria

All participants were over the age of 18. All participants in groups 1, and 2 possessed imaging suggestive of unilateral lumbar nerve root compression secondary to disc herniation, or degenerative changes, such as facet arthropathy, osteophyte formation, ligament hypertrophy, bulging discs and endplate spurring, resulting in narrowing of the lateral recess, or foraminal space at one segment, unilaterally. Participants in group 3 demonstrated no evidence of nerve root compression at any segment in the lumbar spine, on imaging. All participants were able to follow simple instruction and converse in English. A radiology report was used for verification of nerve compression. Determination of nerve root compression involved the use of Pfirrmann's or Van Rijn's terminology. Description may have included: "nerve compression (+/- grade 3 designation)", "possibly nerve compression", or "definitely nerve compression". Not all radiologists use standardized nomenclature. Therefore, confirmation of nerve compression on an imaging report may have also included non-standardized terms, such as "suspected nerve compression", or "likely/probable nerve compression". Suggestion, or likelihood of nerve compression by the evaluator was mandatory.

Exclusion Criteria

Participants were excluded from this study if they possessed symptoms of radiculopathy by other known causes, such as synovial cysts, post-surgical adhesions, fractures, benign, or malignant tumors, epidural lipomatosis, or spinal infection. They were excluded if imaging was suggestive of multi-segmental, or bilateral nerve root compression. Radiologist assessment of "nerve root contact", "nerve root deviation, or displacement" is not synonymous with nerve compression (Pfirrmann et al., 2004), and does not satisfy the designation of nerve compression. Subjects were excluded if they were unable to stand unsupported for 20-30 minutes, or if they required a mobility aid for support. They were not included if they possessed any other medical condition expected to impact performance on a motor control task, such as multiple sclerosis, prior cerebrovascular accident, or peripheral neuropathy.

Apparatus

A 23-inch screen sized image was projected on a custom built platform in front of the participant. The home position was identified as a micro-switch mounted to the proximal edge of the platform, adjacent to the participant. Custom software designed in E-prime (v2.0 Psychology Software Tools Inc., United States) was used to generate images on the computer monitor. An infrared emitting diode (IRED) was secured to the nail bed of the participant's great toe with medical tape to record three dimensional limb displacement data. The position of the IRED was recorded using a Northern Digital Instruments 3D Investigator, sampling at 300Hz.

The Nyquist theory, was considered when determining the sampling rate of the proposed experiment. Harry Nyquist, a researcher for AT&T wrote the paper, "Certain Topics in Telegraph Transmission Theory", in 1928. In the literature work (Nyquist, 1928), the author concluded that the entire analog waveform does not need to be recorded. If sufficient

information from a sample is captured, the primary waveform may be regenerated. A sample must encapsulate representative peaks and troughs of the original waveform. Nyquist concluded that if a waveform is sampled less then twice its frequency, the waveform recreated may represent noise. Hence, to ensure that the sample adequately represents the primary waveform, sampling rate must be twice the frequency (Nyquist, 1928).

Procedure

The clinician conducting surgical screening assessments determined if a patient was a candidate for the study, based on group criteria listed above. Each participant learned about the study by a research assistant, who obtained consent. Prior to the motor performance task, subjects completed a battery of questionnaires, specifically the Quadruple Numeric Pain Rating Scale (QNRS) (for both lower limbs and the lumbar spine), the Pain Catastrophizing Scale (PCS), the Waterloo Footedness Questionnaire-Revised (WFQ-R), the Patient Specific Functional Scale (PSFS), the Roland Morris Questionnaire (RMDQ) and the Oswestry Disability Index (ODI).

Participants stood barefoot on the platform, with their great toe in line with the "home position". The experimenter then initiated the trial. Each trial was initiated by the presentation of a precue (cross that will appear on the screen) at a variable foreperiod. The length and variability of the foreperiod before presentation of a prompt influences reaction time (Bertelson & Barzeele, 1965). Constant foreperiods are associated with faster reaction times then variable foreperiods, as subjects can anticipate presentation of a stimulus in the former (Schroter, Birngruber, Bratzke, Miller, & Ulrich, 2015). There is less temporal predictability when foreperiods are variable. Brief foreperiods in variable events tend to be associated with longer reaction times, and longer foreperiods in a variable event often result in shorter reaction times. It

is postulated that reaction times to variable events are inversely related to the duration of the foreperiod (Bertelson & Barzeele, 1965). There is less certainty about the stimulus when it is presented quickly. In a study by Naatanen et al (1974), subjects were asked to push a button with a variable foreperiod before presentation of a cue (Naatanen, Muranen, & Merisalo, 1974). Accuracy was highest at 1 second foreperiods and least accurate at 4 seconds. Although reaction times in a variable event are inversely related to the duration of the foreperiod, it has been suggested that subjects can maintain a state of readiness for a certain period (Naatanen et al., 1974). It may become difficult to estimate the arrival of a stimulus with longer foreperiods. Therefore, published studies involving Fitts' experiments and the present study use variable foreperiods between the ranges of 1.5- 2.55 seconds (Glazebrook et al., 2015; Passmore et al., 2014).

Following the precue, one of 4 possible targets became illuminated to specify the target location for that trial. Participants were instructed to move their great toe "as quickly and accurately as possible" to the target. The resulting movement was a forward movement of the test limb. The pointing task was repeated for 4 target positions, in front of the patient at 2 widths and at 2 distances. Fitts' Law equation was utilized to identify 4 index of difficulty combinations. Note: There were two sets of indexes of equal value with varying width and distance parameters, to determine the relative effect of both parameters. Each subject completed 40 trials with each foot, 80 in total. See Figure 1, in the Appendix of this paper for description of target widths, amplitudes and indices of difficulty.

DEPENDENT VARIABLES

Behavioural Measures

Reaction time is defined as the lapse in time between display of the target image and initiation of motion of the great toe. Movement time is the period of time between initiation of movement from the home position to the target image (Passmore et al., 2014). Both measures were calculated in seconds (s). Movement onset has been described as a rise in the signal's baseline activity, related to movement (Teasdale, Bard, Fleury, Young, & Proteau, 1993). In this study, movement onset and offset were defined as the first frame where limb velocity in the primary axis rose above, or fell below 30mm/s, respectively (Glazebrook et al., 2015; Grierson & Elliott, 2009). Constant error was used as one measure of accuracy, in millimeters (mm). It is defined as a systemic error that causes values to deviate from their true estimate. Variable error was evaluated, which is defined as the standard deviation of the trials performed. Variable error is a measure of consistency. Absolute error represents deviation of scores from the target, with no regard to direction (Schmidt, Lee, Winstein, Wulf & Zelaznik, 2011).

Kinematic Measures

Kinematic measurements included peak velocity (mm/s), peak acceleration (mm/s^2), time to peak velocity (s), and time to peak acceleration (s). Peak velocity/acceleration is the highest value of velocity/acceleration reached by the pointing toe in the primary axis of movement. Time to peak velocity/acceleration is defined as the lapse in time between movement onset and peak velocity/acceleration. Optotrak (3D-Investigator, Northern Digital, Waterloo, ON) data provided information regarding displacement, which was be used for programmed calculations of kinematic variables cited above.

Self-Report Questionnaires.

Questionnaire based outcome measures were used to subjectively quantify baseline differences between participants in all four groups, with, and without radiographic evidence of

lumbar nerve root compression. Measures included: the Quadruple Numeric Pain Rating Scale (low back, right/left lower limb), the Pain Catastrophizing Scale, the Oswestry Disability Index, the Roland Morris Questionnaire, the Patient Specific Functional Scale, and the Waterloo Footedness Questionnaire-Revised.

Numeric pain rating scale.

In regards to measurement of pain intensity, the Numeric Pain Rating Scale (NPRS) has been found to be one of the five most commonly reported outcome measures in the literature, according to a systematic review by Chapman, et al (J. R. Chapman et al., 2011). It has been found to be responsive for chronic low back populations (J. R. Chapman et al., 2011). In a comparative study between the NPRS, the Visual Analogue Scale (VAS), the Verbal Pain Rating Scale (VPRS), and the Faces Pain Scale (FPS), the NPRS was found to be the most responsive out of all pain scales for detecting the intensity of experimentally derived thermal pain stimuli (Ferreira-Valente, Pais-Ribeiro, & Jensen, 2011). There exists literature evidence of concurrent and predictive validity of the NRPS for measurements of pain (M. P. Jensen, Turner, & Romano, 1994; M. P. Jensen, Turner, Romano, & Fisher, 1999) Chapman et al recommend the use of either the VAS or NPRS when researching chronic lumbar pathologies due to its' frequent usage in research, and ease of administration. It has demonstrated high correlation with the VAS in patients with chronic conditions greater than six months (0.86-0.95), (Ferraz et al., 1990). The use of the NPRS for back and leg pain severity is endorsed by Deyo, for research on populations of patients with low back pathology (Deyo et al., 1998). It is postulated that a composite of pain ratings from 0-10 (best, worst, average, etc.) is more useful when studying smaller sample sizes, due to greater stability of patient responses (M. P. Jensen et al., 1999).

Pain Catastrophizing Scale.

The pain Catastrophizing Scale (PCS) is a 13 item, self-report questionnaire, used to evaluate the extent of maladaptive pain cognitions, related to pain. It consists of three subscales that evaluate the presence of magnification, helplessness and rumination. It was developed by M. Sullivan, S. Bishop and J. Pivik in 1995 (Sullivan, 1995). Pain catastrophizing refers to an exaggerated response to painful and non-painful stimuli. Non-dangerous situations are perceived as threatening. The PCS demonstrates test-retest stability, internal consistency and validity (Lame, Peters, Kessels, Van Kleef, & Patijn, 2008; Osman et al., 2000; Van Damme, Crombez, Bijttebier, Goubert, & Van Houdenhove, 2002). In a study by Sullivan et al (1995), PCS scores predicted pain intensity and emotional suffering for study participants subjected to cold and electrodiagnostic testing (Sullivan, 1995). Compared to other outcome measures concerning mood, feelings, attitudes and cognitions, the PCS demonstrated the strongest correlation to physical and emotional affliction (Sullivan, 1995). An Italian version of the PCS was administered to subjects who reported chronic low back pain. Internal consistency was defined as follows: 0.92 (entire questionnaire), 0.87 (rumination), 0.89 (helplessness) and 0.56 (magnification). The intraclass correlation was deemed to be 0.842, correlating with a high degree of test-retest reliability. Moderate correlation was determined between the PCS and the numeric pain scale (r=0.44), the Roland Morris Questionnaire (r=0.45) and the Tampa Scale for Kinesiophobia (r=0.59) (Monticone et al., 2012).

Oswestry Disability Index.

The ODI was first published in 1980 to describe pain and disability in lumbar populations (Fairbank & Pynsent, 2000). It is available in four versions in English and nine other languages (Fairbank & Pynsent, 2000). It has validity and test-retest reliability (Gronblad et al., 1993).

There are ten questions, each with six possible responses. Its internal consistency has a Cronbach's alpha of 0.87 (Kopec et al., 1995). The Oswestry Disability Index's test-re-test stability has an estimated Pearson's r value of: r=0.99 for 22 patients with non-specific low back pain (Fairbank & Pynsent, 2000). The test-re-test intraclass correlation coefficient was found to be 0.91 (Kopec et al., 1995). It has reported concurrent validity with the Quebec Back Pain Scale, associated with a Pearson's r value of 0.8 (Kopec et al., 1995). There is evidence of content validity for distinguishing different groups of patients with low back dysfunction (Kopec et al., 1995).

Roland Morris Questionnaire.

The Roland Morris is a self-reported 24-item questionnaire, regarding back-related dysfunction. Scores range from 0 (no dysfunction), to a max score of 24 (significant dysfunction). Questionnaire items evaluate impact on activities of daily living, functional mobility, range of movement and emotions (Bombardier, 2000). The Roland Morris constitutes statement from the Sickness Impact Questionnaire, which is a measurement of health status (Roland & Morris, 1983b). The Oswestry Disability Index and the Roland Morris are the two most commonly cited, commonly used and validated outcome measurements for assessing physical function in lumbar populations (Bombardier, 2000). To assess short-term test-retest stability, the Roland Morris was completed by 20 subjects, then repeated hours later. A correlation coefficient of 0.91 was calculated between scores (Roland & Morris, 1983a). In a study by Roland et al (1983), answers to questionnaire items were not correlated with sex, age or social class (Roland & Morris, 1983a). Internal consistency was demonstrated by a reported Cronbach's Alpha of 0.90, and 0.87 (Kopec et al., 1995; Stratford & Binkley, 1997). The

Roland Morris has concurrent validity with the Quebec pain scale (r=0.77) (Kopec et al., 1995) and the Oswestry Disability Index (r=0.82) (Stratford & Binkley, 1997).

Patient Specific Functional Scale.

The Patient Specific Functional Scale is an assessment of the impact of health conditions on one's ability to perform meaningful activities. Validity and responsiveness to change has been demonstrated using the PSFS with spinal conditions and with individuals with reported knee pain (Sterling & Brentnall, 2007). In a study by Pengel et al (2004), the PSFS was found to be more responsive then the Roland Morris Questionnaire and the Numeric Pain Rating Scale in measuring physical impairment for subjects with low back pain (Pengel, Refshauge, & Maher, 2004). A study by Abbott (2014) et al investigated the validity of the PSFS for determining between group disparity and within group changes over time, in respect to self-reported physical function. The results of this study suggest that the PSFS has concurrent, convergent and discriminant validity, responsiveness and scale consistency for intragroup changes and for between group comparisons (Abbott & Schmitt, 2014).

Waterloo Footedness Questionnaire-Revised.

The Waterloo Footedness Questionnaire was originally a 12- item outcome measure, used to reveal leg dominance. An additional 8 tasks that often reveal leg dominance were added to the revised version. It has been used in many research studies involving motor behavior, as it has the ability to assess foot preference for both activities involving limb motion and stabilization (Kapreli, Athanasopoulos, Stavridis, Billis, & Strimpakos, 2015). Psychometric properties of the WRQ-R were evaluated on 30 healthy Greek-speaking subjects in 2015. The questionnaire was translated into Greek, using translation protocols and internationally recognized guidelines. The results of this investigation revealed high internal consistency calculations for the mobility

(Alpha=0.827) and stability items (Alpha=0.820). The Spearman correlation coefficient was found to be statistically significant ($p< 0.01$), for test- retest evaluations. The results of this study reveal moderate construct validity (Kapreli et al, 2015).

Data Analysis

Comparison Between Groups

To test differences in performance between groups, a 3 group (1,2,3) x 4 ID (3,4a,4b,5) mixed model analysis of variance (ANOVA) was performed for all performance variables listed above. Bonferroni correction was used in the post-hoc analyses.

Comparison Between Limbs

To determine if differences exist between limbs, a 2 group (effected vs non-effected; or dominant vs non-dominant limbs) x 4 ID (3,4a,4b,5) ANOVA was also performed for groups 1, 2, and 3 between both limbs.

Comparison Between Limbs (Stratified by Limb Dominance)

The serial hybrid control theory was explored by a 2 Limb (effected, non-effected) x 4 ID (3,4a,4b,5) ANOVA between the effected and non-effected limbs in groups 1 and 2, using limb dominance to define groups. The first 2 ANOVA calculations satisfy the a priori determination of 10 cases per group. The sub-analysis for groups 1 and 2 is an exploratory evaluation, as there were less then 10 cases per group.

Correlation Analyses

Pearson's correlation coefficients were determined to evaluate the strength of the relationship between ODI, RMDQ, PSFS scores and MT, RT, PA, PV, ttPA, ttPV, CE, AE and VE (at the highest ID) (Passmore et al., 2015). Pearson's correlation coefficients were also determined between QNPRS (back, right/left leg) scores and MT, RT, PA, PV, ttPA, ttPV, CE,

AE and VE for all groups (at the highest ID). Statistical analysis was computed, using International Business Machines Corporation's (IBM) Statistical Package for the Social Sciences (SPSS), version 23. Regression analyses were examined, in an attempt to determine if questionnaire scores could predict motor performance variables for all three groups.

A customized program created in MathWorks Inc. (MATLAB, release 2014b, The Mathworks Inc., USA) was used to transform displacement data into kinematic/ behavioural variables associated with this experiment. The customized MATLAB program "smooths" data for each trial, in an attempt to minimize the "noise" captured during sampling. Movement onset and offset velocity was determined when velocity rose, or fell below 30mm/s. The onset/ offset velocity was manually inputted by the experimenter during the processing step. MATLAB computes movement time by multiplication of the number of frames recorded (between movement onset and offset) by the sampling rate. Reaction time is computed by the customized program by multiplying the sampling rate by the number of frames from target presentation to onset of motion. The custom MATLAB program calculates peak velocity/acceleration and time to peak velocity/acceleration from the velocity/acceleration profiles in the primary axis of movement. Constant error was determined by subtracting the end point positions outlined in MATLAB files from the target file location in the primary axis of movement, to determine an average deviation from the target, for each ID (Bayonle, 2017). Absolute error is a similar computation as constant error, but ignores direction. Variable error is estimated by the calculation of the standard deviation of endpoint values in MATLAB files, about the target.

Significance

Previous research has highlighted shortcomings of imaging investigations to predict severity, duration of symptoms and prognosis in lumbar populations (Boos et al., 1995;

Borenstein et al., 2001; Ellenberg et al., 1993; O. K. Jensen, Nielsen, & Stengaard-Pedersen, 2010; Truumees, 2015). A gap in the current knowledge base is that there are very few studies that have explored the relationship between imaging findings of lumbar pathology and measures of function (T. M. Chapman, Jr. et al., 2016; Haig, Tong, Yamakawa, Quint, et al., 2006). There were no studies found that examined correlations between imaging evidence of unilateral lumbar nerve root compression and objective lower limb performance-based measures. The relevance of this experiment is to further evaluate the predictive value of imaging for a specific subcategory of spine-related pathology. Analysis of the behavioral and kinematic measures outlined in this study may also assist in uncovering the impact of lumbar radiculopathy on various aspects of motor control.

The present experiment study examined whether there is justification to include objective evaluations of function when assessing the impact of imaging- confirmed unilateral lumbar nerve root compression. A survey was administered to 817 surgeons in 89 countries to determine common practices for management of lumbar disc herniation (Gadjradj et al., 2017). The most common reason to intervene surgically, based on responses was severity of pain and disability (55%) (Gadjradj et al., 2017). How should function, or disability be estimated in this population? There is literature debate whether an association prevails between objective and subjective measures of function (Lee et al., 2001; Ruiz et al., 2014; Stief et al., 2018). If the performance-based measure to be explored in this study correlates well with self-evaluations of function, and, or disability, then it may not justify the usage of objective measurements in clinical practice. Alternatively, if the Fitts' task is more sensitive in defining differences between groups, or demonstrates a modest, or poor correlation with self-evaluation, it may substantiate a change in clinical practice. Perhaps there is justification to include both subjective

and objective assessment, as suggested by Lee, et al (Lee et al., 2001). It is imperative to accurately define the impact of this condition to assist in determining a need for surgical interventions, and to assist in directing the appropriate non-surgical strategy (Lehman, 2004).

RESULTS

Demographics/Questionnaire Analysis

There were 45 subjects recruited from the Winnipeg Spine Assessment Clinic for this experiment. Group 1 participants all possessed MRI evidence of unilateral lumbar nerve root compression between the levels of L3-S1. They all possessed motor, sensory, and or reflex changes, correlating with the effected segment. The level of suspected nerve root compression and the extent of neurological compromise was not controlled for in this experiment. The average time between imaging and assessment/testing was 117.4 days. The average age of participants in Group 1 was 47.5 (SD=15.7) years old. There were 7 females and 8 males. The Revised Waterloo Questionnaire revealed right leg dominance in 6 subjects, left leg dominance in 1 subject and mixed dominance, or no limb preference in 8.

Group 2 also demonstrated lumbar MRI evidence of unilateral nerve root compression at the levels between L3-S1. They did not possess any objective evidence of neurological change. The average time between imaging and assessment for this group was 195.4 days. The average age of a group 2 subject was 55.9 (SD=15.8) years old. There were 4 females and 11 males recruited. The Revised Waterloo Questionnaire suggested that 13 subjects had a right leg preference, 0 had left leg preference and 2 were classified as mixed dominance, or no limb preference.

Group 3 consisted of patients referred to a spine surgical screening clinic, without evidence of neurological compromise on imaging, and without objective evidence of motor,

sensory, or reflex change. Imaging findings included facet arthropathy, disc space narrowing, disc bulging, osteophyte formation, endplate spurring, lateral recess/foraminal narrowing (without suspected nerve compression), or any combination of the above. The extent, or type of degenerative changes found in group 3 were not controlled for. The average time between imaging and assessment/testing was 231 days. The average age of a group 3 participant was 54.8 (SD=15.8) years old. There were 5 females and 10 males tested. 12 participants were classified as having right leg dominance, 1 was identified as having a preference for the left lower limb, and 2 subjects were defined as mixed, or no limb preference.

