Movement Patterns during Functional Activities in People with Chronic Low Back Pain

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Movement Patterns during Functional Activities in People with Chronic Low Back Pain

by

Quenten Lowell Hooker

A dissertation presented to
The Graduate School
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

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List of Abbreviations

BMI = body mass index
FABQ = fear avoidance beliefs questionnaire
HLM = hierarchical linear modeling
ICC = intra-class correlation
LBP = low back pain
LC = lumbar contribution
LC_Base = baseline lumbar contribution
L1, L2.. = spinous process of the 1st lumbar vertebra, 2nd lumbar vertebra..
MODQ = modified oswestry disability questionnaire
MST = motor skill training
NRS = numeric rating scale
PUO = pick up an object
SFE = strength and flexibility exercise
SF-36 = Short form survey (36 item)
S1 = spinous process of the 1st sacral vertebra
T12 = spinous process of the 12th thoracic vertebra
\( \Delta \) = change
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Washington University in St. Louis
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This dissertation is dedicated to my parents for their unconditional support and providing me the opportunity to pursue my passions.
ABSTRACT OF THE DISSERTATION

Movement Patterns during Functional Activities in People with Chronic Low Back Pain

by

Quenten Lowell Hooker

Doctor of Philosophy in Movement Science

Washington University in St. Louis, 2021

Professor Linda Van Dillen, Chair

People with chronic LBP display an altered movement pattern where the lumbar spine moves more readily than other joints that can contribute to the activity. The pattern is of particular clinical relevance because across multiple studies the magnitude of altered pattern is associated with LBP and function. One session of motor skill training (MST) during functional activities can improve the altered pattern. However, of the few studies investigating MST for people with LBP, none have examined the short-term or long-term effects of MST on the altered pattern. Additionally, no study has systematically examined if person-specific characteristics moderate the altered pattern at baseline or the ability to improve the pattern over time. Third, there has been no testing of whether people with LBP display a consistent pattern across functional activities. The primary purposes of this dissertation were to examine: 1) the short- and long-term effects of two exercise-based treatments on the altered pattern in people with chronic LBP, 2) the role of person-specific characteristics in the altered pattern and change in the pattern with treatment, and 3) if people with chronic LBP display a similar movement pattern across multiple functional activities.

In chapter 2, we examined the short- and long-term effects of MST and strength and flexibility exercise (SFE) on the altered movement pattern during a functional activity test of pick up an object. We found that MST directed at the performance of functional activities is superior to
SFE in the ability to improve and maintain improvements in an altered pattern. In chapter 3, we tested if person-specific characteristics moderate the baseline and change over time in the altered pattern within MST and SFE. We found that gender and age were associated with the pattern at baseline. Also, age and the magnitude of altered movement before treatment were associated with the change over time in movement within MST. In chapter 4 we examined if people with chronic LBP move consistently across multiple functional activity tests. We found a significant but small to medium positive relationship of the pattern across multiple functional activity tests.

The findings of this dissertation further the understanding of movement patterns in people with chronic LBP. The short-term and long-term effects of exercise-based treatments on movement in people in chronic LBP were identified. Person-specific characteristics were explored as moderators of the movement pattern. Small relationships were observed of a movement pattern across multiple functional tests. Further studies are needed to understand if the effectiveness of MST for improving movement patterns generalizes to people with non-chronic LBP. Additional work is necessary to fully confirm that people with LBP display a similar movement pattern across functional activities.
Chapter 1: Introduction
1.1 Low back pain is a public health problem

Low back pain (LBP) represents a significant and growing public health problem. At least 60-80% of all adults experience LBP during their lifetime.\(^1\) Of the people who have an initial episode, up to 75% fail to recover fully within 1 year and transition to chronicity.\(^2\) Chronic LBP is the most common type of chronic pain in adults\(^1,3\) and the prevalence is growing.\(^4,5\) As pain persists, people with LBP frequently have limitations in simple movements and complex functional activities such as self-care, social role and work.\(^6\) Therefore, for many people LBP is a long-term, function-limiting condition.\(^2,7-10\)

1.2 Biological mechanisms of low back pain

LBP is a complex multifactorial condition.\(^3\) Due to the complexity of LBP, the descriptors for biological mechanisms are often organized into three categories. First, nociceptive LBP is pain that is experienced with actual or threatening damage to non-neural tissue and driven by activation of nociceptors.\(^11,12\) Second, neuropathic LBP is defined as pain associated with a lesion or disease of the somatosensory system.\(^11,12\) Third, nociplastic LBP is pain that arises from altered nociception without clear evidence of tissue damage or lesion of the somatosensory system.\(^11,12\) While it is important to recognize the various biological mechanisms of pain, we are primarily focused on investigating factors that potentially contribute to the clinical presentation of nociceptive LBP.

1.3 The altered movement pattern and LBP

How people with LBP move during functional activities may contribute to why limitations in function are a primary problem. It is well documented that people with chronic LBP display an altered movement pattern in which the lumbar spine moves more readily into its available range
of motion compared to other joints (e.g., knee and hip) that can contribute to the activity.\textsuperscript{13-17} The pattern is more prevalent in people with LBP compared to back healthy controls.\textsuperscript{14,15,18} Furthermore, the altered movement pattern is displayed across multiple clinical tests,\textsuperscript{13-15} as well as variations of a functional test of picking up an object (PUO).\textsuperscript{19} Importantly, the magnitude of the altered movement pattern is associated with a person’s LBP symptoms and LBP-related functional limitations.\textsuperscript{19,20} Therefore, the altered movement pattern during functional activities is a relevant factor that may contribute to persistent course of LBP.

### 1.4 Theoretical framework for the development or persistence of LBP

The Kinesiopathologic model is a theoretical framework for understanding how movements and postures used during daily activities may contribute to the development and course of musculoskeletal pain conditions.\textsuperscript{21} It is proposed that when the same direction-specific altered movement is used repetitively across multiple functional activities, the altered pattern can create or increase accumulations of spinal tissue loading and contribute to LBP symptoms.\textsuperscript{21-24} Figure 1 displays a simplified conceptual model for the proposal of how the altered movement pattern may contribute to the course of LBP.

![Figure 1](image)

Figure 1.1 Conceptual model for how the altered movement pattern may contribute to the development and persistence of LBP.

### 1.5 Exercise for low back pain

Exercise is a primary non-pharmacologic and non-surgical treatment for chronic LBP.\textsuperscript{25} Recent systematic reviews report strong short and long-term efficacy for exercise as a treatment
of chronic LBP.\textsuperscript{26,27} In addition, exercise is often more effective than other common interventions such as massage and laser therapy.\textsuperscript{26,27} Although exercise is often recommended,\textsuperscript{28-30} no specific exercise treatment is consistently more beneficial than another in the short-term and over the long-term.\textsuperscript{25,29,30} For example, one treatment that has been extensively investigated in people with LBP is exercise to improve activation of the deep muscles to stabilize the spine (i.e., multifidus and transversus abdominis).\textsuperscript{31-34} In this intervention the goal is isometric and continuous cocontraction of the deep spinal muscles, independent of contraction of the superficial spinal muscles.\textsuperscript{31-34} However exercise to activate deep spinal muscles is not consistently better than other exercise-based treatments in improving function.\textsuperscript{31,33} One potential reason for inconsistent effects is that the exercise-based treatments tested do not directly address how people with LBP perform functional activities. Given the documented relevance of the altered movement pattern to limitations in function\textsuperscript{19}, a logical form of exercise-based treatment would target the altered pattern during the performance of limited functional activities.\textsuperscript{35}

\section*{1.6 Motor skill training for people with LBP}

Motor skill training (MST) is an exercise-based treatment that uses principles of motor learning to promote the learning or relearning of motor skills.\textsuperscript{35-37} The overarching goal of MST applied to LBP-limited functional activities is to replace the person-specific, pain-provoking, altered movement pattern with an improved and symptom-free pattern.\textsuperscript{35,37,38} After a single session of MST, immediate improvement was reported in both the altered movement pattern and pain during the functional activity test of picking up an object (PUO).\textsuperscript{38} Further investigation is warranted to understand whether the altered movement pattern during the PUO activity can be improved over the short-term and long-term using MST.
1.7 Person-specific factors have the potential to influence the altered movement pattern

Although the altered movement pattern was improved after one session of MST, there was substantial variability in the baseline and change in the pattern with MST. One reason for the increased variability is that person-specific characteristics (e.g., gender, age,) may influence the altered movement pattern at baseline and the ability to improve the pattern over time.\textsuperscript{39,40} Prior data suggest that many person-specific characteristics have the potential to influence the altered movement pattern. First, prior studies report on differences in movement patterns between men and women.\textsuperscript{13,41-44} Therefore, gender may influence how people move at baseline and the change over time in the altered movement pattern.\textsuperscript{39} Second, previous work suggests a person’s age is associated with specific movement characteristics (e.g., spinal range of motion),\textsuperscript{45,46} as well as the clinical course of LBP.\textsuperscript{47,48} Thus, age could influence the baseline altered pattern, as well as the effectiveness of the exercise-based intervention to improve the pattern. Third, duration of LBP is frequently reported as a prognostic factor of poor LBP recovery.\textsuperscript{48} Given the previously reported relationship of the altered movement pattern and clinical outcomes of pain and limitations in function,\textsuperscript{19,49,50} duration of LBP may explain baseline or the change over time in the altered movement pattern. Lastly, the magnitude of the altered movement pattern at baseline was associated with the amount of improvement after a one session of MST.\textsuperscript{38} Additional research is needed to understand if a relationship also exists between the magnitude of the baseline altered movement pattern and the short and long-term change over time. Understanding the relationship of these characteristics to the baseline and change over time in the altered pattern may ultimately be used to better refine treatment strategies to the person and provide the best form of care.
1.8 Consistency of a movement pattern in people with LBP

Although several studies have examined movement of people with LBP during a single functional activity test, few studies have reported on the consistency of a person’s movement pattern across multiple functional activity tests. This gap in understanding is of particular relevance because one aspect of the Kinesiopathologic model (Figure 1) suggests that the repetitive use of the same pattern across multiple functional activities across the day contributes to the LBP condition. To date, the specific altered pattern has been investigated only during tests from a clinical examination and a functional activity test of picking up an object (PUO). Additional information is needed to confirm that a person with chronic LBP displays a similar movement pattern across multiple functional activities.

1.9 Critical next steps

Collectively, the available literature suggests that the altered movement pattern is 1) prevalent in people with LBP, 2) associated with the clinical presentation of LBP, and 3) can be improved after one session of MST. However, current gaps in knowledge hinder our ability to fully understand the relevance of the altered pattern to the LBP condition. First, of the few studies investigating motor skill training for people with LBP, none have examined the short-term or long-term effects of MST on the altered movement pattern during functional activities. Second, no study has systematically examined if person-specific characteristics influence the ability to improve the altered movement pattern during functional activities. Third, there has been no testing of whether or not people with LBP display a consistent pattern across functional activities. Accordingly, an understanding of these gaps in knowledge would further establish the (1) short- and long-term effectiveness of motor skill training in people with LBP, and (2) understanding of how the altered
movement pattern may contribute to the LBP condition. This dissertation aims to investigate each of these gaps.

1.10 Primary purposes

The primary purposes of this project were to examine movement of people with chronic LBP. Specifically examine the short- and long-term effects of two exercise-based treatments on movement characteristics in people with chronic LBP, the role of person-specific characteristics in the magnitude of altered pattern and change in the pattern with treatment, and whether people with chronic LBP display a similar movement pattern across multiple functional activities.

Specific Aim 1: Test if motor skill training results in greater short-term and long-term improvements in the altered movement pattern during the performance of a functional activity compared to strength and flexibility exercise.

Hypothesis 1a. Motor skill training will result in greater improvements in the altered pattern than strength and flexibility exercise.

Hypothesis 1b. The improvements in the altered pattern within motor skill training will be maintained over the long-term

Specific Aim 2: Examine if person-specific characteristics are associated with both the baseline and the change in the altered movement pattern within the motor skill training group and strength and flexibility group.

Hypothesis 2a. Gender, age, and LBP duration will moderate the baseline and change over time in the altered pattern.
**Hypothesis 2b.** The magnitude of baseline altered movement will moderate the change over time in the altered pattern.

**Specific Aim 3:** Examine if people with LBP display a consistent movement pattern across multiple functional activity tests

**Hypothesis 3a:** There will be a significant relationship of the movement pattern across multiple functional activity tests.

### 1.11 References


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Chronic Low Back Pain: A Randomized Clinical Trial. *JAMA Neurology.* Published online January 19, 2021.


Chapter 2: Motor skill training improves the altered movement pattern in the short-term and over the long-term

This chapter is under review at Clinical Biomechanics
2.1 Abstract

Background

People with chronic low back pain display the altered movement pattern where the lumbar spine moves more readily into its available range of motion relative to other joints. A logical approach to treatment, therefore, would be to improve this pattern during functional activities. Motor skill training (MST) is challenging practice to modify the pain provoking, altered movement pattern during the performance of functional activities. As such, MST may be more effective at changing the altered pattern compared to other types of exercise.

Objectives

Compare the short- and long-term effects of MST and strength and flexibility exercise (SFE) on knee, hip and lumbar spine early excursion during a functional activity test of picking up an object (PUO) in people with chronic low back pain.

Methods

154 participants were randomized to 6 weeks of MST or strength and flexibility exercise (SFE). MST received person-specific training to modify the altered movement pattern during functional activities. SFE received exercises for trunk strength and trunk and lower-limb flexibility. At baseline, post-treatment and 6-months after treatment participants performed a test of picking up an object using their preferred pattern. 3D marker co-ordinate data were collected. A mixed-model repeated measures ANOVA was used to examine the following effects: Treatment group (Tx), Time and Tx X Time.

Results

Both groups were similar at baseline for knee [MST(CI):11.1°(8.0,4.1), SFE(CI):8.9°(5.8,11.9)], hip [MST(CI):21.2°(19.2,23.1), SFE(CI):20.8°(18.9,22.8)], and lumbar
MST(CI):11.3°(10.4,12.3), SFE(CI):11.2°(10.3,12.2) early excursion. **MST:** Significant improvements were found in knee $[\Delta(CI)=+18.6°(15.4,21.8)]$, hip $[\Delta(CI)=+10.8°(8.8,12.8)]$, and lumbar $[\Delta(CI)=-2.0°(-0.1,-4.0)]$ early excursion from baseline to post-treatment. There were no significant changes from post-treatment to follow-up. **SFE:** There were no significant changes for knee, hip, and lumbar excursion.

**Conclusion**

In people with chronic low back pain, MST was more effective than SFE at changing and maintaining change to the altered movement pattern during a functional activity. If a goal of rehabilitation is to improve the altered movement pattern contributing to low back pain, MST is superior to SFE.

