The Association of Hip Muscle Strength and Flexibility, Hip Mobility, and Asymmetry with Dysfunction and Pain in Individuals with Chronic Low Back Pain

by

Mara Hartoyo

Bachelor of Philosophy, University of Pittsburgh, 2023

Submitted to the Graduate Faculty of the

David C. Frederick Honors College in partial fulfillment

of the requirements for the degree of

Bachelor of Philosophy

University of Pittsburgh

2023

UNIVERSITY OF PITTSBURGH

DAVID C. FREDERICK HONORS COLLEGE

This thesis was presented

by

Mara Hartoyo

It was defended on

April 12, 2023

and approved by

Dr. Charity Patterson, Professor, Department of Physical Therapy

Dr. Karthik Hariharan, Assistant Professor, Department of Physician Assistant Studies

Dr. Megan Sions, Assistant Professor, Department of Physical Therapy

Thesis Advisor/Dissertation Director: Dr. Sara Piva, Professor, Department of Physical Therapy

The Association of Hip Muscle Strength and Flexibility, Hip Mobility, and Asymmetry to Dysfunction and Pain in Individuals with Chronic Low Back Pain

Mara Hartoyo, BPhil

University of Pittsburgh, 2023

Background: Chronic low back pain (CLBP) is difficult to diagnose and treat due to ill-defined pathological causes, resulting in suboptimal outcomes for individuals and substantial cost to the healthcare system. Previous studies have indicated targeting the hip muscles in CLBP treatment may optimize outcomes, but there has been very scarce investigation on whether specific weakness of hip muscles, limited hamstrings flexibility and hip mobility, and asymmetry of these impairments are associated with physical dysfunction and pain in CLBP.

Purpose and Methods: The present study uses data from a large cohort study for a secondary analysis (n=515) to determine whether hip extension, abduction, and flexion strength, hamstrings flexibility, hip internal rotation mobility, and asymmetry in these measures associate with performance-based tests of walking, sit-to-stand, and lifting motions, and patient reported outcomes (PROs) of LBP-related disability, pain interference, and physical dysfunction in CLBP.

Results: In stepwise selection adjusted for age, sex, and body mass index (BMI), hip muscle weakness was associated with poor functional performance, heightened LBP-related disability, heightened pain interference, and perceived physical dysfunction. Specifically, hip extension weakness associated with all performance-based tests and PROs, hip abduction weakness associated with slow walking and the sit-to-stand test, and hip flexion weakness associated with slow walking and high LBP-related disability and physical dysfunction assessed by PROs. Limited and asymmetrical hamstrings flexibility and asymmetry in hip internal rotation were also associated with poor functional performance, heightened LBP-related disability, heightened pain interference, and perceived physical dysfunction. Specifically, hamstrings flexibility associated with all performance-based tests and PROs, asymmetry in hip internal rotation associated with slow walking tests and high disability, pain interference, and physical dysfunction assessed by PROs, and asymmetrical hamstrings flexibility associated with heightened disability assessed by PROs.

Conclusion: The weakness of hip muscles, tightness and asymmetry of the hamstrings, and asymmetric hip internal rotation mobility may be modifiable factors of physical dysfunction, pain interference, and LBP-related disability in CLBP. Further longitudinal investigation is necessary to determine if these associations persist as hip muscle strength and flexibility, hip mobility, and side-to-side asymmetry change over time along with physical dysfunction, pain interference, and LBP-related disability.

Table of Contents

List of Tables

List of Figures

1.0 Introduction and Background

1.1 Introduction to Chronic Low Back Pain and Significance in Public Health

Low back pain (LBP) is one of the leading causes of disability in the United States, and it accounts for a large portion of medical expenses (Parthan et al., 2006). Additionally, it is the most prevalent cause of disability worldwide (Hartvigsen et al., 2018). Hoy et al. demonstrated that LBP becomes more prevalent once a person reaches thirty years of age, with a gradual increase until age sixty-five. They also stated that those with minimal education, increased stress, anxiety, depression, low job satisfaction, and low levels of social support often experience LBP to a more severe degree, which puts populations with lower socioeconomic status at a disadvantage since this population might not have the resources often necessary for treatment of LBP. People with overly demanding physical jobs, physical and mental comorbidities, and smokers are also at risk for LBP, and it is disproportionately more prevalent in obese individuals (Hartvigsen et al., 2018). Currently, there is no specific structural or tissue dysfunction that can explain LBP for most people (Hartvigsen et al., 2018), resulting in treatments that are marginally beneficial and often short-lasting. LBP causes substantial emotional, physical, and financial stress on families and businesses (Hoy et al., 2010). Most people who experience LBP go on to suffer additional LBP episodes in the future, which may be distinguished as *chronic* low back pain (Hoy et al., 2010).

Chronic low back pain (CLBP) is classified in various ways, including LBP that lasts longer than seven to twelve weeks, lasts beyond the expected healing time, or pain that reoccurs frequently (Andersson, 1999). Both the diagnostic criteria and underlying pathological causes of CLBP are ill-defined in many individuals, making CLBP a very difficult and costly condition to accurately diagnose and effectively treat (Andersson, 1999). Gore et al. demonstrated that in comparison to individuals without CLBP, individuals with CLBP are shown to have high levels of comorbidities and high health care costs (Gore et al., 2012). They also showed that when comparing these two groups, individuals with CLBP, have significantly higher incidences of musculoskeletal conditions, anxiety, depression, and sleep disorders. Individuals with CLBP have also been shown to use opioids, NSAIDS, and tramadol at higher rates compared to controls to reduce pain. Health care costs for individuals with CLBP on average was over $4700 more than that of individuals without CLBP ($8386 vs. $3607) in the United States (Gore et al., 2012).

Dagenais et al. demonstrated that the sources of CLBP expenditures in the United States and internationally include physical therapy, inpatient services such as surgery and imaging, pharmacy, and primary care. Additionally, loss of work productivity adds to the costs associated with CLBP (Dagenais et al., 2008). Hong et al. states that individuals who have suffered from LBP for longer than a year are unlikely to ever be able to return to their normal lifestyle, and persons who have been unable to work due to CLBP for over a year are unlikely to be able to work again in the near future. This results in substantial costs not only to the individuals but also the health care system (Hong et al., 2013). In order to implement more effective treatment for CLBP, the factors associated with physical dysfunction and pain in persons with CLBP must be investigated. Hip muscle strength, flexibility, and hip mobility specifically, due to their important function in stabilizing the pelvis and transferring weight from the spine to the lower extremities during movement must be investigated to determine how these factors are associated with physical function and pain, which is what this study proposes.

1.2 Investigation of Hip Muscles in Relation to Chronic Low Back Pain

There are a multitude of biopsychosocial factors associated with CLBP including age, history of rheumatic diseases, poor job satisfaction, having a physically demanding job, and history of depression (Esquirol et al., 2017). Many of these potential associators are challenging to assess and treat. Biomechanical impairments in relation to CLBP, however, may be treatable associators to dysfunction and pain and should be investigated further to lead to longitudinal studies and controlled trials that could improve treatment and outcomes. Specifically, the strength and flexibility of key muscles around the hip as well as specific mobility of this joint should be investigated as associators to dysfunction and pain in persons with CLBP because of their role in pelvis stabilization and load transfer from the lower extremities to the trunk. Large emphasis has been placed on strengthening and stretching low back muscles to treat CLBP, however, there is limited research on how the weakness and inflexibility of specific hip muscles or limited movement of this joint associate to both dysfunction and pain in persons with CLBP, which is what this study proposes to investigate.

1.3 Theoretical Rationale

Although strengthening exercises of extensors, abductors, and flexors of the hips have gained more attention recently, the evidence supporting targeting these hip muscles to improve physical function and pain in CLBP is limited. Specifically, the evidence relating a wide array of both hip strength and mobility measures along with side-to-side asymmetry to performance-based measures like walking and lifting a weight is limited. Lack of strength and mobility due to the modern-day sedentary lifestyle are likely significant factors leading to CLBP. There has been some advancement in physical therapy practice to improve treatment for persons with CLBP. However, further investigation into the effect of hip muscle strength and mobility on function in CLBP is necessary to specify these associating factors. The goal of this study is to investigate whether hip muscle strength, flexibility, hip mobility, and side-to-side asymmetry in hip muscle strength, flexibility, and mobility are associated with physical dysfunction and pain in persons with CLBP. If deficits in hip muscle strength, mobility, and high level of asymmetry of these impairments are associated with dysfunction and pain in persons with CLBP, this may indicate further longitudinal research and controlled trials are necessary to determine if there should be an increased focus on correcting these impairments to improve physical function and mitigate pain.

The hip-spine interaction is an integrated network of the lumbar bone structures, ligaments, thoracolumbar fascia, and hip musculature that all work together for successful load transfer between the lumbar and pelvis during spinal movements (Leinonen et al., 2000). Weak hip muscles that lead to lumbopelvic imbalance and instability are associated with LBP (de Sousa et al., 2019). Weakness in these muscles does not allow for optimal load transfer between the legs and lumbar spine via the thoracolumbar fascia, which can lead to LBP and dysfunction (de Sousa et al., 2019). Research has shown that improvement in thoracolumbar kyphosis and lordosis after exercise therapy is associated with decreased LBP (In et al., 2021), indicating that weak and/or tight hip muscles that lead to abnormalities in spine lordotic/kyphotic curvature associate to LBP. In a study evaluating the influence of tight hamstrings on lumbar lordosis in children with cerebral palsy, there was an association found between decreased hamstrings flexibility and limited lumbar lordosis (McCarthy & Betz, 2000), demonstrating that tight hamstrings can pull the pelvis posteriorly, resulting in limited lumbar lordosis. In a study on participants aged 30-55 years who had CLBP and hyper lordosis, results showed that stretching the iliopsoas muscle reduced both pain and lumbar lordosis angle compared to controls (Malai et al., 2015), demonstrating tight hip flexors can pull the pelvis anteriorly, resulting in hyper lordosis of the lumbar spine.

1.3.1 Hip Muscles Anatomy and Function

The gluteus maximus is the main extensor muscle of the hip. This is a large muscle that is vital for keeping the body in an upright posture. It originates on the gluteal surface of the ilium (Figure 1) and inserts into the gluteal tuberosity of the femur and iliotibial tract (Elzanie & Borger, 2022); (Stecco et al., 2013). The gluteus maximus functions to extend the thigh and is an external rotator of the hip, which makes this muscle important for going between sitting and standing motions, walking up stairs, and running (Elzanie & Borger, 2022). Weakness in the gluteus maximus can lead to inability of this muscle to help the deep abdominal muscles control anterior pelvic rotation (Kim & Kim, 2015), leading to hyper lordosis of the lumbar spine. If the lumbar spine is in constant hyper lordosis, it could increase the load on posterior structures of the vertebral column, resulting in pain (Sorensen et al., 2015).

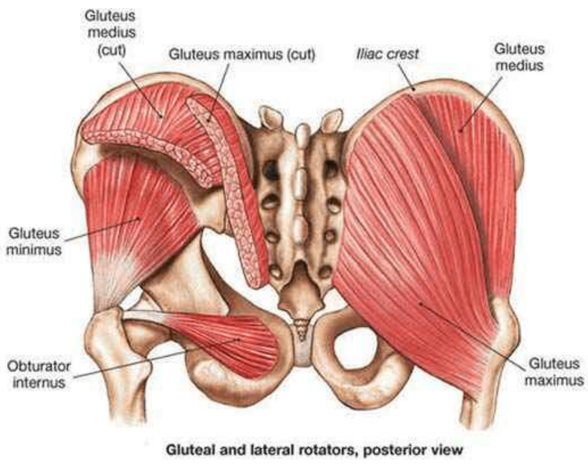

Figure 1. Gluteus maximus, medius, and minimus

Adapted from Luntz, R. (2015, April 12). *Are weak glutes causing your injury?* Melbourne Podiatry Clinic. Retrieved March 8, 2023, from https://www.melbournepodiatryclinic.net.au/are-weak-glutes-causing-your-injury/

The primary hip abductor muscles are the gluteus medius, gluteus minimus, and tensor fasciae latae. The gluteus medius originates on the outer surface of the ilium and inserts into the greater trochanter (Figure 1), with the posterior portion inserting on the proximal tip of the greater trochanter and the anterolateral portion inserting on the lateral facet of the greater trochanter (Tsutsumi et al., 2019). The gluteus minimus originates on the external aspect of the ilium between the anterior and inferior gluteal lines and at the sciatic notch (Figure 1), and it inserts onto the greater trochanter (Beck et al., 2000). The gluteus medius and minimus are responsible for hip abduction and internal rotation, with the anterior fibers assisting in internal rotation and the posterior fibers assisting in lateral rotation when the knee is extended. The gluteus medius is vital to standing on one leg, walking, and running, as it acts to stabilize the pelvis. When one leg is on the ground either in a stationary position or in locomotion, gravitational force acts on the unsupported hip to pull it downwards. The gluteus medius and minimus on the supported side of the hips concentrically contract to pull the unsupported side of the hips up into a neutral position (Shah & Bordoni, 2022). The tensor fasciae latae originates at the anterior superior iliac spine (Figure 2) and the anterior aspect of the iliac crest and inserts into the iliotibial band. The tensor fasciae latae primarily functions to assist the gluteus medius and gluteus minimus to pull the unsupported hip superiorly while walking or running (Trammell et al., 2022).

Weakness of the hip abductors can lead to a Trendelenburg gait, which is an abnormal gait resulting from the gluteal muscles being unable to stabilize the articulation of the pelvis and femur. The weakness causes the hip joint to appear to swing out laterally while walking, giving the unsupported hip a drooping appearance (Gandbhir et al., 2022), potentially causing unstable movement patterns and dysfunction that could lead to LBP. In a systematic review to determine the influence of weakness in the gluteus medius on LBP in adults, results showed that individuals with LBP have weaker gluteus medius muscles compared to those with no back pain (Sadler et al., 2019), indicating that the hip abductor muscles are important stabilizers of the lumbopelvic region. Studies have shown through meta-analysis that average hip abductor and extensor muscle strength is significantly lower in individuals with LBP compared to healthy controls (de Sousa et al., 2019). There is some evidence that weakness in the hip extensors and abductors is associated with LBP, however, there is limited research on how this weakness associates with physical function and limited investigation into populations with CLBP, specifically. This study proposes to assess how weakness in hip extensors and abductors associate with physical dysfunction in performance-based tests and pain in persons with CLBP.