All groups reported experiencing back and leg pain. Please note, the QNPRS (leg) did not distinguish between radicular pain and pain referred into the lower limbs. Therefore, leg pain reported may include radicular pain, pain from lower limb joints/soft tissues, referred pain from the lumbar spine, or any combination of the above. The results of all self-report questionnaires can be found in the Appendix (Table 1). There were high standard deviations for most groups, regarding the PSFS, QNPRS (back/leg), and the PCS. This suggests variability in pain experience, level of reported function and maladaptive pain cognitions within groups. The nature of pain, pain intensity, and location was not controlled for in this experiment. One-way ANOVA reveled no differences between groups for any of the questionnaire scores in the present study, with the exception of PCS scores. Subjects in group 3 demonstrated lower pain catastrophization then subjects in group 1 and 2.

Between Group Comparisons

ANOVA-Between Groups (Legs Collapsed)

Behavioural measures.

Movement time data did not reveal main effects for group $F(2, 28)=0.314$, $p=0.733$, or group by ID interaction $F(6, 84)=1.444$, $p=0.248$, (group 1 M=681.7ms, SD=160.9; group 2 M=650.1ms, SD=142.7; group 3 M=670.4ms, SD=160.0). This suggests that subjects with unilateral lumbar nerve root compression (with, or without neurological changes) do not differ in overall movement time then subjects with multilevel degenerative changes. There was a main effect for ID $F(3,42)=164.191$, $p<0.001$, partial eta squared=0.921, (ID 3a M=568.9ms, SD= 93.0; ID 4a M=565.6ms, SD=90.0; ID 4b M=749.7ms, SD=135.6; ID 5 M=785.4ms, SD=142.3). Post Hoc analysis exposes longer movement times to targets at larger amplitudes. Target amplitude impacted overall movement time more significantly then target width.

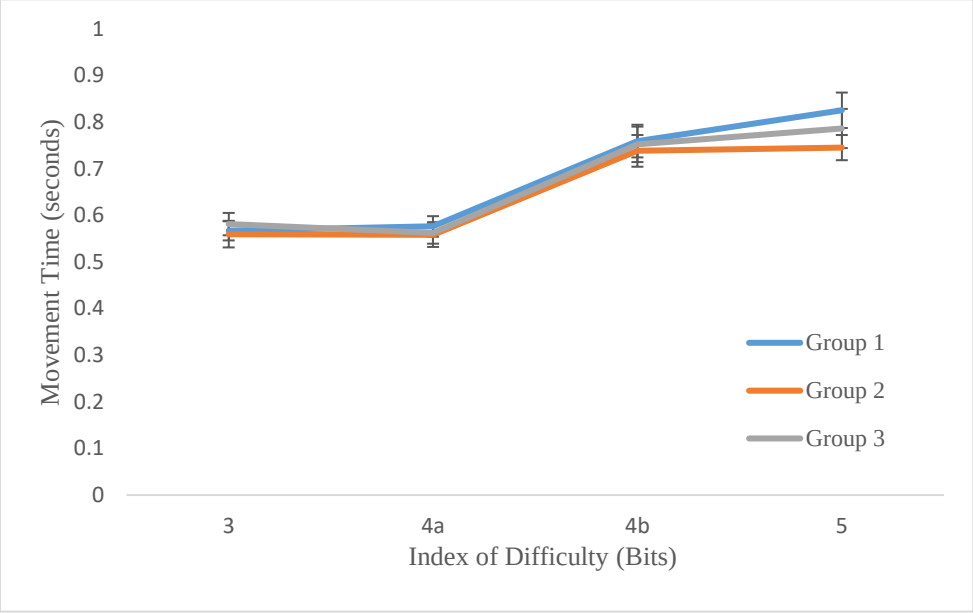

Figure 2. Movement time at each ID for groups 1, 2 and 3. Error bars represent SEM for each ID.

Reaction time data yielded equivocal results across all groups (group 1 M=787.2ms, SD=201.2; group 2 M=709.0ms, SD=122.0; group 3 M=716.7ms, SD=147.4) and IDs (ID 3a M=727.1ms, SD=149.0; ID 4a M=741.4, SD=168.3; ID 4b M=743.0, SD=176.8; ID 5 M=739.0, SD=162.7). There were no main effects for group, ID, or group by ID interactions determined

[F(2, 28)=1.315, p=0.285; F(3,42)=0.895, p=0.452; and F(6,84)=1.803, p=0.146, respectively]. The analysis did not reveal differences in the preparatory phase of motor planning, or neuromuscular recruitment between groups, or between IDs.

Analysis of constant error did not demonstrate differences between groups. Mean constant error estimates for group 1 was -2.7 mm, SD=0.9; -1.6mm, SD=0.9mm for group 2 and -0.8mm, SD=0.6 for group 3. There was a main effect for ID, where ID 3 varied from IDs 4b and 5 (ID3 M=-0.05mm, SD=0.9mm; ID 4a M=-1.1mm, SD=0.7mm; ID 4b M=-3.0mm, SD=0.7mm; ID 5 M=-2.6mm, SD=0.5mm); [F(2, 28)=1.905, p=0.262; F(3,42)=7.15, p=0.001, partial eta squared=21.45 and F(6,84)=1.996, p=0.075, for group, ID and group by ID interactions].

There were no main effects for group, or ID, or group by ID interactions for variable error between groups [F(2, 28)=1.002, p=0.360; F(3,42)=1.858, p=0.151; and F(6,84)=1.191, p=0.319, respectively]. Mean variable error estimates for group 1 was 8.6mm, SD=0.5; 8.1mm, SD=0.6mm for group 2 and 7.6mm, SD=0.3 for group 3. Mean values across IDs are as follows: ID 3a M=7.9mm, SD=0.3; ID 4a M=8.5, SD=0.4; ID 4b M=8.5, SD=0.3; ID 5 M=7.7, SD=0.4.

A main effect was determined for group for absolute error. Post hoc analysis, using Bonferroni correction demonstrated greater deviation from the target, on average, for group 1, compared to group 3 (group 1 M=5.6mm, SD=0.3mm; group 2 M=5.2mm, SD=0.5mm and group 3 M=3.7mm, SD=0.4mm); [F(2, 28)= 5.117, p=0.013, partial eta squared = 0.268; F(3,42)=1.966, p=0.134 and F(6,84)=0.711, p=0.641, for group, ID and group by ID interactions].

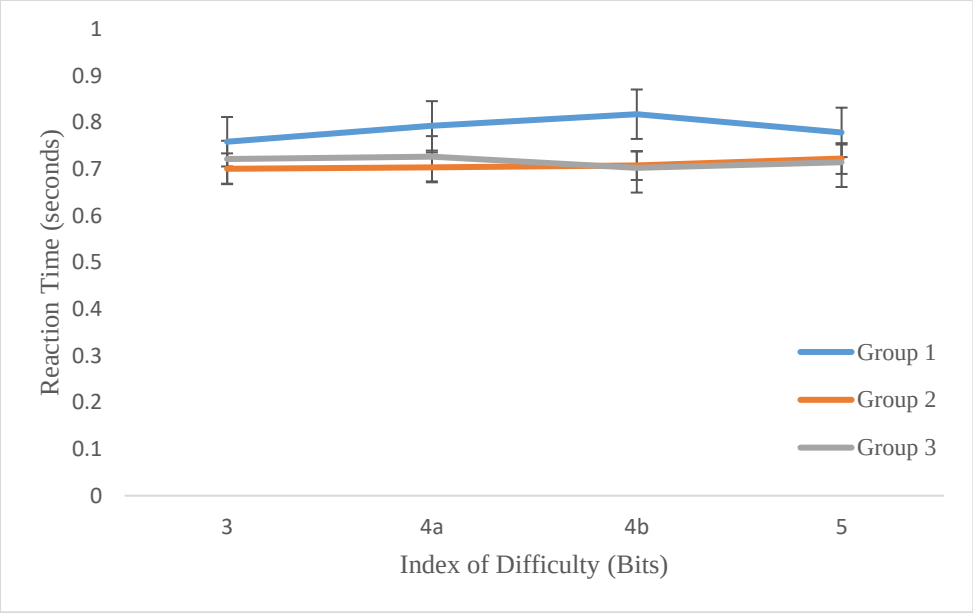

Figure 3. Reaction time across IDs, for groups 1, 2 and 3. Error bars represent SEM for each ID.

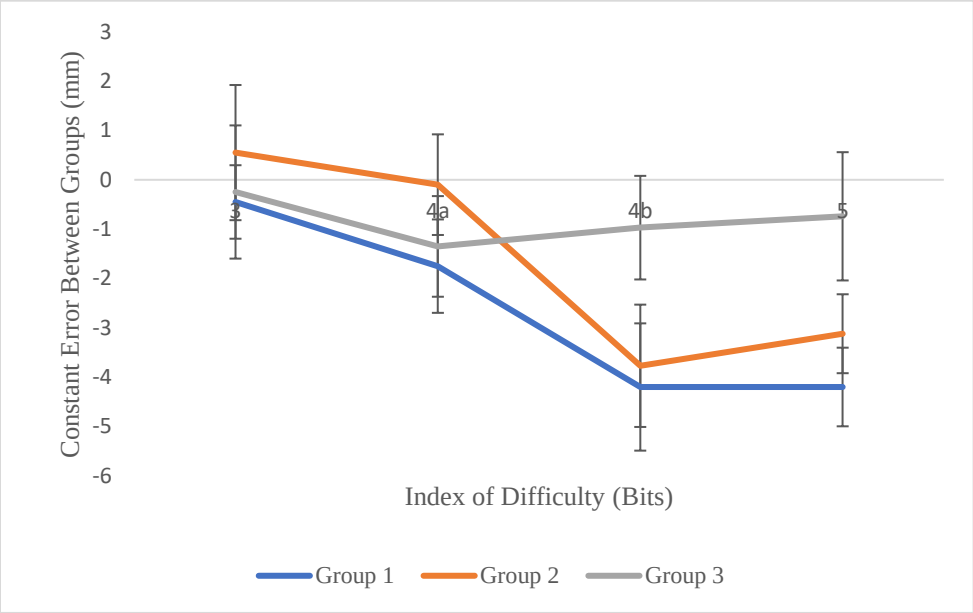

Figure 4. Constant error across all IDs for groups 1, 2 and 3. Error bars represent SEM at each ID.

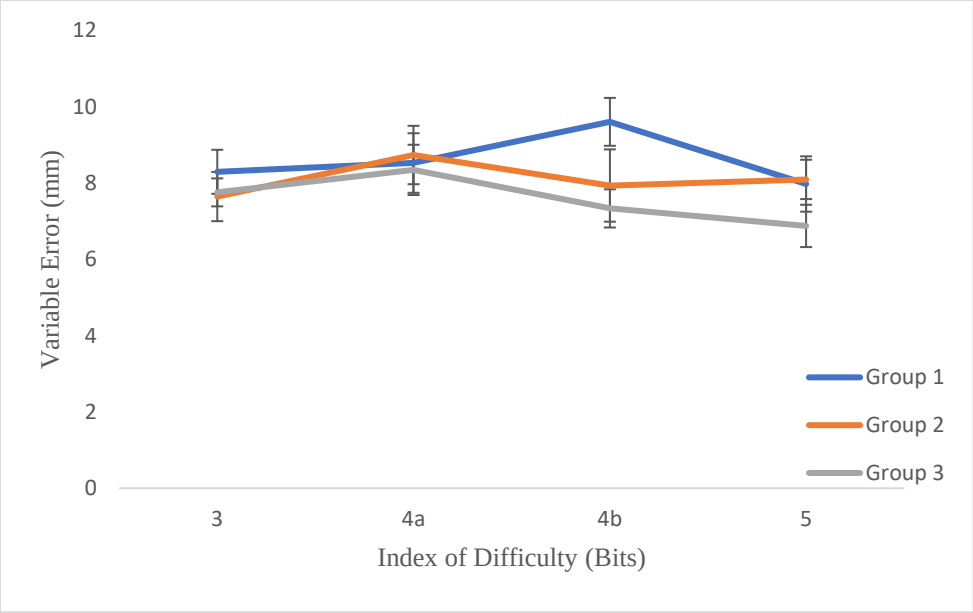

Figure 5. Variable error across all IDs for groups 1, 2 and 3. Error bars represent SEM at each ID.

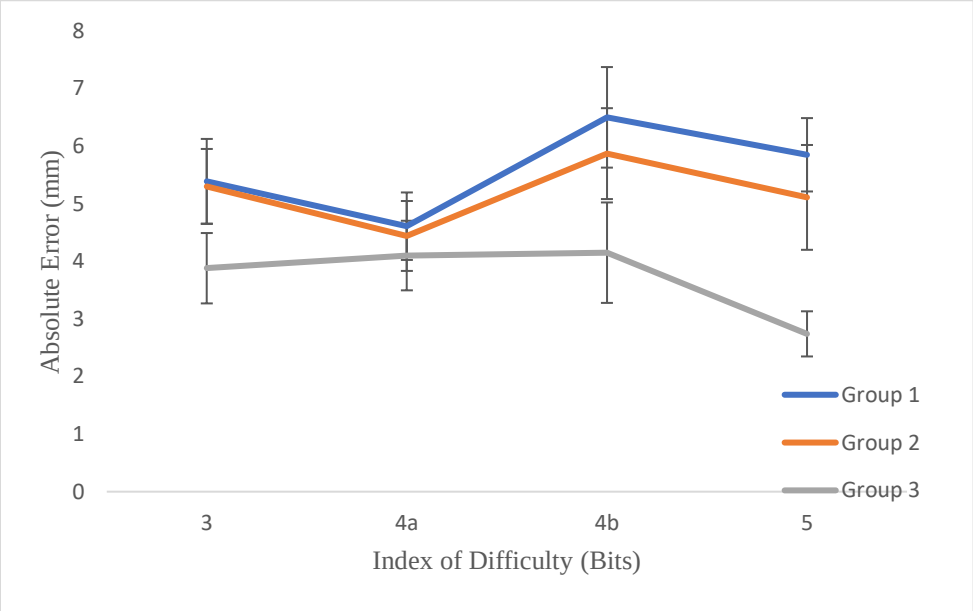

Figure 6. Absolute error across all IDs for groups 1, 2 and 3. Error bars represent SEM at each ID.

Kinematic measures.

There were no main effects determined for peak velocity (group 1 *M*=853.7mm/s, *SD*=252.3; group 2 *M*=871.2mm/s, *SD*=276.2 ; Group 3 *M*=855.2mm/s, *SD*=276.0), time to peak velocity (group 1 *M*=222.2, *SD*=39.2; group 2 *M*=218.9ms, *SD*=42.1; group 3 *M*=210.8ms, *SD*=51.3), peak acceleration (group 1 *M*=6935.9mm/s^2, *SD*=2178.3; group 2 *M*=7506.9mm/s^2, *SD*=2968.0; group 3 *M*=8040.6mm/s^2, *SD*=3530.8) and time to peak acceleration (group 1 *M*=84.6ms, *SD*=43.9; group 2 *M*=71.8ms, *SD*=24.7; group 3 *M*=70.5ms, *SD*=31.7), across all groups [*F*(2,28)=0.67, *p*=0.935; *F*(2,28)=0.339, *p*=0.675; *F*(2,28)=0.966, *p*=0.0.393; *F*(2,28)=1.048, *p*=0.364; respectively]. No group by ID interactions were found for any of the kinematic variables obtained (PV, ttPV, PA, ttPA) [*F*(6,84)=2.173, *p*=0.121; *F*(6,84)=1.062, *p*=0.373; *F*(6,84)=1.069, *p*=0.375; *F*(6,84)=0.414, *p*=0.756; respectively].

There were significant main effects for ID for PV (ID 3 *M*= 657.8mm/s, *SD*= 115.3; ID 4a *M*= 637.0mm/s, *SD*= 121.2; ID 4b *M*= 1069.4mm/s, *SD*= 192.3; ID 5 *M*= 1075.9mm/s, *SD*=99.7), ttPV (ID 3 *M*=197.1ms, *SD*=33.6; ID 4a *M*=193.9ms, *SD*=30.8; ID 4b *M*=235.6ms, *SD*=42.3; ID 5 *M*=242.7ms, *SD*=47.0), PA (ID 3 *M*=6257.9mm/2^2, *SD*=2104.2; ID 4a *M*=5973.2mm/s^2, *SD*=1998.5; ID 4b *M*=8797.2mm/s^2 *SD*=3082.7; ID 5 *M*=8949.7mm/s^2, *SD*=3157.0) and ttPA (ID 3 *M*=67.0ms, *SD*=25.9; ID 4a *M*=60.4ms, *SD*=18.2; ID 4b *M*=85.8ms, *SD*=46.6; ID 5 *M*=89.2ms, *SD*=39.2), [*F*(2,42)=488.374, *p*<0.001, partial eta squared= 0.972; *F*(2,42)=82.932, *p*<0.001, partial eta squared= 0.856; *F*(2,42)=96.289, *p*<0.001, partial eta squared= 0.873; *F*(2,42)=16.681, *p*<0.001, partial eta squared= 0.544; respectively]. Post hoc analysis determined lower PV/PA and longer ttPV/ttPA, associated with targets at greater amplitudes.

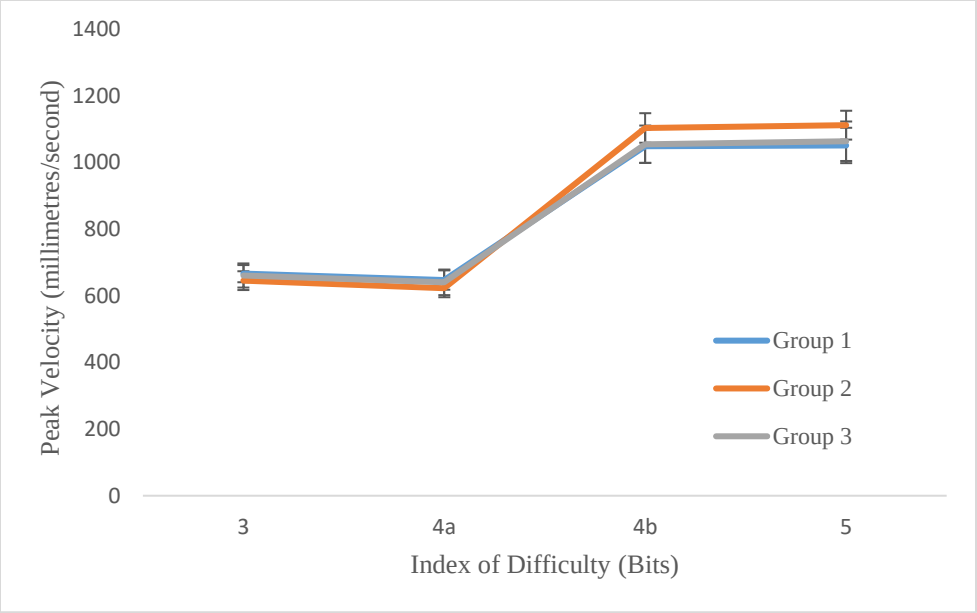

Figure 7. Peak velocity across IDs for groups 1, 2 and 3. Error bars represent SEM for each ID.

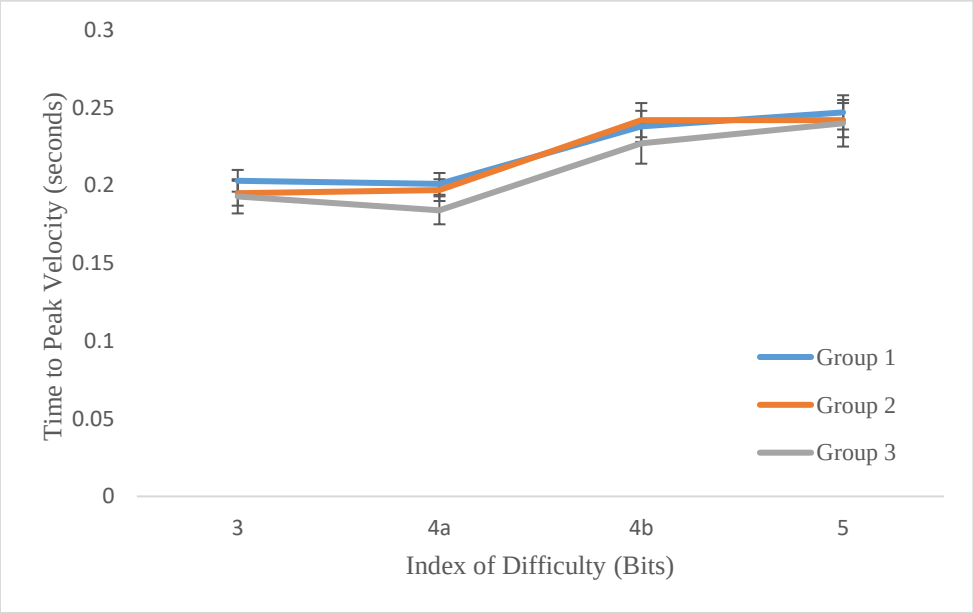

Figure 8. Time to peak velocity across all IDs for groups 1, 2 and 3. Error bars represent SEM for each ID.