### 2.2 Introduction

At least 60-80% of adults experience low back pain (LBP) during their lifetime.\textsuperscript{1,2} Of those who have an initial episode, up to 75% report continued pain and limitation in function at 1 year.\textsuperscript{3,4} Thus, the majority of people who have an episode of LBP will transition to a fluctuating or persistent chronic course. In addition, the primary reason people with LBP seek medical care is a limitation in the performance of functional activities.\textsuperscript{5,6} Therefore, it is logical that treatment should be tailored towards improving the performance of functional activities limited due to LBP.

How people with LBP move during functional activities may contribute to why limitations in function are a primary problem. For example, people with chronic LBP often display an altered movement pattern in which the lumbar spine moves more readily into its available range of motion compared to other joints (e.g., knee and hip) that can contribute to the activity.\textsuperscript{7-11} The alteration is more prevalent in people with LBP compared to back healthy controls\textsuperscript{8,9,12} and, notably, is
displayed across variations of a functional activity of picking up an object. Importantly, the magnitude of the altered movement pattern is associated with a person’s LBP and LBP-related functional limitations. Thus, the altered movement pattern during functional activities is a relevant factor that may contribute to persistent functional limitation in people with LBP.

Exercise is a primary non-pharmacologic treatment for chronic LBP. Although exercise is often recommended, no specific exercise treatment is consistently more beneficial than another in the short-term and long-term. One potential reason for inconsistent effects is that the treatments tested do not directly address how people with LBP perform LBP-limited functional activities. Given the documented relevance of the altered movement pattern to limitations in functional activities, a logical form of exercise-based treatment would target the altered pattern during performance of limited functional activities. Motor skill training (MST) is an exercise-based treatment that employs motor learning principles to promote the learning or relearning of motor skills. The overarching goal of MST applied to LBP-limited functional activities is to replace the person-specific, pain-provoking, altered movement pattern with an improved and symptom-free pattern. After a single session of MST, immediate improvement was reported in both the altered movement pattern and pain during the functional activity test of picking up an object (PUO). Further investigation is warranted to understand whether the altered movement pattern during the PUO activity can be improved over the short-term and long-term using MST.

The purpose of this study was to compare the short-term and long-term effects of MST and strength and flexibility exercise (SFE) on movement of the knee, hip, and lumbar spine during the performance of the functional activity test of picking up an object. We hypothesized that MST would result in greater changes in the altered movement pattern than SFE. Specifically, we
hypothesized that after treatment the MST group would decrease early lumbar movement and increase early knee and hip movement, while the SFE group would not change the movement pattern across these regions. We also hypothesized that the improvements in the altered movement pattern in the MST group would be maintained in the 6 months after treatment.

2.3 Methods

2.3.1 Participants

This is a planned secondary analysis of kinematic data from 154 people with chronic non-specific LBP recruited as part of a single-blind, prospective, randomized controlled clinical trial. Recruitment was through word of mouth, flyers placed in the community, and ads and interviews through media and clinics in the region. Participants included were between 18-60 years of age, had chronic LBP for at least 1 year, experienced LBP but were not in an acute flare-up, had a modified Oswestry Disability Questionnaire (MODQ) score of ≥ 20%, could stand and walk without assistance and could understand and sign a consent form. Participants were excluded if they had (1) a body mass index (BMI) >30, (2) any structural spinal deformity, (3) a spinal tumor or infection, (4) osteoporosis, (5) ankylosing spondylitis, (6) rheumatoid arthritis, (7) symptomatic disc herniation, (8) spondylolisthesis. Additional exclusion criteria can be found on Clinicaltrials.gov (NCT02027623). The study was approved by the Institutional Review Board and all participants provided written informed consent before enrolling in the study.

2.3.2 Data Collection

Participants completed laboratory sessions at baseline, immediately following 6 weeks of treatment (post-treatment), and 6 months after treatment. For this planned secondary analysis we used a subset of self-report measures that were completed during the clinical trial. These included a (1) demographic and LBP history questionnaire, (2) MODQ, (3) Numeric Rating Scale (NRS)
for average (previous 7 days) and worst LBP symptoms (4) Fear-Avoidance Beliefs Questionnaire (FABQ)\textsuperscript{25,26} and (5) Short Form Health Survey (SF-36).\textsuperscript{27} Initially, a standardized examination was performed by a physical therapist to classify the person’s LBP.\textsuperscript{28-31} Classification was based on the person’s altered movements and alignments of the lumbar spine and LBP reports during clinical tests.\textsuperscript{10,32} Classification was used to aid the person-specific aspect of treatment within MST.

Reflective markers were placed on anatomical landmarks of the trunk, pelvis, and lower extremity, according to previously documented procedures.\textsuperscript{8,13} Anthropometric measurements were determined for each participant’s shank and trunk length. Shank length was measured as the vertical distance from the floor to fibular head. Trunk length was measured as the vertical distance between the marker superficial to the spinous process of the 7\textsuperscript{th} cervical (C7) and the marker superficial to the spinous process of the 1\textsuperscript{st} sacral (S1) vertebrae. Participants were instructed to perform three trials of a standardized functional activity test of picking up an object (PUO).\textsuperscript{13} Measures were obtained at baseline, immediately post-treatment and at 6-months post-treatment. For the PUO test, participants stood with their feet pelvis width apart and were told to pick up the container with both hands and return to the starting position. A 20 x 36 x 12 cm, lightweight container was placed at a height equal to the participant’s shank length, and a distance of 50\% of trunk length. No instructions were given to the participant for how to pick up the object. Participants were given a maximum of 10 seconds to complete each movement trial. Marker coordinate data were collected for both a static standing trial and the PUO trials using a three-dimensional motion capture system (Vicon Motion Systems, LTD, Denver, CO) with a sampling rate of 120 Hz.
Marker trajectory data were labeled using Nexus 2.7.1 (Vicon Motion Systems, LTD, Denver, CO). Data were further processed using custom programs written in Visual 3D (C-Motion Inc., Germantown, MD) and MATLAB software (MathWorks Inc., Natick, MA). Marker position data were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 3 Hz. The cut-off frequency was based on residual analysis of similar movement tests. Vectors created between markers were used to describe joint angles (e.g., lumbar: T12-S1 markers) across movement time. The lumbar spine angle was calculated as the displacement of the lumbar segment relative to the pelvis (i.e. CODA pelvis). The hip joint angle was defined as the displacement of the thigh segment relative to the pelvis. The knee joint angle was defined as the shank segment relative to the thigh segment. Early was defined as the 1st half of movement time for the descent phase of the PUO task. Initially a baseline joint angle was determined based on a 25 frame moving average for the knee, hip and lumbar spine. The start value was defined as the first joint angle that was 1 degree greater than baseline. The stop value was defined as the last joint angle value that was 98% of the absolute maximum. The 50% cutoff was determined based on total movement time from start to stop.

After the baseline data collection, participants were randomized to one of two treatment conditions, MST or SFE. Full details of the treatment conditions can be found on Clinicaltrials.gov (NCT02027623). Briefly, MST involved challenging practice to modify patient-specific, pain provoking, altered movement and alignment pattern during the performance of functional activities. The primary objectives of treatment were to train the participant to (1) reduce the amount of early lumbar spine movement related to the participant’s LBP classification (e.g., flexion), (2) increase the movement of other joints (e.g., knees and hips) and (3) avoid end range
movements or alignments of the lumbar spine in the specific direction related to the participant’s LBP classification.\textsuperscript{19} Physical therapists minimized extrinsic feedback during practice and training focused on problem solving by the participant to learn to perform the activities without increased LBP symptoms. MST was progressed within and between visits to match the participant’s motor capabilities.\textsuperscript{19} SFE focused on increasing the strength of all of the trunk muscles and improving trunk and lower limb flexibility in all planes following ACSM guidelines.\textsuperscript{34} SFE was progressed based on the participant’s ability to perform the exercise independently. All participants received 6, 1-hour treatment sessions, scheduled once/week for 6 weeks. Additional laboratory testing sessions were completed immediately post-treatment and 6 months after treatment. Both groups were told to adhere to their home program during both the active treatment and follow-up phase.

### 2.3.3 Data Analysis

Analyses were performed using R v3.5.3.\textsuperscript{35-37} The sample size of 154 participants was determined by a power analysis for detecting a minimal clinically important difference of 6 on the MODQ, which was the primary outcome measure for the clinical trial.\textsuperscript{19} Descriptive statistics were calculated for participant demographics and self-report measures. A two-way, mixed effect analysis of variance (ANOVA) model was used to examine main effects of Treatment group (Tx), Time, and the Tx X Time interaction for the early excursion of the knee, hip, and lumbar spine. When interactions were significant, a priori planned pairwise comparisons were examined using a Tukey’s HSD correction factor. Specifically, planned pairwise comparisons were examined for early movement for the knee, hip, and lumbar spine (1) between treatment groups at each time point and (2) within treatment groups from baseline to post-treatment and post-treatment to 6 month follow up.
2.4 Results

One hundred and fifty-four participants were enrolled in the study. Twenty-one participants dropped out over the study duration; Five were prior to treatment (MST = 3, SFE = 2). Participant characteristics for the sample are summarized in Table 1. At baseline, MST and SFE were similar in age, gender, BMI, duration of LBP, medication use, MODQ scores, average and worst NRS scores, FABQ-work and physical scores, SF-36 physical and mental component scores.

Table 2.1. Mean (95% CI) for participant characteristics by treatment group

<table>
<thead>
<tr>
<th></th>
<th>Strength and Flexibility Exercise (n = 77)</th>
<th>Motor Skill Training (n = 77)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>42.6 (40.0,45.3)</td>
<td>42.5 (39.9,45.1)</td>
</tr>
<tr>
<td>Female, no. (%)</td>
<td>52 (68)</td>
<td>43 (56)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.4 (24.7,26.1)</td>
<td>26.1 (25.4,26.8)</td>
</tr>
<tr>
<td>Duration of LBP (years)</td>
<td>10.9 (8.8,12.9)</td>
<td>9.7 (7.9,11.4)</td>
</tr>
<tr>
<td>LBP Medication Use (%)</td>
<td>48 (62.3)</td>
<td>45 (58.4)</td>
</tr>
<tr>
<td>Function (MODQ, 0-100%)</td>
<td>32.7 (30.4,35.0)</td>
<td>32.5 (29.9,34.5)</td>
</tr>
<tr>
<td>Average Pain (NRS, 0-10)</td>
<td>4.7 (4.3,5.1)</td>
<td>4.7 (4.3,5.0)</td>
</tr>
<tr>
<td>Worst Pain (NRS, 0-10)</td>
<td>6.3 (5.8,6.8)</td>
<td>6.8 (6.4,7.2)</td>
</tr>
<tr>
<td>Fear-Work (FABQ-W, 0-42)</td>
<td>11.0 (9.2,12.9)</td>
<td>11.7 (9.7,13.7)</td>
</tr>
<tr>
<td>Fear-Physical (FABQ-P, 0-24)</td>
<td>14.9 (13.6,16.3)</td>
<td>14.1 (12.9,15.2)</td>
</tr>
<tr>
<td>SF-36 Physical</td>
<td>42.9 (41.4,44.4)</td>
<td>40.7 (39.2,42.3)</td>
</tr>
<tr>
<td>SF-36 Mental</td>
<td>48.8 (46.2,51.4)</td>
<td>52.1 (50.0,54.1)</td>
</tr>
</tbody>
</table>

*a* modified Oswestry Disability Questionnaire scores range between 0% (no LBP-related functional limitation) and 100% (max limitation)

*b* Patient report of average or worst pain in the prior 7 days on verbal numeric pain rating scale between 0 (no pain) and 10 (pain as bad as can be)

*c* Fear-Avoidance Beliefs Questionnaire physical activity subscale score ranges from 0-24 and work subscale score ranges from 0-42 with higher scores indicating higher fear-avoidance

*d* 36-Item Short Form Health Survey (SF-36) Physical and Mental Component summary scores are scaled and normalized to have a mean of 50 and standard deviation of 10.

Prior to treatment, MST and SFE had similar knee [difference (CI) = 2.2° (-6.7, 2.5)], hip [difference (CI) = 0.4° (-2.9, 2.5)], and lumbar spine [difference (CI) = 0.1° (-1.4, 1.2)] early movement (Figure 1). After treatment MST increased early movement of the knee $\Delta$ (CI) = +18.6°
and decreased early movement of the lumbar spine \(\Delta (CI) = -2.0^\circ (-3.0, -1.0)\). SFE did not change early movement for the knee \(\Delta (CI) = -0.5^\circ (-3.5, 2.5)\), hip \(\Delta (CI) = +0.8^\circ (-1.1, 2.7)\), or lumbar spine \(\Delta (CI) = +0.2^\circ (-0.6, 1.0)\). Six months after treatment MST maintained improvements of knee \(\Delta (CI) = 2.2^\circ (-2.5, 6.7)\), hip \(\Delta (CI) = 0.4^\circ (-2.5, 2.9)\), and lumbar spine \(\Delta (CI) = 0.1^\circ (-1.2, 1.4)\) early movement (Figure 1) obtained with treatment. In the SFE group, there was no significant change in early joint movement from post-treatment to the 6-month follow up (all \(p > 0.90\)).
Figure 2.1. Graph of early joint excursion over time. Data show average early excursion of the (A) knee, (B) hip, and (C) lumbar spine during a functional activity test of picking up an object. Outcomes are displayed for motor skill training (MST) and strength and flexibility exercise (SFE) at baseline, post-treatment, and 6 month follow-up time points.

2.5 Discussion

The purpose of this study was to compare the short- and long-term effects of MST and SFE on movement of the knee, hip and lumbar spine during the functional activity test of PUO in people with chronic LBP. As hypothesized, after 6 weeks of treatment we found MST resulted in a significant increase in early movement of the knee and hip and a decrease in early movement of the lumbar spine during the PUO test. Alternatively, SFE resulted in no change in early movement of the knee, hip and lumbar spine during the PUO test. We also hypothesized that the improvements in the altered movement pattern in the MST group would be maintained over the long-term. We found that the improved movement pattern obtained immediately post-MST was maintained 6 months after treatment. In addition, the movement pattern of the knee, hip and lumbar spine in the SFE group observed at baseline and post-SFE was similar 6 months after treatment. Therefore, MST directed at performance of a functional activity of PUO is superior to SFE in the
ability to improve and maintain improvements in an altered movement pattern identified as important in people with chronic LBP.