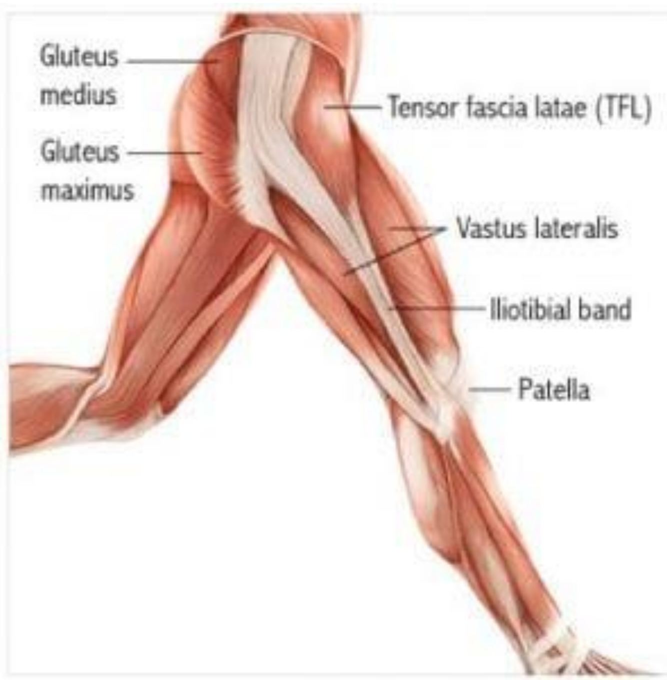

Figure 2. Tensor fascia latae

Adapted from Waldrup, C. (n.d.). *Iliotibial band syndrome with dr. Chase Waldrup*. Vida Integrated Health. Retrieved March 8, 2023, from https://thinkvida.com/blog/dr-chase-waldrup-it-band-syndrome/

The rectus femoris, iliacus, and psoas major serve as primary hip flexor muscles. The psoas major originates on the T5 to L5 vertebrae, and the iliacus originates on the iliac fossa, iliac crest, and sacral ala (Figure 3). These two muscles converge to form a single iliopsoas tendon that inserts into the lesser trochanter of the femur. The iliopsoas functions to anteriorly tilt the pelvis and externally rotate the hip. The psoas major is important clinically because it serves to keep the body upright in a sitting position and serves to pull the leg forward during the swing phase in locomotion (Lifshitz et al., 2020).

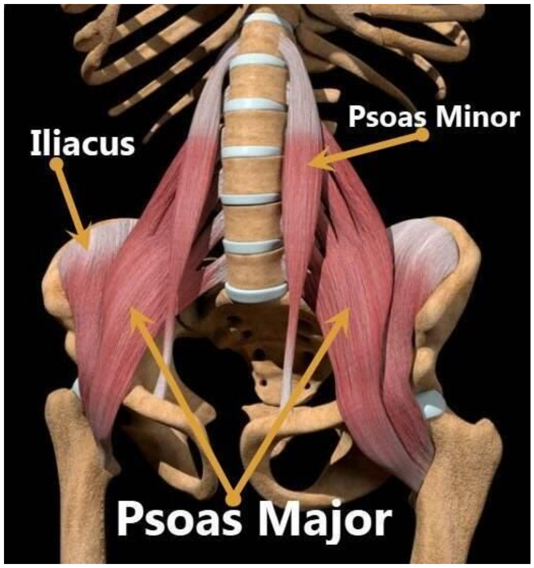

Figure 3. Iliacus and psoas major

Adapted from Heideman, D. (2023). *Hip flexor muscle or flexors of hip*. Jacksonville Orthopaedic Institute. Retrieved March 8, 2023, from https://www.joionline.net/trending/content/hip-flexor-or-hip-flexor-muscle

The rectus femoris originates at the anterior inferior iliac spine (Figure 4) and inserts into the quadriceps tendon that inserts into the patella. The rectus femoris serves as a hip joint stabilizer and hip flexor (Ransom et al., 2022). Weakness of the hip flexor muscles can result in inability to keep the pelvis in a neutral position. If the pelvis is tilted posteriorly for long periods of time, this can cause reduced lumbar lordosis, resulting in elongation and strain on the low back musculature, resulting in CLBP (Bernard et al., 2008). In a meta-analysis purposed with investigating the influence of lumbar lordotic curvature on LBP, results showed that persons with LBP tend to have smaller lordotic curvature angles compared to healthy controls (Chun et al., 2017), indicating that an abnormally decreased lumbar lordotic curvature is associated with pain. There is limited research that investigates the association of hip flexor muscle weakness with physical dysfunction during performance-based tests in persons with CLBP, which is what this study proposes to investigate. Additionally, this study adds an extra level of specificity in looking at CLBP specifically.

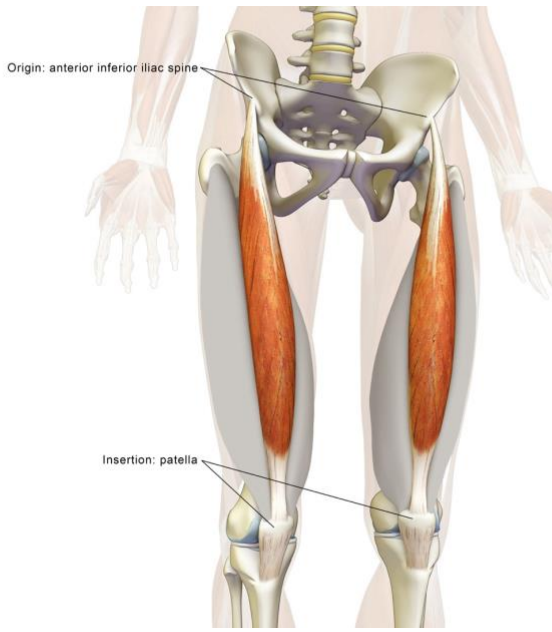

Figure 4. Rectus femoris

Adapted from Long, R. (n.d.). *The rectus femoris muscle in yoga*. The Daily Bandha. Retrieved March 8, 2023, from https://www.dailybandha.com/2014/06/the-rectus-femoris-muscle-in-yoga.html

1.3.2 Hamstrings Flexibility and Hip Internal Rotation Mobility

The hamstrings muscle group contains three individual muscles, the semitendinosus, semimembranosus, and biceps femoris (Figure 5); and all originate on the ischial tuberosity and cross both the femoroacetabular joint and tibiofemoral joint except the short head of the biceps femoris, which originates from the lateral lip of the linea aspera on the femur (Rodgers & Raja, 2022). Both the long and short heads of the biceps femoris insert into the fibular head and lateral condyle of the tibia. The semitendinosus and semimembranosus insert into the medial tibia on the pes anserinus and medial tibial condyle, respectively (Rodgers & Raja, 2022).

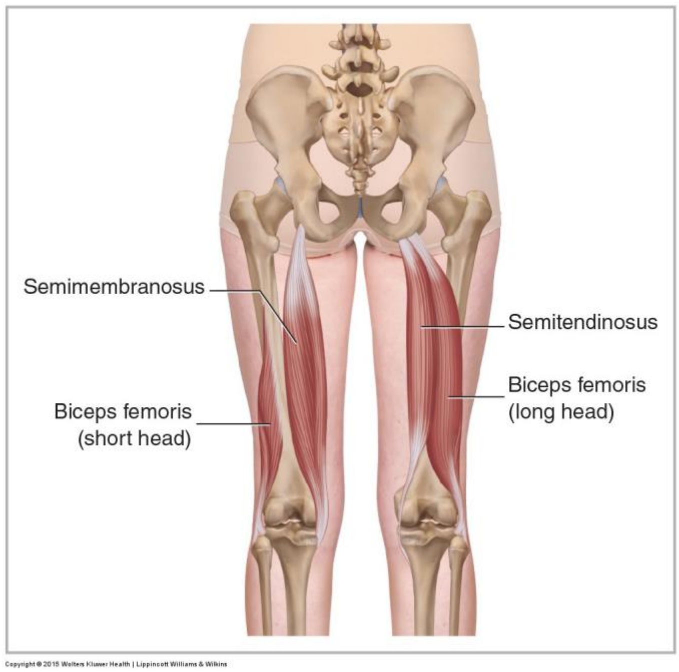

Figure 5. Biceps femoris, semitendinosus, and semimembranosus

Adapted from DeBell, R. (2020, September 14). *Basic anatomy of how to stretch the hamstrings: The movement fix*. Movement Fix. Retrieved March 8, 2023, from https://themovementfix.com/basic-anatomy-stretching-hamstrings/

Studies have shown that restricted hamstring flexibility, which can lead to an abnormal decrease in lumbar lordosis, is associated with increased risk of LBP (Sadler et al., 2017). In a study evaluating LBP in over 500 adolescents, Feldman et al. demonstrated that over a period of a year and a half, tight hamstrings were found alongside other risk factors, to be associated with the development of LBP. This indicates that increasing flexibility at the hamstrings may help prevent the development of CLBP or help to reduce pain and/or disability resulting from tightness (Feldman et al., 2001). There is some evidence that restricted hamstrings flexibility is a risk factor for LBP, but there is limited evidence on how hamstrings inflexibility associates with physical dysfunction during performance-based tests in persons with CLBP. It is necessary to investigate how restricted hamstring flexibility associates with physical dysfunction specifically because improving physical function along with pain is what is most clinically relevant in persons with CLBP.

A cadaver study demonstrated that soft tissue surrounding the hip joint such as the capsule and labrum restricts hip internal rotation range of motion at varying degrees depending on degree of hip flexion (Han et al., 2020). The hip joint capsule is made up of the iliofemoral, pubofemoral, and ischiofemoral ligaments, and it is thickest anteriorly and superiorly and thinnest inferiorly and posteriorly (Glenister & Sharma, 2022). Glenister & Sharma also report that the ischiofemoral ligament attaches to the posterior area of the acetabular rim and labrum and inserts onto the anterior aspect of the femur, restricting hip internal rotation and adduction with flexion. The acetabular labrum acts as a hip joint stabilizer by restricting extreme movements and by deepening the acetabulum, increasing the articulating surface with the femur (Glenister & Sharma, 2022). Another cadaver study demonstrated that hip internal rotation mobility is mainly restricted by the ischiofemoral ligament, and the piriformis and obturator internus help with this restriction at 0° and 60° of hip flexion (Baba et al., 2022). The external rotator muscles of the hip include the piriformis, obturator internus, obturator externus, superior gemellus, and inferior gemellus (Figure 6).

Limited and asymmetrical ranges of motion of hip internal rotation are associated with LBP and disability (Sadeghisani et al., 2015), (Shin, 2020). In persons with CLBP, hip joint range of motion was found to be more limited in individuals with greater low back instability compared to those with less instability, which was evaluated with a questionnaire and lumbar instability test results, indicating that more limited hip mobility is associated with lumbar instability (wk Lee & Kim, 2015). Limited hip joint mobility could lead to compensation through rotation and bending of the lumbar spine to maintain movement patterns, which could lead to LBP. Therefore, restricted hip muscle mobility could be an associator to CLBP that should be focused on during treatment. However, there is limited evidence of whether hip internal rotation mobility associates with physical function in performance-based tests in persons with CLBP specifically, as opposed to the more general classification of persons with LBP, which is why this study is necessary.

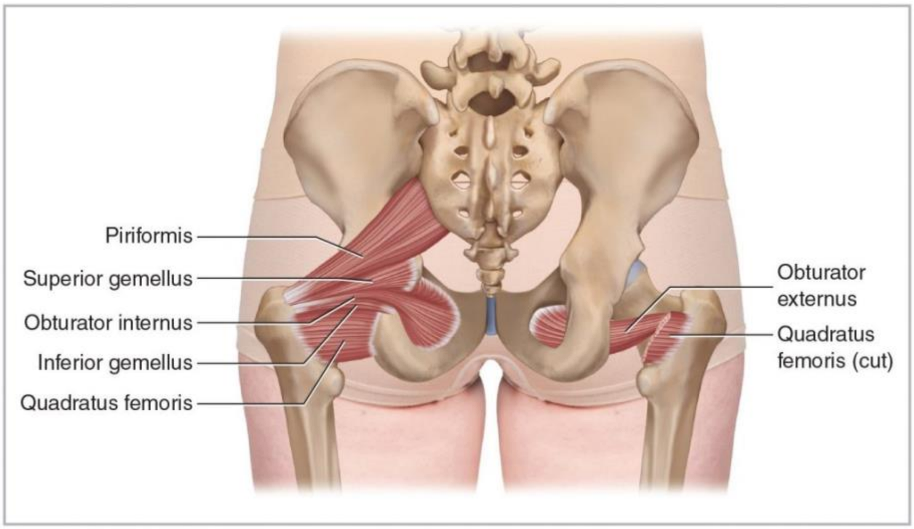

Figure 6. Hip external rotator muscles

Adapted from Rogers, M. (2022, July 11). *Understanding hip rotation and abduction*. National Federation of Professional Trainers. Retrieved March 9, 2023, from https://www.nfpt.com/blog/understanding-hip-rotation-and-abduction

1.3.3 Asymmetry in Hip Muscle Strength and Mobility

Increased asymmetry in hip extension muscle strength was found in female athletes with LBP compared to those without LBP (Nadler et al., 2000). Additionally, a prospective study showed that in female athletes, asymmetry in hip extensor muscle strength was a predictor of whether LBP treatment was required over the ensuing year (Nadler et al., 2001). Very limited information is available on whether asymmetry in strength and flexibility in specific hip muscle groups associates with dysfunction during performance-based tests in CLBP. This study proposes to fill in this gap in research.

1.4 Significance and Innovation

There is limited evidence regarding how hip extension, abduction, and flexion muscle weakness associate with physical dysfunction during performance-based tests in persons with CLBP. It is important to investigate populations with CLBP because physical function and pain interference may be different in CLBP populations compared to non-specific and acute LBP populations. Persons with CLBP, because of longer time dealing with pain, probably have more severe weakness of these muscles. Therefore, findings from research in populations with more acute LBP cannot be generalized to CLBP. Additionally, investigation into the association of restricted hamstrings flexibility and restricted hip internal rotation mobility on physical dysfunction during performance-based tests is limited. There is also a large gap in research on how hip muscle asymmetries in both strength and mobility associate to dysfunction during performance-based tests. This study proposes to fill all these gaps by focusing on the relationship between hip muscle impairments and performance-based tests, such as walking, sitting, and lifting, in addition to patient-reported pain interference, physical dysfunction, and LBP-related disability to enhance our understanding of how hip impairments affect daily function in persons with CLBP. This study is necessary because performance-based tests are clinically relevant as they assess the patient's ability to perform daily activities. For a comprehensive investigation of individuals' perception of their ability to perform daily activities and whether pain influences performance, we will also include patient-reported outcomes (PROs) of LBP-related disability, physical function, and pain interference. If the results of this study show hip muscle impairments to be associators to dysfunction, it may suggest a need for further longitudinal investigation and controlled trials to determine if a greater focus on hip muscle strengthening and flexibility is necessary to more optimally improve physical function in persons with CLBP.