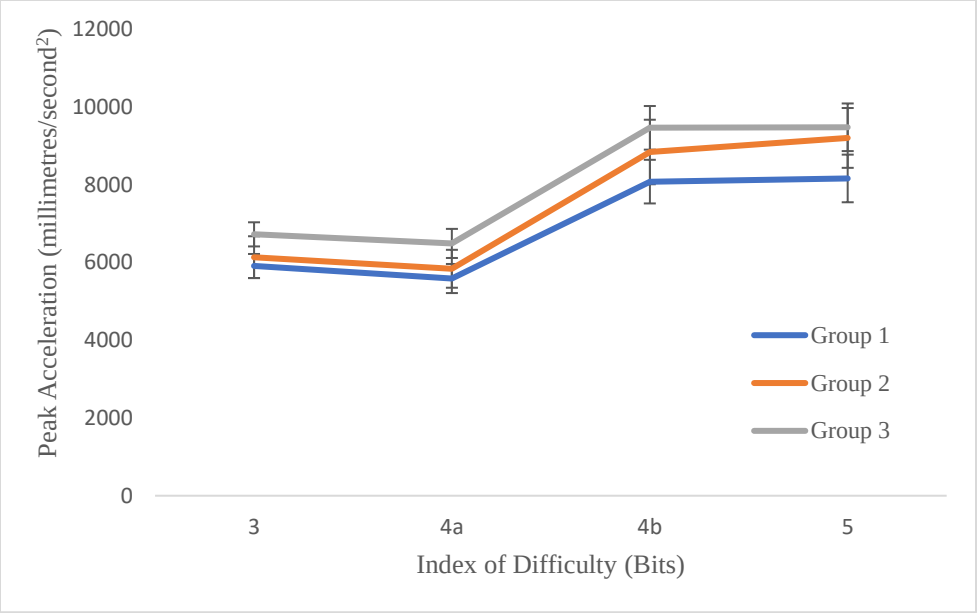

Figure 9. Peak acceleration across all IDs for groups 1, 2 and 3. Error bars represent SEM for each ID.

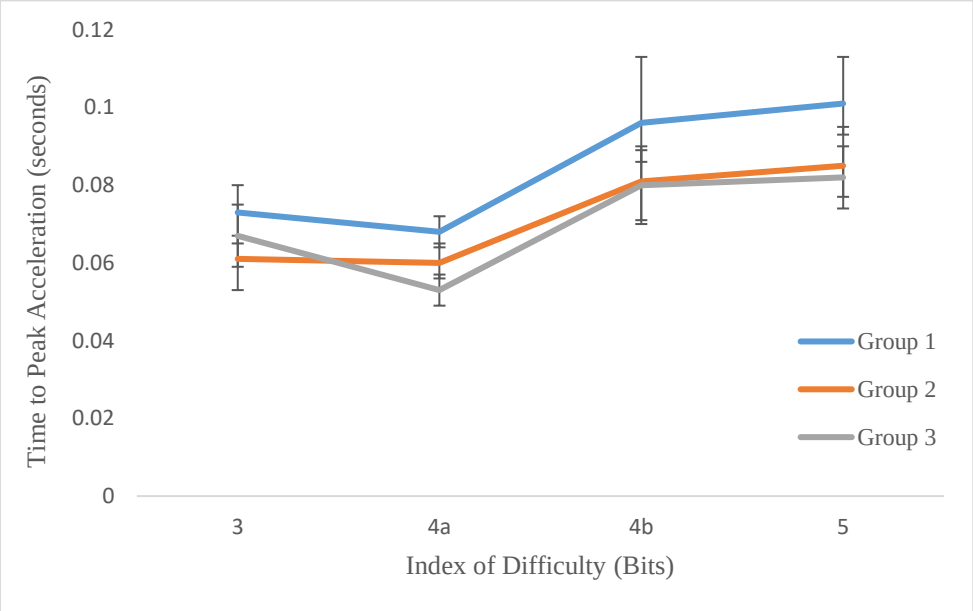

Figure 10. Time to peak acceleration across all IDs, for groups 1, 2 and 3. Error bars represent SEM for each ID.

Please see Table 1, in the appendix for a summary of group 1, 2 and 3 significant main effects for each variable.

Between Limb Comparisons

Group 1: Effected Versus Non-Effected Limbs

A 2 group (effect leg, unaffected leg) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) was performed for all behavioural and kinematic variables between the effected and non-effected limbs in group 1. There were no significant main effects for group or group by ID interaction for any of the performance variables. Main effects were found by ID for MT (ID3 *M*=579.6ms, *SD*=93.4; ID 4a *M*=580.2 ms, *SD*=89.0; ID 4b *M*=765.5ms, *SD*=147.8; ID 5 *M*=823.7, *SD*=158.3), PV (ID3 *M*=663.3mm/s, *SD*=114.1; ID 4a *M*=638.8mm/s, *SD*=134.5 ; ID 4b *M*=1042.0mm/s, *SD*=207.6; ID 5 *M*=1043.8mm/s, *SD*=212.7), ttPV (ID3 *M*=206.2ms, *SD*=40.3; ID 4a *M*=202.9ms, *SD*=31.2; ID 4b *M*=239.1ms, *SD*=40.9; ID 5 *M*=247.7ms, *SD*=47.5), PA (ID3 *M*=5832.1mm/s^2, *SD*=1429.3; ID 4a *M*=5479.9mm/s^2, *SD*=1631.0; ID 4b *M*=7975.4mm/s^2, *SD*=2345.2; ID 5 *M*=7962.4mm/s2, *SD*=2535.3), ttPA (ID3 *M*=75.1ms, *SD*=38.40; ID 4a *M*=70.5ms, *SD*=27.9; ID 4b *M*=95.8ms, *SD*=76.4; ID 5 *M*=100.7, *SD*=50.2) and CE (ID3 *M*=-0.5mm, *SD*=1.4; ID 4a *M*=-1.8mm, *SD*=1.0; ID 4b *M*=-4.2mm, *SD*=1.2; ID 5 *M*=-4.2, *SD*=1.1); [$F(3,42)=77.531$, $p<0.001$, partial eta squared=0.847; $F(3,42)=111.561$, $p<0.001$, partial eta squared=0.889; $F(3,42)=21.237$, $p<0.001$, partial eta squared=0.603; $F(3,42)= 42.672$, $p=<0.001$, partial eta squared=0.889; $F(3,42)=4.653$, $p=0.025$, partial eta squared=0.249 and $F(3,42)=5.13$, $p=0.017$, partial eta squared=0.268 respectively]. Post-hoc analysis demonstrated detrimental performance for MT, PV, ttPV, PA ttPA and CE for targets associated with longer amplitude (ID 4b and 5). This difference was not revealed for target width. No main effects were found for RT, VE, or AE between limbs, in group 1. Please see

table 3 in the appendix for a summary of group 1 (effected and non-effected limb) significant main effects for each variable.

Group 2: Effected Versus Non-Effected Limbs

A 2 group (effected, non-effected) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) was performed between all behavioural and kinematic variables between the effected and non-effected limbs in group 2. Main effects were found for group between the effected and non-effected limbs for MT (effected group MT *M*=660.9ms , *SD*=149.3; non-effected group MT *M*=637.4ms, *SD*=140.0) and PV (effected group *M*=848.8mm/s , *SD*=271.3; non-effected group PV *M*=899.4mm/s, *SD*=276.8), [*F*(1,14)=4.773, p=0.046, partial eta squared=0.839 and *F*(1,14)=9.084, *p*=0.009, partial eta squared=0.955, respectively]. Overall, the effected limb in group 2 demonstrated longer MTs and lower PVs then the non-effected limb.

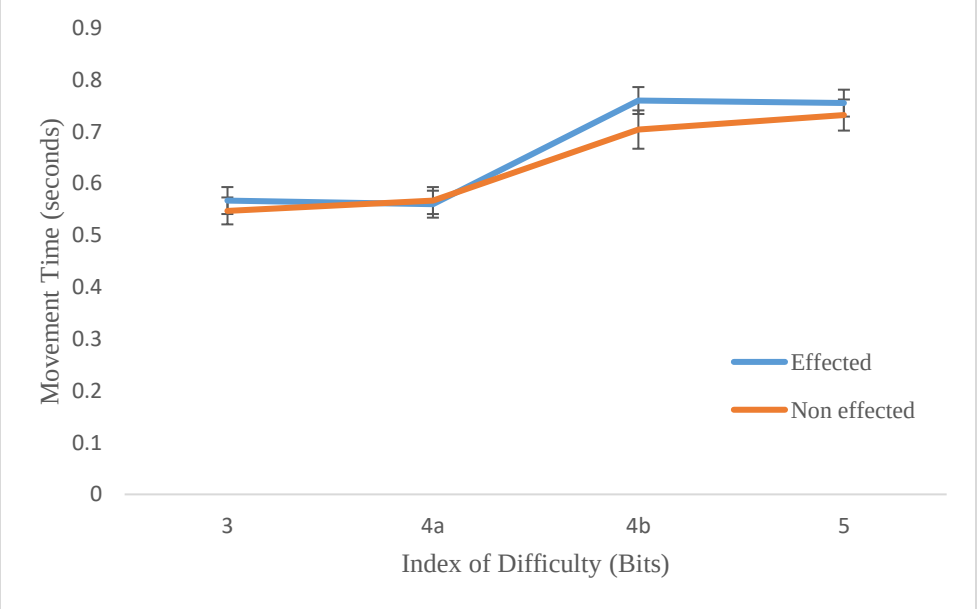

Figure 11. Movement time across all IDs for group 2 (effected and non-effected limbs). Error bars represent the SEM at each ID. Note, the greatest difference between limbs occurs at ID 4b.

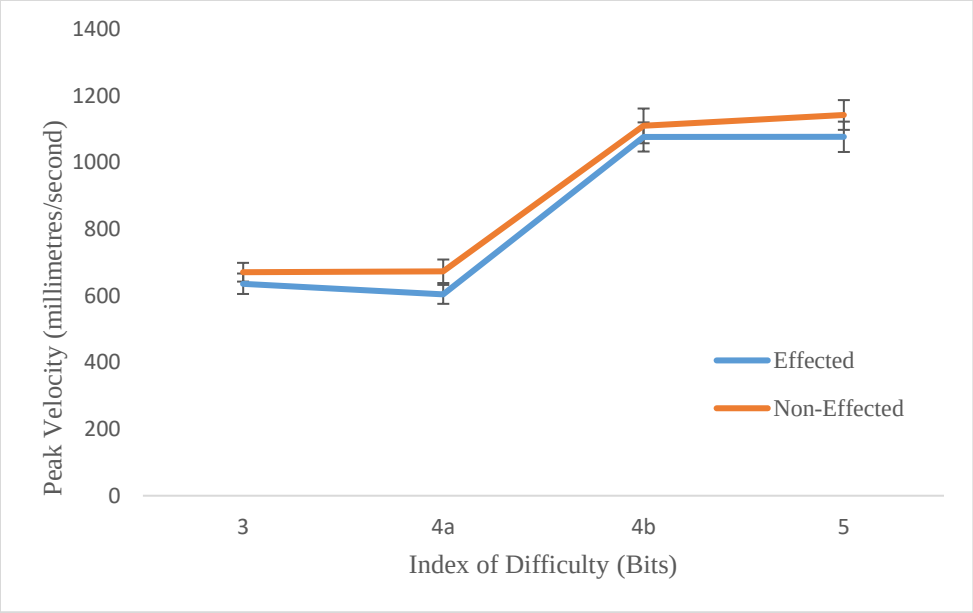

Figure 12. Peak velocity across all IDs for group 2 (effected and non-effected limbs). Error bars represent the SEM at each ID. Note, the greatest difference between limbs occurs at IDs 4a and 5.

There were no other significant main effects for group for the other behavioural and kinematic variables in this analysis. There were no main effects determined for group by ID interaction for any of the performance variables between the effected and non-effected limbs in group 2.

Analysis of ID yielded main effects for MT (ID3 *M*=557.6ms, *SD*=111.7; ID 4a *M*=563.7ms, *SD*=107.3; ID 4b *M*=731.7ms, *SD*=133.0; ID 5 *M*=743.6, *SD*=107.7), PV (ID3 *M*=653.6mm/s, *SD*=113.4; ID 4a *M*=639.1mm/s, *SD*=126.8; ID 4b *M*=1093.5mm/s, *SD*=83.9; ID 5 *M*=1110.2mm/s, *SD*=179.9), ttPV (ID3 *M*=193.9ms, *SD*=32.8; ID 4a *M*=195.7ms, *SD*=30.7; ID 4b *M*=238.6ms, *SD*=45.2; ID 5 *M*=240.1ms, *SD*=44.0), PA (ID3 *M*=6222.7mm/s^2, *SD*=2208.7; ID 4a *M*=6003.5mm/s^2, *SD*=2110.4; ID 4b *M*=8834.5mm/s^2, *SD*=3389.6 ID 5 *M*=9290.9mm/s2, *SD*=3113.6), ttPA (ID3 *M*=58.8ms, *SD*= 3.3; ID 4a *M*=59.0ms, *SD*=24.9; ID 4b *M*=79.0ms, *SD*=33.7; ID 5 *M*=80.5, *SD*=36.8) and CE (ID3 *M*=0.5mm, *SD*=1.4; ID 4a *M*=-0.1mm, *SD*=1.0; ID 4b *M*=-3.8mm, *SD*=1.1; ID 5 *M*=-3.1, *SD*=1.3) [$F(3,42)=72.953$, $p<0.001$,

partial eta squared=0.839; $F(3,42)=299.003$, $p<0.001$, partial eta squared=0.955; $F(3,42)=56.660$, $p<0.001$, partial eta squared=0.787; F(3,42)=54.065, p<0.001, partial eta squared=0.794, F(3,42)=11.290, p<0.001, partial eta squared=0.446 and F(3,42)=6.477, p=0.001, partial eta squared=0.316, respectively]. There were no main effects for ID for RT, VE, or AE between limbs. Post hoc analysis exposed longer MT, ttPV, ttPA and lower PA and PV to targets at larger amplitudes, compared to width . Please see Table 5 in the appendix of this document for a summary of the significant main effects for group 2 (effected and non-effected limbs).

Group 3: Dominant Versus Non-Dominant Limbs

A 2 group (dominant, non-dominant) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) was performed for all behavioural and kinematic variables between limbs in group 3. There were 2 subjects whose WFQ-R score totalled +6 (mixed dominance). Both were considered right dominant, for purposes of analysis. Main effects were found for group for PA (dominant limb $M=7456.1 mm/s^2$, $SD=3092.77$; non-dominant limb $M=8625.11$, $SD=4176.877$) and ttPA (dominant limb $M=81.5$ms, $SD=39.5$; non-dominant limb $M=59.4$ms, $SD=40$), [$F(1,14)=6.296$, $p=0.026$, partial eta squared=0.307; $F(1,14)=10.538$, $p=0.006$, partial eta squared=0.382 respectively]. Lower PAs and longer ttPAs were determined for the dominant limb, compared to the non-dominant limb. No other main effects for group were found for other behavioural and kinematic variables.

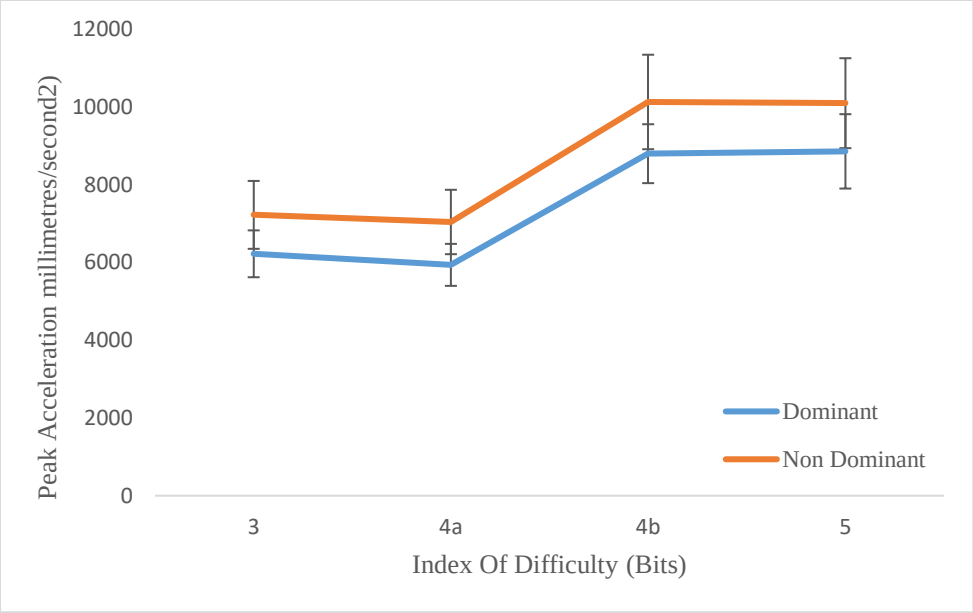

Figure 13. Peak acceleration across all IDs for group 3 (dominant and non-dominant limbs). Error bars represent SEM at each ID.

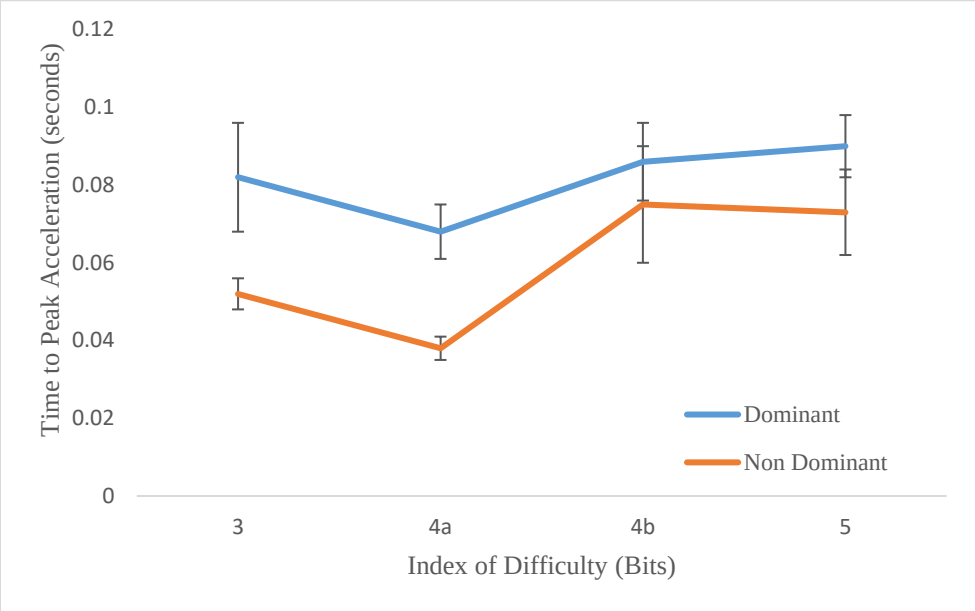

Figure 14. Time to peak acceleration across all IDs for group 3 (dominant and non-dominant limbs). Error bars represent SEM at each ID. The greatest difference between limbs occurs at IDs 3 and 4a.

There were no group by ID interaction for any of the motor performance variables. There were main effects determined across ID for MT (ID3 *M*=580.7; *SD*=98.7; ID 4a *M*=562.7ms, *SD*=104.0; ID 4b *M*=751.6ms, *SD*=162.0.0; ID 5 *M*=786.4, *SD*=170.7), PV (ID3 *M*=661.1mm/s, *SD*=152.0; ID 4a *M*=640.6mm/s, *SD*=162.4; ID 4b *M*=1055.0mm/s, *SD*=230.5; ID 5 *M*=1064.1mm/s, *SD*=243.0), ttPV (ID3 *M*=192.8ms, *SD*=47.0; ID 4a *M*=184.0ms, *SD*=36.7; ID 4b *M*=226.7ms, *SD*=51.4.0; ID 5 *M*=239.6ms, *SD*=63.8), PA (ID3 *M*=6725.2mm/s^2, *SD*=2901.0; ID 4a *M*=6491.6mm/s^2, *SD*=2720.3; ID 4b *M*=9465.7mm/s^2, *SD*=3913.4; ID 5 *M*=9480.0mm/s2, *SD*=4089.1) and ttPA (ID3 *M*=67.0ms, *SD*=42.7; ID 4a *M*=52.9ms, *SD*=26.5; ID 4b *M*=80.3ms, *SD*=49.4; ID 5 *M*=81.6, *SD*=37.6), [$F(3,42)=50.917$, $p<0.001$, partial eta squared=0.784; $F(3,42)=199.086$, $p<0.001$, partial eta squared=0.934; $F(3,42)=60.536$, $p<0.001$, partial eta squared=0.812; $F(3,42)=43.145$, $p<0.001$, partial eta squared=0.755 and $F(3,42)=8.660$, $p<0.001$, partial eta squared=0.382, respectively]. Post-hoc analysis determined detrimental performance measures, associated with longer target amplitudes, compared to target width. Table 8 in the appendix of this document summarizes main effects for kinematic and behavioural variables in group 3 (dominant and non-dominant limbs).