Although MST targeting altered movement patterns during functional activities has not been widely studied in people with LBP, other exercise-based treatments have been examined. One treatment that has been extensively investigated in people with LBP is exercise to improve activation of the deep muscles to stabilize the spine (i.e., multifidus and transversus abdominis). In this intervention the motor skill targeted is isometric, continuous cocontraction of the deep muscles independent of superficial trunk muscle contraction. Typically, a final stage of the treatment is to progress to incorporating appropriate activation of these deep muscles during performance of light and heavy load functional activities. In contrast, rather than aiming to improve activation of specific deep muscles that stabilize the spine as the motor skill, the goal of MST in our clinical trial was to target the altered movement pattern shown to be relevant to the person’s LBP presentation during LBP-limited functional activities. Furthermore, we directly addressed functional activities from the beginning of training rather than starting with a more traditional exercise to improve activation of the deep muscles and then progressing to their use during functional activities. Given the observed short- and long-term improvements in the altered movement pattern during a functional activity test within MST and lack of change in the SFE group, these data further highlight the importance of using motor learning principles to directly address the person-specific altered movement pattern during functional activities.

Prior studies report a short-term change in movement-related variables (e.g., lumbar range of motion, lumbar movement velocity, etc.) in people with chronic LBP. However, studies that report durable change in movement (i.e., greater than 3 months) are scarce; short-term changes in
movement are often not sustained.\textsuperscript{42,43} Results of the current trial suggest the improvements in the altered movement pattern within the MST group were maintained 6 months after treatment. A key component of MST during functional activities is the use of principles of motor learning to drive change. Participants problem-solved how to perform their LBP-limited activities without increased LBP symptoms while extrinsic feedback was minimized. Functional activity demands were repeatedly progressed to further facilitate learning across multiple activities. This aspect of MST, which is unique compared to previous trials examining change in movement, is likely to be contributing to the durable change in movement. Therefore, if a goal of treatment is to change a long-standing altered movement pattern associated with LBP, these data suggest a priority for treatment is to provide person-specific, challenging practice in a manner that promotes learning.

There were limitations to the study. First, the PUO test was standardized to the person. Specifically, participants were asked to stand with their feet pelvis width apart and the object was set at a standardized height and distance. We chose to standardize the test to minimize the potential effect of individual anthropometrics on the performance of the activity. However, the functional activity test of PUO may not be representative of how people typically pick up objects during their day. Second, people with a BMI > 30 were excluded from this study. People were excluded based on this criterion to minimize skin artifact and thus ensure valid motion capture data. However, this exclusion reduces the ability to generalize findings to those with chronic LBP and a BMI > 30.

2.6 Conclusion

Our findings suggest MST is more effective than SFE in improving and maintaining improvements of the altered movement pattern during functional activities commonly observed in people with chronic LBP. After 6 weeks of MST, people reduced early movement of the lumbar
spine and increased early movement of the knee and hip joints with a functional activity test of PUO. These improvements were maintained 6 months after treatment. Alternately, the SFE group had no change in early movement of their knee, hip and lumbar spine across the study duration. Therefore, if a goal of treatment for people with chronic LBP is to improve and maintain the improvement of the altered movement pattern during performance of functional activities, MST is superior to SFE.

2.7 References


Chapter 3: Person-specific characteristics of people with LBP moderate the baseline and change over time in the altered movement pattern
3.1 Abstract

Background

People with chronic low back pain (LBP) display an altered movement pattern where the lumbar spine moves more readily into its available range of motion relative to other joints when performing a movement. Exercise-based treatment can improve the altered pattern. Specifically, motor skill training (MST) is person-specific, challenging practice to drive learning of motor skills. The goal of MST during LBP-limited functional activities is to replace the pain-provoking, altered movement pattern with a pain-free pattern. Recently a randomized clinical trial was completed to compare the effects of MST to strength and flexibility exercise (SFE). On average, MST improved the altered pattern to a greater extent than SFE. However, there was substantial variability in the baseline and the change over time in the movement pattern within both treatment groups. Understanding factors that influence this variability may ultimately be used to better target treatment strategies to the person.

Objectives

Examine if person-specific characteristics of gender, age, LBP duration, and the altered pattern at baseline moderate the baseline altered movement pattern and the change over time in the pattern within MST and SFE.

Methods

154 participants were randomized to 6 weeks of MST or SFE. MST received person-specific training to modify the altered movement pattern during functional activities. SFE received progressive exercises for trunk strength and trunk and lower limb flexibility. At baseline, post-treatment and 6-months after treatment participants performed a standardized test of picking up an
object. 3D marker co-ordinate data were collected. Lumbar contribution (LC), a ratio of early (i.e., first 50% of descent) lumbar movement relative to the early total movement, was the index of the altered movement pattern. Hierarchical linear modeling (HLM) was used to examine the moderating effects of gender, age, LBP duration, and baseline LC on the baseline LC and change over time in the LC.

**Results**

There was not a significant difference in baseline LC between MST and SFE ($\beta=-2.39$, SE=2.73, p=0.38). SFE did not change LC over time ($\beta=-0.11$, SE=0.18, p=0.53). However, there was a significant change over time in LC within MST ($\beta=-2.13$, SE=0.20, p<0.01). Irrespective of treatment group, there was a trend for gender ($\beta=-5.29$, SE=2.69, p=0.05) and age ($\beta=-0.22$, SE=0.12 p=0.05) to moderate baseline LC. LBP duration was not associated with baseline LC. Age ($\beta=0.01$, SE=0.004, p<0.01) and baseline LC ($\beta=-0.07$, SE=0.01, p<0.01) were associated with the change over time in LC within MST only. Gender and LBP duration were not associated with the change over time in LC in MST or SFE.

**Conclusions**

Person-specific characteristics moderate the baseline altered movement pattern within MST and SFE, as well as the change over time in the pattern within MST. Understanding factors that influence person-level variability may ultimately be used to better target treatment strategies to the person.

**3.2 Introduction**

The primary reason people with LBP seek medical treatment is difficulty in performing daily functional activities. Given the importance of function, researchers have investigated aspects of how people with LBP perform functional activities. Numerous differences in movement...
characteristics have been reported between back healthy controls and people with LBP.\textsuperscript{3,4} However, specific movement characteristics (e.g., movement velocity) often do not explain substantial variance in LBP-related function.\textsuperscript{5} One set of studies in particular has documented that compared to back healthy controls, people with chronic LBP display an altered movement pattern where the lumbar spine moves more readily into its available range of motion compared to other joints (e.g., knee and hip).\textsuperscript{6-8} Previously, the altered pattern has been indexed as the magnitude of early (first 50\% of descent) lumbar movement during an activity. This pattern is of particular clinical relevance because across multiple studies the magnitude of altered movement is associated with LBP symptoms and functional limitations.\textsuperscript{6,9,10} Therefore, the altered pattern is prevalent in people with chronic LBP and relevant to the clinical presentation.

Exercise-based treatment can improve the altered movement pattern during functional activities in people with chronic LBP.\textsuperscript{11} For example, motor skill training (MST) uses person-specific, challenging practice to drive learning of new motor skills.\textsuperscript{12-14} The primary goal of MST during LBP-limited functional activities is to replace the long-standing, pain-provoking, altered movement pattern with a pain-free pattern.\textsuperscript{11,13,14} One study documented that one session of MST immediately improved the altered movement pattern during a functional activity test of picking up an object (PUO), and the improved pattern was associated with an immediate reduction in LBP symptoms.\textsuperscript{11} More recently, the short- and long-term effects of MST were compared to strength and flexibility exercise (SFE). After 6 weeks of MST, on average, people with chronic LBP improved their movement pattern.\textsuperscript{15,16} Specifically, there was a significant decrease in early lumbar excursion and increase in early knee and hip excursion during the PUO test.\textsuperscript{15,16} The improved pattern was maintained 6 months after treatment.\textsuperscript{15,16} SFE, however, did not change the movement
pattern across the study duration. Furthermore, the improved movement pattern in MST corresponded with greater improvements in pain and function compared to SFE. Although on average MST improved the altered movement pattern and SFE did not, there was substantial variability in the baseline and the change over time in the pattern within both treatment groups. This variability suggests that some people with LBP improved the pattern to a greater extent than others. In order to better refine MST and SFE for people with LBP, it is critical to understand the variability from one person to another in the (1) altered movement pattern at baseline and (2) change over time in the pattern.

One reason for the substantial variability in the pattern at baseline and change over time is that person-specific characteristics (e.g., gender, age, etc.) may influence the pattern. Based on prior reports, there are many person-specific characteristics that have the potential to influence the pattern. First, prior studies suggest there are differences in movement patterns between men and women. Thus, there may be characteristics specific to gender that influence the altered movement pattern at baseline and the change over time in the pattern. Second, previous work suggests a person’s age is associated with movement characteristics, such as spinal range of motion, as well as the clinical course of LBP. Therefore, age could influence the baseline pattern, as well as the effectiveness of the exercise-based intervention. Third, duration of LBP is frequently reported as a prognostic factor of LBP recovery. Given the previously reported relationship of the altered movement pattern and clinical outcomes, duration of LBP may explain the baseline and change over time in the pattern. Lastly, in prior work the magnitude of the altered movement pattern at baseline was associated with the amount of improvement after one session of MST. Additional research is needed to understand if a relationship also exists between

34
the magnitude of baseline altered movement pattern and the change over time. Understanding the relationship of these person-specific characteristics to the baseline pattern and change over time pattern may ultimately be used to better target treatment strategies to the person and improve the effectiveness and efficiency of care.

The purpose of this study was to examine if person-specific characteristics of gender, age, duration of LBP, and baseline altered movement pattern are associated with both the baseline and the change over time in the altered movement pattern within the MST and SFE treatment groups. We hypothesized that the above mentioned person-specific characteristics would moderate the baseline pattern and change over time in the pattern.

### 3.3 Methods

#### 3.3.1 Participants

This is a planned secondary analysis of kinematic data from a single-blind, prospective, randomized controlled clinical trial (Clinicaltrials.gov: NCT02027623). 154 people with chronic non-specific LBP were recruited by way of word of mouth, ads through local media, clinics in the region and flyers placed in the community. Inclusion criteria for the study included 1) 18-60 years of age, 2) chronic LBP for at least 1 year, 3) experienced LBP but not in an acute flare-up, 4) modified Oswestry Disability Questionnaire (MODQ) score of ≥ 20%, 5) ability to stand and walk without assistance and 6) ability to understand and sign a consent form. Participants were excluded if they had a BMI >30, any structural spinal deformity, spinal tumor or infection and symptomatic disc herniation by clinical examination. Additional exclusion criteria can be found on Clinical.Trials.gov (ID #: NCT02027623). This study was approved by the Institutional Review Board and all participants provided written informed consent before enrolling in the clinical trial (IRB ID#: 201205051).
3.3.2 Data collection

Participants completed laboratory sessions for movement analysis at baseline, immediately post-treatment and 6 months after treatment. For the secondary analysis we used a subset of self-report measures that were completed during the clinical trial to describe the study sample. These included 1) demographic and LBP history questionnaire, 2) MODQ, 3) Numeric Rating Scale (NRS) for average and worst LBP symptoms (previous 7 days), 4) Fear-Avoidance Beliefs Questionnaire (FABQ) and 5) Short Form Health Survey (SF-36). Prior to treatment, a standardized clinical examination was performed by a trained physical therapist to classify the person’s LBP. LBP Classification was used to guide the person-specific treatment within MST. Classification was based on the person’s altered movement and alignment patterns of the lumbar region and LBP symptom reports during clinical tests.

Reflective markers were placed bilaterally on the trunk, pelvis, and lower extremity, according to previously published procedures. Participants were instructed to perform three trials of a standardized functional activity test of picking up an object (PUO). Measures were obtained at baseline, post-treatment and 6-months post-treatment. For the PUO test, participants stood with their feet pelvis width apart and were asked to pick up the light weight container with both hands and return to the starting position. The light weight container was placed at a height equal to the fibular head and distance of 50% of trunk length. No instruction was given as to how to complete the PUO test. Further details of the PUO test can be found in Marich et al.

Marker co-ordinate data were collected for both a standing calibration trial and the PUO trials using a three-dimensional motion capture system (Vicon Motion Systems, LTD, Denver, CO) with a sampling rate of 120 Hz. Marker trajectory data were tracked using Nexus 2.7.1 (Vicon Motion Systems, LTD, Denver, CO). Data were further processed using custom algorithms written
Marker position data were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 3 Hz. The cut-off frequency was based on residual analysis using similar functional activity movement tests. Markers (e.g., lumbar: T12, L3 and S1) were used to create segment specific coordinate systems to track movement across time. Then joint angles were calculated as the distal coordinate system relative to the proximal coordinate system (e.g., hip = femur segment relative to pelvis segment). The primary variable of interest for this study was the magnitude of altered movement pattern. We used lumbar contribution (LC), which was a ratio of early lumbar movement relative to early total movement, to index the magnitude of the altered movement pattern. Early total movement was defined as the summation of early movement of the lumbar spine, hip, and knee joint. Early was defined as the 1st 50% of movement time for the descent phase of the PUO task. The lumbar contribution index was calculated using the following equation:

\[ \text{LC} = \frac{\text{Early Lumbar}}{\text{Early Total}} = \frac{\text{Early Lumbar}}{\text{Early Lumbar} + \text{Early Hip} + \text{Early Knee}}. \]

For example, a LC of 0.50 would be interpreted as the lumbar spine contributing 50% of the total movement during the early phase of the PUO test. Therefore, a greater LC represents a greater magnitude of altered movement pattern.

Participants were randomized to either MST or SFE. All participants received 6, 1-hour treatment sessions, scheduled once/week for 6 weeks. Complete details of the treatment conditions can be found on Clinicaltrials.gov (NCT02027623). SFE focused on increasing the strength of all of the trunk muscles and improving all planes of trunk and lower limb flexibility based on ACSM guidelines. MST involved challenging, person-specific practice to improve pain provoking, altered movement and alignment patterns during the performance of functional activities. The
primary objectives of treatment were to train the participant to 1) decrease the amount of early lumbar spine movement related to the person’s LBP classification (e.g., flexion), 2) increase the contribution of movement of other joints (e.g., knees and hips) and 3) avoid end range movements or alignments of the lumbar spine in the specific direction related to the participant’s LBP classification. Physical therapists minimized the extrinsic feedback given to participants during practice. Training focused on problem solving by the participant to learn to perform the activities without increasing LBP symptoms. Both treatment conditions were progressed based on the participant’s ability to perform the exercise or activity independently.\(^{46}\)

### 3.3.3 Data analysis

All analyses were performed using R v3.5.3.\(^{47-49}\) Descriptive statistics were calculated for participant demographics and self-report measures. Two-sample t-tests and chi-square tests of independence were used to test for significant differences (p < 0.05) in characteristics between treatment groups at baseline.