1.5 Current Guidelines

In a 2021 revision of the Academy of Orthopedic Physical Therapy clinical practice guidelines, it is recommended that physical therapists use trunk muscle strengthening and endurance exercises, trunk muscle activation exercises, trunk mobility exercises, and other general exercises for persons with CLBP (George et al., 2021). These guidelines focus treatment solely on the trunk, with minimal emphasis on surrounding musculature that is robustly and functionally interconnected with the low back musculature, such as the hip muscles.

According to a clinical practice guideline from the American College of Physicians, recommended nonpharmacological treatments for CLBP include exercise therapy, mindfulness-based stress reduction, yoga, relaxation techniques, and motor control exercise. Pharmacological treatment recommendations for CLBP include nonsteroidal anti-inflammatory drugs, tramadol, duloxetine, and opioids for people who do not respond to other treatments (Qaseem et al., 2017).

As mentioned, the cost of CLBP on the health care system is still astronomical, suggesting that strengthening and stretching of the low back muscles alone, other general exercise, and relaxation techniques may be insufficient treatments for CLBP. It is necessary to look outside the direct area of pain in the low back and further investigate the association of the hip muscles and hip mobility with physical dysfunction and pain in persons with CLBP, which is what this study proposes to investigate.

1.6 Interventions with a Focus on Hip Muscle Impairments and Further Investigation Needed

Hip muscle stretching and strengthening has been shown to improve pain and disability in individuals with LBP. A randomized controlled trial assessed individuals who had LBP for more than three months and split participants into either a hip muscle stretching group, hip muscle strengthening group, or a control group (Kim & Yim, 2020). All three groups of participants also performed core stability exercises along with the respective stretching, strengthening, or sham tasks three times a week for six weeks. The results showed that all three groups had improved low back stability, as measured by the passive straight leg raising test, reduced pain intensity, and reduced disability level, suggesting core stability or its combination with hip exercises can be an effective treatment for LBP. Between group analysis showed that low back stability and hip muscle flexibility were more improved in the stretching group compared to the strengthening and sham groups. Additionally, the stretching and strengthening groups had greater improvements in pain intensity and disability level than the sham group (Kim & Yim, 2020). This indicates that while focus on the core and trunk muscles can improve LBP, incorporation of stretching and strengthening of the hip muscles may result in greater pain and disability reduction than just core and trunk treatment alone. This study focused only on non-specific LBP and did not investigate persons with CLBP. It is unknown whether persons with CLBP and longer-term pain and disability would respond similarly to treatment. Additionally, this study did not assess muscle strength to determine whether the exercise programs improved muscle strength to test a more direct relationship between gains in muscle strength and improvement in LBP and LBP-related disability.

Another study has shown that lumbar stabilization exercises combined with exercises to strengthen the gluteus muscles resulted in a larger improvement in pain, disability, lumbar muscle strength, and balance compared to lumbar stabilization exercises alone in middle-age females with LBP (Jeong et al., 2015). While this study offers some credence that gluteus strengthening exercises are beneficial, it was limited to females only, there is no indication that the sample had CLBP (while stated in title), the volume of exercise and clinician attention was considerably higher in the combined group, and hip muscle strength was not measured. Because of a lack of assessment on whether the strength of hip muscles improved, the observed effects could be a result of higher volume of exercise and increased attention in the combined exercise group. More research is needed to investigate the direct association of hip impairments to pain and disability in CLBP.

Results of a meta-analysis show that posterior chain resistance training that targets the thoracic, lumbar, and hip extensor muscles results in greater improvements in pain and disability and larger increases in muscle strength than general exercise in individuals with CLBP (Tataryn et al., 2021). Although this study assessed isometric lifting capacity, which was assessed through low-load motor control and high-load lifting exercises, isometric lumbar extension, knee extension torque, and leg press performance as muscle strength outcome measures, these assessments do not enable understanding of the association of strength impairments of specific hip muscle groups with function. The limitations in current intervention studies assessing the association of hip muscles strengthening with physical function in CLBP justifies the in-depth investigation of specific hip muscle impairments as associators to physical dysfunction during performance-based tests in persons with CLBP proposed by this study.

1.7 Specific Aims and Hypotheses

1.7.1 Aim 1

To determine the association of hip muscle strength and hip muscle strength asymmetry with performance-based measures of function and self-reported pain interference, physical dysfunction, and LBP-related disability in persons with CLBP.

1.7.2 Hypothesis for Aim 1

Individuals with stronger hip muscles and smaller hip muscle strength asymmetry will have high levels of physical function and low self-reported pain interference, physical dysfunction, and LBP-related disability.

1.7.3 Aim 2

To determine the association of hamstrings flexibility, hip internal rotation mobility, and mobility asymmetry with performance-based measures of function and self-reported pain interference, physical dysfunction, and LBP-related disability in persons with CLBP.

1.7.4 Hypothesis for Aim 2

Individuals with more flexible hamstrings, more hip internal rotation mobility, and more symmetry of these mobility measures will have high levels of physical function and low self-reported pain interference, physical dysfunction, and LBP-related disability.

2.0 The Association of Hip Muscle Strength and Flexibility, Hip Mobility, and Asymmetry with Dysfunction and Pain in Individuals with Chronic Low Back Pain

2.1 Background and Significance

Low back pain (LBP) is one of the leading causes of disability in the United States and worldwide (Hartvigsen et al., 2018; Parthan et al., 2006). Chronic LBP (CLBP) happens when LBP lasts longer than the expected period of healing, lasts longer than seven to twelve weeks, or when LBP reoccurs frequently, causing substantial disability (Andersson, 1999). With non-specific CLBP, there is an absence of structural or tissue dysfunction (Andersson, 1999), which results in treatments that are nonspecific and tend to produce small and short-lasting benefits (Qaseem et al., 2017). Investigating factors that associate with pain and physical dysfunction experienced by persons with CLBP is key to justify longitudinal research and controlled trials to inform the use of more tailored interventions and improve outcomes.

Weakness of the hip muscles, limited hamstrings flexibility, limited hip internal rotation mobility, and asymmetry in these impairments may be underappreciated factors contributing to CLBP. The hip muscles are important in stabilizing the pelvis and transferring weight from the spine to the lower extremities during locomotion (Leinonen et al., 2000). Weakness of hip muscles has shown to be more prevalent in persons with LBP compared to controls (de Sousa et al., 2019). The hamstrings help maintain the pelvis in a neutral position and shortening may produce posterior pelvic tilt, resulting in decreased lumbar lordosis (McCarthy & Betz, 2000), which could contribute to CLBP. Limited hip mobility has been associated to instability in the lumbar spine in CLBP (wk Lee & Kim, 2015), which could be due to increased lumbar spine compensatory movement requirements, resulting in pain. It has also been shown that hip extension strength asymmetry is higher in female athletes with LBP compared to controls (Nadler et al., 2000). Although the collective evidence offers some credence to the association of these impairments with CLBP, the current evidence is limited to small samples generally not representative of clinical populations with CLBP, and studies that fail to adjust for demographic variables, such as sex and BMI, which could confound results; further, studies investigating whether these impairments associate with physical dysfunction and disability are lacking.

To address the current gaps in evidence, the goal of this study is to investigate whether hip muscle strength, hamstrings flexibility, hip internal rotation mobility, and side-to-side asymmetry in these measures are associated with physical dysfunction and/or self-reported pain interference, physical function, and LBP-related disability in persons with CLBP. Specifically, it will determine the association of hip muscle strength, hamstrings flexibility, hip internal rotation mobility, and the asymmetry of these physical impairments with performance-based measures of function and patient-reported outcomes (PROs) assessing pain interference, physical function, and LBP-related disability in persons with CLBP. If these impairments and their asymmetries are associated with these performance-based tests and PROs in persons with CLBP, this may suggest the need for longitudinal investigation and controlled trials to determine if there is a need for increased focus on correcting these impairments to improve physical function and decrease LBP-related disability.

2.2 Methods

This is a cross-sectional study with a secondary analysis of pre-existing data from the *Healing Lower Back Pain: Profiling Biomechanical, Biological, and Behavioral phenotypes*

(LB3P) study. The NIH Grant Number for LB3P is 1U19AR076725. LB3P is a prospective observational study that aims to characterize the biological, biomechanical, behavioral, and clinical biomarkers of CLBP and response to treatment. The analysis for this study uses the baseline data for which participants completed questionnaires evaluating their pain interference, physical function, and LBP-related disability and a physical examination including hip muscle strength, hip muscle flexibility, and hip mobility testing.

2.3 Participants

Participants enrolled in the LB3P study met the following inclusion criteria: LBP for greater than three months, LBP that has been on ongoing problem for at least half the days in the past six months, which are the two criteria in the definition of CLBP proposed by the Task Force for Research Standards (Deyo et al., 2015), age 18 years or older, ability to speak and understand English to complete informed consent procedures and respond to study questions, willingness to comply with all study procedures, and provide signed informed consent form. The exclusion criteria were: individual not identified in the UPMC Electronic Health Record (EHR) System, participation in a blinded intervention study for LBP, or any medical condition or characteristic that would place the participant at increased risk or preclude them from complying with study procedures. The LB3P study aims to enroll 1,000 participants over 30 months. Recruitment strategies included mainly identification of participants by clinical partners, research registries, and media announcements in the greater Pittsburgh area. The first participant was enrolled in LB3P in November of 2020.

2.4 Independent and Dependent Measures

Independent variables include measures of bilateral hip muscle strength and flexibility, hip mobility, and side-to-side asymmetry in these measures.

Hip extensors strength test. The participant lies prone with tested knee bent. A handheld dynamometer (HHD) is placed just proximal to the popliteal space. The participant pushes the leg upwards against the opposing force exerted by the tester for three to five seconds, and the dynamometer is held stationary against the participant's force (Figure 7). Three trials are completed separated by five second breaks. All three trials are completed on the left side first, followed by the three trials on the right side. The results are recorded in kilograms and averaged. Hip strength tests using a hand-held dynamometer have shown to have good test-retest reliability between two trials with the same tester, with an intraclass correlation coefficient (ICC) of 0.78 to 0.86 for hip extension strength testing (Thorborg et al., 2010). In healthy women aged 20-29 years, average hip extensor strength, measured as a proportion of body weight, is 0.27 (Alvarenga et al., 2019). For muscle strength measures assessed by the HHD in kg (hip extensors and hip abductors) we divide the average values by body weight. This is done to provide a muscle strength value proportionate to participants' body size and reduce the confounding variability related to body size (de Lima et al., 2021). Relative contralateral asymmetry is calculated by taking the difference between the adjusted left and right-side measurements.

Figure 7. Hip Extensors Strength Test

Hip abductors strength test. Participant lies supine with feet past the table edge. The tester stays on the side of the abductor being measured. A HHD is placed proximal to the lateral malleolus of the side being tested. The participant is asked to push against the HHD for three to five seconds with maximal effort while the tester applies an opposing force, and the dynamometer is held stationary against the participant's force (Figure 8). Three trials are completed separated by five second breaks. The trials are completed on the left side first, followed by the right side. The results are recorded in kilograms and averaged. Hip abduction strength tests in the supine position using a HHD have shown to have excellent test-retest reliability between two trials with the same tester, with an ICC of 0.97 (Thorborg et al., 2010). Previous study shows that healthy individuals aged 20-42 years had an average hip abduction strength, measured in proportion of body mass, of 0.21 (Piva et al., 2005).

Figure 8. Hip Abductors Strength Test

Hip flexion manual muscle test. Participant sits upright marching their leg upwards just above the table. The tester applies a downward force on the distal thigh just proximal to the patella for five seconds while the participant pushes against it (Figure 9). The degree of muscle strength is rated on an ordinal scale from 0-5 where: 0 = no contraction; 1 = flicker or trace of contraction with minimal or no motion; 2 = active movement with gravity eliminated; 3 = active movement against gravity, but not against resistance; 4 = active movement against gravity with some resistance; and 5 = active movement against gravity with full resistance as noted in the LB3P study. For analysis, the scale from 0 to 5 was categorized as weak (combined scores from 0 to 4) and strong (score of 5). Asymmetry is calculated as subtracting the ordinal values from both sides; no contralateral difference is scored as 0 and any contralateral difference present was scored as 1.

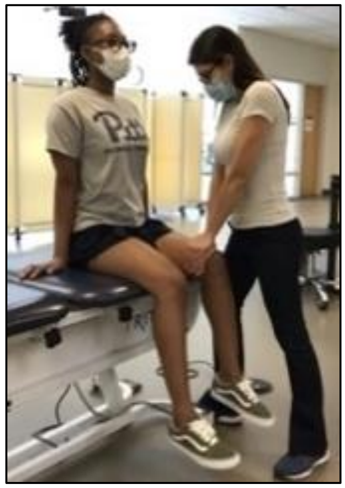

Figure 9. Hip Flexion Manual Muscle Test

Straight leg raise test (hamstrings length). Participant is supine. The tester places an inclinometer distal to the tibial tubercle and zeroes the device. The tester passively places the ankle in dorsiflexion and lifts the leg off the table, while keeping the knee extended and ankle dorsiflexed. The tester stops raising the leg once the maximum hip flexion angle is reached with a firm end-feel (Figure 10) and records the movement in degrees. One trial is completed on each side. Trials that provoke radicular symptoms are not used. Average hamstrings length in healthy individuals aged 20-42 is 88.6° (Piva et al., 2005). The asymmetry in hamstrings mobility is calculated by taking the absolute value of the difference between the left and right-side.

Figure 10. Straight Leg Raise Test

Hip internal rotation mobility test. Participant is prone with tested knee flexed to 90 degrees. The tester grasps the distal leg and stabilizes the pelvis with the other hand. The inclinometer is zeroed perpendicular to the table and is placed on the medial distal tibia, about one inch proximal to the medial malleolus (Figure 11). The tester moves the hip passively until the maximum range of hip internal rotation. Results are recorded in degrees for the side with more and less limited hip mobility and asymmetry is calculated by taking the absolute value of the difference between both sides. Hip range of motion measurements have been shown to have good-to-excellent intra-rater agreement (ICCs ranging from 0.76 to 0.97), and good inter-rater reliability (ICC=0.79) was found for prone hip internal rotation measurements (Prather et al., 2010). In healthy Japanese students, average hip internal rotation range of motion, assessed in prone, is 45.8° (Han et al., 2015).