Between Limb Comparisons (Stratified by Limb Dominance)

Group 1: Dominant Effected and Non-Dominant Effected

A 2 group (effected, non-effected) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) was executed between effected and non-effected limbs for subjects in group, 1 who reported dominance of the effected limb and for those who reported non-dominance of the effected limb. This type of analysis was performed to test the serial hybrid control theory. For this analysis, 7 subjects were classified as dominant limb effected, and 8 were classified as non-dominant limb effected. Caution should be used when interpreting these results, as 8 of 15

subjects were classified as having "mixed dominance" in group 1, according to the Revised Waterloo Footedness Questionnaire. For analysis purposes, those with a negative score were labelled as "left dominant" and those with a positive score were labelled as "right dominant". Ambiguity regarding dominance for this group is a limitation.

Main effects were found for CE between limbs, when the non-dominant limb was effected (non-dominant effected limb M=-1.9, SD=0.5; dominant non-effected limb M=-0.7, SD=0.9), [F(1,7)=8.490, p=0.023, partial eta squared= 0.548). The non-dominant effected limb demonstrated greater negative values for CE, signifying a greater tendency to undershoot the target. There were no other significant effects for group, or group by ID interactions for the dominant effected and non-dominant effected analyses.

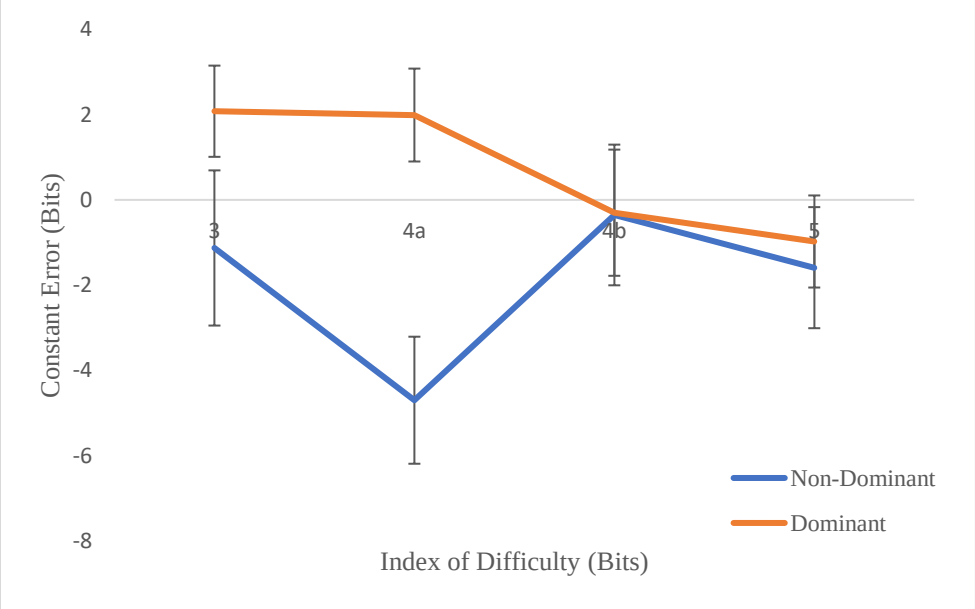

Figure 15. Constant Error across all IDs for group 1 (non-dominant effected and dominant non-effected limbs). Error bars represent SEM at each ID. The greatest difference between limbs occurs at IDs 3 and 4a.

There were significant main effects for ID for the dominant effected investigation for MT (ID3 *M*=594.6ms, *SD*=120.1; ID 4a *M*=581.7ms, *SD*=113.7; ID 4b *M*=800.1ms, *SD*=178.5; ID 5 *M*=865.2, *SD*=191.0), PV (ID3 *M*=635.9mm/s, *SD*=134.7; ID 4a *M*=606.8mm/s, *SD*=149.1; ID 4b *M*=991.1mm/s, *SD*=234.5; ID 5 *M*=1006.2mm/s, *SD*=258.8), ttPV (ID3 *M*=210.9ms, *SD*=34.3; ID 4a *M*=210.0ms, *SD*=33.5; ID 4b *M*=254.4ms, *SD*=54.0; ID 5 *M*=271.2ms, *SD*=58.8), PA (ID3 *M*=5472.0mm/s^2, *SD*=1654.3; ID 4a *M*=4962.4mm/s^2, *SD*=1801.2; ID 4b *M*=7151.6mm/s^2, *SD*=2551.1; ID 5 *M*=7266.1mm/s2, *SD*=2987.9) and ttPA (ID3 *M*=92.1ms, *SD*=46.9; ID 4a *M*=77.4ms, *SD*=30.8; ID 4b *M*=123.7ms, *SD*=104.9; ID 5 *M*=129.7ms, *SD*=54.7), [*F*(3,18)=39.019, *p*<0.001, partial eta squared=0.867; *F*(3, 18)=55.697, *p*<0.001, partial eta squared=0.903; *F*(3,18)=14.437, *p*=0.005, partial eta squared=0.706; *F*(3,18)=12.597, *p*=0.005, partial eta squared=0.683; *F*(3,18)=3.266, *p*=0.045, partial eta squared=0.352, respectively].

Main effects for ID were determined for the non-dominant analysis for MT (ID3 *M*=566.4ms, *SD*=63.0; ID 4a *M*=579.0ms, *SD*=64.0; ID 4b *M*=735.2ms, *SD*=112.0; ID 5 *M*=787.3, *SD*=117.6), PV (ID3 *M*=687.3mm/s, *SD*=90.2; ID 4a *M*=666.8mm/s, *SD*=118.0; ID 4b *M*=1086.6mm/s, *SD*=176.5; ID 5 *M*=1076.7mm/s, *SD*=164.2), ttPV (ID3 *M*=202.1, *SD*=26.9; ID 4a *M*=196.7ms, *SD*=28.6; ID 4b *M*=225.7ms, *SD*=17.3; ID 5 *M*=227.0ms, *SD*=19.8), PA (ID3 *M*=6147.2mm/s^2, *SD*=1162.3; ID 4a *M*=5932.7mm/s^2, *SD*=1364.8; ID 4b *M*=8696.2mm/s^2, *SD*=1950.8; ID 5 *M*=8571.6mm/s2, *SD*=1960.0) and ttPA (ID3 *M*=60.2ms, *SD*=21.0; ID 4a *M*=64.5ms, *SD*=24.4; ID 4b *M*=71.4ms, *SD*=19.5; ID 5 *M*=75.4, *SD*=29.3), [*F*(3,21)=41.871, *p*<0.001, partial eta squared=0.857; *F*(3,21)=51.653, *p*<0.001, partial eta squared=0.881; *F*(3,21)=10.304, *p*<0.001, partial eta squared=0.595; *F*(3,21)=32.445, *p*<0.001, partial eta

squared=0.823; $F(3,21)=4.492$, $p=0.014$, partial eta squared=0.391, respectively]. There were no main effects found for ID for RT, CE, VE, or AE between limbs.

Post hoc analysis exposed longer MT, ttPV, ttPA and lower PA and PV to targets at larger amplitudes for both analyses. Target amplitude impacted motor performance variables more significantly then target width for dominant effected and non-dominant effected analyses. Please see tables 3 and 4 in the Appendix section of this document for summary of the significant main effects for group 1 (dominant effected and non-dominant effected) for each measure.

Group 2: Dominant Effected

The serial hybrid theory was further tested by evaluating limbs of subjects with the dominant limb effected and those with the non-dominant limb effected for group 2. In this analysis, there were 2 subjects who identified themselves as "mixed dominant" by the WFQ-R. One was categorized as "dominant effected" and the other as "non-dominant effected". In total, there were 8 subjects in group 2 that were classified as "dominant effected", and 7 classified as "non-dominant effected". A limitation of the following results is that 2 subjects were defined as having "mixed dominance", by the WFQ-R.

Main effects were found for group for PV (dominant effected limb PV $M=867.2$, $SD=272.4$; non-dominant non-effected limb PV $M=932.1$, $SD=255.4$) and PA (dominant effected limb PA $M=7175.6$, $SD=2737.5$; non-dominant non-effected limb PA $M=8684.9$, $SD=3171.3$) between limbs, when the dominant limb was effected, [$F(1,7)=6.798$, $p=0.035$ and $F(1,7)=7.043$, $p=0.033$, respectively]. In both cases, the dominant effected limb demonstrated lower values for PV and PA, in comparison to the non-dominant, non-effected limb. This may be an attempt to reduce speed of the movement task, or may signify impairment in online control of movement of

the effected limb. No other main effects for group were determined for the other motor performance variables. There were no significant main effects for group, ID or group by ID interaction for CE, VE, or AE. As in previous analyses, there was no suggestion of alteration in the preparatory phase of motor planning, as no main effects for RT were found for group, ID or group by ID interaction.

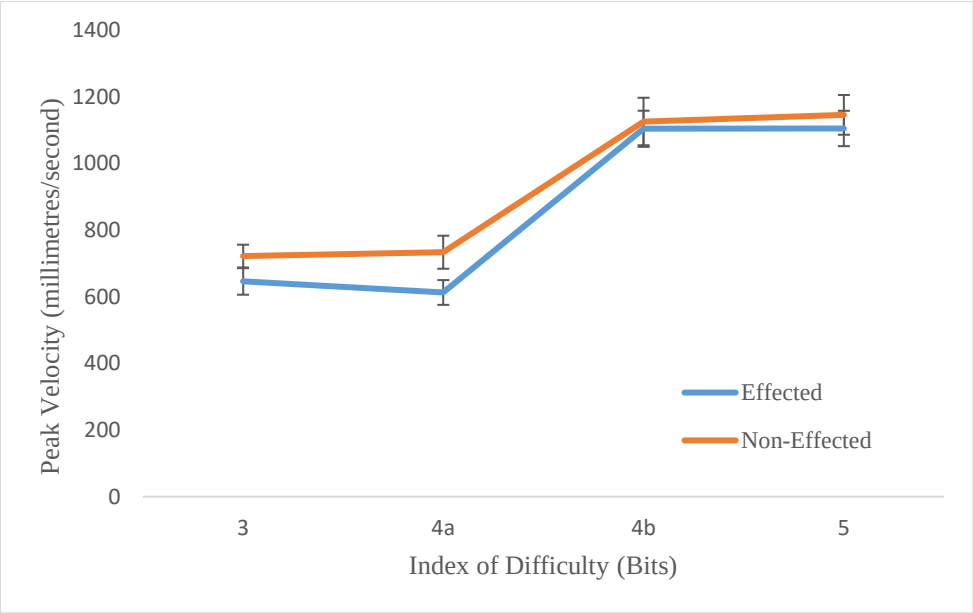

Figure 16. Peak velocity across all IDs for group 2 (dominant effected and non-dominant non-effected limbs). Error bars represent SEM for each ID. Note, the greatest difference between limbs occurred at IDs 3 and 4a.

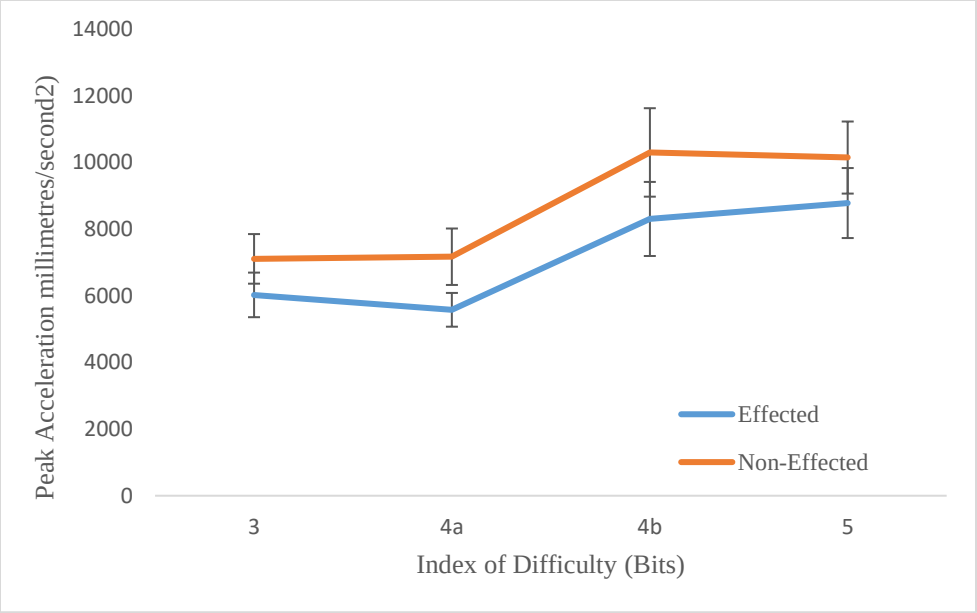

Figure 17. Peak acceleration across all IDs for group 2 (dominant effected and non-dominant non-effected limbs). Error bars represent SEM for each ID. Note, the greatest difference between limbs occurs at IDs 4a and 4b.

Significant main effects were found for ID for MT (ID3 *M*=517.2ms, *SD*=77.4; ID 4a *M*=533.1ms, *SD*=80.1; ID 4b *M*=725.6ms, *SD*=124.3; ID 5 *M*=738.8, *SD*=106.4), PV (ID3 *M*= 684.2mm/s, *SD*=108.8; ID 4a *M*=673.4mm/s, *SD*=135.0 ; ID 4b *M*=1115.3mm/s, *SD*=173.5; ID 5 *M*=1125.7mm/s, *SD*=155.8), ttPV (ID3 *M*=192.3ms, *SD*=31.9; ID 4a *M*=195.0ms, *SD*=33.6; ID 4b *M*=236.4ms, *SD*=44.1; ID 5 *M*=238.0ms, *SD*=47.6), PA (ID3 *M*=6569.1mm/s^2, *SD*=2013.0; ID 4a *M*=6377.3mm/s^2, *SD*=2077.4; ID 4b *M*=9306.2mm/s^2, *SD*=3500.9; ID 5 *M*=468.4mm/s2, *SD*=997.7) and ttPA (ID3 *M*=54.1ms, *SD*=24.0; ID 4a *M*=53.3ms, *SD*=24.1; ID 4b *M*=69.8ms, *SD*=27.3; ID 5 *M*=74.4, *SD*=39.4), between dominant effected and non-dominant effected limbs in group 2 [$F(3,21)=71.357$, $p<0.001$, partial eta squared=0.911; $F(3, 21)=127.374$, $p<0.001$, partial eta squared=0.948; $F(3,21)=30.393$, $p<0.001$, partial eta squared=0.813; $F(3,21)=21.266$, $p=0.001$, partial eta squared=0.752 and $F(3,21)=4.732$, $p=0.038$, partial eta squared=0.403, respectively]. As in previous analyses, longer MT, ttPV,

ttPA, lower PA and lower PV, associated with targets at larger amplitude, compared to width was observed. Table 6 in the appendix of this document summarizes the significant main effects of all motor performance variables between the dominant effected and non-dominant non-effected limbs for Group 2.

Group 2: Non-Dominant Effected

A 2 group (non-dominant effected, dominant non-effected) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) was performed between all behavioural and kinematic variables for 7 group 2 subjects, with presumed non-dominant leg effect. Main effects were found for CE between limbs, when the non-dominant limb was effected (non-dominant effected limb M=-2.991mm, SD=1.3; dominant non-effected limb M=0.166, SD=1.6), [F(1,6)=11.244, p=0.015, partial eta squared= 0.652). The non-dominant effected limb demonstrated greater negative values for CE, signifying a greater tendency to undershoot the target. There were no other main effects for group for any of the performance variables. However, there was a group by ID interaction for MT, (ID3 MT *M*=603.7ms, *SD*=129.0; ID4a MT *M*=598.6ms, *SD*=125.7; ID4b MT *M*=738.7ms, *SD*=146.7; ID5 MT *M*=749.0ms, *SD*=112.9), [*F*(3, 18)=4.160, *p*=0.021, partial eta squared=0.409]. Post hoc evaluation determined the greatest difference between means at ID 4b, compared to the other targets.

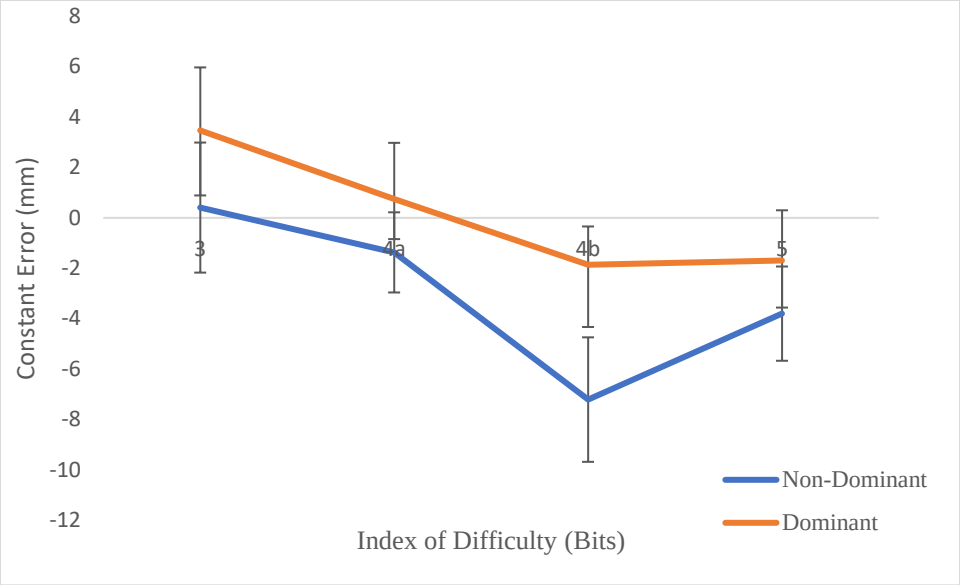

Figure 18. Constant error across all IDs, for group 2 (non-dominant effected and dominant non-effected limbs). Error bars represent SEM at each ID. Note, the greatest difference between limbs occurs at ID 4b.

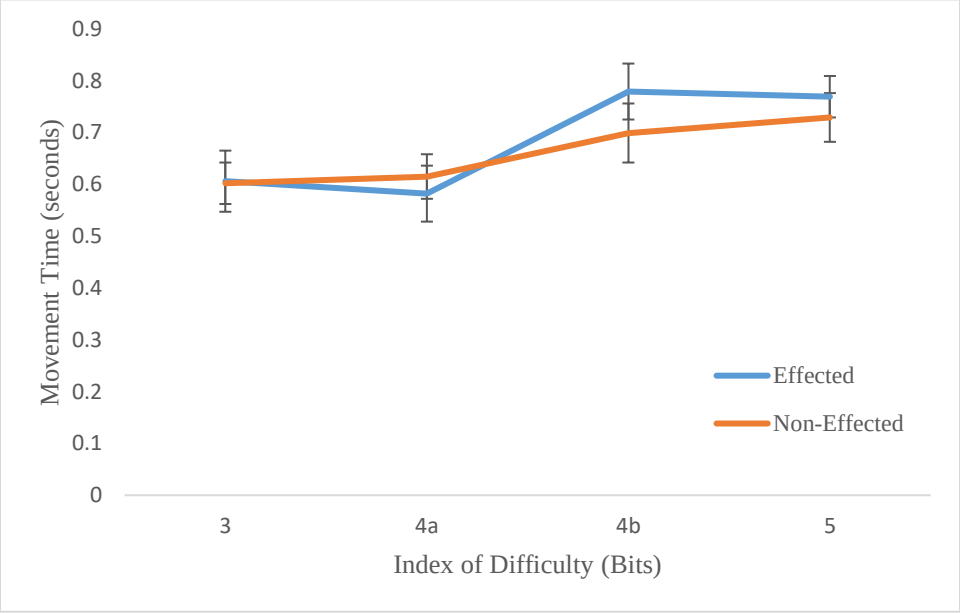

Figure 19. Movement time across all IDs, for group 2 (non-dominant effected and dominant non-effected limbs). Error bars represent SEM at each ID. Note, the greatest difference between limbs occurs at ID 4b.