We used hierarchical linear modeling (HLM) to examine the moderating effects of gender, age, LBP duration, and baseline LC on the baseline and change over time in LC. HLM is a regression-based approach that represents trajectories of participants over time by modeling responses at multiple levels of measurement.\(^{50}\) HLM is a recommended strategy for longitudinal data that 1) differ in measurement intervals, 2) are nested in separate levels of measurement (e.g., time within each participant) and 3) contain outcomes of either continuous or categorical data.\(^{50}\) Given our study design and variables fit these criteria HLM is an appropriate analytic technique. Initially, the LC outcomes were modeled over time at level 1 (i.e., baseline, post-treatment, and 6 month follow up). The level 1 analysis estimated each person-specific intercept, linear time
component, and non-linear time component (i.e., quadratic). Moderators of the person-specific LC outcome trajectories were modeled at level 2. The moderators were treatment group (TxGroup), gender, age, duration of LBP, and baseline LC). Also at level 2, we included the variability in coefficients from level 1, as a function of TxGroup, person-specific characteristics, and the interactions of TxGroup X each characteristic. Specific contrasts of the level 2 effects were calculated to test for the 1) main effect of time, TxGroup, and each person-specific characteristic and 2) interactions amongst the three domains of variables.

### 3.4 Results

#### 3.4.1 Study sample

The study sample included 154 participants. Twenty-one (13.6%) participants withdrew over the study duration. Participant characteristics, grouped by treatment group, are summarized in Table 1. There were no significant differences between MST and SFE for any participant characteristic at baseline (Table 1).

**Table 3.1. Mean +/- SD of demographic and clinical characteristics at baseline**

<table>
<thead>
<tr>
<th></th>
<th>Strength and Flexibility Exercise (n = 77)</th>
<th>Motor Skill Training (n = 77)</th>
<th>p value</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>42.6 ± 11.7</td>
<td>42.5 ± 11.8</td>
<td>0.94</td>
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<tr>
<td>Female, no. (%)</td>
<td>52 (68)</td>
<td>43 (56)</td>
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<td>BMI (kg/m²)</td>
<td>25.4 ± 3.2</td>
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<td>Duration of LBP (years)</td>
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<td>LBP Medication Use no. (%)</td>
<td>48 (62.3)</td>
<td>45 (58.4)</td>
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<td>Function (MODQ, 0-100%)</td>
<td>32.7 ± 10.2</td>
<td>32.5 ± 9.3</td>
<td>0.90</td>
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<td>Average Pain (NRS, 0-10)b</td>
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<td>0.96</td>
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<td>Worst Pain (NRS, 0-10)b</td>
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<td>6.8 ± 1.6</td>
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</tr>
<tr>
<td>Fear-Work (FABQ-W, 0-42)c</td>
<td>11.0 ± 8.3</td>
<td>11.7 ± 8.9</td>
<td>0.62</td>
</tr>
<tr>
<td>Fear-Physical (FABQ-P, 0-24)c</td>
<td>14.9 ± 6.1</td>
<td>14.1 ± 5.1</td>
<td>0.35</td>
</tr>
<tr>
<td>SF-36 Physicald</td>
<td>42.9 ± 6.8</td>
<td>40.7 ± 6.9</td>
<td>0.05</td>
</tr>
<tr>
<td>SF-36 Mentald</td>
<td>48.8 ± 11.5</td>
<td>52.1 ± 9.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>
a modified Oswestry Disability Questionnaire scores range between 0% (no LBP-related functional limitation) and 100% (max limitation)
b Patient report of average or worst pain in the prior 7 days on verbal numeric pain rating scale between 0 (no pain) and 10 (pain as bad as can be)
c Fear-Avoidance Beliefs Questionnaire physical activity subscale score ranges from 0-24 and work subscale score ranges from 0-42 with higher scores indicating higher fear-avoidance
d 36-Item Short Form Health Survey (SF-36) Physical and Mental Component summary scores are scaled and normalized to have a mean of 50 and standard deviation of 10 in the normal 1998 US population

3.4.2 Treatment Effects

There was not a significant difference in baseline LC between MST and SFE (β = -2.39, SE =2.73, p = 0.38). Within SFE there was not a significant linear slope (β = -0.11, SE = .18, p = 0.53) or quadratic component (β = 0.001, SE = 0.005, p = 0.86). The specific treatment group comparisons in the change over time in LC indicate that there was a significant difference in the linear slope and curvilinearity (ps < 0.05, Table 2). Within MST there was a significant overall linear slope (β = -2.13, SE = 0.20, p < 0.01) and quadratic component (β = 0.05, SE = .01, p < 0.01). The effects within MST were a result of a decrease in LC during the treatment phase, plateauing after the completion of treatment, and regressing at 6 months (β = 1.04, SE = .18, p < 0.01).

3.4.3 Person-specific Effects

Gender: Irrespective of treatment group there was a trend for a significant difference in baseline LC between men and women (β = -5.29, SE = 2.69, p = 0.05). Specifically, men had a greater LC than women across all time points in the study (Figure 1). There was not a significant difference in the linear change over time in LC between men and women within SFE or MST (Table 2). Age: Irrespective of treatment group there was a trend for a relationship of age and LC at baseline (β = -0.22, SE = 0.12 p = 0.06). This corresponds to a 0.22 unit decrease in LC for every additional 1 year of age; older people tend to have a smaller baseline LC. Within SFE there
was no significant moderating effect of age on the change over time in LC. Alternatively within MST, age moderated the linear change over time (β = 0.01, SE = .004, p < 0.01). Specifically older participants have a flatter (less negative) slope than younger participants (Figure 2). *LBP Duration:* Across MST and SFE there was not a significant relationship of duration of LBP and baseline LC (β = -0.19, SE = .16, p = 0.24) or the linear change over time in LC (Table 2). *Baseline LC:* Within SFE there was no significant relationship of baseline LC and the linear change over time in LC (Table 2). However, in MST there was a significant relationship of baseline LC and the linear change over time in LC (β = -.07, SE = .01, p < 0.01). People within MST with a greater baseline LC had a more negative slope than those with less baseline LC (Figure 1).

Table 3.2. Results of hierarchical linear modeling analyses of lumbar contribution over time at baseline, post-treatment and 6 month follow up

<table>
<thead>
<tr>
<th>Fixed effect</th>
<th>Beta coefficient</th>
<th>SE</th>
<th>p-value</th>
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<td>LBP Duration</td>
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<td>0.005</td>
<td>0.391</td>
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<tr>
<td>Baseline LC</td>
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<td>0.197</td>
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<tr>
<td>TxGroup</td>
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<td>0.007</td>
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<td>Baseline LC</td>
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<td>TxGroup X Baseline LC</td>
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<td>0.0003</td>
<td>&lt; 0.001</td>
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41
<table>
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<th>SE</th>
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<tr>
<td>TxGroup</td>
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<td>&lt; 0.001</td>
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<td>Baseline LC</td>
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<td>TxGroup X Baseline LC</td>
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<td>0.0003</td>
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6-month follow up

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<td>0.635</td>
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<td>TxGroup X LBP Duration</td>
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<td>0.695</td>
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<td>TxGroup X Baseline LC</td>
<td>0.048</td>
<td>0.012</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Quadratic&lt;sup&gt;c,d,e&lt;/sup&gt;</td>
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<td></td>
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<tr>
<td>TxGroup</td>
<td>0.052</td>
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<td>&lt; 0.001</td>
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<td>Baseline LC</td>
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<tr>
<td>TxGroup X Baseline LC</td>
<td>0.002</td>
<td>0.001</td>
<td>0.011</td>
</tr>
</tbody>
</table>

TxGroup represents the difference in lumbar contribution (LC) effect between strength and flexibility exercise and motor skill training.

\(^a\) Gender, Age and LBP Duration are differences in the grand means, irrespective of TxGroup

\(^b\) Linear slope at the centered time point of baseline, post-treatment or 6 month follow up

\(^c\) Main effects are within strength and flexibility exercise

\(^d\) Interaction effects represent the difference between strength and flexibility exercise and motor skill training.

\(^e\) Quadratic component at the centered time point of baseline, post-treatment or 6 month follow up
Figure 3.1. Predicted values based on hierarchical linear modeling analysis of lumbar contribution (LC) for motor skill training (MST) and strength and flexibility exercise (SFE). Confidence intervals are displayed at the three centering locations of baseline, post-treatment and 6 months post-treatment. Person-specific moderating effects are displayed for 1A. Gender, 1B. Age, 1C. Duration of LBP and 1D. Baseline lumbar contribution (LC_base).

3.5 Discussion

The purpose of this study was to examine if the person-specific characteristics of gender, age, duration of LBP, and magnitude of baseline LC were associated with the baseline pattern and change over time in the pattern within MST and SFE. Our hypothesis that person-specific characteristics would moderate the altered movement pattern was partially supported. First, there was a trend for differences between men and women in baseline LC, but gender did not moderate the change over time in LC within either treatment group. Second, there was a trend for a relationship of age and the baseline LC. However, age only significantly moderated the change over time in LC within MST. Third, duration of LBP was not associated with the baseline or change over time in the altered movement pattern. Finally, baseline LC was associated with the
change over time in LC only within MST. Therefore, these data support that person-specific characteristics are relevant to the magnitude of the altered movement pattern at baseline and the change over time in the pattern in MST.

Irrespective of treatment group, there was a trend for a significant difference in baseline LC between men and women. Specifically, men had 5.3% greater LC than women. The modeled differences in LC between men and women were observed consistently across the study duration (ps = 0.03 to 0.05); men moved more in their lumbar spine early relative to other joints compared to women. There also was no difference in the trajectory of change over time in LC between men and women within MST and SFE. Similar to prior research, these data suggest men and women perform functional activity tests differently.\textsuperscript{21,22} However, if given the appropriate training to directly improve the altered movement pattern, men and women can both improve to a similar extent. Therefore, a clinician may expect men and women to perform a functional activity test differently, but both genders have a similar capacity to improve the altered movement pattern.\textsuperscript{24}

There was a trend for age and baseline lumbar contribution to be associated. Specifically, for people who are 1 standard deviation older (mean + 1SD = 54.3 years) than the mean (42.6 years) there is a 2.6% reduction in lumbar contribution; the opposite effect holds for people who are younger than the sample mean. Interestingly, age also moderated the change over time in lumbar contribution within MST (Figure 1B). For example, older people had a smaller change over time in LC, compared to younger people. Older people also did not retain the improved pattern as well as younger people. Although these relationships are statistically significant, these findings should be interpreted with caution. Even across multiple decades of age, people within MST improve the magnitude of altered movement pattern during a functional activity test of PUO.
Therefore, age has a relatively small effect on baseline and the change over time in LC, and MST improved the altered movement pattern in both younger and older people.

We found that the number of years someone has LBP is not associated with the magnitude of altered movement pattern at baseline or the change in the pattern over time. Previously, a moderate positive relationship (r = 0.39) was reported between LBP duration and change in the altered movement pattern after one session of MST.\textsuperscript{11} Specifically, the prior study reported that the longer the person had LBP the greater improvement in the altered pattern after one session of MST.\textsuperscript{11} One reason for the discrepancy from the current study is that prior work examined the change in the pattern after 1, 20 minute session of MST, as opposed to 6, 1-hour treatment sessions that were once/week for 6 weeks.\textsuperscript{11} Thus, the moderate relationship of duration of LBP and change in the altered movement pattern after one session of MST is not observed over the short-term (i.e., 6 weeks) or long-term (i.e., 6 months). The lack of association of LBP duration and change in the pattern over time is of particular importance for those within the MST group, because these data highlight that repeated sessions of MST improved a long-standing, pain-provoking, altered movement pattern, irrespective of how long the person had LBP.

Baseline LC moderated the change over time in LC within MST. Specifically, people with greater LC in MST initially had a greater improvement (more negative slope) compared to people with less LC (Figure 2D). These data mirror the relationship of baseline early lumbar excursion and the change in early lumbar excursion after one 20-minute session of motor skill training.\textsuperscript{31} The people with the greatest magnitude of altered movement pattern at baseline change the most following MST because they have the greatest potential to change. Furthermore, comparing the trajectories of the change over time for those with greater LC in SFE and MST, people with greater
baseline lumbar contribution have a distinctly different trajectory. Those with a higher level of altered movement pattern in SFE do not improve the altered pattern; whereas those in MST have a rapid improvement. These data further indicate that if a goal of treatment for people with chronic LBP is to improve the altered movement pattern associated with function, MST is superior to SFE.

Although our findings support that there are person-specific factors that may help refine treatment, this study has limitations. First, these findings are relevant to the altered movement pattern during one functional activity test. Additional research is necessary to determine whether these effects are similar in other functional activities that are limited in people with LBP. Second, we excluded people with a BMI > 30 and specific LBP conditions (e.g., disc herniation). Therefore, these data may not be generalizable to all people with chronic LBP. In addition, other person-specific characteristics not tested in this study should be examined.

3.6 Conclusion

Our findings suggest that person-specific characteristics such as gender, age and baseline lumbar contribution moderate the baseline and change over time in the magnitude of the altered movement pattern. Alternatively, duration of LBP is not associated with the pattern at baseline or the change over time. These person-specific characteristics, in part, explain the variable movement pattern trajectories over time. These findings are of specific importance because understanding factors that influence person-level variability can ultimately be used to better target treatment strategies to the person. Lastly, our findings are clinically relevant because even accounting for the person-specific variability in the movement pattern, MST is superior to SFE in improving the altered movement pattern in people with chronic LBP.
3.7 References


Chapter 4: The relationship of movement patterns across multiple functional activity tests in people with chronic low back pain

This chapter is under review at Physical Medicine & Rehabilitation
4.1 Abstract

Background

People with chronic low back pain (LBP) display an altered movement pattern in which the lumbar spine moves more readily than other joints. It is proposed that the use of the same movement pattern across multiple functional activities across the day contributes to the development or persistence of LBP. However, no prior study has tested if people with chronic LBP display a similar movement pattern across multiple functional activity tests.

Objectives

Examine if there was a relationship of movement patterns across three tests of everyday functional activities in people with chronic LBP.

Methods

This was a secondary analysis of baseline kinematic data from 154 people with chronic LBP, who were recruited as part of a randomized controlled clinical trial. People completed functional activity tests of 1) pick up an object, 2) sit to stand, and 3) sit and reach in randomized order. 3D marker co-ordinate data were collected. Lumbar contribution (LC), a ratio of early (i.e., first 50% of descent) lumbar movement relative to the early total movement, indexed the movement pattern. Pearson product-moment correlations were performed to examine the relationship of LC among the functional activity tests.