Figure 11. Hip Internal Rotation Mobility Test

Dependent variables include performance-based measures and PROs of pain interference, physical function, and LBP-related disability.

Four-Meter Walk Test. Participant stands behind a start line and is instructed to walk at their normal speed while the tester times the test from stepping over the start line to the participant's first foot crossing the finish line four meters from the start line. Two trials are completed, and the fastest time is recorded in seconds. Gait speed is calculated by dividing four meters by the time in seconds. The Four-Meter Walk Test has shown to have excellent test-retest reliability (ICC=0.99) in a chronic ambulatory post-stroke sample (Cabanas-Valdés et al., 2023). In healthy individuals, the mean normal gait speed ranges from 1.3 m/s for women in their seventies to 1.5 m/s for men in their forties (Bohannon, 1997). In another study on 18–85-year-old men and women performing the four-meter walk test, the mean normal walking speed was 1.12 m/s (Bohannon & Wang, 2019).

Five Times Sit-to-Stand Test. This test assesses the time a participant takes to stand up and sit down in a chair five times with their arms crossed over their chest. The tester starts the timer when the participant stands up the first time and stops it when the participant stands up completely for the fifth time. The Five Times Sit-to-Stand Test is a robust predictor of disability (Guralnik et al., 1995). In healthy participants aged 14-85, with an average age of 46.5, the time taken to complete five repetitions of sit-to-stand ranged from 3.9 to 17.7 seconds, with a mean of 7.5 seconds (Bohannon et al., 2010).

Two-Minute Walk Test. This test assesses the distance walked in two minutes. The participant is asked to cover as much ground as possible over two minutes. The total distance in meters is used as a measure of walking capacity. In adults aged 18-85 years old, the distances walked in two minutes ranged from 64.6 meters to 300.8 meters, with a mean of 180.9 meters (Bohannon et al., 2015). The Two-Minute Walk Test has proven to have good test-retest reliability, with an ICC of 0.82 (Bohannon et al., 2015).

Postural lifting strategy test. This is an assessment of body ergonomics while lifting a box. The participant is asked to lift a weighted box four times or for twenty seconds (whichever comes first) from the floor to a 75-cm high table and back to the floor in a continuous motion. The box weight is 3.6 kg for women and 5.85 kg for men. A lift is counted once the box is on the table. The tester observes and scores the lifting strategy in five categories: spine neutral, flexion dominance, base of support, aberrant movement, and box proximity to body. Participants can either score a 0 or 1 in each category, with 0 representing optimal lifting strategy. The total score ranges from 0 to 5.

Oswestry Disability Index (ODI). The ODI contains ten items, scored 0 to 5, that ask participants to assess their limitations due to LBP. The items focus on pain, personal care, living, and social life. The ODI overall score ranges from 0% (no disability) to 100% (maximum disability), with scores of 0-20% indicating minimal disability, 21-40% indicating moderate disability, and >40% indicating severe disability. The ODI has high internal consistency and good-to-excellent test re-test reliability, with an ICC of 0.84 (Smeets et al., 2011).

Patient-Reported Outcomes Measurement Information System (PROMIS) is a person-centered measure consisting of questions that evaluate physical, mental, and social health in healthy individuals and in those with chronic conditions. The T-score is used for the PROMIS measures because it allows for a comparison of outcomes with the general United States population (Chen et al., 2018). The average T-score for PROMIS measures in the United States general population is 50 with a standard deviation of 10 (Rothrock et al., 2020). These PROMIS measures have been validated for use in LBP cohorts by multiple studies (Thompson et al., 2022). The PROMIS Pain Interference and PROMIS Physical Function questionnaires were used in this study.

PROMIS Pain Interference (PROMIS-INT). The PROMIS-INT consists of four questions assessing how pain hinders relevant aspects of a participant's life in the past seven days. A T-score greater than 50 on the PROMIS-INT indicates the participant has pain interference that is worse than the average for the United States general population (Thompson et al., 2022). The PROMIS-INT is sensitive to changes in pain levels in participants with CLBP (Askew et al., 2016).

PROMIS Physical Function (PROMIS-PF). The PROMIS-PF consists of six questions assessing a participant's capability in completing activities of daily living, such as errands. A T-score greater than 50 on the PROMIS-PF indicates the participant has better physical function than the average for the United States general population (Thompson et al., 2022).

2.5 Data Analysis

To test the first hypothesis that individuals with strong hip muscles and small asymmetry of these muscles have high levels of physical function and low self-reported low back pain and disability, data analysis was done in several steps. We first calculated descriptive statistics. For continuous variables we used means and standard deviations while for categorical variables we used counts and frequencies. We checked normality of data and linearity by visual inspection of histograms and scatter plots, respectively. Bivariate correlation among the independent variables and between independent and dependent variables used Pearson, Spearman, Kendall's tau, or point-biserial correlation coefficients, dependent on data distribution and variable type. Pearson correlation coefficients were used for associations between two continuous variables, Spearman correlation coefficients were used for associations between an ordinal and continuous variable, Kendall's tau correlation coefficients were used for associations between an ordinal and categorical variable, and point-biserial correlation coefficients were used for associations between a continuous and categorical variable. Cohen's correlation cut points were used to interpret the strength of correlations: $r < 0.1$ = very small, $0.1 \leq r < 0.3$ = small, $0.3 \leq r < 0.5$ = moderate, and $r \geq 0.5$ = large. If independent variables demonstrated correlations amongst them above $r=0.80$, which was expected for values of muscle strength and mobility between left and right sides, we selected one of the variables to be used in the subsequent regression models (more limited side for hip internal rotation mobility and left side for all other independent variables).

We used regression models to determine the association between the measures of hip muscle strength and asymmetry (independent variables) and performance-based measures and PROs of pain interference, physical function, and LBP-related disability (dependent variables). Independent variables were analyzed in regression analysis separately and all together with stepwise selection procedures. We used individual models to understand the association of each individual independent variable with each dependent variable, and we used stepwise selection to come up with the most parsimonious set of associators to explain variability in each dependent variable. In individual independent variable regression analysis, the alpha value was 0.05, and for stepwise selection the alpha values for entry and removal were 0.05 and 0.10, respectively. Sex, age, and BMI were held constant because these variables have been shown to be associated with our independent and/or dependent variables (Miller et al., 1993); (Samson et al., 2001); (Ten Hoor et al., 2018). We ran separate regression models for each dependent variable in both individual analyses and stepwise selection. Independent variables considered for each dependent variable in stepwise selection for the first hypothesis were hip extension, abduction, and flexion strength, and asymmetry in hip extension, abduction, and flexion strength. The second hypothesis was tested in the same way but using hamstrings length, hip internal rotation mobility, asymmetry in hamstrings length, and asymmetry in hip internal rotation mobility as the independent variables.

2.6 Results

This study included 515 participants and all contributed data for demographics and PROs of pain interference, physical dysfunction, and LBP-related disability. While most participants (n=505) were able to participate in gait speed testing, a smaller number participated in the other performance-based tests due to LBP symptoms (e.g., 420 in postural lift strategy). The assessments that only involved mobility were performed by at least 454 participants and no participation was mainly due to pain or inability to lie on the examination table (n=26 and 61 participants unable to participant hip internal rotation mobility and hamstrings flexibility tests, respectfully) . Some additional participants were unable to perform strength tests that required maximum muscle contraction because they did not pass the safety screening due to high blood pressure, cardiovascular diseases, or other contra-indications to physical effort. Asymmetry measurements could not be calculated if participants were either missing the left or right-side measurement, which resulted in a smaller number of cases for these variables (Tables 1 and 2).

Table 1. Demographic Characteristics of Sample

Variable	**N**=515**
Age, mean (SD), years	58 (17)
Female, N (%)	323 (63%)
***Race, N (%)	
White	395 (77)
African American	100 (19)
Asian	18 (3.5)
American Indian or Alaskan Native	12 (2.3)
Not reported	7 (1.4)
Hawaiian	3 (0.58)
Hispanic or Latino, N (%)	10 (1.9)
**Education level, N (%)	
Did not complete high school	27 (5.3)
Completed high school	118 (23)
College degree completed	226 (44)
Postgraduate degree completed	143 (28)
**Marital status, N (%)	

Divorced	77 (15)
Married	238 (46)
Never married/separated/widowed	167 (32)
Domestic partner	32 (6.2)
Annual household income, N (%)	
Less than $25,000	114 (22)
$25,000-$49,999	99 (19)
$50,000-$74,999	69 (13)
$75,000-$99,999	69 (13)
$100,000-$199,999	88 (17)
$200,000 or more	16 (3.1)
Prefer not to answer	60 (12)
BMI (kg/m^2), mean (SD)	32 (8.1)
***Type of comorbidity, N (%)	
Osteoarthritis*	277 (54)
Osteoarthritis in hip	107 (21)
Herniated Disk*	173 (34)
Scoliosis*	116 (23)
Osteoporosis*	56 (11)
Fibromyalgia*	54 (10)
Vertebral fracture*	45 (8.7)
Spinal cord injury*	20 (3.9)
Kyphosis*	9 (1.7)

*Comorbidities experienced in the past and/or ongoing; **N=514 for education level and marital status; *** Race and comorbidities percentages are higher than 100% because these variables are not mutually exclusive

The average age of participants in this study was 58 years, 63% were female, 77% were white, average BMI was 32 kg/m^2, 72% completed a college degree, and osteoarthritis was the most prevalent comorbidity, with 39% reporting hip osteoarthritis (Table 1). Participants displayed moderate levels of disability (ODI=31%). Pain interference was higher (PROMIS-INT=60) and physical function lower (PROMIS-PF=40) than the average for the United States general population (Table 2).

Table 2. Biomedical Characteristics of Sample

Variable	Mean or (N)	SD or (%)	Median	Min	Max	95% lower bound	95% upper bound	N
Hip Strength Measures								
Hip extension strength left*	0.16	0.081	0.14	0.02	0.54	0.15	0.16	372
Hip extension strength right*	0.16	0.087	0.15	0.03	0.52	0.15	0.17	373
Asymmetry in hip extension strength*	0.023	0.022	0.017	0.00	0.12	0.021	0.026	368
Hip abduction strength left*	0.12	0.044	0.11	0.02	0.27	0.11	0.12	396
Hip abduction strength right*	0.12	0.046	0.12	0.03	0.27	0.12	0.13	396
Asymmetry in hip abduction strength*	0.017	0.014	0.013	0.00	0.080	0.015	0.018	395
Hip flexion strength left – N (%)			-	-	-	-	-	441
Weak, less than active movement against gravity w/full resistance	(175)	(40%)						
Strong, Active movement against gravity w/full resistance	(266)	(60%)						
Hip flexion strength right – N (%)			-	-	-	-	-	468
Weak, less than active movement against gravity w/full resistance	(161)	(34%)						
Strong, Active movement against gravity w/full resistance	(307)	(66%)						
Asymmetry in hip flexion strength – N (%)			-	-	-	-	-	441
No asymmetry (0)	(380)	(86%)						
Asymmetry present (1)	(61)	(14%)						
Hip Mobility Measures								
Hamstrings flexibility left (°)	71	14	70	28	116	70	73	454
Hamstrings flexibility right (°)	71	14	69	30	114	69	72	462
Asymmetry in hamstrings flexibility (°)	5.7	5.1	4	0	50	5.2	6.2	434
Hip internal rotation more limited side (°)	30	11	29	7	69	29	31	489
Hip internal rotation less limited side (°)	37	11	37	9	76	36	37	489
Asymmetry in hip internal rotation (°)	6.5	5.8	5	0	33	6	7	485
Performance-Based Measures								
Gait Speed (m/s)	0.91	0.21	0.92	0.16	1.5	0.90	0.93	505
5 times sit-to-stand (seconds)	13	4.7	12	4.7	42	13	13	434
2-minute walk test (meters)	168	44	171	38	295	164	172	458
Postural lift test – total score (0-5)	2.3	1.2	2	0	5	2.2	2.4	420
PROs of Pain and Disability								
ODI score (0-100)	31	15	28	0	94	30	32	515
PROMIS-INT T-score (T-score)	60	7.1	60	42	76	60	61	515
PROMIS-PF T-score (T-score)	40	6	40	25	59	40	41	515

ODI=Oswestry Disability Index; PROMIS-INT = Patient-Reported Outcomes Measurement Information System-Pain Interference; PROMIS-PF = Patient-Reported Outcomes Measurement Information System-Physical Function
*Extension and abduction strength adjusted by body weight

On average, participants' adjusted muscle strength was about 0.16 and 0.12 for hip extension and abduction, respectively, with negligible asymmetry in strength of these muscles. Most participants (60% on the left side and 66% on the right side) could actively contract the hip flexors against gravity with full resistance and 14% demonstrated asymmetry in these muscles (Table 2). On average, participants had 71° of range of motion on the straight leg raise test for hamstrings length with less than 6° of asymmetry. Average hip internal rotation was 30° and 37° on the more and less limited sides, with 6.5° in hip internal rotation asymmetry (Table 2).

2.6.1 Bivariate Correlations of Hip Impairments and Outcome Measures

Correlation analysis indicated that individuals with weak hip muscles had poor functional performance and heightened disability, physical dysfunction, and pain interference. The magnitude of correlations between hip muscle strength and the walking tests (gait speed and Two-Min Walk) and Five Times Sit-to-Stand were larger for hip abduction (coefficients ranging from 0.46 to 0.63 in absolute values), followed by hip extension (0.42 to 0.54) and hip flexion (0.21 to 0.34). Correlations of hip muscle strength and postural lift strategy test were all small ($\leq$0.20). Hip extension and abduction strength correlated moderately (0.31 to 0.45) whereas hip flexion strength had small correlations ($\leq$0.29) with PROs of pain interference, physical dysfunction, and LBP-related disability, which could be due to the manual muscle testing technique used in hip flexion strength testing or the categorical nature of the hip flexion variables. Measures of asymmetry in hip strength with performance-based tests and PROs were all very small ($\leq$0.14) (Top section of Table 3).