Main effects were found for ID for MT (ID3 *M*=603.7ms, *SD*=129.0; ID 4a *M*=598.6ms, *SD*=125.7.0; ID 4b *M*=738.7ms, *SD*=146.7; ID 5 *M*=749.0, *SD*=112.9), PV (ID3 *M*=618.6mm/s, *SD*=112.1; ID 4a *M*=599.9mm/s, *SD*=108.5 ; ID 4b *M*=1068.3mm/s, *SD*=198.6; ID 5 *M*=1092.3mm/s, *SD*=199.0), ttPV (ID3 *M*=195.7ms, *SD*=28.4; ID 4a *M*=196.4ms, *SD*=28.4; ID 4b *M*=241.1ms, *SD*=47.9; ID 5 *M*=242.6ms, *SD*=41.2), PA (ID3 *M*=5826.8mm/s^2, *SD*=427.1; ID 4a *M*=5576.3mm/s^2, *SD*=2141.8; ID 4b *M*=8295.5mm/s^2, *SD*=3290.3; ID 5 *M*=9088.1mm/s2, *SD*=3342.8), ttPA (ID3 *M*=64.2ms, *SD*=22.2; ID 4a *M*=65.5ms, *SD*=25.0; ID 4b *M*=89.6ms; *SD*=38.1; ID 5 *M*=87.5, *SD*=33.7) and CE (ID3 *M*=1.939mm, *SD*=2.3; ID 4a *M*=-0.310mm, *SD*=1.6; ID 4b *M*=-4.5mm; *SD*=1.6; ID 5 *M*=-2.7mm, *SD*=1.7) [$F(3,18)=21.272$, $p<0.001$, partial eta squared=0.780; $F(3,18)=165.843$, $p=0.001$, partial eta squared=0.965; $F(3,18)=19.296$, $p<0.001$, partial eta squared= 0.763; $F(3,18)=35.216$, $p<0.001$, partial eta squared= 0.854, $F(3,18)=6.250$, p=0.004, partial eta squared=0.510 and $F(3,18)=4.160$, p=0.21, partial eta squared=0409, respectively]. As in previous analyses, target amplitude had a detrimental effect on performance, opposed to target width. No main effects were found for ID for RT, VE, or AE. Table 7 in the appendix summarizes significant main effects for measured variables

Correlation and Regression Analyses

Group 1

Pearson's correlation coefficients were calculated between all performance variables obtained in group 1 (effected and non-effected limbs) and self-report questionnaires, regarding pain, function and dysfunction. The intent was to measure the strength of the relationship

between variables. Are high values of one variable associated with high values of another (positive correlation), or are high values of a variable associated with low values of another (negative correlation)? In accordance with the accepted interpretation of Spearman's Rho coefficient, a value above r=0.5 will be considered a strong correlation. Values between 0.3 to 0.4 will be considered a moderately strong association. The following correlations were determined to be statistically significant at an alpha of 0.05, for 2-tailed correlation analyses, for group 1:

There is a strong positive correlation between ttPA of the effected limb and scores on the QNRS (effected limb), r=0.597, N=15, p=0.019. Time for group 1 participants to reach their peak acceleration during trials increased for their effected leg, as scores on the QNRS (effected limb) increased. Similarly, ttPV of the effected limb increased in this population, as scores on the Oswestry Disability Index increased, r=0.598, N=15, p=0.019. This signifies a strong positive correlation. Another strong positive correlation was found between AE (effected limb) and QNRS scores for the non-effected leg, r=0.623, N=15, p=0.013. Individuals were less accurate with the effected leg with higher QNRS scores for the non-effected leg.

Multiple linear regression was performed in the data analysis of this study, in an attempt to determine if the independent variables (self-report questionnaire scores, demographics) can make predictions, regarding the dependent variables (motor performance variables). The regression analysis for this study used forward regression. All possible bivariate regressions were calculated for each performance variable and each independent variable (ie: self-report questionnaire scores, age and sex). The outcomes associated with the highest R-square and model F values were combined to create two-predictor models. The best two-predictor model was then used to create three-predictor models, and so forth. Once the addition of another

predictor no longer improved R-square, and/or model F values, no further independent variables were added to the model. If there were no statistically significant bivariate regressions between any of the independent variables and the dependent variable, therefore, a multiple regression model was not determined.

For group 1, there was no bivariate regression found that was determined to be statistically significant with the assumptions of regression met (linearity of relationship, normality of residuals, homoscedasticity, independence of errors).

Group 2

Similar correlation calculations were performed for group 2 participants between motor performance variables of the effected and non-effected limbs and results of self-report questionnaires obtained in this study. The following correlations were determined to be statistically significant at an alpha of 0.05, for 2-tailed correlation analyses, for group 2: There was a strong positive correlation between group 2 measures of MT (effected limb) and scores on the RM and ODI. Scores signifying dysfunction increase as MT of the effected limb increase, ($r=0.580$, $N=15$, $p=0.023$; $r=622$, $N=15$, $p=0.013$, respectively). The PA of the effected limb increased, as RMDQ scores decreased, signified by a strong negative Spearman's Rho coefficient, $r= -0.539$, $N=15$, p=0,038. Group 2 also demonstrated higher scores on the ODI, associated with greater AE scores for the effected limb, $r=0.571$, $N=15$, $p=0.048$.

Forward regression was also used to determine if independent variables (self-report questionnaires) can make predictions regarding the dependent variables for group 2 (motor performance variables). For group 2, there was no regression model that was determined statistically significant, where the assumptions of regression were met (linearity of relationship, normality of residuals, homoscedasticity, independence of errors).

Group 3

Correlation coefficient analyses were performed between motor performance variables measured for the dominant and non-dominant limbs and self-report questionnaires for group 3 participants. The following correlations were determined to be statistically significant at an alpha of 0.05, for 2-tailed correlation analyses, for group 3:

Strong negative associations were found between PV measures of the non-dominant limb and the ODI, r= -0.657, N=15, p=0.008. Conversely, there was a strong positive correlation between PV of the non-dominant limb for group 3 and the PSFS, r=0.560, N=15, p=0.030. Measures of PV increased in the non-dominant limb, associated with lower disability, or ODI scores. Patients reported higher levels of function on the PSFS, while PV measures also increased. On average, group 3 participants took longer to reach PV of the non-dominant limb, associated with increased scores on the ODI, r=0.536, MN=15, p=0.040. Measurements of ttPV for the non-dominant limb are negatively correlated with self-reported function (PSFS), r= -0.519, N=15, p=0.048. Self- evaluations of function improved as time to reach peak velocity decreased. Correlation analysis also revealed strong negative associations between the PA achieved by group 3 participants (non-dominant limb) and scores on the ODI, r= -0.535, N=15, p=0.040. PA values were higher, on average, associated with lower disability self- evaluations (ODI). Only one significant correlation was revealed for the dominant limb in group 3, the association between ttPA of the dominant limb and scores on the QNRS (non-dominant limb), r= -0.568, N=15, p=0.027. The interpretation of this calculation is that participants reached their peak acceleration quicker for the dominant limb, as pain in their non-dominant limb increased.

For group 3, there was no bivariate regression found that was determined to be significantly significant with the assumptions of regression met (linearity of relationship, normality of residuals, homoscedasticity, independence of errors).

Discussion

Comparisons Between Groups

ANOVA- Between Groups (Collapsed by leg)

There were no significant differences determined between groups 1, 2 and 3 (collapsed by leg) for any of the performance variables measured, with the exception of absolute error. A lack of significant difference was not predicted by the hypothesis, which speculated a greater detriment in performance for group 1, compared to groups 2 and 3. The execution of movement of subjects in groups 1 and 2 did not differ from each other, and they did not differ from a group of subjects with multilevel lumbar degenerative changes. However, group 1 demonstrated greater deviation from target location, compared to group 3. Although subjects with LR demonstrated similar movement strategies as groups 2 and 3, they were not as accurate with end point positioning.

Lumbar nerve root compression on imaging and objective neurological deficit resulted in a greater tendency of subjects to deviate from the target location, compared to those with lumbar degenerative change, who were neurologically intact. Prior research by Passmore et al (2014) revealed greater movement times, but maintenance of accuracy across all IDs for the stenosis population, compared to age matched controls. The neurological function of the targeted population was not reported. It is known that subjects with alterations in sensorimotor function may exhibit tendency for errors in an aiming task (Marchand, Cantin, Murphy, Stern, & Descarreaux, 2014).

Overall interpretation of the findings in this study is challenging, due to a lack of a true "negative-negative" control group, for comparison. Group 3 was selected as a control group, because imaging was devoid of neurological compromise. However, self-report questionnaires completed in this study reveal equivocal low back and leg pain between groups. All groups reported a moderate amount of dysfunction, related to symptoms.

It is difficult to make inferences, regarding the impact of lumbar radiculopathy on kinematic and behavioural variables, in consideration of an absence of a true control group for this study. There may exist further alterations in aspects of motor planning, muscle recruitment, and or online motor control in a group of subjects with confirmed unilateral, unisegmental lumbar radiculopathy, compared to those without this diagnosis.

Another plausible reason for an absence of significant main effects between groups may include within group variability. An analysis of variance reveals significant main effects if the difference between groups is greater than the difference within groups (Kim, H., 2014). The clinical manifestation of lumbar radiculopathy, lumbar nerve root irritation and mechanical low back pain (related to multilevel degenerative changes) is variable (Govind, 2004; Lipetz, 2002). Nerve root compression varied between levels L3-S1. Therefore, motor and sensory deficit measured correlated with different dermatomal and myotomal levels, possibility contributing to heterogeneity within this group.

It was postulated that the presence of neurological deficit in group 1 may negatively impact most aspects of motor performance, compared to those without neurological deficit. If the function of a nerve root changes, due to conduction block, there should be positive motor and sensory findings (Govind, 2004). It is thought that such deficits in sensorimotor control of a lower limb could be revealed with a Fitts' motor control task (Passmore et al., 2014). However,

the extent of neurological involvement in group 1 was somewhat subtle. There were participants who presented with a simple reflex change, others with unisegmental motor, or sensory deficit, and those with varying combinations of all three. The extent and type of neurological deficit was not controlled for in this experiment. Those with significant neurological compromise were not recruited due to inability to participate in prolonged unsupported standing. The Fitts' task utilized in this study demanded that participants stand unsupported for 20 to 30 minutes. Those with extreme radicular pain, and/or dysfunction related to motor/sensory deficit often declined participation, were unable to stand unsupported during their exam, and/or required the use of a mobility aid. Therefore, this study was not designed to evaluate the impact of severe radiculopathy.

Main effect for ID was determined in this study, consistent with Fitts' law regarding movement time (Fitts, 1954). Main effects for ID were revealed for all analyses in this document for MT, PV, ttPV, PA, ttPA, but not for RT, AE, or VE. The difficulty of the task did not impact variability, absolute deviation from the target, or motor planning. However, the analysis between groups also revealed main effects for target for CE. Subjects tended to undershoot the target at IDs of greater amplitude (4a and 5), across all groups. Alteration in accuracy has been reported in the literature, in relation to an increase in target amplitude when pain is present (Lemay & Proteau, 2001).

Fitts' equation implies that there is a linear relationship between movement time and the index of difficulty (Fitts, 1954). As the amplitude of movement increases, or as the size of the target width decreases, movement time is lengthened. There was a greater perceived impact of movement amplitude, then target width for all groups. The impact of amplitude over target width is evident at overlapping IDs 4a and 4b, for all study analyses.

Comparisons Between Limbs

Group 1: Effected Versus Non-Effected Limbs

No differences in motor performance were revealed between limbs in group 1. The finding provides evidence that there were no differences in performance between the effected and non-effected limbs. Conversely, differences were observed between limbs in group 2 (imaging evidence of nerve compression, without neurological deficit). The presence, or absence of neurological deficit is the defining feature between both groups. It was hypothesized that differences between limbs would be greater in group 1, because the performance of the effected limb may be influenced by pain, motor, and or sensory deficit (Govind, 2004). However, the present study provides evidence of the contrary, there is less discrepancy in performance between limbs when neurological deficit is evident.

Group 2: Effected Versus Non-Effected Limbs

The 2 group (effected, non-effected) x 4 ID (3, 4a, 4b, 5) mixed model analysis of variance (ANOVA) performed between limbs in group 2 exposed longer MTs and lower PVs for the effected limb, compared to the non-effected limb. This is similar to the findings of Passmore et al, 2015, where stenosis subjects demonstrated longer MTs and lower PVs, compared to healthy controls. It was suggested that reduced speed may be a strategy to improve accuracy of motion (Passmore et al., 2015). There were no main effects for group for any of the error analyses. However, there was a main effect for ID for CE in both group 1 and group 2 between limb comparisons, where subjects in both groups tended to undershoot the target at IDs associated with larger amplitudes. This finding was not revealed with the group 3 between limb analysis. The defining feature between group 1 and 2, compared to group 3 is the presence of radicular

pain. This implies that as the task difficulty increases, subjects with radicular pain are less accurate with target location.

Group 3: Dominant Versus Non-Dominant Limbs

The dominant and non-dominant limbs demonstrated equivocal MTs across IDs in this group. However, there were main effects for group for PA and ttPA, where the dominant limb demonstrated lower PAs and longer ttPAs. Differences between limbs was most evident for group 3, became less obvious for group 2 and non-distinguishable for group 1. Gait asymmetry and the concept of lateralization has been studied. It has been proposed that asymmetry between limbs may be the result of differing contributions of each limb, regarding propulsion and control (Sadeghi, Allard, Prince, & Labelle, 2000). Literature also suggests that asymmetry between the dominant and non-dominant limbs may also be influenced by factors, such as leg length, muscle strength, muscle mass, muscle activation patterns and compensatory mechanisms (Sadeghi et al., 2000; Sung & Danial, 2017).

Subjects with low back pain are known to demonstrate compensatory mechanisms, such as trunk rotation to the dominant side (Sung & Danial, 2017). The study by Sung and Daniels (2017) determined that a group of subjects with low back pain had longer initial double support time for the non-dominant limb, and longer terminal double support time for the dominant limb, compared to a control group. It is unknown how this alteration in gait mechanics influences motor performance. Literature regarding how compensatory strategies effect a low back pain subject's kinematic and behavioural variables during a reaching task was not found. Age may also influence symmetry between limbs. Authors have reported a 15-20% rate of asymmetry in leg strength in older populations, compared to a 5-10% rate in younger subjects (Perry, Carville, Smith, Rutherford, & Newham, 2007)

Literature suggests that asymmetry in performance of the dominant and non-dominant limb is complex. It may relate to other extraneous variables, such as muscle strength, muscle mass, leg length, etc. These variables were not evaluated, or controlled for in this population.

Comparisons Between Limbs (Stratified by Limb Dominance)

Group 1- Dominant Effected and Non-Dominant Effected Limbs

Support for the serial hybrid control theory is evidenced by the comparison between limbs, when the non-dominant limb is effected. It was hypothesized that alterations in accuracy would be exposed, due to the non-dominant's limb role in impedance control. When the non-dominant limb was impacted in both group 1 and 2, there was a main effect for group for CE, where the effected limb tended to undershoot the target, compared to the dominant limb.

Support for the serial hybrid theory is not evidenced by the dominant effected statistical analysis performed in group 1. No significant main effects for group, or group by ID interaction (between limbs) were discovered for any of the performance variables measured. However, estimation of limb dominance, using the RWFQ exposes ambiguity regarding designation of limb preference for this group of subjects. Eight of the fifteen subjects fell into the mixed dominance, or no limb preference category. Perhaps the presence of neurological deficit altered prior limb preference. Therefore, this group is not ideal for testing of the serial hybrid theory, as the division between dominance and non-dominance is less clear.

Group 2: Dominant Effected

The dominant effected limb demonstrated lower values for PV and PA, in comparison to the non-dominant, non-effected limb, which is predicted by interpretation of the serial hybrid control theory. Prior research by Haaland et al (2009), determined lower values for PV, MT, increased duration of acceleration and less of an increase in PA as amplitude increases (Haaland et al.,

2009). The serial hybrid control theory predicts alterations in predictive control when the dominant limb is impacted and involved in the movement task (Haaland et al., 2009). There were two patients who were deemed to be mixed dominant, or to possess no preference for either limb. For analysis purposes, one subject was placed into the dominant effected and the other into the non-dominant effected groups. To determine group allocation a negative score was labelled as left preference, and a positive score was labeled as right preference. The small sample size also suggests that the sub-analyses performed in this study are explorative in nature.

Group 2: Non-Dominant Effected

A significant effect found when comparing the non-dominant effected to the dominant non-effected limbs in group 2 was a group by ID interaction for MT. The post-hoc analysis determined that the difference between means for MT was greatest at ID 4b and 5. The non-dominant effected limb demonstrated longer movement times, compared to the dominant non-effected limb at the targets associated with longer amplitudes and greater index of difficulty. The serial control theory suggests greater contribution of impedance control of the non-dominant limb. Prior studies on stroke patients have demonstrated alterations in accuracy at movement end if there is impact on the hemisphere contralateral to the non-dominant limb, but preservation of movement trajectory control (Schaefer et al., 2009). As in the sub-analysis for group one, impact on the non-dominant limb resulted in an increase in CE, or subjects tending to undershoot the target location. Such alterations in accuracy is predicted by the serial hybrid control theory.

Correlation and Regression Analyses

Group 1

There were more statistically significant correlations established for groups 2 and 3, compared to group 1. For group 1, ttPA (effected limb) increases with pain of the effected limb; and ttPV (effected limb) increases with disability. Both associations were considered strong (ie: $r>0.5$). A significant Pearson's calculation was found between accuracy (AE) of the effected limb and pain in the non-effected limb. A previous study indicates that a tendency towards error coincides with increasing pain within the stance limb (Hadizadeh, Mousavi, Sedaghatnejad, Talebian, & Parnianpour, 2014). However, correlation does not suggest causation, association only.

A lack of significant correlation between objective measures of performance and self-report questionnaires implies that subjects in group 1 experienced difficulty defining their functional capability and level of disability. The defining feature within this group is the presence of neurological deficit. The clinical manifestations of this condition vary significantly between individuals, despite similar imaging findings (Boos et al., 1995; Govind, 2004). The nature of neurological deficit also varies within an individual (Govind, 2004). In consideration of the variance in clinical presentation and nature of symptoms, there may exist a discourse between objective and subjective evaluations of performance for subjects with lumbar radiculopathy.

A lack of significant correlation coefficients for group 1 suggests that self-report questionnaires used in clinical practice should not replace objective measures of function for a population of patients with unilateral lumbar nerve root compression, with neurological deficits, if objective functional parameters are used to make clinical decisions. Impact on function is considered when screening patients for spine surgery . A survey was administered to 817

surgeons in 89 countries to determine common practices for management of lumbar disc herniation (Gadjradj et al., 2017). The most common reason to intervene surgically, based on survey responses was severity of pain and disability (55%). Patients with unilateral lumbar nerve root compression may be considered surgical candidates, if there are significant neurological deficits and if there is significant impact on functional capability. However, this group of subjects demonstrated the greatest discourse between their self-evaluation and objective measures of performance.

There were no statistically significant bivariate linear regression models determined for group 1 variables, where the assumptions of regression were met. This suggests that questionnaires scores do not predict motor performance for a group of subjects with unilateral lumbar nerve root compression and neurological deficits.

Group 2

It was hypothesized that a lack of correlation between questionnaire scores and performance measures may relate to catastrophization, or PCS scores (Stief et al., 2018). Group 1 PCS scores (M=28.5, SD=11.3) were greater then group 2 (M=26.2, SD=29.2) and 3 (M=17.7, SD=10.3). Group 3 exhibited significantly lower PCS scores, however, group 1 and 2 scores did not differ significantly. There were a number of significant Pearson's correlation coefficients determined between aspects of objective motor performance and questionnaires used in this study for group 2, however, fewer significant correlations then what were determined for group 3. Movement times of the effected limb correlated strongly with disability scores on the ODI and RMDQ. The PA of the effected limb also increased, while disability declined. Group 2 also demonstrated higher levels of disability (ODI, RMDQ), associated with higher levels of error

(AE, VE) of the effected limb. Disability appears to be associated with measures of inaccuracy of the effected limb.

Another interesting observation is a greater association between subjective questionnaires and objective performance variables of the effected limb. There is a greater association between motor performance of the effected limb and questionnaire data for subjects in group 1 and 2. For group 2, there were no statistically significant regression models to predict motor performance from questionnaire data. Performance cannot be predicted by knowledge of questionnaire scores for subjects with unilateral lumbar nerve root compression and normal neurological function.

Group 3

Strong correlations found for group 3 provide support that self-report questions regarding pain, function and dysfunction mirror actual performance for the non-dominant limb. Peak velocity of the non-dominant limb increased with lower levels of disability and higher levels of function. Peak acceleration increased with lower levels of disability, where ttPV increased with higher disability scores. Time to peak velocity in the non-dominant limb increased, while function declined. Group 3 participant's self-reported function, or disability correlates best with motor performance of their non-dominant limb.