Results

There were significant small and medium relationships of LC between (1) pick up an object and sit to stand ($r = 0.23$, $p < 0.01$) and (2) sit to stand and sit and reach tests ($r = 0.35$, $p < 0.01$). The relationship of LC for the pick up an object and sit and reach functional tests was not significant ($r = 0.12$, $p = 0.16$).
Conclusion

We found small to medium direct relationships of the movement pattern used when performing functional tests of pick up an object, sit to stand, and sit and reach. These findings in part support that people show a similar pattern across tests. Future studies are necessary to fully understand if people with LBP display the same movement pattern with multiple functional activities throughout the day.

4.2 Introduction

Chronic low back pain (LBP) is the most common type of chronic pain in adults and the prevalence is growing. In addition to persistent or fluctuating symptoms, people with chronic LBP often report limitations in the performance of simple and complex functional activities, such as social and occupational roles. People with LBP primarily seek initial and repeated medical treatment because of their limitation in daily functional activities. Given the importance of function, it is essential to examine how people with LBP perform daily functional activities. Specifically, examination of the movements used when performing activities that are limited in people with LBP may provide insight into the movement-related factors that contribute to this disabling condition.

People with chronic LBP often display an altered movement pattern in which the lumbar spine moves more readily than other joints that can contribute to the movement goal. One index of the altered pattern that has previously been used is the magnitude of early (e.g., first 50% of movement time) lumbar movement during an activity. The pattern is observed more frequently in people with LBP compared to back healthy controls, and it is displayed across a variety of clinical tests (e.g., forward bend and prone hip rotation). Importantly, the magnitude of the
altered pattern is associated with a person’s symptoms and LBP-related functional limitations; the greater the altered pattern the greater the LBP and functional limitation and vice versa.\textsuperscript{5,8,10} Therefore, the altered movement pattern is prevalent in people with chronic LBP and is a relevant factor that can contribute to limitations in function.

The Kinesiopathologic model is a theoretical framework for understanding how movements during daily functional activities may contribute to the development and course of musculoskeletal pain conditions.\textsuperscript{11} Specific to LBP, it is proposed that people adopt a direction-specific altered movement pattern during functional activities.\textsuperscript{11} When the same direction-specific pattern is used repetitively across multiple functional activities, the pattern is proposed to lead to an accumulation of lumbar tissue stress, LBP symptoms, and micro- or macro-level injury.\textsuperscript{11-13} Indeed, several studies have examined movement of people with LBP during a single functional activity test.\textsuperscript{5,8,14-20} However, few studies have reported on the consistency of a person’s movement pattern across multiple tests of functional activities.\textsuperscript{8,21} This knowledge gap is of particular relevance because a primary assumption of the Kinesiopathologic model is that the use of the same pattern with multiple functional activities throughout the day contributes to the LBP condition. Further examination of the assumption is important to test if people with LBP display a similar movement pattern across different functional activities.

The primary purpose of this study was to examine if people with LBP display a consistent movement pattern across different functional activity tests. Specifically, we tested if there was a relationship of the pattern with the functional activity tests of 1) pick up an object, 2) sit to stand, and 3) sit and reach. We chose these specific functional activity tests because they are (1) performed repetitively across the day and (2) often reported as painful activities for people with
chronic LBP. We hypothesized that there would be a significant direct relationship of the movement pattern among the three functional activity tests.

4.3 Methods
4.3.1 Participants
This was a secondary analysis of baseline data from 154 people with chronic non-specific LBP, who were recruited as part of a randomized controlled clinical trial. Recruitment was through word of mouth, flyers placed in the community, ads through media and clinics in the area. Specific participant inclusion and exclusion criteria are listed in Table 4.1. Additional exclusion criteria can be found on Clinicaltrials.gov (NCT02027623). This study was approved by the Institutional Review Board (IRB ID#: 201205051). All participants provided informed consent prior to enrolling in the study.

Table 4.1. Study inclusion and exclusion criteria

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<td>3. Chronic LBP for at least 12 months</td>
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<td>4. ≥ 20% on the Modified Oswestry Disability Questionnaire (mODQ)</td>
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<td>5. Not in an acute flare up of LBP</td>
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<td>6. ≥ 3 limitations in functional activities by self-report</td>
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<td>7. Can stand and walk without assistance</td>
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<table>
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<td>2. Prior spinal surgery</td>
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<td>Rheumatoid arthritis</td>
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<td>Spondylolisthesis</td>
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<tr>
<td>Marked kyphosis/scoliosis</td>
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<tr>
<td>Spinal stenosis</td>
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<td>Spinal fracture or dislocation</td>
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Symptomatic disc herniation
4. Pain, numbness, or tingling below the knee
5. Pregnant
6. Etiology of LBP other than the lumbar spine (e.g., hip joint)
7. History of neurologic disease requiring hospitalization

*Additional inclusion and exclusion criteria on Clinicaltrials.gov (NCT02027623). 26

4.3.2 Data Collection

Initially, participants completed the following questionnaires: 1) demographic and LBP history questionnaire, 2) modified Oswestry Disability questionnaire (MODQ) 27 measured LBP-related functional limitation, 3) Numeric Pain Rating Scale (NRS) 28 for average and worst LBP in the prior 7 days, 4) Fear-Avoidance Beliefs Questionnaire (FABQ) 29,30 for perception of how physical activity and work may contribute to LBP and 5) Short Form Health Survey (SF-36) 31 as a measure of general physical and mental health status. These specific self-report measures were included to describe key demographic characteristics, as well as frequently reported LBP clinical characteristics in this sample. 32

After the completion of self-report measures, reflective markers were secured to the skin at predetermined locations on the subject’s trunk, pelvis and lower extremities (Table 4.2). The intra-rater reliability for marker placement and collection of similar movement characteristics are good to excellent (ICC [3,K] = 0.70-0.92). 33 Anthropometric measurements were determined for each participant’s shank and trunk length to aid in the standardization of functional activity tests. Shank length was measured as the vertical distance from the floor to fibular head. Trunk length was measured as the vertical distance between the markers superficial to the spinous process of the 7th cervical (C7) and the 1st sacral (S1) vertebrae.

Participants performed three trials of each of the following functional activity tests: 1) pick up an object, 2) sit to stand, and 3) sit and reach in randomized order. For the pick up an object
test a lightweight container was placed at a height equal to the participant’s shank length, and a distance of 50% of the participant’s trunk length.\textsuperscript{5,8} Participants were asked to stand with their feet pelvis width apart and pick up the container with both hands and return to the starting position. Participants were instructed to pick up the object without bending their knees. This instruction was given to examine relative movement of the hip and lumbar spine across the three functional tests, without contributions of the knee joint. For the sit to stand test, participants were instructed to sit on a stool with no armrests or back rest. The stool height was equal to the distance from the participants’ fibular head to the floor. The knees were positioned in 90 degrees of flexion, feet flat on the floor, and knees in alignment with the anterior-superior iliac spines of the pelvis in the frontal plane. A member of the research team aligned the participant such that their lumbar spine alignment was flat (i.e. acromion over greater trochanter) with 90 degrees of hip flexion. Then participants were asked to keep their arms at their sides and move from sitting to standing. For the sit and reach movement test, participants were aligned using identical procedures as described above. A small red target was placed on a vertical post at shoulder height (i.e., acromion process) and a distance based on the participant’s characteristics. Next, participants were asked to start with their arms by their sides and then reach forward with their dominate arm, touch the target and return to the starting position. For each test a maximum of 10 seconds was allowed for each movement trial.

4.3.3 Data Processing

Marker trajectory data were tracked using Nexus 2.7.1 (Vicon Motion Systems, LTD, Denver, CO) and processed using programs written in Visual 3D (C-Motion Inc., Germantown, MD) and MATLAB software (MathWorks Inc., Natick, MA). Marker position data were filtered using a 4\textsuperscript{th} order low-pass Butterworth filter with a cut-off frequency of 3 Hz.\textsuperscript{34} The cut-off
frequency was based on residual analysis\textsuperscript{34}, which was previously completed with similar tests of hip and spine movement.\textsuperscript{5,8} Vectors created between markers were used to describe segment angles (e.g., lumbar: S1, L3, and T12 landmarks) across movement time. The lumbar spine joint angle was calculated as the angular displacement of the lumbar spine segment relative to the pelvis segment. The hip joint angle was defined as the displacement of the thigh segment relative to the pelvis. The knee joint angle was described as the displacement of the shank segment relative to the femur.

Table 4.2. Marker set and segment definitions for movement testing.

<table>
<thead>
<tr>
<th>Segment</th>
<th>1\textsuperscript{st} Markers</th>
<th>2\textsuperscript{nd} Markers</th>
<th>3\textsuperscript{rd} Markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbar</td>
<td>S1</td>
<td>T12</td>
<td>L3 (Lateral to L3)</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Anterior superior iliac spines</td>
<td>Posterior superior iliac spines</td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td>Greater trochanter</td>
<td>Lateral &amp; medial femoral condyle</td>
<td>Lateral Thigh Cluster</td>
</tr>
<tr>
<td>Shank</td>
<td>Lateral &amp; medial femoral condyle</td>
<td>Lateral &amp; medial malleolus</td>
<td>Lateral Shank Cluster</td>
</tr>
</tbody>
</table>

S1 = spinous process of the 1\textsuperscript{st} sacral vertebrae  
T12 = spinous process of the 12\textsuperscript{th} thoracic vertebrae  
L3 = spinous process of the 3\textsuperscript{rd} lumbar vertebrae

4.3.4 Primary Outcome Variable

Lumbar contribution (LC) was the primary variable of interest. LC was a ratio of early lumbar movement relative to early total movement. Early total movement was defined as the summation of early movement of the lumbar spine, hip and knee. Early was defined as the 1\textsuperscript{st} 50\% of movement time for the (1) descent phase of the pick up an object task, (2) flexion phase of sit to stand, and (3) reaching for sit and reach.\textsuperscript{5,8,14} The lumbar contribution index was calculated using the following equation:  
\[ LC = \frac{\text{Early Lumbar}}{\text{Early Total}} + \frac{\text{Early Lumbar}}{\text{Early Hip + Early Knee}}. \]  
A greater
LC represented a greater amount of lumbar movement relative to early total movement. These calculations were completed for all trials of the 3 functional activity tests. The three trials for each test were then averaged to calculate a LC value for each test.

### 4.3.5 Data Analysis

All analyses were completed in R v3.5.3.\textsuperscript{35-37} Descriptive statistics, including means and standard deviations, were calculated for demographic and clinical characteristics of the study sample (Table 3). Next, the primary outcome measure for each of the three functional activity tests was examined for distributional abnormalities and outliers. This step was completed to ensure data integrity and confirm the assumptions of the planned statistical procedures.\textsuperscript{38} Data distributions were tested using visual methods including histograms and quantile-quantile plots and formal significance tests (e.g., Shapiro-Wilk test of normality) to confirm the random study sample approximates a normal distribution. Next, box plots and Grubb’s test for outliers were used to check for outliers. Data points for a particular test were excluded only if the value was outside 1.5 times the interquartile range (IQR) of the upper or lower quartile and determined as a significant outlier (p < 0.05) by Grubb’s test. A total of 2 out of 462 data points were identified as outliers and were removed from the subsequent analyses.

Pearson product-moment correlations were performed to examine the relationship of LC among the functional activity tests of 1) pick up an object, 2) sit to stand and 3) sit and reach. Bivariate correlations were considered significant at p < 0.05 and interpreted as either negligible (0.0 ≤ r < 0.1), small (0.1 ≤ r < 0.3), medium (0.3 ≤ r < 0.5), large (0.5 ≤ r ≤ 1.0).\textsuperscript{39}
4.4 Results

Demographic and clinical characteristics for the sample of 154 people with chronic LBP are summarized in Table 4.3. Based on values for self-report low back pain related function and symptoms, our sample experienced moderate limitation and pain. Average early excursion for the knee, hip, lumbar spine, and lumbar contribution for the functional tests of pick up an object, sit to stand and sit and reach are displayed in Table 4.4.

Table 4.3. Mean ± SD or Mean (%) for demographic and clinical characteristics for the study sample

<table>
<thead>
<tr>
<th>Demographic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>42.6 ± 11.7</td>
</tr>
<tr>
<td>Female (%)</td>
<td>95 (62)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.7 ± 3.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clinical</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of LBP (years)</td>
<td>10.3 ± 8.6</td>
</tr>
<tr>
<td>Function (MODQ, 0-100%)</td>
<td>32.6 ± 9.7</td>
</tr>
<tr>
<td>Average Pain (NRS, 0-10)</td>
<td>4.7 ± 1.7</td>
</tr>
<tr>
<td>Worst Pain (NRS, 0-10)</td>
<td>6.6 ± 1.9</td>
</tr>
<tr>
<td>Fear-Work (FABQ-W, 0-42)</td>
<td>11.4 ± 8.6</td>
</tr>
<tr>
<td>Fear-Physical (FABQ-P, 0-24)</td>
<td>14.5 ± 5.6</td>
</tr>
<tr>
<td>SF-36 Physical</td>
<td>41.8 ± 6.9</td>
</tr>
<tr>
<td>SF-36 Mental</td>
<td>50.4 ± 10.5</td>
</tr>
</tbody>
</table>

*a Modified Oswestry Disability Questionnaire scores range between 0% (no LBP-related functional limitation) and 100% (max limitation)

*b Patient report of average, current, worst, or best pain on verbal numeric pain rating scale between 0 (no pain) and 10 (pain as bad as can be)

*c Fear-Avoidance Beliefs Questionnaire physical activity subscale score ranges from 0-24 and work subscale score ranges from 0-42 with higher scores indicating higher fear-avoidance*

*d Short Form Health Survey for Physical and Mental components. Scores range from 0-100, with higher scores indicating better physical or mental health.
Table 4.4. Early joint excursion and early lumbar contribution for functional tests of picking up an object, sit to stand, and sit and reach

<table>
<thead>
<tr>
<th>Test</th>
<th>Knee (deg)</th>
<th>Hip (deg)</th>
<th>Lumbar (deg)</th>
<th>Lumbar contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pick up an object</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.4 ± 4.4</td>
<td>17.4 ± 7.2</td>
<td>11.8 ± 4.1</td>
<td>39.9 ± 15.0</td>
</tr>
<tr>
<td><strong>Sit to stand</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.1 ± 2.2</td>
<td>5.6 ± 3.3</td>
<td>4.0 ± 2.0</td>
<td>41.2 ± 16.8</td>
</tr>
<tr>
<td><strong>Sit and reach</strong>&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-0.3 ± 0.8</td>
<td>10.6 ± 3.7</td>
<td>4.9 ± 2.5</td>
<td>32.2 ± 17.0</td>
</tr>
</tbody>
</table>

deg = degrees of early excursion (1<sup>st</sup> 50% of descent)

<sup>a</sup> Pick up an object. Participants were instructed to pick up the lightweight object without bending their knees.