Correlation analysis indicated that limited and asymmetrical hamstrings flexibility and limited and asymmetrical hip internal rotation mobility were weakly correlated to poor functional performance and heightened LBP-related disability, physical dysfunction, and pain interference. Small magnitude of correlations ($\leq$0.24) was observed between hamstrings flexibility and hip internal rotation or asymmetry of these impairments with performance-based tests and PROs (Bottom section of Table 3). The correlations of hip impairments on left and right sides were all above 0.82 (Tables 4 and 5), indicating that these impairments are measuring the same domain despite the side assessed. To prevent multicollinearity, we selected only measures on one side (left side for hip muscle strength and straight leg raise measures, and the most limited side for hip internal rotation) for regression analysis. Hip extension strength and hip abduction strength were correlated close to 0.8, (correlation coefficient of 0.78) but both variables were still included in regression analysis to adhere to the strict cut-off point for multicollinearity of 0.8 chosen for this study.

Table 3. Correlation Coefficients Between Hip Strength/Flexibility/Mobility/Asymmetry and Performance-Based Measures and PROs of Pain Interference, Physical Function, LBP-Related Disability

	Performance-Based Measures				PROs of Pain and Disability		
	Gait speed (m/s)	5 times Sit-to-Stand (seconds)	2-minute Walk Test (meters)	Postural lift total score (0-5)	ODI score (0-100%)	PROMIS-INT T-score (T-score)	PROMIS-PF T-score (T-score)
Hip Muscle Strength Measures							
Hip extension strength left	0.45**	-0.48**	0.54**	-0.19** ρ	-0.35**	-0.33**	0.42**
Hip extension strength right	0.42**	-0.48**	0.51**	-0.19** ρ	-0.36**	-0.34**	0.42**
Asymmetry in hip extension strength	0.087	-0.11*	0.14**	-0.12* ρ	-0.040	-0.079	0.097
Hip flexion strength left	0.29** ϑ	-0.21** ϑ	0.34** ϑ	-0.13** τ	-0.27** ϑ	-0.17** ϑ	0.26** ϑ
Hip flexion strength right	0.30** ϑ	-0.23** ϑ	0.34** ϑ	-0.077 τ	-0.29** ϑ	-0.21** ϑ	0.27** ϑ
Asymmetry in hip flexion strength	-0.11* ϑ	0.053 ϑ	-0.075 ϑ	0.10* τ	0.13** ϑ	0.027 ϑ	-0.087 ϑ
Hip abduction strength left	0.50**	-0.47**	0.63**	-0.20** ρ	-0.39**	-0.31**	0.45**
Hip abduction strength right	0.50**	-0.46**	0.61**	-0.19** ρ	-0.38**	-0.35**	0.45**
Asymmetry in hip abduction strength	0.095	-0.050	0.081	-0.072 ρ	-0.014	-0.017	0.063
Hip Muscle Mobility Measures							
Hamstrings flexibility left (°)	0.24**	-0.21**	0.12*	-0.18** ρ	-0.12*	-0.10*	0.11*
Hamstrings flexibility right (°)	0.20**	-0.21**	0.074	-0.15** ρ	-0.058	-0.063	0.096*
Asymmetry in hamstrings flexibility (°)	-0.13**	0.051	-0.082	0.041 ρ	0.14**	0.00	-0.066
Hip internal rotation more limited side (°)	0.20**	-0.11*	0.17**	-0.096 ρ	-0.076	-0.069	0.065
Hip internal rotation less limited side (°)	0.10*	-0.080	0.060	-0.10* ρ	0.005	0.012	-0.017
Asymmetry in hip internal rotation (°)	-0.20**	0.060	-0.22**	0.002 ρ	0.16**	0.15**	-0.16**

** Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level
ODI = Oswestry Disability Index; PROMIS-INT = Patient-Reported Outcomes Measurement Information System-Pain Interference; PROMIS-PF = Patient-Reported Outcomes Measurement Information System-Physical Function

Extension and abduction strength reported as adjusted by body weight
Pearson's correlation coefficient unless otherwise specified
Spearman's correlation coefficient = ρ; Kendall's tau = τ; Point-biserial = ϑ

The bivariate correlations between hip muscle strength/mobility and the study outcomes restricted only to complete cases for all the variables in the models (Table 6 and 8) demonstrated the same pattern of bivariate correlations not restricted to complete cases (Table 3)

Table 4. Hip Muscle Strength Measure Correlation Coefficient Matrix

	Hip ext left	Hip ext right	Asymmetry ext	Hip flex left	Hip flex right	Asymmetry flex	Hip abd left	Hip abd right	Asymmetry abd
Hip ext left	1	0.93**	0.32**	0.29** ϑ	0.29** ϑ	-0.079 ϑ	0.78**	0.79**	0.18**
Hip ext right		1	0.42**	0.30** ϑ	0.29** ϑ	-0.087 ϑ	0.78**	0.80**	0.17**
Asymmetry ext			1	0.13* ϑ	0.12* ϑ	-0.021 ϑ	0.23**	0.29**	0.17**
Hip flex left				1 ϑ	0.82** ϑ	-0.49** ϑ	0.39** ϑ	0.36** ϑ	-0.037 ϑ
Hip flex right					1 ϑ	-0.021 ϑ	0.37** ϑ	0.38** ϑ	0.045 ϑ
Asymmetry flex						1 ϑ	-0.16** ϑ	-0.090 ϑ	0.15** ϑ
Hip abd left							1	0.90**	0.074
Hip abd right								1	0.26**
Asymmetry abd									1

Hip ext left = hip extension strength left; Hip ext right = hip extension strength right; Asymmetry ext = asymmetry in hip extension strength
Hip flex left = hip flexion strength left; Hip flex right = hip flexion strength right; Asymmetry flex = asymmetry in hip flexion strength
Hip abd left = hip abduction strength left; Hip abd right = hip abduction strength right; Asymmetry abd = asymmetry in hip abduction strength

Table 5. Hip Muscle Flexibility and Hip Mobility Measures Correlation Coefficient Matrix

	Hamstrings left	Hamstrings right	Asymmetry hamstrings	Hip IR more limited	Hip IR less limited	Asymmetry hip IR
Hamstrings left	1	0.86**	-0.016	0.22**	0.20**	-0.038
Hamstrings right		1	0.047	0.20**	0.19**	-0.011
Asymmetry hamstrings			1	-0.014	-0.009	0.039
Hip IR more limited				1	0.85**	-0.28**
Hip IR less limited					1	0.27**
Asymmetry hip IR						1

Hamstrings left = hamstrings flexibility left; Hamstrings right = hamstrings flexibility right; Asymmetry hamstrings = asymmetry in hamstrings flexibility
Hip IR more limited = hip internal rotation more limited side; Hip IR less limited = hip internal rotation less limited side; Asymmetry hip IR = asymmetry in hip internal rotation

2.6.2 Results of Regression Analysis for the Association between Hip Muscle Strength and Outcomes of Physical Performance and PROs of Pain Interference, Physical Function, and LBP-Related Disability

In models adjusted by age, sex, and BMI, when only one independent variable was tested at a time; individuals with weaker hip extensor, abductor, and flexor muscles walked slower in the Four-Meter and Two-Minute Walk Tests, were slower standing from a chair five times, and had heightened LBP-related disability (per ODI) and reduced physical function (per PROMIS-physical function); individuals with weaker hip extensors and abductors had higher pain interference (measured by PROMIS-pain interference), and individuals with weaker hip extensors, abductors, and less asymmetry in hip extension strength used worse movement strategies during the postural lift strategy test (Table 6). The directional relationship found between asymmetry in hip extension strength and the postural lift strategy test was likely due to expected statistical error.

Table 6. Association of Hip Muscle Strength and Asymmetry to Performance-Based Measures and PROs of Pain Interference, Physical Function, LBP-Related Disability

	Pearson Correlation Coefficient	Unstandardized beta-β (SE β), β†	Unstandardized beta-β (SE β), β‡
Outcome - Gait speed N=347			
Hip extension strength	0.47**	0.84 (0.14), 0.35 **	0.50 (0.18), 0.21 *
Hip abduction strength	0.48**	1.8 (0.29), 0.40 **	1.1 (0.38), 0.25 *
Hip flexion strength	0.23**	0.056 (0.021), 0.14 *	-
Asymmetry in extension strength	0.097*	0.17 (0.46), 0.019	-
Asymmetry in abduction strength	0.084	0.20 (0.70), 0.015	-
Asymmetry in flexion strength	-0.037	-0.019 (0.030), -0.031	-
Outcome - Five Times Sit-to-Stand N=335			
Hip extension strength	-0.50**	-24 (3.2), -0.46 **	-18 (4.0), -0.34 **
Hip abduction strength	-0.46**	-45 (6.7), -0.46 **	-21 (8.4), -0.22 *
Hip flexion strength	-0.22**	-1.5 (0.49), -0.16 *	-
Asymmetry in extension strength	-0.12*	-11 (10), -0.056	-
Asymmetry in abduction strength	-0.028	8.7 (16), 0.028	-
Asymmetry in flexion strength	0.087	1.1 (0.69), 0.084	-
Outcome - Two-Minute Walk Test N=344			
Hip extension strength	0.55**	167 (26), 0.34 **	69 (33), 0.14 *
Hip abduction strength	0.61**	404 (54), 0.44 **	281 (70), 0.31 **
Hip flexion strength	0.32**	15 (3.9), 0.18 **	9.4 (3.8), 0.11 *
Asymmetry in extension strength	0.14*	45 (85), 0.024	-
Asymmetry in abduction strength	0.059	-116 (132), -0.040	-
Asymmetry in flexion strength	-0.040	-3.2 (5.6), -0.026	-
Outcome - Postural lift strategy test total score N=330			
Hip extension strength	-0.22**	-3.5 (1.0), -0.23 **	-3.5(1.0), -0.23 **
Hip abduction strength	-0.20**	-6.0 (2.2), -0.21 *	-
Hip flexion strength	-0.14*	-0.28 (0.15), -0.11	-
Asymmetry in extension strength	-0.16*	-8.3 (3.2), -0.15 *	-
Asymmetry in abduction strength	-0.052	-3.2 (5.0), -0.036	-
Asymmetry in flexion strength	0.095*	0.35 (0.22), 0.088	-
Outcome – Oswestry Disability Index N=348			
Hip extension strength	-0.35**	-45 (10), -0.28 **	-40 (10), -0.25 **
Hip abduction strength	-0.36**	-89 (21), -0.30 **	-
Hip flexion strength	-0.23**	-4.6 (1.5), -0.17 *	-3.6 (1.5), -0.13 *
Asymmetry in extension strength	-0.053	5.7 (32), 0.010	-
Asymmetry in abduction strength	0.010	63 (49), 0.067	-
Asymmetry in flexion strength	0.088	3.5 (2.1), 0.087	-
Outcome - PROMIS Pain Interference T-score N=348			
Hip extension strength	-0.32**	-23 (5.4), -0.27 **	-23 (5.4), -0.27 **

Hip abduction strength	-0.28**	-34 (11), -0.22 *	-
Hip flexion strength	-0.14*	-1.4 (0.80), -0.099	-
Asymmetry in extension strength	-0.087	-10 (17), -0.031	-
Asymmetry in abduction strength	-0.004	25 (26), 0.050	-
Asymmetry in flexion strength	-0.039	-0.82 (1.1), -0.038	-
Outcome - PROMIS Physical Function T-score N=348			
Hip extension strength	0.42**	22 (4.4), 0.29 **	20 (4.5), 0.27 **
Hip abduction strength	0.42**	42 (9.2), 0.31 **	-
Hip flexion strength	0.24**	2.1 (0.65), 0.17 *	1.6 (0.65), 0.12 *
Asymmetry in extension strength	0.10*	6.7 (14), 0.024	-
Asymmetry in abduction strength	0.050	-9.1 (22), -0.021	-
Asymmetry in flexion strength	-0.050	-0.90 (0.92), -0.048	-

**p<0.001; *p<0.05; PROMIS = Patient-Reported Outcomes Measurement Information System
Measures of hip muscle strength represent values from the left side.
† Coefficients for models when only one independent variable was tested at a time (adjusted by age, sex and BMI).
‡ Coefficients for stepwise selection with all independent variables tested together (adjusted for age, sex, BMI). The betas are from the last step of stepwise selection; thus, they don't match the values of the stepwise tables for models with >2 steps.

In the adjusted stepwise selection, the three variables of muscle strength (hip extension, abduction, and flexion) continued to associate with the Two-Minute Walk Test; hip extension and abduction strength continued to associate with gait speed and the Five Times Sit-to-Stand test; hip extension and flexion strength continued to associate with ODI and PROMIS-physical function; and only strength of hip extension continued to associate with postural lift strategy and PROMIS-pain interference (Table 6) .

Sex, age and BMI explained as low as 2% (R^2 adj = 0.02) to as high as 31% (R^2 adj = 0.31) of the variability in the outcomes of functional performance (Table 7). For gait speed, the strength of hip abduction and extension explained 10%, and the total model explained 26% of variability (R^2 adj = 0.26) in this outcome. Hip extension and abduction strength explained 15% of variability in Five Time-Sit-to-Stand with the total model explaining 26%. Hip abduction, flexion, and extension explained 11% of variability in the Two-Min Walk Test with the total model explaining 42%. Hip extension strength explained 3% of variability in postural lift test with the total model explaining 5% (Table 7).