For group 3, there was no bivariate regression found that was determined to be significantly significant with the assumptions of regression met (linearity of relationship, normality of residuals, homoscedasticity, independence of errors).

There were far more significant correlation associations found then significant regression models in this study. Although many self-report questionnaires were associated with actual

motor performance, very few questionnaires/ demographic data predicted objective measures. This exposes limitations of questionnaire data to predict actual performance.

Limitations of This Study

The greatest limitation to this study is the lack of a true negative-negative control group for comparison of motor performance variables to the lumbar pathology groups studied. It is uncertain whether a lack of difference between groups represents minimal impact of lumbar imaging findings/ symptoms, or whether differences simply do not exist between these three populations of patients, with limbs collapsed. However, recruitment of a group of subjects with normal imaging and an absence of spinal/leg pain and neurological deficit poses challenges. Firstly, asymptomatic patients are not often imaged. The average age of participants in this study was over 50. Research indicates that up to 90% of individuals over the age of 50 have degenerative changes in their spine (Teraguchi et al., 2014). Therefore, it would be challenging to find a group of age-matched subjects with no segmental changes on imaging films.

Another limitation is the possibility of heterogeneity within groups. For example, the subjects within group 1 had varying neurological changes from a simple reflex change to more significant motor/sensory deficits. The extent of neurological involvement was multifarious. The lumbar nerve root involved ranged between the L3, L4, L5 and S1segments. Because each nerve innervates different muscles and follows different dermatomal patterns for sensory loss, the clinical manifestation varied between participants. Variability of nerve root involvement likely resulted in disparate impact on performance. Another factor to consider is the time between imaging confirmation of lumbar nerve root compression and the date of testing/assessment. On average, group 1 participants were studied four-months post imaging. Radicular pain and neurological symptoms related to nerve compression are often transient in

nature (Kreiner et al., 2014). Subsequent imaging of disc herniation demonstrates regression of disc material over time (Cribb et al., 2007). Therefore, natural healing may have occurred between date of testing and imaging confirmation of pathology.

The nature of the perceived difficulty in executing the Fitts' test itself may have created a recruitment selection bias. This experiment demanded that participants stand unsupported and reach with one of their limbs towards a designated target projected on the floor. Patients with significant motor, and/or sensory loss and those with significant radicular pain often declined participation in this study, or were not deemed to be a study candidate because of their limited tolerance to unilateral weight-bearing. Those significantly impacted by lumbar radiculopathy were not appropriate for this test as their diminished function disabled their ability to perform the task.

Bilateral comparisons performed in this study and questionnaire data regarding limb dominance supported testing of the serial hybrid control motor control theory. However, ambiguity regarding limb dominance posed challenges for defining groups. Inclusion cut-offs were created to facilitate the analysis. Small sample sizes for the repeat measures ANOVA performed reflect an exploratory analysis, as the a priori calculation for the present study recommended a minimum of 10 participants per group. Larger sample sizes are needed to further evaluate the concept of lateralization.

Twenty-two of thirty subjects had nerve root compression effecting the L5, or S1 nerve roots. The present study involves flexion of the acetabular joint with the knee extended in the sagittal plane. The prime movers of the foot pointing motion include quadriceps and hip flexor muscle activation. Nerve root innervation varies from L2 to L4 for the prime movers. Therefore, the study task may not have been appropriate to evaluate L5/S1 segmental nerve compression.

Future Research

To investigate the impact of unilateral lumbar nerve root compression with, or without neurological changes, one might consider comparing a group of subjects with imaging confirmation of nerve compression to an asymptomatic age-matched population. This will enable the investigator to determine the impact of a lumbar nerve root compression condition on aspects of motor performance, to a group of healthy subjects, who do not have this clinical diagnosis. Comparisons of populations with and without clinical evidence of lumbar pathology cannot answer questions regarding the prognostic value of MRI for lumbar spine pathology, as healthy age-matched participants may have abnormalities on imaging, suggestive of nerve compression. However, clinical practice guidelines do not support imaging of asymptomatic healthy individuals (Delitto et al., 2012; Oliveira et al., 2018).

For group 1, consideration could be given to inclusion of those with motor, sensory and reflex changes, correlating with the same effected lumbar segment, due to the same etiology. Improving consistency within target group will allow for testing of those most impacted by suggested imaging findings. Consideration could also be given to recruitment of patients from a radiology clinic, where testing could occur soon after imaging is interpreted and confirmation of nerve compression is made. However, those very influenced by nerve compression, or those with very acute symptoms may not be appropriate for unsupported unilateral lower limb reaching, demanded by the Fitts' task.

A possible explanation for lack of difference in performance between limbs in group 1 may relate to similar alterations in movement of the non-effected limb, due to reliance on the stance, effected limb for impedance control. Comparisons could be performed between limbs in

group 1 in standing and in sitting, for the lower limb pointing task. Sitting would negate the impact of the stance limb.

Future studies may also want to determine if aspects of motor performance for nerve root compression groups improve following a course of care, by way of initial and post-treatment Fitts' task analyses. Repeat testing may reveal aspects of motor performance that are amendable to conservative, and/or surgical interventions. The results of this type of analysis may inform stakeholders of the value/ limitations of surgical/conservative interventions. Results may also support changes in clinical practice, in an effort to address specific aspects of motor control.

To conduct a more in depth inquiry into the serial hybrid control theory, one may consider recruitment of those with suggested limb preference,(as dictated by the WFQ-R) and to recruit a larger sample size, to satisfy the a priori calculation.

To investigate the impact of low back pain on kinematic and behavioral variables obtained in this study between limbs, one should conduct a comparison of an age-matched, asymptomatic population of subjects to those with reported low back pain/dysfunction. If the influence of age is studied, there may exist four distinct groups for a 4 x 4 ANOVA analysis: young healthy asymptomatic, older healthy asymptomatic, younger low back pain and older low back pain populations.

Consideration should be given to alterations to the lower limb reaching task, to address specific segmental involvement. A seated toe pointing motion in sitting with the ankle in plantarflexion may be more appropriate for an S1 radiculopathy, compared to the protocol employed in the present study.

Conclusion

Lumbar imaging and self-report questionnaires conducted in this experiment did not define groups of patients with lumbar pathology. Specifically, groups of subjects with imaging evidence of unilateral lumbar nerve root compression, with and without sensorimotor deficits demonstrated similar movement strategies as a group of participants with multilevel lumbar degenerative changes, who described low back pain related dysfunction.

Evaluation of error revealed variations in the accuracy of the reaching task. There were alterations in accuracy noted for group 1 and 2 motor performance, that were not revealed with evaluation of the lumbar degenerative change group. Groups 1 and 2 demonstrated main effects for ID for CE. Imaging of lumbar nerve root compression resulted in a tendency to undershoot the target when the amplitude of movement increased for both nerve compression groups. However, deviation from target location (AE) was unique to the group with sensorimotor change. Neurological deficit resulted in less end point accuracy.

The Fitts' task was able to further differentiate groups, by way of within group between limb comparisons. The presence of radicular pain and imaging evidence of nerve compression (negative neurological involvement) resulted in longer MTs and lower PVs of the effected leg, compared to the non-effected leg for group 2.

Conversely, there were no differences in kinematic or behavioral variables between limbs for group 1. Both group 1 and 2 participants had evidence of unilateral lumbar nerve root compression on imaging, and similar questionnaire scores regarding pain intensity, disability and function. The defining difference between groups is the presence of neurological deficit in group 1. The presence of motor, sensory and or reflex change for subjects with unilateral lumbar nerve root compression translated into similar motor performance between limbs.

Group 3 participants demonstrated higher values of PA and shorter values of ttPA for the non-dominant limb, compared to the dominant limb. This may reflect alterations in kinematics, secondary to compensatory patterns of movement possessed by individuals with low back pain, or other extraneous variables (Sadeghi et al., 2000; (Sung & Danial, 2017). The greatest difference between limbs was observed for group 3 subjects with lumbar degenerative change. Differences between limbs is less evident when radicular leg pain is present, and even less significant when pain and neurological change is observed.

Group 1 correlation analysis revealed the fewest number of significant correlations between subjective self-report questionnaires regarding function, disability and pain with objective motor performance variables collected. A lack of association between subjective and objective measures, associated with higher levels of catastrophization was predicted (Stief et al., 2018). However, a lack of significant correlations for group 1, over groups 2 and 3 may implicate neurological deficit as an impedance of evaluation of actual performance. Pearson's correlation calculations exposed many significant associations between objective and subjective measures of function for groups 2 and 3. Both groups were superior to group 1 in their ability to define performance on a functional weight-bearing task.

Group 3 had the greatest number of statistically significant correlations between motor performance variables and questionnaire scores. The lumbar degeneration group also had the lowest values of pain catastrophization (PCS scores), which offers support for the original hypothesis that greater associations would be found between variables and self-report scales if PCS values were low, and vice versa (Stief et al., 2018)

Subjects with imaging evidence of unilateral lumbar nerve root compression demonstrate stronger correlations between motor performance variables of their effected limb with self-report

scales regarding pain, function and dysfunction. For subjects with lumbar radiculopathy, the relationships between ttPA and ttPV of the effected limb and disability scores provide evidence that impaired online motor control during the initiation of movement occurs with higher levels of pain and disability. Relationships between absolute error and pain in the non-effected limb imply that there is a tendency for error, as pain in the stance limb increases. For neurologically intact subjects with imaging evidence of nerve compression, relationships between MT (effected) and disability scores indicate that there is longer time to execute tasks, associated with higher levels of disability. The associations between PA (effected) with disability scores indicate that superior execution of movement coincides with lower levels of disability. Relationships between absolute error (effected) and disability provide evidence of a tendency for error as perceived disability increases.

Alternatively, most of the statistically significant correlations obtained between group 3 motor performance variables and questionnaires relate to variables obtained for the non-dominant limb. The relationships between PA, PV (non-dominant) and disability/functional reports indicate that superior online motor control is associated with higher levels of function and lower levels of disability. The significant associations between ttPV (non-dominant) provides evidence for impaired online motor control coinciding with lower levels of function and higher levels of disability. The one statistically significant association between ttPA (dominant) and pain implies that there is a tendency to reach PA faster, when pain in the stance limb increases. In regard to the prediction value for the battery of questionnaires used in this experiment, there was no statistically significant bivariate regression model found for any of the groups, where motor performance can be predicted by questionnaire scores. Therefore, there is support for the notion of including both subjective and objective evaluations, when attempting to define

function, or level of dysfunction for groups of subjects with unilateral lumbar nerve root compression and subjects with reported back-related dysfunction, secondary to degenerative changes.

In conclusion, the present study provides evidence of the shortcomings of imaging to define, or predict motor performance for three groups of patients with lumbar pathology and varying clinical presentations. However, a Fitts' task may be utilized to define differences between groups by way of accuracy evaluation and between limb comparisons.

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APPENDIX A

Figures

A (cm)	W (cm)	ID (Bits)	Home
20	5	3	
20	2.5	4a	
40	5	4b	
40	2.5	5	

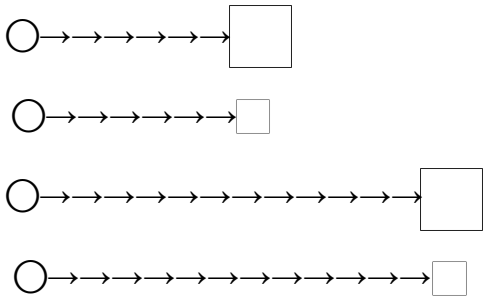

Figure 1. Representation of the 4 combinations of movement amplitude (A) and target width (W), which describe the index of difficulty (ID). Circles represent the home position, and squares represent the targets. IDs range from 3 to 5 (5 being most difficult). IDs 4a and 4b have different amplitudes and target widths, but the same index of difficulty.

APPENDIX B

Tables

Table 1.
Demographics and Summary of Questionnaire Data for Groups 1, 2 and 3

	Group 1M (SD)	Group 2 M(SD)	Group 3 M (SD)	One-Way ANOVA
Age	47.5 (15.7)	55.9 (15.8)	54.8 (15.8)	
Sex	7 Females	4 Females	5 Females	
ODI	20.7 (9.8)	13.8 (9.3)	16.3 (8)	F(2,42)= 2.264 p= 0.116
RM	13.3 (5.9)	9.4 (6.6)	11.3 (6.1)	F(2,42)= 1.468 p= 0.242
PSFS	43.0 (21.9)	49.6 (20.6)	46.3 (21.9)	F(2,42)= 0.333 p= 0.704
QNRS (Back)	53.2 (21.2)	44.3 (23.1)	50.8 (14.5)	F(2,42)= 0.791 p= 0.460
QNRS (E, or D)	49.4 (23.9)	41.5 (26.2)	25.1 (19.2)	F(2,42)= 0.017 p= 0.983
QNRS (NE, or ND)	9.7 (10.3)	10.7 (14.7)	32.4 (17.1)	F(2,42)= 0.418 p= 0.661
WRQ-R				
Right	6	13	12	
Left	1	0	1	
Mixed	8	2	2	
PCS	28.5 (11.3)	38.5 (26.2)	17.7 (10.3)	F(2,42)= 5.318 p= 0.009

ODI= Oswestry Disbility Index
RM= Roland Morris Questionnaire
PSFS= Patient Specific Functional Scale
QNRS= Quadruple Numeric Pain Rating Scale
WFQ-R= Waterloo Footedness Questionnaire
PCS= Pain Catastrophizing Scale

M= Mean
SD= Standard Deviation
E= Effected Limb
D= Dominant Limb
NE= Non-effected Limb
ND= Non-dominant Limb
*= Signifies significant p value <0.05

Table 2.
Summary of Significant Effects for Motor Performance Variables for All Groups (Legs Collapsed)

	Group	ID	Group by ID
MT	F(2,28)=0.314 p= 0.733	F(3,42)=164.191 **p=<0.001	F(6,84)=1.444 p=0.248
RT	F(2,28)=1.315 p=0.285	F(3,42)=0.895 p=0.452	F(6,84)=1.803 p=0.146
PV	F(2,28)=0.067 p=0.935	F(3,42)=488.374 p=0.452	F(6,84)=1.803 p=0.146
ttPV	F(2,28)=0.339 p=0.675	F(3,42)=82.932 **p=<0.001	F(6,84)=1.062 p=0.373
PA	F(2,28)=0.966 p=0.393	F(3,42)=96.289 p=<0.001	F(6,84)=1.062 p=0.375
ttPA	F(2,28)= 1.048 p=0.364	F(3,42)= 16.681 **p=<0.001	F(6,84)= 0.414 p=0.756
CE	F(2,28)=1.905 p= 0.262	F(3,42)= 7.15 *p= 0.001	F(6,84)= 1.996 p= 0.075
AE	F(2,28)= 5.117 *p=0.013	F(3,42)= 1.966 p= 0.134	F(6,84)= 0.711 p= 0.641
VE	F(2,28)= 1.002 p=0.36	F(3,42)= 1.858 p=0.151	F(6,84)= 1.191 p=0.319

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 3.
Summary of Significant Effects for Motor Performance Variables for Group 1 (Effected Versus Non-Effected Limbs)

	Group	ID	Group by ID
MT	F(1,14)= 0.003 p= 0.958	F(3,42)= 77.531 **p= <0.001	F(3,42)= 0.596 p= 0.556
RT	F(1,14)= 0.193 p= 0.667	F(3,42)= 2.110 p= 0.113	F(3,42)= 0.302 p= 0.718
PV	F(1,14)= 0.002 p= 0.967	F(3,42)= 111.561 **<p= 0.001	F(3,42)= 3.443 p= 0.065
ttPV	F(1,14)= 0.630 p= 0.440	F(3,42)= 21.237 **p= <0.001	F(3,42)= 0.522 p= 0.669
PA	F(1,14)= 1.034 p= 0.326	F(3,42)= 42.672 p= <0.001	F(3,42)= 0.448 p= 0.720
ttPA	F(1,14)= <0.001 p= 0.989	F(3,42)= 4.653 *p= 0.025	F(3,42)= 2.299 p= 0.119
CE	F(1,14)= 0.001 p= 0.999	F(3,42)=5.130 *p= 0.017	F(3,42)=0.538 p= 0.659
AE	F(1,14)= 0.433 p= 0.521	F(3,42)= 1.074 p= 0.370	F(3,42)= 0.227 p= 0.877
VE	F(1,14)= 0.646 p= 0.435	F(3,42)= 1.323 p= 0.280	F(3,42)= 0.210 p= 0.806

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 4.
Summary of Significant Effects for Motor Performance Variables for Group 1 (Dominant Effected Versus Non-Dominant, Non-effected Limbs)

	Group	ID	Group by ID
MT	F(1,6)= 0.025 p= 0.880	F(3,18)= 39.019 **p= <0.001	F(3,18)=0.359 p= 0.784
RT	F(1,6)= 0.808 p= 0.403	F(3,18)= 0.996 p= 0.417	F(3,18)= 0.628 p= 0.490
PV	F(1,6)= 0.350 p= 0.576	F(3,18)= 55.697 **p= <0.001	F(3,18)=0.798 p=0.434
ttPV	F(1,6)= 0.444 p= 0.530	F(3,18)= 14.437 *p= 0.005	F(3,18)= 0.433 p= 0.732
PA	F(1,6)=0.055 p= 0.822	F(3,18)= 12.917 *p= 0.005	F(3,18)= 0.616 p= 0.613
ttPA	F(1,6)= 0.116 p= 0.745	F(3,18)= 3.266 *p= 0.045	F(3,18)= 1.868 p= 0.171
CE	F(1,6)= 0.328 p= 0.588	F(3,18) = 0.309 p= 0.818	F(3,18) =0.581 p= 0.635
AE	F(1,6)= 0.501 p= 0.506	F(3,18)= 0.753 p= 0.546	F(3,18)= 778 p= 0.521
VE	F(1,6)= 1.983 p= 0.209	F(3,18)= 1.436 p= 0.265	F(3,18)= 0.201 p= 0.894

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 5.
Summary of Significant Effects for Motor Performance Variables for Group 1 (Non-Dominant Effected Versus Dominant Non-Effected Limbs)

	Group	ID	Group by ID
MT	F(1,7)= 0.0.25 p= 0.880	F(3,21)= 41.871 **p= <0.001	F(3,21)= 0.217 p= 0.727
RT	F(1,7)= 3.121 p= 0.121	F(3,21)= 2.010 p= 0.143	F(3,21)=1.002 p= 0.411
PV	F(1,7)= 0.979 p= 0.355	F(3,21)= 51.653 **p= <0.001	F(3,21)=2.898 p= 0.124
ttPV	F(1,7)= 0.151 p= 0.709	F(3,21)= 10.304 **p= <0.001	F(3,21)= 1.375 p= 0.278
PA	F(1,7)= 3.052 p= 0.124	F(3,21)= 32.445 p= <0.001	F(3,21)= 0.490 p= 0.693
ttPA	F(1.7)= 0.516 p= 0.496	F(3,21)= 4.492 *p= 0.014	F(3,21)= 2.504 p= 0.693
CE	F(1,7)= 8.490 *p= 0.023	F(3,21)= 0.707 p= 0.559	F(3,21)= 2.6 p= 0.079
AE	F(1,7)= 3.389 p= 0.108	F(3,21)= 0.279 p= 0.890	F(3,21)= 0.432 p= 0.732
VE	F(1,7)= 0.007 p= 0.937	F(3,21)= 0.846 p= 0.484	F(3,21)= 0.391 p= 0.760

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 6.
Summary of Significant Effects for Motor Performance Variables for Group 2 (Effected Versus Non-Effected Limbs)

	Group	ID	Group by ID
MT	F(1,14)= 0.4.773 *p= 0.046	F(3,42)= 72.953 **p= <0.001	F(3, 42)= 2.506 p= 0.106
RT	F(1,14)= 1.492 p= 0.242	F(3,42)= 0.974 p= 0.452	F(3,42)= 1.268 p= 0.298
PV	F(1,14)= 9.084 *p= 0.009	F(3,42)= 299.003 **p= <0.001	F(3,42)= 0.570 p= 0.512
ttPV	F(1,14)= 3.318 p= 0.090	F(3,42)= 56.660 **p= <0.001	F(3,42)= 1.231 p= 0.311
PA	F(1,14)= 3.480 p= 0.083	F(3,42)= 54.065 **p= <0.001	F(3,42)= 1.172 p= 0.326
ttPA	F(1,14)= 0.277 p= 0.607	F(3,42)= 11.290 **p= <0.001	F(3,42)= 1.053 p= 0.379
CE	F(1,14)= 0.010 p= 0.920	F(3,42)= 6.477 p= 0.001	F(3,42)= 0.488 p= 0.693
AE	F(1,14)= 0.075 p= 0.788	F(3,42)= 0.760 p= 0.523	F(3,42)= 0.679 p= 0.570
VE	F(1,14)= 0.014 p= 0.909	F(3,42)= 1.207 p= 0.318	F(3,42)= 0.433 p= 0.730