<sup>b</sup> Sit to stand. Participants were aligned in 90 degrees of hip/knee flexion and flat lumbar spine (i.e. acromion over greater trochanter). Participants were asked to keep their arms at their sides and move from sitting to standing.

<sup>c</sup> Sit and reach. Participants were aligned in 90 degrees of hip/knee flexion and flat lumbar spine. Participants were asked to start with their arms by their sides and then reach forward and touch the red target and return to the starting position.
Scatterplots with Pearson-product moment correlations of LC across pick up an object, sit to stand, and sit and reach functional tests are displayed in Figure 4.1. There were significant small and medium relationships, respectively, of LC between (1) pick up an object and sit to stand ($r = 0.23$, $p < 0.01$) and (2) sit to stand and sit and reach tests ($r = 0.35$, $p < 0.01$). The relationship of LC for the pick up an object and sit and reach functional tests was small and not statistically significant ($r = 0.12$, $p = 0.16$).
Figure 4.1. Scatterplot of lumbar contribution (LC) for A) pick up an object and sit to stand, B) pick up an object and sit and reach, and C) sit to stand and sit and reach. Pearson product-moment correlations (Confidence intervals) are shown for each scatterplot.

4.5 Discussion

The primary objective of this study was to examine if people with chronic LBP display a consistent movement pattern across multiple functional activity tests. Our hypothesis was partially confirmed in that we found a significant direct relationship of LC between (1) pick up an object and sit to stand and (2) sit to stand and sit and reach. However, the relationships of the previously mentioned tests were small to medium in magnitude. Furthermore, the relationship of LC for pick up an object and the sit and reach functional tests was small and not significant. Therefore, these data support that small to medium but stable relationships exist between movement patterns among multiple functional tests in people with chronic LBP.

Prior findings suggest that people with LBP consistently display a movement pattern during simple clinical tests (e.g., forward bending) and variations of a functional activity test of pick up an object. For example, there was a significant and large relationship \((r = 0.73, p < 0.01)\) of movement of the lumbar spine during forward bending and pick up an object. This relationship is much larger than the relationship found in this sample among the three functional activity tests.
in this study \((r = 0.12-0.35, p = 0.01-0.16)\). One potential reason for the smaller effect sizes in this analysis is that the movement goals for forward bending and pick up an object are more similar than the goals of the complex functional tests examined in this study. Concepts of motor control suggest a person’s movement goal has the potential to influence movement performance.\(^{40-42}\) Specifically, as the goal of a movement test is varied, such as changing the demands of reaching for an object, the kinematics (e.g., joint angles and velocities) of movement are modified to meet the demands.\(^{40-43}\) Furthermore as the demands of the test are varied, the initial control strategy to achieve the movement goal is dynamically modified based on internal and external feedback during the test.\(^{44-46}\) Together, these findings suggest internal and external aspects of the movement goal can influence the performance of a functional activity.\(^{47}\) Thus, it is reasonable to expect that different movement goals elicit variability in a person’s movement pattern across tests, which likely contributes to the size of the relationships detected in this study.

A second potential reason for the small relationships in this study are the differences in start position of the knee, hip, and lumbar spine joint angles across the three functional tests. Specifically, people started the pick up an object test in standing, but the other two tests start in a seated position with the hips and knees in 90 degrees of flexion. There are a variety of aspects pertaining to the start position that could impact the relative contribution of the lumbar spine to total movement. For instance, people with LBP may have reduced passive range of motion for hip flexion, when compared to back healthy controls.\(^{48-50}\) Given the sit to stand and sit and reach tests require the hip to start in 90 degrees of flexion, it is plausible that some people with LBP may not be able to move their hips into more flexion to complete the test. Thus, a restriction in hip flexion may require more lumbar spine movement to complete the test. Alternatively when starting with the hip fully extended, as in the pick up an object test, the same person may more easily distribute
movement to the hip and knee. Further supporting the potential role of the start position, we found the largest effect size when examining the relationship of the two tests that start in the same position (i.e. sit to stand and sit and reach). Therefore, the different start positions could be a confounding factor that explains our small relationships among functional activity tests.

The primary outcome measure of LC could also play a role in the size of the relationships detected. We chose to examine the lumbar contribution variable to better understand how much lumbar spine movement was occurring relative to other joints, rather than examining a single joint excursion.\textsuperscript{5,8} However, our data display a restricted range of LC, especially in the functional test of sit and reach (mean ± SD = 32.2 ± 17.0\%). It is well accepted that when all other aspects of the data are held constant, the relationship is greater if there is more variability among the observations than if there is less variability.\textsuperscript{38,51} Therefore, our restricted range of values in the data can inherently reduce our ability to detect a relationship across functional activity tests.\textsuperscript{38} Our findings should be interpreted with the consideration that the relationships may be larger when examining a sample with a greater range of LC values. Future research should ensure the primary outcome measure has a large enough distribution across the measurement range to detect a relationship.

This study had limitations. First, we used surface measures to track lumbar spine and joint movement to calculate the LC index. The documented noise when estimating small amounts of joint movement and relative contributions of movement could impact these relationships across tests.\textsuperscript{52} Second, we did not include movement of the scapula and upper extremity in the LC index. Future studies should include the upper extremity in the index of movement across joints, especially in reaching tests. Third, our sample only included people with chronic\textsuperscript{23}, non-specific\textsuperscript{25} LBP. Therefore these findings may not generalize to people with acute LBP or a specific LBP diagnosis. Lastly, our study was highly controlled with standardized functional tests based on each
person’s anthropometrics. As such, these specific functional tests may not accurately represent how people with LBP perform all functional activities throughout the day.

4.6 Conclusion

In conclusion, we found small to medium direct relationships of the movement pattern used when performing functional tests of pick up an object, sit to stand, and sit and reach. This is the first study to investigate whether people with LBP display the same movement pattern, when accounting for multiple joints, across multiple functional tests. These findings are of particular relevance because they, in part, support that people show a similar pattern across tests. Furthermore, we discussed multiple confounding factors that should be considered in future work. Therefore, future studies are necessary to fully understand if people with LBP display the same movement pattern with multiple functional activities across the day.

4.7 References


Chapter 5: Summary, Significance of Findings, and Future Studies
5.1 Summary

The primary goal of this dissertation was to examine movement patterns during functional activities in people with chronic LBP. Specifically, we aimed to further the understanding of 1) the effect of exercise-based interventions on an important altered movement pattern, 2) the role of person-specific characteristics on the altered pattern and 3) the consistency of a person’s movement across multiple functional activity tests.

The purpose of chapter 2 was to compare the short- and long-term effects of MST and SFE on the altered movement pattern during a functional activity test of PUO. This purpose was of particular importance because a prior report documented that after one session of MST there was an immediate improvement in the pattern and LBP symptoms during a functional activity test. However, there were no data testing if MST improved the pattern in the short-term (after 6 weeks of treatment) or if the improvements could be maintained over the long-term (6 months after treatment). We found that 6 weeks of MST resulted in a significant improvement in the movement pattern. Specifically, there was an increase in early knee and hip excursion and a decrease in early lumbar excursion. Alternatively, SFE resulted in no change in movement of the knee, hip, or lumbar spine. We also found that the improved movement pattern obtained post-MST was maintained 6 months after treatment. The movement of the knee, hip and lumbar spine in the SFE group observed at baseline and post-SFE was similar 6 months after treatment. Thus, our data suggest MST directed at the performance of a functional activity is superior to SFE in the ability to improve and maintain improvements in an altered movement pattern in people with chronic LBP.

The objective of chapter 3 was to examine if person-specific characteristics moderate the baseline and change over time in the altered pattern within MST and SFE. Based on prior literature,
we expected gender, age, LBP duration, and the movement pattern before treatment would be associated with the baseline and change over time in the pattern. Our hypothesis was partially supported; gender and age were associated with the pattern at baseline. Also, age and the magnitude of altered movement before treatment were associated with the change over time in movement, but only within MST. Interestingly, duration of LBP was not associated with the baseline or change over time in the altered pattern in MST or SFE. Therefore, people who had LBP for multiple decades improved the pattern to a similar extent to those who had LBP for only 1 year. These findings suggest key person-specific characteristics moderate the baseline and change over time in the magnitude of the altered movement pattern during a functional activity test. Furthermore, these results are of particular clinical relevance because understanding factors that influence person-level variability can ultimately be used to better refine treatment strategies to the person.

The purpose of chapter 4 was to examine if people with chronic LBP move consistently across multiple functional activity tests. We tested if the movement patterns were associated across the functional tests of 1) pick up an object, 2) sit to stand, and 3) sit and reach. We found a significant direct relationship of the pattern between (1) pick up an object and sit to stand and (2) sit to stand and sit and reach. Although these relationships were statistically significant, it is important to emphasize that these relationships were small to medium (r = 0.12 to 0.35) in magnitude. In addition, the relationship between a person’s movement pattern for the pick up an object and sit and reach tests was small and not significant. Thus, we concluded that small to medium but stable relationships exist between movement patterns among multiple functional activity tests in people with chronic LBP, and we provided a multitude of possible confounding variables that could explain the small relationships across tests.
5.2 Significance of Findings

In this examination of movement patterns in people with chronic LBP, we report multiple findings that add to the current scientific body of knowledge. First, although exercise is often recommended for the treatment of LBP,\textsuperscript{8-10} no specific exercise-based treatment has been found to be consistently better than another. We proposed that the primary reason for the inconsistent effects is that the previous treatments (e.g., exercise to increase cocontraction of deep spinal muscles) do not directly address how people with LBP move during functional activities. Thus, identifying an exercise-based treatment that is proposed to improve how people with LBP move in the short-term and long-term could provide a more effective and efficient form of care. Our study was the first to test the short- and long-term effects of an exercise-based intervention to improve an identified and relevant altered movement pattern in people with LBP. Importantly, we found that after 6 weeks of MST people with LBP increased movement of the knee and hip and decreased early movement of the lumbar spine during a functional activity test of PUO. We also found that the improved movement pattern obtained immediately post-MST was maintained 6 months after treatment. The maintenance of the improved pattern is particularly important because multiple studies report a short-term change in movement-related variables,\textsuperscript{11} but the changes in movement are often not sustained. One reason for our durable improvements in the movement pattern is that MST during functional activities employed principles of motor learning to drive change. This unique aspect of MST, where participants problem-solved how to perform LBP-limited activities without increased LBP symptoms, likely is responsible for the long-lasting effects. Therefore, if the goal of treatment is to change a long-standing, pain provoking, movement pattern during functional activities our findings suggest a priority for treatment is to provide person-specific, challenging practice in a way that promotes learning.
Another important finding from this dissertation was that SFE does not change movement of the knee, hip, and lumbar spine in the short-term or long-term. SFE is the primary non-surgical and non-pharmacologic approach to the treatment of LBP. Further SFE has been shown to improve LBP symptoms and function a statistically significant amount. However, recent findings suggest MST improves LBP and LBP-related functional limitations faster and to a greater extent than SFE. In combination with findings of this dissertation, one may postulate that one reason for greater improvement in clinical outcomes in MST is that SFE does not improve the person-specific altered movement pattern during LBP-limited functional activities.

A third relevant finding that contributes to the current body of knowledge is an understanding of the relationship of person-specific characteristics to the baseline and change over time in the altered movement pattern. Although on average MST improved the altered movement pattern and SFE did not, there was substantial variability in the baseline and change over time in the pattern (Figure 5.1). We used lumbar contribution, a ratio of early lumbar movement relative to early total movement, to index the altered movement pattern. The goal of understanding this variability in movement is to better target treatment strategies to the person with the goal of providing the most effective and efficient form of LBP care.
Figure 5.1. Individual trajectories of baseline and change over time in lumbar contribution. Lumbar contribution was a ratio of early (1st 50% of the descent phase) lumbar movement relative to early total movement.

We used HLM to understand the association of person-specific characteristics, such as gender, age, LBP duration, and baseline lumbar contribution to the baseline and change over time in lumbar contribution. The use of HLM in this study is unique and relevant because this data analytic approach is able to examine the relative associations of several continuous and categorical variables to lumbar contribution over time. Further, HLM as opposed to a standard regression approach, can better use all available data and handle variances of different levels of measurement (i.e., within a person vs. between people). To date, no prior study has modeled baseline movement and the change over time in movement after exercise-based interventions using these methods. The novelty of using this analytic approach in rehabilitation science is that it allows us to address many important questions such as: Which person-specific characteristics explain how a person
moves prior to treatment? How can a clinician expect their patient with a given set of characteristics to change their movement pattern over time when given a specific exercise-based treatment? Therefore, HLM is a superior analysis to understand both baseline and longitudinal data, and the findings of a HLM model can provide more specific information about relationships at a person-specific level.

Findings from the HLM model support that gender and age are associated with the movement pattern during a PUO test prior to treatment. Also, age and the baseline movement pattern are associated with the change over time in the pattern within MST only. Specifically, those who are younger than the sample mean (42.6 years) and display greater lumbar contribution at baseline improve the pattern more than older individuals or people who display less lumbar contribution at baseline. Further, we found that the number of years someone has LBP does not moderate the magnitude of altered movement pattern at baseline or the improvement in the pattern over time. This is of particular importance for those within the MST group, who significantly improved the altered movement pattern. Therefore, these data highlight that person-specific characteristics moderate a person’s movement pattern at baseline, as well as the change over time in the pattern after repeated sessions of MST.

Another finding from the HLM model was that person-specific characteristics do not moderate the change over time in the altered movement pattern within SFE. This finding is relevant as it extends the understanding of the effect of SFE on changing a movement pattern during a functional activity. Regardless of gender or the range of age, LBP duration, and baseline movement, SFE did not change an altered movement pattern that is associated with the clinical presentation. Therefore, these data support that even when examining the data at the person-
specific level, SFE is not an effective stimulus for changing a movement pattern in people with chronic LBP.

As mentioned in chapter 4, the Kinesiopathologic model is a conceptual framework for understanding how movements during daily functional activities may contribute to the development or persistence of musculoskeletal pain conditions. Briefly, the model proposes that people adopt a direction-specific altered movement pattern during functional activities. When the same direction-specific pattern is used repetitively across multiple functional activities, the pattern is proposed to lead to an accumulation of lumbar tissue stress, LBP symptoms, and micro- or macro-level injury. A key gap in understanding of this model was whether people display the same direction-specific movement pattern across multiple functional activities. We found small but stable direct relationships of a person’s movement pattern across functional tests of pick up an object, sit to stand, and sit and reach. These findings contribute to the understanding of LBP conditions because they, in part, provide support that people show a similar pattern across functional tests. However, given the small effects and multiple potential confounders, future studies are needed to fully understand if people with LBP display the same movement pattern with multiple functional activities across the day.