Table 7. Stepwise Selection Regression Models for the Association of Hip Muscle Strength and Asymmetry to Performance-Based Tests and PROs of Pain Interference, Physical Function, LBP-Related Disability

	Confounder variable	Independent variable	Standardized β	Unstandardized β (SE)	R	R^2	R^2 adj.	R^2 Δ	FΔ	Sig FΔ
Outcome - Gait speed N=347										
Step 1	Sex		-0.018	-0.007 (0.020)	0.41	0.17	0.16	0.17	23	<0.001
	Age		-0.31	-0.004 (0.001)						
	BMI		-0.27	-0.007 (0.001)						
Step 2		Hip abduction	0.40	1.8 (0.29)	0.50	0.25	0.24	0.079	36	<0.001
Step 3		Hip extension	0.21	0.50 (0.18)	0.52	0.27	0.26	0.016	7.5	0.006
Outcome - Five Times Sit-to-Stand N=335										
Step 1	Sex		-0.007	-0.061 (0.46)	0.34	0.12	0.11	0.12	14	<0.001
	Age		0.23	0.060 (0.013)						
	BMI		0.24	0.14 (0.031)						
Step 2		Hip extension	-0.46	-24 (3.2)	0.50	0.25	0.24	0.14	60	<0.001
Step 3		Hip abduction	-0.22	-21 (8.4)	0.52	0.27	0.26	0.014	6.4	0.012
Outcome - Two-Minute Walk Test N=344										
Step 1	Sex		-0.11	-9.0 (3.7)	0.56	0.31	0.31	0.31	51	<0.001
	Age		-0.42	-1.0 (0.11)						
	BMI		-0.36	-2.0 (0.25)						
Step 2		Hip abduction	0.44	404 (54)	0.64	0.41	0.40	0.099	57	<0.001
Step 3		Hip flexion	0.12	9.7 (3.8)	0.65	0.42	0.41	0.011	6.6	0.011
Step 4		Hip extension	0.14	69 (33)	0.66	0.43	0.42	0.007	4.4	0.036
Outcome - Postural lift strategy test – total score N=330										
Step 1	Sex		0.025	0.063 (0.14)	0.17	0.028	0.020	0.028	3.2	0.024
	Age		0.17	0.013 (0.004)						
	BMI		0.027	0.005 (0.009)						
Step 2		Hip extension	-0.23	-3.5 (1.0)	0.25	0.062	0.051	0.034	12	<0.001
Outcome - Oswestry Disability Index sum score N=348										
Step 1	Sex		0.048	1.3 (1.4)	0.29	0.086	0.078	0.086	11	<0.001
	Age		0.21	0.16 (0.040)						
	BMI		0.21	0.37 (0.093)						
Step 2		Hip extension	-0.28	-45 (10)	0.37	0.14	0.13	0.050	20	<0.001
Step 3		Hip flexion	-0.13	-3.6 (1.5)	0.39	0.15	0.14	0.015	6.0	0.015
Outcome - PROMIS Pain Interference T-score N=348										
Step 1	Sex		0.043	0.60 (0.74)	0.25	0.065	0.056	0.065	7.9	<0.001
	Age		0.13	0.052 (0.022)						
	BMI		0.22	0.21 (0.050)						
Step 2		Hip extension	-0.27	-23 (5.4)	0.33	0.11	0.10	0.047	18	<0.001
Outcome - PROMIS Physical Function T-score N=348										
Step 1	Sex		-0.044	-0.53 (0.61)	0.39	0.15	0.14	0.15	20	<0.001
	Age		-0.28	-0.098 (0.018)						
	BMI		-0.27	-0.23 (0.041)						
Step 2		Hip extension	0.29	22 (4.4)	0.45	0.21	0.20	0.055	24	<0.001
Step 3		Hip flexion	0.12	1.6 (0.65)	0.47	0.22	0.21	0.013	5.8	0.017

PROMIS = Patient-Reported Outcomes Measurement Information System
Hip extension = hip extension strength; Hip flexion = hip flexion strength; Hip abduction = hip abduction strength

Sex, age and BMI explained from 6% (R^2 adj = 0.056) to 14% (R^2 adj = 0.14) of variability in PROs of pain interference, physical function, and LBP-Related disability (Table 7). Hip extension and flexion strength explained 6% of variability in ODI, with the total models explaining 14%. Hip extension strength explained 4% of variability in PROMIS-pain interference with the total model explaining 10%. The model with PROMIS-physical function as the dependent variable demonstrated that hip extension and flexion strength explained 7% of variability with the total model explaining 21% (Table 7).

2.6.3 Results of Regression Analysis for the Association between Hamstrings Flexibility and Hip Internal Rotation and Outcomes of Physical Performance and PROs of Pain Interference, Physical Function, and LBP-Related Disability

In models adjusted by age, sex, and BMI, when only one independent variable was tested at a time; individuals with limited and asymmetrical hamstrings flexibility and asymmetrical hip internal rotation mobility had heightened disability (measured by ODI); individuals with limited hamstrings flexibility and limited and asymmetrical hip internal rotation mobility walked slower during the Four-Meter Walk Test; individuals with limited hamstrings flexibility and asymmetrical hip internal rotation mobility walked slower in the Two-Minute Walk Test and had increased pain interference and decreased physical function (measured by PROMIS-pain interference and PROMIS-physical function, respectively); and individuals with limited hamstrings flexibility were slower standing from a chair five times and used worse movement strategies during the postural lift strategy test (Table 8).

Table 8. Association of Hip Muscle Flexibility, Mobility, and Asymmetry to Performance-Based Measures and PROs of Pain Interference, Physical Function, LBP-Related Disability

	Pearson Correlation Coefficient	Unstandardized beta-β (SE β), β†	Unstandardized beta-β (SE β), β‡
Outcome - Gait speed N=421			
Hamstrings flexibility	0.22 **	0.003 (0.001), 0.23 **	0.003 (0.001), 0.22 **
Hip internal rotation more limited side	0.21 **	0.002 (0.001), 0.12 *	-
Asymmetry in hamstrings flexibility	-0.093 *	-0.003 (0.002), -0.076	-
Asymmetry in hip internal rotation	-0.15 *	-0.004 (0.002), -0.12 *	-0.004 (0.002), -0.11 *
Outcome - 5 Times Sit-to-Stand N=376			
Hamstrings flexibility	-0.22 **	-0.066 (0.016), -0.22 **	-0.066 (0.016), -0.22 **

Internal rotation more limited side	-0.13 *	-0.006 (0.023), -0.015	-
Asymmetry in hamstrings flexibility	0.037	0.025 (0.044), 0.027	-
Asymmetry in hip internal rotation	0.055	0.016 (0.037), 0.021	-
Outcome - Two-Minute Walk Test N=387			
Hamstrings flexibility	0.11 *	0.38 (0.14), 0.13 *	0.34 (0.14), 0.12 *
Internal rotation more limited side	0.19 **	0.35 (0.19), 0.093	-
Asymmetry in hamstrings flexibility	-0.051	-0.29 (0.38), -0.033	-
Asymmetry in hip internal rotation	-0.22 **	-1.1 (0.31), -0.16 **	-1.1 (0.30), -0.15 **
Outcome - Postural lift strategy test total score N=362			
Hamstrings flexibility	-0.16 *	-0.017 (0.005), -0.18 *	-0.017 (0.005), -0.18 *
Internal rotation more limited side	-0.099 *	-0.008 (0.007), -0.065	-
Asymmetry in hamstrings flexibility	0.051	0.013 (0.014), 0.048	-
Asymmetry in hip internal rotation	-0.008	-0.009 (0.012), -0.038	-
Outcome - ODI sum score N=422			
Hamstrings flexibility	-0.12 *	-0.13 (0.049), -0.13 *	-0.12 (0.048), -0.13 *
Internal rotation more limited side	-0.12 *	-0.076 (0.066), -0.062	-
Asymmetry in hamstrings flexibility	0.16 *	0.39 (0.13), 0.14 *	0.39 (0.13), 0.14 *
Asymmetry in hip internal rotation	0.16 *	0.32 (0.11), 0.14 *	0.29 (0.11), 0.13 *
Outcome - PROMIS Pain Interference T-score N=422			
Hamstrings flexibility	-0.11 *	-0.056 (0.025), -0.12 *	-0.052 (0.025), -0.11 *
Internal rotation more limited side	-0.095 *	-0.026 (0.035), -0.042	-
Asymmetry in hamstrings flexibility	0.055	0.052 (0.070), 0.036	-
Asymmetry in hip internal rotation	0.14 *	0.16 (0.057), 0.13 *	0.15 (0.057), 0.13 *
Outcome - PROMIS Physical Function T-score N=422			
Hamstrings flexibility	0.12 *	0.049 (0.021), 0.12 *	0.046 (0.021), 0.11 *
Internal rotation more limited side	0.075	-0.020 (0.029), -0.036	-
Asymmetry in hamstrings flexibility	-0.069	-0.058 (0.058), -0.045	-
Asymmetry in hip internal rotation	-0.15 *	-0.13 (0.047), -0.12 *	-0.12 (0.047), -0.12 *

**p<0.001; *p<0.05; PROMIS = Patient-Reported Outcomes Measurement Information System
Measures of hip muscle strength represent values from the left side.
† Coefficients for models when only one independent variable was tested at a time (adjusted by age, sex and BMI).
‡ Coefficients for stepwise selection with all independent variables tested together (adjusted for age, sex, BMI). The betas are from the last step of stepwise selection; thus, they don't match the values of the stepwise tables for models with >2 steps

In the adjusted stepwise selection; both the flexibility and asymmetry in flexibility of hamstrings muscles and asymmetry of hip internal rotation mobility continued to associate with the ODI; hamstrings flexibility and asymmetry of hip internal rotation were associated with gait speed, Two-Minute Walk Test, and PROMIS-pain interference and physical function; and hamstrings flexibility remained the only impairment associated with Five Times Sit-to-Stand test and postural lift strategy test (Table 8).

For gait speed, hamstrings flexibility and asymmetry of hip internal rotation mobility explained 5%, and the total model explained 20% of variability in this outcome. Flexibility of hamstrings muscles explained 3% of variability in Five Times Sit-to-Stand and the total model explained 14%. Flexibility of hamstrings muscles and asymmetry of hip internal rotation explained 3% of variability in the Two-Min Walk Test with the total model explaining 30%. Flexibility of hamstrings muscles explained 3% of variability in postural lift test with the total model explaining 6% (Table 9).

Table 9. Stepwise Selection Regression Models for the Association of Hip Muscle Flexibility, Mobility, and Asymmetry to Performance-Based Tests and PROs of Pain Interference, Physical Function, LBP-Related Disability

	Confounder variable	Independent variable	Standardized β	Unstandardized β (SE)	R	R^2	R^2 adj.	$R^2\Delta$	FΔ	Sig FΔ
Outcome - Gait speed N=421										
Step 1	Sex		-0.005	-0.002 (0.018)	0.40	0.16	0.15	0.16	26	<0.001
	Age		-0.29	-0.003 (0.001)						
	BMI		-0.29	-0.007 (0.001)						
Step 2		Hamstrings flexibility	0.23	0.003 (0.001)	0.45	0.20	0.19	0.042	22	<0.001
Step 3		Asymmetry hip IR	-0.11	-0.004 (0.002)	0.46	0.21	0.20	0.011	5.9	0.016
Outcome - Five Times Sit-to-Stand N=376										
Step 1	Sex		-0.001	-0.008 (0.42)	0.34	0.11	0.11	0.11	16	<0.001
	Age		0.27	0.065 (0.012)						
	BMI		0.22	0.12 (0.027)						
Step 2		Hamstrings flexibility	-0.22	-0.066 (0.016)	0.39	0.15	0.14	0.039	17	<0.001
Outcome - Two-Minute Walk Test N=387										
Step 1	Sex		-0.12	-9.8 (3.5)	0.53	0.28	0.27	0.28	49	<0.001
	Age		-0.41	-0.97 (0.10)						
	BMI		-0.35	-1.8 (0.23)						
Step 2		Asymmetry hip IR	-0.16	-1.1 (0.31)	0.55	0.30	0.30	0.025	14	<0.001
Step 3		Hamstrings flexibility	0.12	0.34 (0.14)	0.56	0.31	0.30	0.011	6.3	0.013
Outcome - Postural lift strategy test total score N=362										
Step 1	Sex		0.043	0.11 (0.13)	0.19	0.037	0.029	0.037	4.6	0.003
	Age		0.18	0.013 (0.004)						
	BMI		0.075	0.012 (0.008)						
Step 2		Hamstrings flexibility	-0.18	-0.017 (0.005)	0.26	0.066	0.056	0.029	11	0.001
Outcome - Oswestry Disability Index sum score N=422										
Step 1	Sex		0.031	0.81 (1.3)	0.31	0.099	0.092	0.099	15	<0.001
	Age		0.20	0.16 (0.037)						

	BMI		0.26	0.43 (0.077)					
Step 2		Asymmetry hamstrings	0.14	0.39 (0.13)	0.34	0.12	0.11	0.018	8.7	0.003
Step 3		Asymmetry hip IR	0.13	0.31 (0.11)	0.37	0.13	0.12	0.017	8.1	0.005
Step 4		Hamstrings flexibility	-0.13	-0.12 (0.048)	0.38	0.15	0.14	0.014	6.7	0.010
Outcome - PROMIS Pain Interference T-score N=422										
Step 1	Sex		-0.011	-0.15 (0.65)	0.25	0.063	0.056	0.063	9.4	<0.001
	Age		0.12	0.049 (0.019)						
	BMI		0.23	0.19 (0.040)						
Step 2		Asymmetry hip IR	0.13	0.16 (0.057)	0.28	0.080	0.071	0.017	7.6	0.006
Step 3		Hamstrings flexibility	-0.11	-0.052 (0.025)	0.30	0.089	0.078	0.009	4.3	0.038
Outcome - PROMIS Physical Function T-score N=422										
Step 1	Sex		-0.017	-0.21 (0.55)	0.39	0.15	0.14	0.15	25	<0.001
	Age		-0.27	-0.091 (0.016)						
	BMI		-0.31	-0.23 (0.033)						
Step 2		Asymmetry hip IR	-0.12	-0.13 (0.047)	0.41	0.17	0.16	0.015	7.4	0.007
Step 3		Hamstrings flexibility	0.11	0.046 (0.021)	0.42	0.18	0.17	0.010	4.9	0.028

PROMIS = Patient-Reported Outcomes Measurement Information System
Asymmetry hamstrings = asymmetry in hamstrings flexibility; IR = internal rotation

The flexibility and asymmetry in flexibility of hamstrings muscles and asymmetry of hip internal rotation explained 5% of variability in ODI, with the total models explaining 14%. The flexibility of hamstrings muscles and asymmetry of hip internal rotation explained 2% of variability in PROMIS-pain interference with the total model explaining 8% and these same two impairments explained 3% of the variability in PROMIS-physical function with the total model explaining 17% (Table 9).

2.7 Discussion

2.7.1 Aim 1: Hip Muscle Strength in Relation to Physical Function and PROs of Pain Interference, Physical Function, and LBP-Related Disability in CLBP

The present study demonstrated that hip extension, abduction, and flexion weakness are associated with physical dysfunction during performance-based tests and PROs of pain interference, physical function, and LBP-related disability in persons with CLBP, though asymmetry in hip muscle strength does not associate, supporting only half of our first hypothesis. Weak hip extensors consistently associated with poor physical function in all measures of functional performance and PROs. Next to hip extension, hip abduction weakness associated with poor functional performance except for the postural lift strategy test and hip flexion weakness only associated with slow walking in the Two-Minute Walk Test. Next to hip extension, hip flexors strength was the only additional strength measure associated with lower levels of LBP-related disability and higher levels of physical function as reported in the ODI and PROMIS-PF PROs. The present study is the first to account for potential covariates such as sex, age, and BMI. Additionally, the strength measures in this study take variability in body size into consideration, since hip strength is reported as a proportion of body weight. This is important because individuals with larger body mass will be able to exert more force against a dynamometer or tester than someone with less body mass. Adjusting strength measures by body weight allows for a measure of strength proportionate to individual body size and these adjusted strength values serve as better clinical predictors of functional impairments than absolute values of strength (de Lima et al., 2021).