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 7.
Summary of Significant Effects for Motor Performance Variables for Group 2 (Dominant Effected Versus Non-Dominant, Non-Effected Limbs)

	Group	ID	Group by ID
MT	F(1,7)= 4.390 p= 0.074	F(3,21)= 71.357 **p= <0.001	F(3,21)= 0.507 p= 0.682
RT	F(1,7)= 0.055 p= 0.821	F(3,21)= 0.660 p= 0.586	F(3,21)= 0.588 p= 0.630
PV	F(1,7)= 6.798 *p= 0.035	F(3,21)= 127.374 *p= <0.001	F(3,21)= 1.446 p= 0.271
ttPV	F(1,7)= 4.364 p= 0.075	F(3,21)= 30.393 **p= <0.001	F(3,21)= 0.668 p= 0.581
PA	F(1,7)= 7.043 *p= 0.033	F(3,21)= 21.266 p= <0.001	F(3,21)= 0.881 p= 0.467
ttPA	F(1,7)= 2.476 p= 0.160	F(3,21)= 4.732 *p= 0.038	F(3,21)= 1.384 p= 0.283
CE	F(1,7)= 1.523 p= 0.257	F(3,21)= 2.958 p= 0.056	F(3,21)= 0.253 p= 0.858
AE	F(1,7)= 0.175 p= 0.688	F(3,21)= 0.245 p= 0.864	F(3,21)= 2.286 p= 0.246
VE	F(1,7)= 1.144 p= 0.320	F(3,21)= 0.649 p= 0.592	F(3,21)= 0.855 p= 0.465

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 8.
Summary of Significant Effects for Motor Performance Variables for Group 2 (Non-Dominant Effected Versus Dominant, Non-Effected Limbs)

	Group	ID	Group by ID
MT	F(1,6)= 1.301 p= 0.297	F(3,18)= 21.272 **p= <0.001	F(3,18)= 4.160 *p= 0.021
RT	F(1,6)= 1.924 p= 0.215	F(3,18)= 0.308 p= 0.820	F(3,18)= 0.629 p= 0.606
PV	F(1,6)= 2.348 p= 0.176	F(3,18)= 165.843 **p= <0.001	F(3,18)= 2.194 p= 0.178
ttPV	F(1,6)= 0.133 p= 0.727	F(3,18)= 19.296 **p= <0.001	F(3,18)= 0.565 p= 0.645
PA	F(1,6)= 0.026 p= 0.878	F(3,18)= 35.216 **p= <0.001	F(3,18)= 0.362 p= 0.781
ttPA	F(1,6)= 1.184 p= 0.318	F(3,18)= 6.250 *p= 0.004	F(3,18)= 0.031 p= 0.992
CE	F(1,6)= 11.244 p= 0.015	F(3,18)= -2.991 p= 1.259	F(3,18)= 0.166 p= 1.578
AE	F(1,6)= 2.281 p= 0.182	F(3,18)= 1.118 p= 0.368	F(3,18)= 0.448 p= 0.722
VE	F(1,6)= 1.141 p= 0.280	F(3,18)= 0.364 p= 0.780	F(3,18)= 1.235 p= 0.326

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 9.
Summary of Significant Effects for Motor Performance Variables for Group 3 (Dominant Versus Non-Dominant Limbs)

	Group	ID	Group by ID
MT	F(1,14)= 0.012 p= 0.915	F(3,42)= 50.917 **p= <0.001	F(3,42)= 0.037 p= 0.990
RT	F(1,14)= 0.015 p= 0.996	F(3,42)= 0.970 p= 0.416	F(3,42)= 1.301 p= 0.297
PV	F(1,14)= 0.587 p= 0.456	F(3,42)= 199.086 **p= <0.001	F(3,42)= 1.045 p= 0.178
ttPV	F(1,14)= 2.843 p= 0.114	F(3,42)= 60.536 **p= <0.001	F(3,42)= 0.817 p= 0.449
PA	F(1,14)= 6.216 *p= 0.026	F(3,42)= 43.145 **p= <0.001	F(3,42)= 0.223 p= 0.880
ttPA	F(1,14)= 10.538 *p= 0.006	F(3,42)= 8.660 **p= <0.001	F(3,42)= 0.642 p= 0.520
CE	F(1,14)= 4.551 p= 0.051	F(3,42)= 0.297 p= 0.828	F(3,42)= 1.082 p= 0.367
AE	F(1,14)= 0.992 p= 0.336	F(3,42)= 1.326 p= 0.279	F(3,42)= 0.318 p= 0.812
VE	F(1,14)= 0.253 p= 0.623	F(3,42)= 1.757 p= 0.194	F(3,42)= 0.381 p= 0.767

* Signifies significant p value <0.05
** Signifies significant p value <0.001.

Table 10.
Summary of Correlation Coefficient Calculations between Group 1 Motor Performance Variables and Self-Report Questionnaire Scores (ODI, RM &PSFS)

	ODI	RM	PSFS
MT (E)	r= 0.193 p= 0.490 N= 15	r= 0.163 p= 0.561 N= 15	r= 0.015 p= 0.957 N= 15
MT (NE)	r= 0.215 p= 0.495 N= 15	r= 0.339 p= 0.217 N= 15	r= 0.145 p= 0.607 N= 15
RT (E)	r= -0.121 p= 0.667 N= 15	r= 0.132 p= 0.638 N= 15	r= 0.170 p= 0.545 N= 15
RT (NE)	r= 0.350 p= 0.201 N= 15	r= 0.278 p= 0.316 N= 15	r= 0.231 p= 0.408 N= 15
PV (E)	r= -0.275 p= 0.321 N= 15	r= -0.164 p= 0.560 N= 15	r= -0.044 p= 0.877 N= 15
PV (NE)	r= -0.266 p= 0.337 N= 15	r= -0.264 p= 0.342 N= 15	r= 0.014 p= 0.960 N= 15
ttPV (E)	r= 0.598 *p= 0.019 N= 15	r= 0.308 p= 0.265 N= 15	r= -0.172 p= 0.540 N= 15
ttPV (NE)	r= 0.181 p= 0.520 N= 15	r= 0.116 p= 0.680 N= 15	r= 0.050 p= 0.860 N= 15
PA (E)	r= -0.285 p= 0.303 N= 15	r= -0.117 p= 0.677 N= 15	r= -0.037 p= 0.895 N= 15
PA (NE)	r= 0.195 p= 0.486 N= 15	r= -0.316 p= 0.252 N= 15	r= 0.100 p= 0.724 N= 15

ttPA (E)	r= 0.458 p= 0.086 N= 15	r= 0.375 p= 0.168 N= 15	r= -0.185 p= 0.510 N= 15
ttPA (NE)	r= 0.311 p= 0.260 N= 15	r= 0.001 p= 0.998 N= 15	r= -0.119 p= 0.672 N= 15
AE (E)	r= 0.337 p= 0.220 N= 15	r= 0.214 p= 0.493 N= 15	r= 0.623 *p= 0.013 N= 15
AE (NE)	r= -0.073 p= 0.795 N= 15	r= -0.027 p= 0.925 N= 15	r= 0.224 p= 0.422 N= 15
VE (E)	r= 0.012 p= 0.967 N= 15	r= -0.229 p= 0.412 N= 15	r= -0.035 p= 0.900 N= 15
VE (E)	r= -0.403 p= 0.136 N= 15	r= -0.396 p= 0.144 N= 15	r= -0.354 p= 0.196 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

Table 11.

Summary of Correlation Coefficient Calculations between Group 1 Motor Performance Variables and Self-Report Questionnaire Scores (QNRS)

	QNRS (BACK)	QNRS (E)	QNRS (NE)
MT (E)	r= 0.165 p= 0.558 N= 15	r= 0.096 p= 0.734 N= 15	r= -0.095 p= 0.737 N= 15
MT (NE)	r= 0.106 p= 0.708 N= 15	r= 0.024 p= 0.934 N= 15	r= -0.037 p= 0.896 N= 15
RT (E)	r= 0.072 p= 0.798 N= 15	r= 0.173 p= 0.538 N= 15	r= -0.177 p= 0.529 N= 15
RT (NE)	r= -0.080 p= 0.778 N= 15	r= 0.214 p= 0.443 N= 15	r= -0.134 p= 0.635 N= 15
PV (E)	r= -0.042 p= 0.886 N= 15	r= 0.017 p= 0.951 N= 15	r= 0.138 p= 0.623 N= 15
PV (NE)	r= -0.208 p= 0.457 N= 15	r= -0.066 p= 0.815 N= 15	r= 0.029 p= 0.918 N= 15
ttPV (E)	r= -0.071 p= 0.801 N= 15	r= 0.364 p= 0.183 N= 15	r= 0.050 p= 0.860 N= 15
ttPV (NE)	r= 0.015 p= 0.957 N= 15	r= 0.115 p= 0.591 N= 15	r= -0.135 p= 0.632 N= 15
PA (E)	r= -0.065 p= 0.818 N= 15	r= -0.113 p= 0.689 N= 15	r= -0.014 p= 0.960 N= 15
PA (NE)	r= -0.308 p= 0.264	r= -0.139 p= 0.622	r= 0.117 p= 0.677

	N= 15	N= 15	N= 15
ttPA (E)	r= 0.268 p= 0.334 N= 15	r= 0.597 *p= 0.019 N= 15	r= 0.167 p= 0.552 N= 15
ttPA (NE)	r= -0.025 p= 0.929 N= 15	r= 0.281 p= 0.311 N= 15	r= -0.207 p= 0.460 N= 15
AE (E)	r= 0.011 p= 0.970 N= 15	r= 0.135 p= 0.632 N= 15	r= -0.024 p= 0.933 N= 15
AE (NE)	r= -0.114 p= 0.686 N= 15	r= -0.046 p= 0.870 N= 15	r= 0.293 p= 0.289 N= 15
VE (E)	r= -0.346 p= 0.209 N= 15	r= -0.530 p= 0.851 N= 15	r= -0.024 p= 0.933 N= 15
VE (NE)	r= -0.344 p= 0.209 N= 15	r= -0.306 p= 0.267 N= 15	r= 0.205 p= 0.302 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

Table 12.
Summary of Correlation Coefficient Calculations between Group 2 Motor Performance Variables and Self-Report Questionnaire Scores (ODI, RM &PSFS)

	ODI	RM	PSFS
MT (E)	r= 0.580 *p= 0.023 N=15	r= 0.622 *p= 0.013 N= 15	r= -0.158 p= 0.575 N= 15
MT (NE)	r= 0.345 p= 0.207 N= 15	r= 0.509 p= 0.052 N= 15	r= -0.141 p= 0.615 N= 15
RT (E)	r= -0.341 p= 0.214 N= 15	r= -0.165 p= 0.557 N= 15	r= 0.287 p= 0.300 N= 15
RT (NE)	r= 0.486 p= 0.066 N= 15	r= 0.314 p= 0.255 N= 15	r= 0.426 p= 0.114 N= 15
PV (E)	r= -0.234 p= 0.401 N= 15	r= -0.320 p= 0.245 N= 15	r= 0.069 p= 0.807 N= 15
PV (NE)	r= -0.369 p= 0.176 N= 15	r= -0.472 p= 0.075 N= 15	r= 0.120 p= 0.671 N= 15
ttPV (E)	r= 0.207 p= 0.459 N= 15	r= 0.398 p= 0.142 N= 15	r= -0.120 p= 0.670 N= 15
ttPV (NE)	r= 0.235 p= 0.399 N= 15	r= 0.370 p= 0.245 N= 15	r= 0.075 p= 0.791 N= 15
PA (E)	r= -0.478 p= 0.071 N= 15	r= -0.539 *p= 0.038 N= 15	r= 0.328 p= 0.232 N= 15
PA (NE)	r= -0.375 p= 0.168	r= -0.470 p= 0.077	r= -0.100 p= 0.724

	N= 15	N= 15	N= 15
ttPA (E)	r= 0.119 p= 0.673 N= 15	r=-0.373 p= 0.170 N= 15	r= 0.206 p= 0.462 N= 15
ttPA (NE)	r= 0.167 p= 0.553 N= 15	r= 0.227 p= 0.415 N= 15	r= 0.255 p= 0.358 N= 15
AE (E)	r= 0.517 *p= 0.048 N= 15	r= 0.506 p= 0.054 N= 15	r= -0.357 p= 0.192 N= 15
AE (NE)	r= 0.096 p= 0.734 N= 15	r= 0.182 p= 0.516 N= 15	r= 0.152 p= 0.589 N= 15
VE (E)	r= -0.124 p= 0.659 N= 15	r= 0.037 p= 0.895 N= 15	r= 0.198 p= 0.479 N= 15
VE (NE)	r= 0.339 p= 0.210 N= 15	r= 0.527 *p= 0.43 N= 15	r= 0.335 p= 0.222 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

Table 13.
Summary of Correlation Coefficient Calculations between Group 2 Motor Performance Variables and Self-Report Questionnaire Scores (QNRS)

	QNRS (Back)	QNRS (E)	QNRS (NE)
MT (E)	r= 0.507 p= 0.054 N=15	r= 0.349 p= 0.202 N= 15	r= 0.071 p= 0.800 N= 15
MT (NE)	r= 0.221 p= 0.430 N= 15	r= 0.200 p= 0.475 N= 15	r= 0.133 p= 0.635 N= 15
RT (E)	r= -0.230 p= 0.410 N= 15	r= -0.172 p= 0.539 N= 15	r= -0.496 p= 0.060 N= 15
RT (NE)	r= 0.136 p= 0.628 N= 15	r= -0.047 p= 0.868 N= 15	r= 0.199 p= 0.476 N= 15
PV (E)	r= -0.237 p= 0.395 N= 15	r= -0.372 p= 0.172 N= 15	r= 0.196 p= 0.485 N= 15
PV (NE)	r= -0.186 p= 0.507 N= 15	r= -0.274 p= 0.323 N= 15	r= 0.392 p= 0.148 N= 15
ttPV (E)	r= -0.083 p= 0.770 N= 15	r= -0.076 p= 0.789 N= 15	r= 0.162 p= 0.565 N= 15
ttPV (NE)	r= 0.064 p= 0.821 N= 15	r= 0.160 p= 0.569 N= 15	r= 0.118 p= 0.676 N= 15
PA (E)	r= -0.437 p= 0.103 N= 15	r= -0.290 p= 0.295 N= 15	r= -0.124 p= 0.659 N= 15
PA (NE)	r= -0.181 p= 0.518	r= -0.176 p= 0.529	r= 0.130 p= 0.645

	N= 15	N= 15	N= 15
ttPA (E)	r= -0.151 p= 0.591 N= 15	r= -0.406 p= 0.133 N= 15	r= -0.158 p= 0.574 N= 15
ttPA (NE)	r= 0.016 p= 0.956 N= 15	r= 0.222 p= 0.426 N= 15	r= 0.136 p= 0.629 N= 15
AE (E)	r= 0.474 p= 0.074 N= 15	r= 0.238 p= 0.393 N= 15	r= 0.116 p= 0.680 N= 15
AE (NE)	r= 0.174 p= 0.535 N= 15	r= -0.268 p= 0.334 N= 15	r= -0.451 p= 0.091 N= 15
VE (E)	r= -0.058 p= 0.838 N= 15	r= 0.147 p= 0.601 N= 15	r= 0.104 p= 0.712 N= 15
VE (NE)	r= 0.242 p= 0.385 N= 15	r= 0.192 p= 0.493 N= 15	r= 0.069 p= 0.735 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

Table 14.
Summary of Correlation Coefficient Calculations between Group 3 Motor Performance Variables and Self-Report Questionnaire Scores (ODI, RM &PSFS)

	ODI	RM	PSFS
MT (D)	r= 0.190 p= 0.497 N=15	r= 0.188 p= 0.501 N= 15	r= -0.136 p= 0.629 N= 15
MT (ND)	r= 0.449 p= 0.093 N= 15	r= 0.273 p= 0.324 N= 15	r= -0.444 p= 0.097 N= 15
RT (D)	r= -0.207 p= 0.460 N= 15	r= -0.222 p= 0.425 N= 15	r= 0.081 p= 0.774 N= 15
RT (ND)	r= 0.030 p= 0.917 N= 15	r= -0.033 p= 0.906 N= 15	r= -0.076 p= 0.787 N= 15
PV (D)	r= -0.329 p= 0.231 N= 15	r= -0.125 p= 0.657 N= 15	r= 0.156 p= 0.579 N= 15
PV (ND)	r= -0.657 **p= 0.008 N= 15	r= -0.470 p= 0.077 N= 15	r= 0.560 *p= 0.030 N= 15
ttPV (D)	r= 0.131 p= 0.642 N= 15	r= -0.179 p= 0.524 N= 15	r= -0.222 p= 0.427 N= 15
ttPV (ND)	r= 0.536* p= 0.040 N= 15	r= 0.241 p= 0.387 N= 15	r= -0.519 *p= 0.048 N= 15
PA (D)	r= -0.248 p= 0.374 N= 15	r= 0.039 p= 0.889 N= 15	r= 0.242 p= 0.384 N= 15
PA (ND)	r= -0.535 *p= 0.040	r= -0.323 p= 0.240	r= 0.464 p= 0.081

	N= 15	N= 15	N= 15
ttPA (D)	r= 0.255 p= 0.359 N= 15	r= 0.342 p= 0.213 N= 15	r= -0.083 p= 0.769 N= 15
ttPA (ND)	r= 0.082 p= 0.770 N= 15	r= 0.069 p= 0.806 N= 15	r= 0.170 p= 0.545 N= 15
AE (D)	r= -0.096 p= 0.734 N= 15	r= -0.086 p= 0.759 N= 15	r= 0.024 p= 0.933 N= 15
AE (NN)	r= -0.123 p= 0.662 N= 15	r= -0.149 p= 0.595 N= 15	r= 0.074 p= 0.793 N= 15
VE (D)	r= -0.075 p= 0.790 N= 15	r= -0.160 p= 0.569 N= 15	r= -0.010 p= 0.971 N= 15
VE (ND)	r= 0.154 p= 0.584 N= 15	r= 0.110 p= 0.695 N= 15	r= 0.027 p= 0.923 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

Table 15.
Summary of Correlation Coefficient Calculations between Group 3 Motor Performance Variables and Self-Report Questionnaire Scores (QNRS)

	QNRS (Back)	QNRS (E)	QNRS (NE)
MT (D)	r= -0.345 p= 0.208 N=15	r= -0.040 p= 0.886 N= 15	r= 0.130 p= 0.645 N= 15
MT (ND)	r= -0.176 p= 0.530 N= 15	r= -0.888 p= 0.755 N= 15	r= 0.160 p= 0.570 N= 15
RT (D)	r= -0.016 p= 0.955 N= 15	r= 0.359 p= 0.189 N= 15	r= -0.002 p= 0.994 N= 15
RT (ND)	r= -0.040 p= 0.887 N= 15	r= 0.334 p= 0.224 N= 15	r= -0.048 p= 0.865 N= 15
PV (D)	r= -0.177 p= 0.528 N= 15	r= -0.225 p= 0.420 N= 15	r= -0.457 p= 0.087 N= 15
PV (ND)	r= -0.019 p= 0.945 N= 15	r= -0.031 p= 0.912 N= 15	r= -0.124 p= 0.660 N= 15
ttPV (D)	r= 0.185 p= 0.510 N= 15	r= -0.031 p= 0.914 N= 15	r= 0.170 p= 0.545 N= 15
ttPV (ND)	r= 0.100 p= 0.724 N= 15	r= -0.049 p= 0.861 N= 15	r= 0.042 p= 0.881 N= 15
PA (D)	r= -0.281 p= 0.310 N= 15	r= -0.127 p= 0.653 N= 15	r= -0.360 p= 0.187 N= 15
PA (ND)	r= -0.091 p= 0.748 N= 15	r= -0.144 p= 0.608 N= 15	r= -0.159 p= 0.571 N= 15

ttPA (D)	r= -0.028 p= 0.920 N= 15	r= -0.227 p= 0.417 N= 15	r= -0.568 *p= 0.027 N= 15
ttPA (ND)	r= 0.047 p= 0.868 N= 15	r= -0.018 p= 0.949 N= 15	r= -0.166 p= 0.555 N= 15
AE (D)	r= -0.904 p= 0.135 N= 15	r= 0.185 p= 0.508 N= 15	r= -0.400 p= 0.140 N= 15
AE (ND)	r= 0.399 p= 0.140 N= 15	r= 0.514 p= 0.050 N= 15	r= 0.163 p= 0.561 N= 15
VE (D)	r= 0.145 p= 0.606 N= 15	r= 0.354 p= 0.195 N= 15	r= -0231. p= 0.408 N= 15
VE (ND)	r= 0. 307 p= 0.266 N= 15	r= 0.363 p= 0.184 N= 15	r= -0.363 p= 0.184 N= 15

*Signifies p value <0.05; **Signifies p value <0.001.
E= Effected Limb; NE= Non-Effected Limb
MT= Movement Time; RT= Reaction Time; PV= Peak Velocity; ttPV= Time to Peak Velocity; PA= Peak Acceleration; ttPA= Time to Peak Acceleration; CE= Constant Error

APPENDIX C

Informed Consent

RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM

Title of Study: Evaluation of the Impact of Core Training vs Reconditioning in Lumbar Radiculopathy, A Fitts' Task Analysis

Principal Investigator: Shelley Sargent, RR140, Rehab Hospital, 787-2216; Co-Investigators: Dr. Steven Passmore, RR309, Rehab Hospital, 787-1899

You are being asked to participate in a research study. Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this study. Please ask the study staff to explain any information that you do not clearly understand.