5.3 Future Studies

In chapter 2 MST improved an altered movement pattern in people with chronic, non-specific LBP. We excluded people that were in an acute flare up of LBP because this presentation has the potential to influence the person’s movement. Furthermore, movements of people in an acute episode of LBP are not well understood. For this reason future studies should first investigate whether the same altered movement pattern found in people with chronic LBP is observed in people in an acute episode. We also excluded people with specific structural spinal
conditions, such as a disc herniation. It is plausible that 1) the movement pattern discussed in this study exists in people with specific LBP, and 2) MST is effective in improving the altered movement pattern and clinical presentation in people with specific LBP conditions. Therefore, future research should examine these effects in people with non-chronic, specific LBP to understand the generalizability of MST.

Chapter 2 reports on the short- and long-term effects of MST and SFE on knee, hip, and lumbar spine early excursion during a single functional activity test of pick up an object. Although movements during this test are associated with LBP symptoms and functional limitations, we do not know if MST improves the pattern during other functional tests. Studies investigating the effects of MST on other functional activity tests could further support the efficacy of MST for improving movements during LBP-limited activities. It is also not well understood if MST improves alignment patterns during functional activities, such as standing and sitting. Understanding the effectiveness of MST to improve alignments is important because these postures are often 1) repetitively performed across the day and 2) often reported as painful activities for people with LBP. Therefore, additional studies should aim to understand the effects of MST on more LBP-limited functional activities.

Although we found MST improves movement of people with chronic LBP and other published data support MST improves LBP and LBP-related function greater than SFE, we do not know if the improved pattern is directly associated with the greater improvement in function in the short-term or over the long-term. Prior data support that after a single session of MST, there was an immediate improvement in both the altered movement pattern and pain. Investigating the relationship over time of the altered movement pattern during the pick up an object test and LBP symptoms and function is the next logical step. This would further the understanding of both 1)
the relevance of the altered movement pattern to the course of LBP, and 2) the clinical meaningfulness of the initially promising findings of MST for people with chronic LBP. These findings could bring much needed knowledge to the management of chronic LBP conditions and potentially inform clinical practice guidelines.

We also do not know the mechanism for how MST improves the altered movement pattern, pain or function. Recent neuroimaging studies have reported that there are structural and functional alterations within the central nervous system (CNS) of people with chronic or recurrent LBP compared to back healthy controls.22,23 Given MST is an exercise-based intervention that targets the CNS, it is plausible that MST changes representations of the motor cortex in people with LBP. The possible improved structure and function of the nervous system may be the primary contributing factor for the new movement pattern and improved pain and function after treatment of MST. Future studies should aim to understand the mechanism of MST for improving movement, pain and function in people with LBP. Knowledge of the specific mechanism could be used to tailor similar MST interventions for other musculoskeletal pain conditions (e.g., chronic hip pain).

Future studies should also aim to understand many of the potential confounders in the study described in chapter 4. For example, the differences in the movement goal across functional tests likely contributes to the small observed relationships. The scientific field of motor control is well advanced, particularly in studying people with neurological conditions. However, the role of internal and external aspects of motor control in people with pain is far less understood. Specifically many interesting questions need to be explored such as 1) do current LBP symptoms play a role in the complex motor planning prior to and during movement performance? 2) are aspects of learned movement performance a result of the pain condition or present prior to initial
pain symptoms? Such investigation would further the understanding of the factors that contribute to movement patterns found to be important in people with LBP conditions.

5.4 References


Appendix A: Supplementary Materials for Chapter 2
Data distributions over time

Early Knee Excursion

Baseline Early Knee Excursion (degrees)

Post-Treatment Early Knee Excursion (degrees)
Supplementary Figure 1. Data distributions of early knee excursion by treatment group

**Early Hip Excursion**
Supplementary Figure 2. Data distributions of early hip excursion by treatment group
Early Lumbar Excursion

![Histograms showing early lumbar excursion](image)

Baseline Early Lumbar Excursion (degrees)

Post-Treatment Early Lumbar Excursion (degrees)
Supplementary Figure 3. Data distributions of early lumbar excursion by treatment group
Appendix B: Supplemental Materials for Chapter 3
Sequence of HLM models

Preliminary step

Unconditional Model

Level 1: \( LC_{ui} = \pi_{0i} + e_{ui} \)
Level 2: \( \pi_{0i} = \beta_{00} + r_{0i} \)

Building up the Most Parsimonious Level 1 Model

Linear Time

Level 1: \( LC_{ui} = \pi_{0i} + \pi_{1i} Time_{ui} + e_{ui} \)
Level 2: \( \pi_{0i} = \beta_{00} + r_{0i} \)
\( \pi_{1i} = \beta_{10} + r_{1i} \)

Non-Linear (Quadratic) Time

Level 1: \( LC_{ui} = \pi_{0i} + \pi_{1i} Time_{ui} + \pi_{2i} Time_{ui}^2 + e_{ui} \)
Level 2: \( \pi_{0i} = \beta_{00} + r_{0i} \)
\( \pi_{1i} = \beta_{10} + r_{1i} \)
\( \pi_{2i} = \beta_{20} + r_{2i} \)

Building up the Most Parsimonious Level 2 Model

Treatment group as a between-subjects factor

Level 1: \( LC_{ui} = \pi_{0i} + \pi_{1i} Time_{ui} + \pi_{2i} Time_{ui}^2 + e_{ui} \)
Level 2: \( \pi_{0i} = \beta_{00} + \beta_{01} TxGroup + r_{0i} \)
\( \pi_{1i} = \beta_{10} + \beta_{11} TxGroup + r_{1i} \)
\( \pi_{2i} = \beta_{20} + \beta_{21} TxGroup + r_{2i} \)
**Person-specific characteristics simultaneously as a between-subjects factor**

Level 1: $\text{LC}_{it} = \pi_{0i} + \pi_{1i}\text{Time}_i + \pi_{2i}\text{Time}_i^2 + e_i$

Level 2: $\pi_{0i} = \beta_{00} + \beta_{01}\text{TxGroup} + \beta_{02}\text{Gender} + \beta_{03}\text{Age} + \beta_{04}\text{LBP}_\text{duration} + r_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}\text{TxGroup} + \beta_{12}\text{Gender} + \beta_{13}\text{Age} + \beta_{14}\text{LBP}_\text{duration} + \beta_{15}\text{Base}_\text{LC} + r_{1i}$

$\pi_{2i} = \beta_{20} + \beta_{21}\text{TxGroup} + r_{2i}$

**Interaction of person-specific characteristics with TxGroup and linear time component**

Level 1: $\text{LC}_{it} = \pi_{0i} + \pi_{1i}\text{Time}_i + \pi_{2i}\text{Time}_i^2 + e_i$

Level 2: $\pi_{0i} = \beta_{00} + \beta_{01}\text{TxGroup} + \beta_{02}\text{Gender} + \beta_{03}\text{Age} + \beta_{04}\text{LBP}_\text{duration} + r_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}\text{TxGroup} + \beta_{12}\text{Gender} + \beta_{13}\text{Age} + \beta_{14}\text{LBP}_\text{duration} + \beta_{15}\text{Base}_\text{LC} + \beta_{16}\text{TxGroup}\ast\text{Gender} + \beta_{17}\text{TxGroup}\ast\text{Age} + \beta_{18}\text{TxGroup}\ast\text{LBP}_\text{duration} + \beta_{19}\text{TxGroup}\ast\text{Base}_\text{LC} + r_{1i}$

$\pi_{2i} = \beta_{20} + \beta_{21}\text{TxGroup} + r_{2i}$

**Test quadratic interaction with significant linear person-specific characteristics**

Level 1: $\text{LC}_{it} = \pi_{0i} + \pi_{1i}\text{Time}_i + \pi_{2i}\text{Time}_i^2 + e_i$

Level 2: $\pi_{0i} = \beta_{00} + \beta_{01}\text{TxGroup} + \beta_{02}\text{Gender} + \beta_{03}\text{Age} + \beta_{04}\text{LBP}_\text{duration} + r_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}\text{TxGroup} + \beta_{12}\text{Gender} + \beta_{13}\text{Age} + \beta_{14}\text{LBP}_\text{duration} + \beta_{15}\text{Base}_\text{LC} + \beta_{16}\text{TxGroup}\ast\text{Gender} + \beta_{17}\text{TxGroup}\ast\text{Age} + \beta_{18}\text{TxGroup}\ast\text{LBP}_\text{duration} + \beta_{19}\text{TxGroup}\ast\text{Base}_\text{LC} + r_{1i}$

$\pi_{2i} = \beta_{20} + \beta_{21}\text{TxGroup} + \beta_{22}\text{Base}_\text{LC} + \beta_{23}\text{Age} + \beta_{24}\text{TxGroup}\ast\text{Base}_\text{LC} + \beta_{25}\text{TxGroup}\ast\text{Age} + r_{2i}$

**Final model**

Level 1: $\text{LC}_{it} = \pi_{0i} + \pi_{1i}\text{Time}_i + \pi_{2i}\text{Time}_i^2 + e_i$

Level 2: $\pi_{0i} = \beta_{00} + \beta_{01}\text{TxGroup} + \beta_{02}\text{Gender} + \beta_{03}\text{Age} + \beta_{04}\text{LBP}_\text{duration} + r_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}\text{TxGroup} + \beta_{12}\text{Gender} + \beta_{13}\text{Age} + \beta_{14}\text{LBP}_\text{duration} + \beta_{15}\text{Base}_\text{LC} + \beta_{16}\text{TxGroup}\ast\text{Gender} + \beta_{17}\text{TxGroup}\ast\text{Age} + \beta_{18}\text{TxGroup}\ast\text{LBP}_\text{duration} + \beta_{19}\text{TxGroup}\ast\text{Base}_\text{LC} + r_{1i}$

$\pi_{2i} = \beta_{20} + \beta_{21}\text{TxGroup} + \beta_{22}\text{Base}_\text{LC} + \beta_{23}\text{TxGroup}\ast\text{Base}_\text{LC} + r_{2i}$
Data distributions and outliers

Modeling diagnostics identified a sample distribution that approximates the normal population distribution. Furthermore, we did not identify a statistically significant outlier in lumbar contribution for the pick up an object test. Below are example figures and model diagnostics to examine data distributions, outliers, and assumptions of HLM models. Specifically, Supplementary Figure 6 shows Cook’s distance for lumbar contribution for all time points. This figure shows there is not an influential value at any time point that may bias the results of the HLM model. Second, Supplementary Figure 7 displays the fitted vs. residuals for the final HLM model, which confirms the assumption of homoscedasticity.

Supplementary Figure 4. Violin plot of sample distribution and potential outliers of lumbar contribution for the pick up an object test.
Supplementary Figure 5. Quantile-quantile plot of the lumbar contribution sample distribution relative to expected population theoretical distribution.

Supplementary Figure 6. Cook’s Distance for lumbar contribution at all time points.
Supplementary Figure 7. Plot of fitted vs. residuals of final HLM model. Even spread around the center line confirms to the assumption of homoscedasticity
Interpretation of HLM results from Chapter 3

Final model

Level 1: \[ \text{LC}_i = \pi_{0i} + \pi_{1i}\text{Time}_i + \pi_{2i}\text{Time}_i^2 + e_i \]

Level 2: \[ \pi_{0i} = \beta_{00} + \beta_{01}\text{TxGroup} + \beta_{02}\text{Gender} + \beta_{03}\text{Age} + \beta_{04}\text{LBP}_\text{duration} + r_{0i} \]

\[ \pi_{1i} = \beta_{10} + \beta_{11}\text{TxGroup} + \beta_{12}\text{Gender} + \beta_{13}\text{Age} + \beta_{14}\text{LBP}_\text{duration} + \beta_{15}\text{Base}_\text{LC} + \beta_{16}\text{TxGroup}\times\text{Gender} + \beta_{17}\text{TxGroup}\times\text{Age} + \beta_{18}\text{TxGroup}\times\text{LBP}_\text{duration} + \beta_{19}\text{TxGroup}\times\text{Base}_\text{LC} + r_{1i} \]

\[ \pi_{2i} = \beta_{20} + \beta_{21}\text{TxGroup} + \beta_{22}\text{Base}_\text{LC} + \beta_{23}\text{TxGroup}\times\text{Base}_\text{LC} + r_{2i} \]

The sample means across all participants (i.e., grand mean) are shown below.