Hip abductor strength associated most with walking tests such as the Four-Meter Walk Test and the Two-Minute Walk Test, and hip extension strength associated most with the Five Times Sit-to-Stand Test and postural lift test, as expected. The hip abductors act to prevent the unsupported side of the pelvis from dropping in the swing phase while walking, so hip abductor weakness can lead to a contralateral hip drop in locomotion referred to as Trendelenburg gait (Gandbhir et al., 2022), which could result in suboptimal gait pattern and LBP. It was expected that hip extension weakness would associate most with movements that require extension at the hip (sit-to-stand and lifting from the floor). Hip muscle weakness associated more with physical dysfunction in performance-based measures (3-15% of variability in adjusted stepwise selection) than to PROs of pain interference, physical function, and LBP-related disability (4-7% of variability in adjusted stepwise selection), suggesting there is a difference between performance and perception. These performance-based measures are clinically relevant because they measure ability to function in daily activities.

We cannot directly compare the results of this study to other investigations because to our knowledge, there is no other study that has run similar correlation analysis and regression models. Previous studies have mainly focused on LBP, as opposed to CLBP specifically, and only show how hip weakness is associated with the presence of LBP, omitting analysis of how specific hip muscle group weakness actually associates to the dysfunction in CLBP (de Sousa et al., 2019) (Sadler et al., 2019).

There has been research on the effect of combining core/trunk and hip muscle interventions for treatment of LBP (Jeong et al., 2015; Kim & Yim, 2020; Tataryn et al., 2021), but these studies fail to test hip muscle strength as an outcome measure, fail to evaluate hip muscle weakness and asymmetry as associators to physical dysfunction during performance-based measures, and/or only analyze LBP as opposed to CLBP. The present study fills these gaps and justifies further longitudinal investigation and controlled trials to determine if a more tailored hip muscle strengthening approach should be added to exercise programs based on impairments found during performance-based tests in a clinical exam. The results of this study show the relative magnitude of the association of hip extension, abduction, and flexion weakness with activities such as walking, sit-to-stand motions, and lifting motions, demonstrating how specific impairments in hip muscle strength relate to various performance deficits. Performance-based measures such as these provide an objective assessment of how a patient functions in daily life, which is clinically relevant to providers when determining an exercise plan.

Demonstrating hip muscle weakness to be an associator to dysfunction and pain in CLBP in the present study provides the basis for further longitudinal research and controlled trials on the intricacies of implementation of hip muscle strengthening in CLBP treatment. Further longitudinal investigation into specific exercises that increase hip extension, abduction, and flexion strength should be pursued among those with CLBP specifically.

2.7.2 Aim 2: Hamstrings Flexibility, Hip Internal Rotation Mobility, and Asymmetry in Relation to Physical Function and PROs of Pain Interference, Physical Function, and LBP-Related Disability in CLBP

The findings in the present study demonstrated that limited and asymmetrical hamstrings flexibility and asymmetry in hip internal rotation mobility associate with physical dysfunction during performance-based measures and PROs of pain interference, physical function and LBP-related disability in persons with CLBP, supporting our second hypothesis, with the exception that hip internal rotation mobility was not shown to be an associator. Limited hamstrings flexibility consistently associated with poor physical function in all measures of functional performance and PROs and was the only mobility measure associating with slower sit-to-stand motions and worse movement strategies during the postural lift strategy test. Next to hamstrings flexibility, asymmetry in hip internal rotation associated with all outcomes except the Five Times Sit-to-Stand and postural lift strategy tests. Asymmetry in hamstrings flexibility associated with heightened disability expressed in the ODI.

Hamstrings flexibility was the strongest associator to the Four-Meter Walk Test, Five Times Sit-to-Stand Test, and postural lift test, while asymmetry in hip internal rotation mobility was the strongest associator to the Two-Minute Walk Test. Hip muscle mobility and asymmetry in mobility associated less with physical dysfunction and PROs of pain interference, physical function, and LBP-related disability (2-5% of variability in adjusted stepwise selection) than hip muscle weakness (3-15% of variability in adjusted stepwise selection).

Previous studies have shown tight hamstrings to be associated with development of LBP (Feldman et al., 2001), but failed to measure physical function during walking and sit-to-stand tests as outcome measures, which is clinically relevant to providers. Research has also shown that limited and asymmetrical hip internal rotation range of motion is associated with LBP (Sadeghisani et al., 2015), but there is very limited research on how limited and asymmetrical hip joint mobility associate with physical dysfunction during performance-based tests in CLBP. The findings of the present study agree with these previous investigations and provide complimentary information on how hip muscle flexibility, mobility, and asymmetry in these measures associate with dysfunction in specific daily activities such as walking, sitting, and lifting a weight, and also show the relative magnitudes of association to functional tasks for specific mobility measures.

LBP with a radicular cause has shown to be improved with hamstrings stretching (Lee & Kim, 2017), and the results of the present study show how vast an association hamstrings flexibility has with physical function and PROs. Hamstrings tightness showed to be an associator to every outcome measure, which makes it an important associator to CLBP symptoms, suggesting additional implementation of hamstrings stretching in treatment of CLBP could optimize outcomes if longitudinal investigation and controlled trials show these same associations. Further longitudinal investigation needs to be pursued to confirm these associations over time, determine the optimal duration and frequency of hamstrings stretching, and determine how to optimally decrease asymmetry in contralateral hamstrings over time.

It should be noted that hip impairments alone do not account for all variability in the dependent variables in this study. Age, sex, and BMI explain 2-31% of variability in the dependent variables. Losing weight to decrease BMI, a modifiable variable, may be necessary as part of any treatment plan, but further investigation is necessary.

Large asymmetries in hip internal rotation mobility may be due to hip joint pathology or hip surgery in this cohort, making it unclear whether hip internal rotation range of motion was limited by osseous structures from pathologies such as arthritis or from soft tissue. Correcting asymmetries in hip internal rotation mobility will be more difficult than correcting tight hamstrings, since asymmetries in bone structure due to pathology or surgery may be impossible to correct through stretching. Future studies should investigate how asymmetry in hip internal rotation associates with CLBP dysfunction and pain in persons with versus without degenerative hip pathology.

Overall, in this cohort, performance-based measures indicated worse physical function than the average in the general United States population with a gait speed of 0.9 m/s in our study versus

1.1 m/s in the general population (Bohannon & Wang, 2019) and distance walked in two minutes of 168 meters in our study versus 181 in the general population (Bohannon et al., 2015). The participants in this study had weaker hip muscles (Alvarenga et al., 2019) (Piva et al., 2005), less flexible hamstrings (Piva et al., 2005), and less hip mobility (Han et al., 2015) than the general population.

2.7.3 Limitations

This study is not without limitations. Analysis of a control group of participants without CLBP was not available for this study, which would be helpful to replicate findings from previous studies. The associations found in this study could also be present in populations without CLBP, but we were unable to test this due to the lack of a control group. Further research is necessary to determine the magnitude of these associations in populations without CLBP. This study was a cross-sectional analysis limited only to baseline data, which did not allow for assessment of how hip muscle strength, flexibility, mobility, and asymmetry change over time as performance and PROs change with time. This cross-sectional analysis also did not allow for establishment of causal relationships. Though hip extension and abduction strength were highly correlated (0.78), they were both included in stepwise regression analysis as independent variables to adhere to the exact set cutoff point of 0.80. There was some missing data for various participants, which reduced the sample size for some regression models. However, the sample size for all analyses was still very robust. We checked the demographics and biomedical characteristics for participants with missing data and those without missing data, and they were similar (data not shown). Hip flexion strength, a categorical variable based on manual muscle testing is unable to assess muscle strength with the same precision as dynamometry-based measures. It is possible that participants with scores of normal strength of hip flexion would have variable values of muscle strength using dynamometry. However, the secondary analysis nature of this study dictated how each domain was measured. The comprehensiveness of data collection and large sample size of the LB3P study provided a thorough study of associators to dysfunction, pain interference, and LBP-related disability in CLBP.

2.8 Conclusion and Significance

Weakness in hip extensor, abductor, and flexor muscles, limited and asymmetrical hamstrings flexibility, and asymmetry in hip internal rotation mobility are important associators with physical dysfunction measured by performance-based tests and PROs of pain interference, physical function, and LBP-related disability. Hip extension strength and hamstrings flexibility were the only measures that associated with all performance-based tests and PROs. The findings of this study indicate the need for further longitudinal investigation and controlled trials to determine if emphasis should be placed on intense and specific hip muscle strengthening, improving hip muscle flexibility and mobility, and decreasing asymmetry in hip muscle mobility in treatment of persons with CLBP.

3.0 Closing Remarks

This study marks my first experience in initiating a research question, writing aims, requesting access to primary data from other projects, robust literature review, data analysis, and in writing a thesis paper. Under the guidance of my incredible mentors Dr. Sara Piva and Dr. Charity Patterson, I learned the importance and rigor of managing datasets, effective data cleaning, and data organization. After writing many drafts of this thesis and receiving feedback from Dr. Piva and my committee members, I learned how to condense complex findings into clear meanings for clinical advancement.

Our goal for this project is to add valuable insights to set the stage for further longitudinal investigation to improve the treatment of CLBP. Because of my own experience with scoliosis, I've struggled a lot with the pain and asymmetry that comes with an unbalanced structure, which is why we made a point to not only investigate hip strength and mobility but also to investigate hip muscle asymmetries that can affect function. We hope the future publication of this study will provide another push to conduct further research to advance treatment for CLBP.

I will take so much valuable knowledge about data analysis and research writing with me when I continue on to medical school in the fall. I plan to continue supplementing my education through inquiry and investigation, and I'm confident I will excel in research skills because of what I have learned from this project. I aspire to become a physician who works to continuously improve medicine, and this project has given me a jumpstart on that mission.

I truly appreciate the participation from my committee members and am grateful for their mentorship in the review and defense process. I am especially grateful to Dr. Piva who spent countless hours patiently guiding me from start to finish through initial scientific inquiry to presenting our findings. Her excellent mentorship made me the student researcher I am now. I look forward to continuing my journey of research and discovery.

Bibliography

Alvarenga, G., Kiyomoto, H. D., Martinez, E. C., Polesello, G., & Alves, V. (2019). Normative Isometric Hip Muscle Force Values Assessed by a Manual Dynamometer. *Acta Ortop Bras*, *27*(2), 124-128. https://doi.org/10.1590/1413-785220192702202596

Andersson, G. B. (1999). Epidemiological features of chronic low-back pain. *Lancet*, *354*(9178), 581-585. https://doi.org/10.1016/s0140-6736(99)01312-4

Askew, R. L., Cook, K. F., Revicki, D. A., Cella, D., & Amtmann, D. (2016). Evidence from diverse clinical populations supported clinical validity of PROMIS pain interference and pain behavior. *J Clin Epidemiol*, *73*, 103-111. https://doi.org/10.1016/j.jclinepi.2015.08.035

Beck, M., Sledge, J. B., Gautier, E., Dora, C. F., & Ganz, R. (2000). The anatomy and function of the gluteus minimus muscle. *J Bone Joint Surg Br*, *82*(3), 358-363. https://doi.org/10.1302/0301-620x.82b3.10356

Bernard, J. C., Bard, R., Pujol, A., Combey, A., Boussard, D., Begue, C., & Salghetti, A. M. (2008). Muscle assessment in healthy teenagers, Comparison with teenagers with low back pain. *Ann Readapt Med Phys*, *51*(4), 263-283. https://doi.org/10.1016/j.annrmp.2008.03.010

Bohannon, R. W. (1997). Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. *Age Ageing*, *26*(1), 15-19. https://doi.org/10.1093/ageing/26.1.15

Bohannon, R. W., Bubela, D. J., Magasi, S. R., Wang, Y. C., & Gershon, R. C. (2010). Sit-to-stand test: Performance and determinants across the age-span. *Isokinet Exerc Sci*, *18*(4), 235-240. https://doi.org/10.3233/IES-2010-0389

Bohannon, R. W., & Wang, Y. C. (2019). Four-Meter Gait Speed: Normative Values and Reliability Determined for Adults Participating in the NIH Toolbox Study. *Arch Phys Med Rehabil*, *100*(3), 509-513. https://doi.org/10.1016/j.apmr.2018.06.031

Bohannon, R. W., Wang, Y. C., & Gershon, R. C. (2015). Two-minute walk test performance by adults 18 to 85 years: normative values, reliability, and responsiveness. *Arch Phys Med Rehabil*, *96*(3), 472-477. https://doi.org/10.1016/j.apmr.2014.10.006

Cabanas-Valdés, R., García-Rueda, L., Salgueiro, C., Pérez-Bellmunt, A., Rodríguez-Sanz, J., & López-de-Celis, C. (2023). Assessment of the 4-meter walk test test-retest reliability and concurrent validity and its correlation with the five sit-to-stand test in chronic ambulatory stroke survivors. *Gait Posture*, *101*, 8-13. https://doi.org/10.1016/j.gaitpost.2023.01.014

Chen, C. X., Kroenke, K., Stump, T. E., Kean, J., Carpenter, J. S., Krebs, E. E., Bair, M. J., Damush, T. M., & Monahan, P. O. (2018). Estimating minimally important differences for the PROMIS pain interference scales: results from 3 randomized clinical trials. *Pain*, *159*(4), 775-782. https://doi.org/10.1097/j.pain.0000000000001121

Chun, S. W., Lim, C. Y., Kim, K., Hwang, J., & Chung, S. G. (2017). The relationships between low back pain and lumbar lordosis: a systematic review and meta-analysis. *Spine J*, *17*(8), 1180-1191. https://doi.org/10.1016/j.spinee.2017.04.034

Dagenais, S., Caro, J., & Haldeman, S. (2008). A systematic review of low back pain cost of illness studies in the United States and internationally. *Spine J*, *8*(1), 8-20. https://doi.org/10.1016/j.spinee.2007.10.005

de Lima, T. R., Sui, X., & Silva, D. A. S. (2021). Normalization of Muscle Strength Measurements in the Assessment of Cardiometabolic Risk Factors in Adolescents. *Int J Environ Res Public Health*, *18*(16). https://doi.org/10.3390/ijerph18168428

de Sousa, C. S., de Jesus, F. L. A., Machado, M. B., Ferreira, G., Ayres, I. G. T., de Aquino, L. M., Fukuda, T. Y., & Gomes-Neto, M. (2019). Lower limb muscle strength in patients with low back pain: a systematic review and meta-analysis. *J Musculoskelet Neuronal Interact*, *19*(1), 69-78. https://www.ncbi.nlm.nih.gov/pubmed/30839305

Deyo, R. A., Dworkin, S. F., Amtmann, D., Andersson, G., Borenstein, D., Carragee, E., Carrino, J., Chou, R., Cook, K., DeLitto, A., Goertz, C., Khalsa, P., Loeser, J., Mackey, S., Panagis, J., Rainville, J., Tosteson, T., Turk, D., Von Korff, M., & Weiner, D. K. (2015). Report of the NIH Task Force on Research Standards for Chronic Low Back Pain. *Int J Ther Massage Bodywork*, *8*(3), 16-33. https://doi.org/10.3822/ijtmb.v8i3.295

Elzanie, A., & Borger, J. (2022). Anatomy, Bony Pelvis and Lower Limb, Gluteus Maximus Muscle. In *StatPearls*. StatPearls Publishing

Copyright © 2022, StatPearls Publishing LLC.