Purpose of Study

The purpose of this study is to determine if movement of the lower limbs is effected by the condition lumbar radiculopathy. We are attempting to evaluate the effectiveness of two exercise-based programs at Health Sciences Centre by evaluating lower limb movement before and after completion of one of the two exercise classes.

This information may assist clinicians in determining which aspects of lower limb movement are impacted by lumbar radiculopathy. It will also assist in evaluating the benefit of two exercise programs for people with this condition.

Study Procedures

Participants will be recruited for this study by a clinician who performs surgical screening assessments within the Winnipeg Spine Assessment Clinic. In this study, you will be tested in two sessions, which will include foot pointing motions towards various targets displayed on the ground.

If you chose to participate in this study, you will be asked to do the following:

- **Visit with the principal investigator of the study.**
- **Complete three questionnaires regarding back, leg pain, and assessment of overall health.**
- **Wear an infrared emitting diode on your big toe (a small device that looks like a disc which is worn on your toe and collects information about limb position and movement), which will be secured with medical tape.**
- **Move your big toe to a target illuminated on the floor in standing, in a sideways direction.**
- **Repeat the pointing movements towards different targets, of different sizes, at different distances from the midline, with both lower extremities.**

- **Complete six weeks of an exercise-based program at Health Sciences Center. This program may involve upper/lower body and low back stretching, core stabilization, endurance training on exercise machines, or via walking, and upper/lower body strengthening with weights, or gym-based machines.**
- **Re-visit with the principal investigator after completion of your exercise program for re-evaluation of the foot/toe pointing assessment described above.**

Each visit with the principal investigator will take approximately 30-45 minutes. Exercise classes run between 60-120 minutes, 2 times per week, for six weeks.

Risks and Discomforts

There are no significant risks involved in participating in the foot pointing assessments. You will be allowed to rest between trials if needed, or you can discontinue at any time. You may however, experience a temporary increase in symptoms during testing. It is anticipated that symptoms will only increase for a short duration and will not be more than what you may experience during a regular physical examination. Risks associated with participation in either exercise program may include musculoskeletal injury, and less commonly: cardiac complications such as arrhythmia (if underlying heart disease is present), or a heart attack (for patients with multiple cardiac risk factors), as well as bronchospasm (in asthma conditions).

Benefits

You have been selected for this study because your Spine Clinic Assessment indicated that you my benefit from adherence to a regular exercise program. The benefits of exercise may include: assistance in weight management, and hypertension; a reduction in the risk of cardiac disease; improvement in bone density; improvement in strength and flexibility; improved mood; and assistance in the control of blood sugars in the condition of diabetes mellitus type 2. Literature also suggests that adherence to exercise may decrease pain intensity and improve reported function in the case of lumbar radiculopathy. Please note, each participant may experience some, or none of the listed benefits. We hope the information learned from this study will help advance the scientific understanding of the impact of lumbar radiculopathy on functional lower limb motion. We hope to formally assess the benefit of two of the structured exercise programs at Health Science Center for this patient population.

Costs

All the procedures which will be performed as part of this study are provided at no cost to you.

Payment for Participation

There is no compensation or payment for this study

Confidentiality

Information gathered in this research study may be published or presented in public forums; however, your name and other identifying information will not be used or revealed. Research records that contain your identity will be treated as confidential in accordance with the Personal Health Information Act of Manitoba.

Please note, the study may be conducted at either a Health Science Centre or University of Manitoba site. No information such as your name, address, or telephone number will leave the Health Sciences Centre, or the University of Manitoba, wherever the study is conducted. Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

The University of Manitoba Health Research Ethics Board may review records related to the study for quality assurance purposes.

Voluntary Participation/Withdrawal From the Study

Your decision to take part in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time for any reason by communication in any form with the study staff. Your decision not to participate or to withdraw from the study will not affect your care at this center. If the study staff feels that it is in your best interest to withdraw you from the study, they will remove you without your consent.

If you are an employee of name of institution your participation or discontinuance in the study will not constitute an element of your job performance or evaluation nor will it be part of your personnel record at any of these Institutions.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study.

Medical Care for Injury Related to this Study

You are not waiving any of your legal rights by signing this consent form nor are you releasing to the investigator(s) from their legal and professional responsibilities.

Questions

You are free to ask any questions that you may have about your rights as a research participant. If any questions come up during or after the study or if you have a research related injury, contact the study staff: Shelley Sargent at 787-2216 or Dr. Steven Passmore at 787-1899.

For questions about your rights as a research participant, you may contact The University of Manitoba, Bannatyne Campus Research Ethics Board Office at (204) 789-3389.

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

Statement of Consent

I have read this consent form. I have had the opportunity to discuss this research study with, Shelley Sargent or Dr. Steven Passmore. I have had my questions answered by them in language I understand. The risks and benefits have been explained to me. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this study is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed. I authorize the inspection of any of my records that relate to this study by The University of Manitoba Research Ethics Board, for quality assurance purposes.

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

I agree to be contacted for future follow-up in relation to this study:

Yes __ No __

Participant signature _____ Date: _____

Participant printed name _____

Relationship (if any) to study team members _____

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Person obtaining consent _____ Date: _____

Person obtaining consent printed name _____

APPENDIX D: Ethics Approval

HEALTH RESEARCH ETHICS BOARD (HREB)
CERTIFICATE OF FINAL APPROVAL FOR NEW STUDIES
Full Board Review

PRINCIPAL INVESTIGATOR:	INSTITUTION/DEPARTMENT:	ETHIC S#:
Shelley Sargent	U of M/Medical Rehabilitation	HS22343 (H2018:443)
HREB MEETING DATE:	**APPROVAL DATE:**	**EXPIRY DATE:**
November 26, 2018	January 18, 2019	**November 28 2018**
STUDENT PRINCIPAL INVESTIGATOR SUPERVISOR (if applicable):		
Dr. Steven Passmore		

PROTOCOL NUMBER:	PROJECT OR PROTOCOL TITLE:
NA	Correlation Between Self-Report Measures of Function and Lower Limb Motor Performance in Patients With and Without Imaging Evidence of Lumbar Nerve Root Compression
SPONSORING AGENCIES AND/OR COORDINATING GROUPS:	
NA	

Submission Date(s) of Investigator Documents:	REB Receipt Date(s) of Documents:
November 3, December 15, 2018 and January 18, 2019	November5,December17,2018and January 18,2019

THE FOLLOWING ARE APPROVED FOR USE:

Document Name	Version/ if applic.	Date
Protocol:		
Protocol including Clarifications as per Letter dated December 15, 2018 and Revised REB Submission Form submitted December 15, 2018 and Email Clarification dated January 18, 2019	V. 1	June 23, 2018
Consent and Assent Form(s):		
Research Participant Information and Consent Form	V. 1	June 23, 2018
Other:		
Questionnaires/Scales/Instruments Appendix		November 3, 2018
Roland Morris Questionnaire (Undated)[]		submitted January 18, 2019

CERTIFICATION

The University of Manitoba (UM) Health Research Board (HREB) has reviewed the research study/project named on this ***Certificate of Final Approval*** at the ***full board meeting*** date noted above and was found to be acceptable on ethical grounds for research involving human participants. The study/project and documents listed above was granted final approval by the Chair or Acting Chair, UM HREB.

HREB ATTESTATION

The University of Manitoba (UM) Health Research Board (HREB) is organized and operates according to Health Canada/ICH Good Clinical Practices, Tri-Council Policy Statement 2, and the applicable laws and regulations of Manitoba. In respect to clinical trials, the HREB complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations of Canada and carries out its functions in a manner consistent with Good Clinical Practices.

QUALITY ASSURANCE

The University of Manitoba Research Quality Management Office may request to review research documentation from this research study/project to demonstrate compliance with this approved protocol and the University of Manitoba Policy on the Ethics of Research Involving Humans.

CONDITIONS OF APPROVAL:

1. The study is acceptable on scientific and ethical grounds for the ethics of human use only. ***For logistics of performing the study, approval must be sought from the relevant institution(s).***
2. This research study/project is to be conducted by the local principal investigator listed on this certificate of approval.
3. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to the research study/project, and for ensuring that the authorized research is carried out according to governing law.
4. **This approval is valid until the expiry date noted on this certificate of approval.** A **Bannatyne Campus Annual Study Status Report** must be submitted to the REB within 15-30 days of this expiry date.
5. Any changes of the protocol (including recruitment procedures, etc.), informed consent form(s) or documents must be reported to the HREB for consideration in advance of implementation of such changes on the **Bannatyne Campus Research Amendment Form.**
6. Adverse events and unanticipated problems must be reported to the REB as per Bannatyne Campus Research Boards Standard Operating procedures.
7. The UM HREB must be notified regarding discontinuation or study/project closure on the Bannatyne Campus **Final Study Status Report.**

APPENDIX E: Questionnaires

Waterloo Footedness Questionnaire Revised

Questions for determining leg dominance	**Left**	**Right**
If you were asked to shoot a ball on a target, which leg would you use to shoot the ball?*		
If you had to pick up marbles while standing and put the marbles in a box, which foot would you use to pick them up?*		
When you had to trace a figure drawn on the floor, which foot would you use?		
Which foot would you use if you had to stomp out a small fire while standing?		
If you were asked to stand on one leg, on which leg would you stand?*		
Which foot would you use to smooth sand while standing?*		
If you had to step up onto a chair, which foot would you place on the chair first?*		
Which foot would you use to stomp an insect while you were standing?*		
If you were to balance on one foot on a railway track, which foot would you use?*		
If you had to hop on one foot, which foot would you use?*		
Which foot would you use to help push a shovel into the ground while digging?*		
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?*		
Are you right or left handed?		
Questions for inclusion/exclusion	**Yes**	**No**
Have you ever had an anterior cruciate ligament rupture and/or reconstruction?		
Have you underwent any surgery to legs and/or lower back in the past 3 years? If yes, what kind of surgery and when?		
In this moment, do you suffer from an injury to your lower back, hip, leg, ankle or foot?		
Do you use medication which may influence your balance?		
Do you suffer from a disease which may affect you balance and/or coordination?		
In the past, have you had any special training which stimulates the use of a certain leg in a certain situation or activity? (Sports and/or work related?)*		
Is there a reason why your leg preference has changed, such as an injury?*		

Date:_____ Participant code number:_____

Quadruple Numerical Rating Scale

BACK PAIN

Instructions: Please circle the number that best describes the question being asked.

Note: If you have more than one complaint, please answer each question for each individual complaint and indicate the score for each complaint. Please indicate your pain level right now, average pain, and pain at its best and worst.

Example:

Headache Neck Low Back

No pain 0 1 (2) 3 4 (5) 6 7 (8) 9 10 worst possible pain

1. What is your pain **RIGHT NOW**?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

2. What is your **TYPICAL** or **AVERAGE** pain?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

3. What is your pain level **AT ITS BEST** (How close to "0" does your pain get at its best)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

4. What is your pain level **AT ITS WORST** (How close to "10" does your pain get at its worst)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

OTHER COMMENTS:

_____

_____

Reprinted from Spine, 18, Von Korff M, Deyo RA, Cherkin D, Barlow SF, Back pain in primary care: Outcomes at 1 year, 855-862, 1993.

Version 1 – 11/03/2018

Date:_____ Participant code number:_____

Quadruple Numerical Rating Scale

LEFT LEG PAIN

Instructions: Please circle the number that best describes the question being asked.

Note: If you have more than one complaint, please answer each question for each individual complaint and indicate the score for each complaint. Please indicate your pain level right now, average pain, and pain at its best and worst.

Example:

Headache Neck Low Back

No pain 0 1 (2) 3 4 (5) 6 7 (8) 9 10 worst possible pain

1. What is your pain **RIGHT NOW**?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

2. What is your **TYPICAL** or **AVERAGE** pain?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

3. What is your pain level **AT ITS BEST** (How close to "0" does your pain get at its best)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

4. What is your pain level **AT ITS WORST** (How close to "10" does your pain get at its worst)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

OTHER COMMENTS:

_____

_____

Reprinted from Spine, 18, Von Korff M, Deyo RA, Cherkin D, Barlow SF, Back pain in primary care: Outcomes at 1 year, 855-862, 1993.

Version 1 – 11/03/2018

Date:_____ Participant code number:_____

Quadruple Numerical Rating Scale

RIGHT LEG PAIN

Instructions: Please circle the number that best describes the question being asked.

Note: If you have more than one complaint, please answer each question for each individual complaint and indicate the score for each complaint. Please indicate your pain level right now, average pain, and pain at its best and worst.

Example:

Headache Neck Low Back

No pain 0 1 (2) 3 4 (5) 6 7 (8) 9 10 worst possible pain

1. What is your pain **RIGHT NOW**?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

2. What is your **TYPICAL** or **AVERAGE** pain?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

3. What is your pain level **AT ITS BEST** (How close to "0" does your pain get at its best)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

4. What is your pain level **AT ITS WORST** (How close to "10" does your pain get at its worst)?

No pain 0 1 2 3 4 5 6 7 8 9 10 worst possible pain

OTHER COMMENTS:

_____

_____

Reprinted from Spine, 18, Von Korff M, Deyo RA, Cherkin D, Barlow SF, Back pain in primary care: Outcomes at 1 year, 855-862, 1993.

ROLAND MORRIS QUESTIONNAIRE

When your back hurts, you may find it difficult to do some of the things you normally do. This list contains some sentences that people have used to describe themselves when they have back pain. When you read them, you may find some that stand out because they describe you today. As you read the list, think of yourself today. When you read a sentence that describes you today, put a circle around its number. If the sentence does not describe you, then leave the space blank and go on to the next one.
Remember, only circle the number of the sentence if you are sure that it describes you today.

1. I stay at home most of the time because of my back.
2. I change positions frequently to try to get my back comfortable.
3. I walk more slowly than usual because of my back.
4. Because of my back, I am not doing any of the jobs that I usually do around the house.
5. Because of my back, I use a handrail to get upstairs.
6. Because of my back, I lie down to rest more often.
7. Because of my back, I have to hold on to something to get out of an easy chair.
8. Because of my back I try to get other people to do things for me.
9. I get dressed more slowly than usual because of my back.
10. I only stand for short periods of time because of my back.
11. Because of my back, I try not to bend or kneel down.
12. I find it difficult to get out of a chair because of my back.
13. My back is painful almost all the time.
14. I find it difficult to turn over in bed because of my back.
15. My appetite is not very good because of my back pain.
16. I have trouble putting on my socks (or stockings) because of the pain in my back.
17. I only walk short distances because of my back pain.
18. I sleep less well because of my back.
19. Because of my back pain, I get dressed with help from someone else.
20. I sit down for most of the day because of my back.
21. I avoid jobs around the house because of my back.
22. Because of my back pain, I am more irritable and bad tempered with people than usual.
23. Because of my back, I go up and down stairs more slowly than usual.
24. I stay in bed most of the time because of my back.

Ψ

PCS

Client No.: _____ Age: _____ Sex: M(__) F(__) Date: _____

Everyone experiences painful situations at some point in their lives. Such experiences may include headaches, tooth pain, joint or muscle pain. People are often exposed to situations that may cause pain such as illness, injury, dental procedures or surgery.

We are interested in the types of thoughts and feelings that you have when you are in pain. Listed below are thirteen statements describing different thoughts and feelings that may be associated with pain. Using the following scale, please indicate the degree to which you have these thoughts and feelings when you are experiencing pain.

0 – not at all **1** – to a slight degree **2** – to a moderate degree **3** – to a great degree **4** – all the time

When I'm in pain …

1. ☐ I worry all the time about whether the pain will end.
2. ☐ I feel I can't go on.
3. ☐ It's terrible and I think it's never going to get any better.
4. ☐ It's awful and I feel that it overwhelms me.
5. ☐ I feel I can't stand it anymore.
6. ☐ I become afraid that the pain will get worse.
7. ☐ I keep thinking of other painful events.
8. ☐ I anxiously want the pain to go away.
9. ☐ I can't seem to keep it out of my mind.
10. ☐ I keep thinking about how much it hurts.
11. ☐ I keep thinking about how badly I want the pain to stop.
12. ☐ There's nothing I can do to reduce the intensity of the pain.
13. ☐ I wonder whether something serious may happen.

…Total

The Patient-Specific Functional Scale

This useful questionnaire can be used to quantify activity limitation and measure functional outcome for patients with any orthopaedic condition.

Clinician to read and fill in below: Complete at the end of the history and prior to physical examination.

Initial Assessment:

I am going to ask you to identify up to three important activities that you are unable to do or are having difficulty with as a result of your _____ problem. Today, are there any activities that you are unable to do or having difficulty with because of your _____ problem? (Clinician: show scale to patient and have the patient rate each activity).

Follow-up Assessments:

When I assessed you on (state previous assessment date), you told me that you had difficulty with (read all activities from list at a time). Today, do you still have difficulty with: (read and have patient score each item in the list)?

Patient-specific activity scoring scheme (Point to one number):

0 1 2 3 4 5 6 7 8 9 10

(Date and Score)

Activity Initial						
1.						
2.						
3.						
4.						
5.						
Additional						

Total score = sum of the activity scores/number of activities
Minimum detectable change (90%CI) for average score = 2 points
Minimum detectable change (90%CI) for single activity score = 3 points

PSFS developed by: Stratford, P., Gill, C., Westaway, M., & Binkley, J. (1995). Assessing disability and change on individual patients: a report of a patient specific measure. Physiotherapy Canada, 47, 258-263.

Oswestry Low Back Pain Disability Questionnaire

Instructions

This questionnaire has been designed to give us information as to how your back or leg pain is affecting your ability to manage in everyday life. Please answer by checking ONE box in each section for the statement which best applies to you. We realise you may consider that two or more statements in any one section apply but please just shade out the spot that indicates the statement which most clearly describes your problem.

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 causes extra pain
- ☐ 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, I 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 placed eg. 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 very light weights
- ☐ I cannot lift or carry anything at all

Section 4 – Walking*

- ☐ Pain does not prevent me walking any distance
- ☐ Pain prevents me from walking more than 1 mile
- ☐ Pain prevents me from walking more than 1/2 mile
- ☐ Pain prevents me from walking more than 100 yards
- ☐ I can only walk using a stick or crutches
- ☐ I am in bed most of the time

Oswestry Low Back Disability Questionnaire

Section 5 – Sitting

- ☐ I can sit in any chair as long as I like
- ☐ I can only sit in my favourite chair as long as I like
- ☐ Pain prevents me sitting more than one hour
- ☐ Pain prevents me from sitting more than 30 minutes
- ☐ Pain prevents me from sitting 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
- ☐ I can stand as long as I want but it gives me extra pain
- ☐ Pain prevents me from standing for more than 1 hour
- ☐ Pain prevents me from standing for more than 30 minutes
- ☐ 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
- ☐ Because of pain I have less than 6 hours sleep
- ☐ Because of pain I have less than 4 hours sleep
- ☐ Because of pain I have less than 2 hours sleep
- ☐ Pain prevents me from sleeping at all

Section 8 – Sex life (if applicable)

- ☐ My sex life is normal and causes no extra pain
- ☐ My sex life is normal but causes some extra pain
- ☐ My sex life is nearly normal but is very painful
- ☐ My sex life is severely restricted by pain
- ☐ My sex life is nearly absent because of pain
- ☐ Pain prevents any sex life at all

Section 9 – Social life

- ☐ My social life is normal and gives 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 eg, sport
- ☐ Pain has restricted my social life and I do not go out as often
- ☐ Pain has restricted my social life to my home
- ☐ I have no social life because of pain

Section 10 – Travelling

- ☐ I can travel anywhere without pain
- ☐ I can travel anywhere but it gives me extra pain
- ☐ Pain is bad but I manage journeys over two hours
- ☐ Pain restricts me to journeys of less than one hour
- ☐ Pain restricts me to short necessary journeys under 30 minutes
- ☐ Pain prevents me from travelling except to receive treatment