Esquirol, Y., Niezborala, M., Visentin, M., Leguevel, A., Gonzalez, I., & Marquié, J.-C. (2017). Contribution of occupational factors to the incidence and persistence of chronic low back pain among workers: results from the longitudinal VISAT study. *Occupational and Environmental Medicine*, *74*(4), 243-251.

Feldman, D. E., Shrier, I., Rossignol, M., & Abenhaim, L. (2001). Risk factors for the development of low back pain in adolescence. *American journal of epidemiology*, *154*(1), 30-36.

Gandbhir, V. N., Lam, J. C., & Rayi, A. (2022). Trendelenburg Gait. In *StatPearls*. StatPearls Publishing

Copyright © 2022, StatPearls Publishing LLC.

George, S. Z., Fritz, J. M., Silfies, S. P., Schneider, M. J., Beneciuk, J. M., Lentz, T. A., Gilliam, J. R., Hendren, S., & Norman, K. S. (2021). Interventions for the Management of Acute and Chronic Low Back Pain: Revision 2021. *Journal of Orthopaedic & Sports Physical Therapy*, *51*(11), CPG1-CPG60. https://doi.org/10.2519/jospt.2021.0304

Glenister, R., & Sharma, S. (2022). Anatomy, Bony Pelvis and Lower Limb, Hip. In *StatPearls*. https://www.ncbi.nlm.nih.gov/pubmed/30252275

Gore, M., Sadosky, A., Stacey, B. R., Tai, K.-S., & Leslie, D. (2012). The burden of chronic low back pain: clinical comorbidities, treatment patterns, and health care costs in usual care settings. *Spine*, *37*(11), E668-E677.

Guralnik, J. M., Ferrucci, L., Simonsick, E. M., Salive, M. E., & Wallace, R. B. (1995). Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. *N Engl J Med*, *332*(9), 556-561. https://doi.org/10.1056/nejm199503023320902

Han, H., Kubo, A., Kurosawa, K., Maruichi, S., & Maruyama, H. (2015). Hip rotation range of motion in sitting and prone positions in healthy Japanese adults. *J Phys Ther Sci*, *27*(2), 441-445. https://doi.org/10.1589/jpts.27.441

Han, S., Owens, V. L., Patel, R. V., Ismaily, S. K., Harrington, M. A., Incavo, S. J., & Noble, P. C. (2020). The continuum of hip range of motion: From soft-tissue restriction to bony impingement. *J Orthop Res*, *38*(8), 1779-1786. https://doi.org/10.1002/jor.24594

Hartvigsen, J., Hancock, M. J., Kongsted, A., Louw, Q., Ferreira, M. L., Genevay, S., Hoy, D., Karppinen, J., Pransky, G., Sieper, J., Smeets, R. J., & Underwood, M. (2018). What low back pain is and why we need to pay attention. *Lancet*, *391*(10137), 2356-2367. https://doi.org/10.1016/s0140-6736(18)30480-x

Hong, J., Reed, C., Novick, D., & Happich, M. (2013). Costs associated with treatment of chronic low back pain: an analysis of the UK General Practice Research Database. *Spine*, *38*(1), 75-82.

Hoy, D., Brooks, P., Blyth, F., & Buchbinder, R. (2010). The Epidemiology of low back pain. *Best Pract Res Clin Rheumatol*, *24*(6), 769-781. https://doi.org/10.1016/j.berh.2010.10.002

In, T. S., Jung, J. H., Jung, K. S., & Cho, H. Y. (2021). Effects of the Multidimensional Treatment on Pain, Disability, and Sitting Posture in Patients with Low Back Pain: A Randomized Controlled Trial. *Pain Res Manag*, *2021*, 5581491. https://doi.org/10.1155/2021/5581491

Jeong, U.-C., Sim, J.-H., Kim, C.-Y., Hwang-Bo, G., & Nam, C.-W. (2015). The effects of gluteus muscle strengthening exercise and lumbar stabilization exercise on lumbar muscle strength and balance in chronic low back pain patients. *Journal of physical therapy science*, *27*(12), 3813-3816.

Kim, B., & Yim, J. (2020). Core Stability and Hip Exercises Improve Physical Function and Activity in Patients with Non-Specific Low Back Pain: A Randomized Controlled Trial. *Tohoku J Exp Med*, *251*(3), 193-206. https://doi.org/10.1620/tjem.251.193

Kim, T. W., & Kim, Y. W. (2015). Effects of abdominal drawing-in during prone hip extension on the muscle activities of the hamstring, gluteus maximus, and lumbar erector spinae in subjects with lumbar hyperlordosis. *J Phys Ther Sci*, *27*(2), 383-386. https://doi.org/10.1589/jpts.27.383

Lee, J. H., & Kim, T. H. (2017). The treatment effect of hamstring stretching and nerve mobilization for patients with radicular lower back pain. *J Phys Ther Sci*, *29*(9), 1578-1582. https://doi.org/10.1589/jpts.29.1578

Leinonen, V., Kankaanpää, M., Airaksinen, O., & Hänninen, O. (2000). Back and hip extensor activities during trunk flexion/extension: effects of low back pain and rehabilitation. *Arch Phys Med Rehabil*, *81*(1), 32-37. https://doi.org/10.1016/s0003-9993(00)90218-1

Lifshitz, L., Bar Sela, S., Gal, N., Martin, R., & Fleitman Klar, M. (2020). Iliopsoas the Hidden Muscle: Anatomy, Diagnosis, and Treatment. *Curr Sports Med Rep*, *19*(6), 235-243. https://doi.org/10.1249/jsr.0000000000000723

Malai, S., Pichaiyongwongdee, S., & Sakulsriprasert, P. (2015). Immediate Effect of Hold-Relax Stretching of Iliopsoas Muscle on Transversus Abdominis Muscle Activation in Chronic Non-Specific Low Back Pain with Lumbar Hyperlordosis. *J Med Assoc Thai*, *98 Suppl 5*, S6-11.

McCarthy, J. J., & Betz, R. R. (2000). The relationship between tight hamstrings and lumbar hypolordosis in children with cerebral palsy. *Spine (Phila Pa 1976)*, *25*(2), 211-213. https://doi.org/10.1097/00007632-200001150-00011

Miller, A. E., MacDougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol*, *66*(3), 254-262. https://doi.org/10.1007/bf00235103

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik, T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clinical Journal of Sport Medicine*, *10*(2), 89-97.

Nadler, S. F., Malanga, G. A., Feinberg, J. H., Prybicien, M., Stitik, T. P., & DePrince, M. (2001). Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. *American journal of physical medicine & rehabilitation*, *80*(8), 572-577.

Parthan, A., Evans, C. J., & Le, K. (2006). Chronic low back pain: epidemiology, economic burden and patient-reported outcomes in the USA. *Expert Rev Pharmacoecon Outcomes Res*, *6*(3), 359-369. https://doi.org/10.1586/14737167.6.3.359

Piva, S. R., Goodnite, E. A., & Childs, J. D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, *35*(12), 793-801.

Prather, H., Harris-Hayes, M., Hunt, D. M., Steger-May, K., Mathew, V., & Clohisy, J. C. (2010). Reliability and agreement of hip range of motion and provocative physical examination tests in asymptomatic volunteers. *PM R*, *2*(10), 888-895. https://doi.org/10.1016/j.pmrj.2010.05.005

Qaseem, A., Wilt, T. J., McLean, R. M., Forciea, M. A., Clinical Guidelines Committee of the American College of, P., Denberg, T. D., Barry, M. J., Boyd, C., Chow, R. D., Fitterman, N., Harris, R. P., Humphrey, L. L., & Vijan, S. (2017). Noninvasive Treatments for Acute, Subacute, and Chronic Low Back Pain: A Clinical Practice Guideline From the American College of Physicians. *Ann Intern Med*, *166*(7), 514-530. https://doi.org/10.7326/M16-2367

Ransom, A. L., Sinkler, M. A., & Nallamothu, S. V. (2022). Anatomy, Bony Pelvis and Lower Limb, Femoral Muscles. In *StatPearls*. StatPearls Publishing

Copyright © 2022, StatPearls Publishing LLC.

Rodgers, C. D., & Raja, A. (2022). Anatomy, Bony Pelvis and Lower Limb, Hamstring Muscle. In *StatPearls*. https://www.ncbi.nlm.nih.gov/pubmed/31536294

Rothrock, N. E., Amtmann, D., & Cook, K. F. (2020). Development and validation of an interpretive guide for PROMIS scores. *J Patient Rep Outcomes*, *4*(1), 16. https://doi.org/10.1186/s41687-020-0181-7

Sadeghisani, M., Manshadi, F. D., Kalantari, K. K., Rahimi, A., Namnik, N., Karimi, M. T., & Oskouei, A. E. (2015). Correlation between Hip Rotation Range-of-Motion Impairment and Low Back Pain. A Literature Review. *Ortop Traumatol Rehabil*, *17*(5), 455-462. https://doi.org/10.5604/15093492.1186813

Sadler, S., Cassidy, S., Peterson, B., Spink, M., & Chuter, V. (2019). Gluteus medius muscle function in people with and without low back pain: a systematic review. *BMC musculoskeletal disorders*, *20*(1), 1-17.

Sadler, S. G., Spink, M. J., Ho, A., De Jonge, X. J., & Chuter, V. H. (2017). Restriction in lateral bending range of motion, lumbar lordosis, and hamstring flexibility predicts the development of low back pain: a systematic review of prospective cohort studies. *BMC Musculoskelet Disord*, *18*(1), 179. https://doi.org/10.1186/s12891-017-1534-0

Samson, M. M., Crowe, A., de Vreede, P. L., Dessens, J. A., Duursma, S. A., & Verhaar, H. J. (2001). Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight. *Aging (Milano)*, *13*(1), 16-21. https://doi.org/10.1007/bf03351489

Shah, A., & Bordoni, B. (2022). Anatomy, Bony Pelvis and Lower Limb, Gluteus Medius Muscle. In *StatPearls*. StatPearls Publishing

Copyright © 2022, StatPearls Publishing LLC.

Shin, D. (2020). Correlation between non-specific chronic low back pain and physical factors of lumbar and hip joint in office workers. *Med Hypotheses*, *144*, 110304. https://doi.org/10.1016/j.mehy.2020.110304
Smeets, R., Köke, A., Lin, C. W., Ferreira, M., & Demoulin, C. (2011). Measures of function in low back pain/disorders: Low Back Pain Rating Scale (LBPRS), Oswestry Disability Index (ODI), Progressive Isoinertial Lifting Evaluation (PILE), Quebec Back Pain Disability Scale (QBPDS), and Roland-Morris Disability Questionnaire (RDQ). *Arthritis Care Res (Hoboken)*, *63 Suppl 11*, S158-173. https://doi.org/10.1002/acr.20542
Sorensen, C. J., Norton, B. J., Callaghan, J. P., Hwang, C.-T., & Van Dillen, L. R. (2015). Is lumbar lordosis related to low back pain development during prolonged standing? *Manual therapy*, *20*(4), 553-557.
Stecco, A., Gilliar, W., Hill, R., Fullerton, B., & Stecco, C. (2013). The anatomical and functional relation between gluteus maximus and fascia lata. *J Bodyw Mov Ther*, *17*(4), 512-517. https://doi.org/10.1016/j.jbmt.2013.04.004
Tataryn, N., Simas, V., Catterall, T., Furness, J., & Keogh, J. W. L. (2021). Posterior-Chain Resistance Training Compared to General Exercise and Walking Programmes for the Treatment of Chronic Low Back Pain in the General Population: A Systematic Review and Meta-Analysis. *Sports Med Open*, *7*(1), 17. https://doi.org/10.1186/s40798-021-00306-w
Ten Hoor, G. A., Plasqui, G., Schols, A., & Kok, G. (2018). A Benefit of Being Heavier Is Being Strong: a Cross-Sectional Study in Young Adults. *Sports Med Open*, *4*(1), 12. https://doi.org/10.1186/s40798-018-0125-4
Thompson, N. R., Lapin, B. R., Steinmetz, M. P., Benzel, E. C., & Katzan, I. L. (2022). Mapping PROMIS physical function and pain interference to the modified low back pain disability questionnaire. *Qual Life Res*, *31*(12), 3467-3482. https://doi.org/10.1007/s11136-022-03174-3
Thorborg, K., Petersen, J., Magnusson, S. P., & Hölmich, P. (2010). Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports*, *20*(3), 493-501. https://doi.org/10.1111/j.1600-0838.2009.00958.x
Trammell, A. P., Nahian, A., & Pilson, H. (2022). Anatomy, Bony Pelvis and Lower Limb, Tensor Fasciae Latae Muscle. In *StatPearls*. StatPearls Publishing
Copyright © 2022, StatPearls Publishing LLC.
Tsutsumi, M., Nimura, A., & Akita, K. (2019). The Gluteus Medius Tendon and Its Insertion Sites: An Anatomical Study with Possible Implications for Gluteus Medius Tears. *J Bone Joint Surg Am*, *101*(2), 177-184. https://doi.org/10.2106/jbjs.18.00602
wk Lee, S., & Kim, S. Y. (2015). Effects of hip exercises for chronic low-back pain patients with lumbar instability. *Journal of physical therapy science*, *27*(2), 345-348.