Gender = 95 women, 59 male

Age = 42.5 ± 11.7 years

Duration of low back pain (LBP\_duration) = 10.3 ± 8.6 years

Baseline lumbar contribution (Base\_LC) = 32.6 ± 17.6%

Continuous Person-specific characteristics were centered at the sample mean. Centering involves rescaling predictors by subtracting a constant (e.g., mean). Centering the person-specific characteristic has no effect on the statistical significance of the variables. However, centering decisions impact the interpretation of the intercept. In this study time was centered at 3 points: 1) average baseline (0 weeks), 2) average post-treatment (8.9 weeks) and 3) average 6 month follow-up (35.6 weeks). This step was completed to test the various fixed effects at the time points of interest. A dummy coding method was used for the following categorical variables: 1) TxGroup (SFE = 0, MST = 1), 2) Gender (male = 0, female = 1). The table below shows the interpretation of the various fixed effects when centered at baseline.
<table>
<thead>
<tr>
<th>Variable Name</th>
<th>HLM Term</th>
<th>Fixed effect (SE)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>$\beta_{00}$</td>
<td>36.500 (2.432)</td>
<td>LC in SFE group</td>
</tr>
<tr>
<td>TxGroup</td>
<td>$\beta_{01}$</td>
<td>-2.385 (2.731)</td>
<td>Difference in LC between SFE and MST</td>
</tr>
<tr>
<td>Gender</td>
<td>$\beta_{02}$</td>
<td>-5.288 (2.699)</td>
<td>Difference in LC between men and women</td>
</tr>
<tr>
<td>Age</td>
<td>$\beta_{03}$</td>
<td>-0.224 (0.117)</td>
<td>Relationship of Age and LC</td>
</tr>
<tr>
<td>LBP Duration</td>
<td>$\beta_{04}$</td>
<td>-0.187 (0.159)</td>
<td>Relationship of LBP Duration and LC</td>
</tr>
<tr>
<td>Linear</td>
<td>$\beta_{10}$</td>
<td>-0.115 (.0183)</td>
<td>LC slope within SFE</td>
</tr>
<tr>
<td>TxGroup</td>
<td>$\beta_{11}$</td>
<td>-2.012 (0.272)</td>
<td>Difference in slope between SFE and MST</td>
</tr>
<tr>
<td>Gender</td>
<td>$\beta_{12}$</td>
<td>0.056 (0.086)</td>
<td>Difference in slope between men and women in SFE</td>
</tr>
<tr>
<td>Age</td>
<td>$\beta_{13}$</td>
<td>-0.004 (0.003)</td>
<td>Relationship of age and slope within SFE</td>
</tr>
<tr>
<td>LBP Duration</td>
<td>$\beta_{14}$</td>
<td>0.004 (0.005)</td>
<td>Relationship of LBP duration and slope within SFE</td>
</tr>
<tr>
<td>Baseline LC</td>
<td>$\beta_{15}$</td>
<td>-0.013 (0.010)</td>
<td>Relationship of baseline LC and slope within SFE</td>
</tr>
<tr>
<td>TxGroup X Gender</td>
<td>$\beta_{16}$</td>
<td>-0.177 (0.124)</td>
<td>Difference in slope between men and women from SFE to MST</td>
</tr>
<tr>
<td>TxGroup X Age</td>
<td>$\beta_{17}$</td>
<td>0.015 (0.005)</td>
<td>Difference in relationship of age and slope from SFE to MST</td>
</tr>
<tr>
<td>TxGroup X LBP Duration</td>
<td>$\beta_{18}$</td>
<td>-0.010 (0.007)</td>
<td>Difference in relationship of LBP duration and slope from SFE to MST</td>
</tr>
<tr>
<td>Term</td>
<td>Parameter</td>
<td>Estimate (SE)</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------</td>
<td>---------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td>TxGroup X Baseline LC</td>
<td>$\beta_{19}$</td>
<td>-0.058 (0.014)</td>
<td>Difference in relationship of Baseline LC and slope from SFE to MST</td>
</tr>
<tr>
<td><strong>Quadratic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta_{20}$</td>
<td>0.001 (0.005)</td>
<td>Quadratic LC slope within SFE</td>
</tr>
<tr>
<td>TxGroup</td>
<td>$\beta_{21}$</td>
<td>0.049 (0.007)</td>
<td>Difference in quadratic LC slope between SFE and MST</td>
</tr>
<tr>
<td>Baseline LC</td>
<td>$\beta_{22}$</td>
<td>0.001 (0.001)</td>
<td>Relationship of baseline LC and quadratic slope within SFE</td>
</tr>
<tr>
<td>TxGroup X Baseline LC</td>
<td>$\beta_{23}$</td>
<td>0.001 (0.000)</td>
<td>Difference in relationship of Baseline LC and quadratic slope from SFE to MST</td>
</tr>
</tbody>
</table>

*Interpretation of HLM model is shown centered at baseline.*
*Variables are partialed effects and interpreted as controlling for the other fixed effects.

a Gender, Age and LBP duration were tested as the effect on the grand mean.

LC = lumbar contribution
Appendix C: Supplemental Materials for Chapter 4
Data distributions and outliers

Pick up an object

Supplementary Figure 8. Quantile-quantile plot and box plot for pick up an object lumbar contribution

Shapiro-Wilk’s statistic = 0.99, p = 0.17
Supplementary Figure 9. Quantile-quantile plot and box plot for sit to stand lumbar contribution

All data: Shapiro-Wilk’s statistic = 0.94, p < 0.01; Grubb’s test = 5.21, p < 0.01
Outlier removed: Shapiro-Wilk’s statistic = 0.99, p = 0.49; Grubb’s test = 2.87, p = 0.28
Sit and reach

Supplementary Figure 10. Quantile-quantile plot and box plot for sit and reach lumbar contribution

All data: Shapiro-Wilk’s statistic = 0.99, p = 0.57; Grubb’s test = 3.52, p = 0.02
Outlier removed: Shapiro-Wilk’s statistic = 0.99, p = 0.71; Grubb’s test = 2.41, p = 0.90
Appendix D: Key Self-report Measures
Demographic, LBP, Medication and Medical History Questionnaire

Please check off the one best response.

A. Demographic Information

1. Age:
   ____ years

2. Sex:
   Male__
   Female__

3. Right-handed __
   Left-handed __

4. Current marital status:
   Married/living with significant other __
   Divorced/separated __
   Widowed __
   Single (never married) __

5. Race/Ethnicity:
   American Indian/Alaska Native: __
   Asian or Asian American: __
   Black or African American: __
   Hispanic or Latino: __
   Native Hawaiian or Other Pacific Islander: __
White: __
More than one race/ethnicity: __
Other: __

6. Primary occupation: __________________________________________________

7. Current employment situation:
   Currently working full time outside the home __
   Currently working part-time outside the home __
   Working full time from the home __
   Working part-time from the home __
   On paid leave __
   On unpaid leave __
   Unemployed __
   Homemaker __
   Student __
   Retired (not due to health) __
   Disabled &/or retired because of low back problem __
   Disabled due to health problem not related to low back problem __
   Other, please specify __________________________________________________

8. Education completed:
   Completed less than high school __
   Graduated from high school __
   Completed 1-3 yrs of college __
   Graduated from 2 yr associate degree or technical school __
Graduated from college (bachelor's degree or equivalent) __
Completed post-graduate or professional degree __

9. What is the amount of time between 1 minute and 12 hours that you can sit before low back pain starts or worsens? Please write 1 minute if your pain starts immediately and 12 hours if you can perform the activities for a full day or more before developing pain.

Sitting time before pain: __________ hours __________ minutes

10. What is the amount of time between 1 minute and 12 hours that you can stand before low back pain starts or worsens? Please write 1 minute if your pain starts immediately and 12 hours if you can perform the activities for a full day or more before developing pain.

Standing time before pain: __________ hours __________ minutes

11. What is the amount of time between 1 minute and 12 hours that you can walk before low back pain starts or worsens? Please write 1 minute if your pain starts immediately and 12 hours if you can perform the activities for a full day or more before developing pain.

Walking time before pain: __________ hours __________ minutes

12. Check all body areas where you have a history of musculoskeletal injury or pain:

   Face/Jaw_____ Neck_____ Upper back____ Low back_____ Pelvis_____  
   Shoulder_____ Upper arm____ Elbow_____ Forearm_____ Wrist_____ Hand_____  
   Hip_____ Thigh_____ Knee_____ Calf/Shin____ Ankle_____ Foot____
MEDICAL SCREENING FORM

Instructions: Please check off the appropriate answers.

1. Have you had a complete medical check-up within the last year?
   a. Yes __
   b. No __

2. Do you now have or have you recently had any of the following complaints?
   a. Shortness of breath __
   b. Dizziness/lightheadedness __
   c. Pain or a feeling of heaviness in your chest __
   d. Pulsating pain anywhere in your body __
   e. Constant and severe pain in lower leg (calf) __
   f. Discolored or painful feet __
   g. Swelling __
   h. Persistent pain at night __
   i. Constant pain anywhere in your body __
   j. Unexplained weight loss/10-15 lbs in 2 weeks __
   k. Loss of appetite __
   l. Unusual lumps or growths __
   m. Fatigue __
   n. Frequent or severe abdominal pain __
   o. Frequent heartburn or indigestion __
   p. Frequent nausea or vomiting __
   q. Change or problems with bladder function; i.e. urinary tract infection __
   r. Change or problems with bowel function __
   s. Unusual menstrual irregularities __
   t. Changes in hearing __
   u. Frequent or severe headaches __
   v. Problems with swallowing or changes in speech __
   w. Changes in vision (i.e. blurred vision or loss of sight) __
   x. Problems with balance or falling __
   y. Fainting spells __
   z. Problems with coordination __
   aa. Sudden weakness __
bb. Changes in sensation (i.e. numbness or tingling) __
c. Fever/night sweats __
dd. Recent severe emotional disturbances __
ee. Swelling or redness in any joints__
ff. Pregnant, or possibility of being pregnant __
gg. Recent weight increase or fluctuation __
Modified Oswestry Questionnaire

This questionnaire has been designed to give your therapist information as to how your low back pain has affected your ability to manage in everyday life.

Please answer each of the 10 questions by placing a mark in the one box that best describes your condition over the past week. We realize you may feel that 2 of the statements may describe your condition, but please mark only the box that most closely describes your condition over the past week.

CHECK OFF ONLY ONE ANSWER PER ITEM

1. **Pain Intensity (in the past week)**
   ___ I can tolerate the pain I have without having to use pain medication.
   ___ The pain is bad, but I can manage without having to take pain medication.
   ___ Pain medication provides me with complete relief from pain.
   ___ Pain medication provides me with moderate relief from pain.
   ___ Pain medication provides me with little relief from pain.
   ___ Pain medication has no effect on my pain.

2. **Personal Care (eg, Washing, Dressing) (in the past week)**
   ___ I can take care of myself normally without causing increased pain.
   ___ I can take care of myself normally, but it increases my pain.
   ___ It is painful to take care of myself, and I am slow and careful.
   ___ I need help, but I am able to manage most of my personal care.
   ___ I need help every day in most aspects of my care.
   ___ I do not get dressed, wash with difficulty, and stay in bed.
3. **Lifting (in the past week)**
   ___ I can lift heavy weights without increase pain.
   ___ I can lift heavy weights, but it causes increased pain.
   ___ Pain prevents me from lifting heavy weights off the floor, but I can manage if the weights are conveniently positioned (e.g., on a table).
   ___ Pain prevents me from lifting heavy weights, but I can manage light to medium weights if they are conveniently positioned.
   ___ I can lift only very light weights.
   ___ I cannot lift or carry anything at all.

4. **Walking (in the past week)**
   ___ Pain does not prevent me from walking any distance.
   ___ Pain prevents me from walking more than 1 mile. (1 mile = 1.6 km)
   ___ Pain prevents me from walking more than ½ mile.
   ___ Pain prevents me from walking more than ¼ mile.
   ___ I can only walk with crutches or a cane.
   ___ I am in bed most of the time and have to crawl to the toilet.

5. **Sitting (in the past week)**
   ___ I can sit in any chair as long as I like.
   ___ I can only sit in my favorite chair as long as I like.
   ___ Pain prevents me from sitting for more than 1 hour.
   ___ Pain prevents me from sitting for more than ½ hour.
   ___ Pain prevents me from sitting for more than 10 minutes.
   ___ Pain prevents me from sitting at all.

6. **Standing (in the past week)**
___ I can stand as long as I want without increased pain.
___ I can stand as long as I want, but it increases my pain.
___ Pain prevents me from standing more than 1 hour.
___ Pain prevents me from standing more than ½ hour.
___ Pain prevents me from standing more than 10 minutes.
___ Pain prevents me from standing at all.

7. **Sleeping (in the past week)**
   ___ Pain does not prevent me from sleeping well.
   ___ I can sleep well only by using pain medication.
   ___ Even when I take pain medication, I sleep less than 6 hours.
   ___ Even when I take pain medication, I sleep less than 4 hours.
   ___ Even when I take pain medication, I sleep less than 2 hours.
   ___ Pain prevents me from sleeping at all.

8. **Social Life (in the past week)**
   ___ My social life is normal and does not increase my pain.
   ___ My social life is normal, but it increases my level of pain.
   ___ Pain prevents me from participating in more energetic activities (eg, sports, dancing)
   ___ Pain prevents me from going out very often.
   ___ Pain has restricted my social life to my home
   ___ I have hardly any social life because of my pain.

9. **Traveling (in the past week)**
   ___ I can travel anywhere without increased pain.
   ___ I can travel anywhere, but it increases my pain.
___ My pain restricts my travel over 2 hours.
___ My pain restricts my travel over 1 hour.
___ My pain restricts my travel to short necessary journeys under ½ hour.
___ My pain prevents all travel except for visits to the physician/therapist or hospital.

10. Employment/Homemaking (in the past week)
___ My normal homemaking/job activities do not cause pain.
___ My normal homemaking/job activities increase my pain, but I can still perform all that is required of me.
___ I can perform most of my homemaking/job duties, but pain prevents me from performing more physically stressful activities (eg, lifting, vacuuming).
___ Pain prevents me from doing anything but light duties.
___ Pain prevents me from doing even light duties.
___ Pain prevents me from performing any job or homemaking chores.

11. Total score: (0-100%) ___ (For therapist’s use only)
Subject Code: ____________  Date: ____________  Lab Visit #: _____  Clinic Visit #: _____

Numeric Rating Scale of Symptoms

Please rate your LBP symptoms on a numeric scale of 0-10 with 0 = no symptoms and 10 = symptoms as bad as can be, rating you current symptoms, your average over the last 7 days, your worst over the last 7 days, your best over the last 7 days.

Numeric rating of LBP symptoms (0 = no symptoms 10 = symptoms as bad as can be)
  a. Current symptoms __
  b. Average symptoms in the last 7 days __
  c. Worst symptoms in the last 7 days __
  d. Best symptoms in the last 7 days __
Fear-Avoidance Beliefs Questionnaire (FABQ) \(^{3,4}\)

<table>
<thead>
<tr>
<th></th>
<th>Completely Disagree</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>My pain was caused by physical activity</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Physical activity makes my pain worse</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3.</td>
<td>Physical activity might harm my back</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>I should not do physical activities which (might) make my pain worse</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5.</td>
<td>I cannot do physical activities which (might) make my pain worse</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The following statements are about how your **normal work** affects (or would affect) your back pain.

<table>
<thead>
<tr>
<th></th>
<th>Completely Disagree</th>
<th>Unsure</th>
<th>Completely Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.</td>
<td>My pain was caused by my work or by an accident at work</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7.</td>
<td>My work aggravated my pain</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8.</td>
<td>I have a claim for compensation for my pain</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
9. My work is too heavy for me 0 1 2 3 4 5 6
10. My work makes or would make my pain worse 0 1 2 3 4 5 6
11. I should not do normal work with my present pain 0 1 2 3 4 5 6
12. I cannot do my normal work with my present pain 0 1 2 3 4 5 6
13. I cannot do my normal work until my pain is treated 0 1 2 3 4 5 6
14. I do not think that I will be back to my normal work within 3 months 0 1 2 3 4 5 6
15. I do not think that I will ever be able to go back to that work 0 1 2 3 4 5 6

References


CURRICULUM VITAE

NAME: Quenten Lowell Hooker

DATE: May 15, 2021

ADDRESS and TELEPHONE:

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PRESENT POSITION:

Doctoral Candidate in Movement Science Program  
Washington University in St. Louis

EDUCATION:

2013 Illinois Central College  
East Peoria, Illinois  
Associate of Engineering Science

2015 Quincy University  
Quincy, Illinois  
Bachelor of Science in Mathematics  
Minor in Biology

2017 University of Kentucky  
Lexington, Kentucky  
Master of Science in Kinesiology-Biomechanics  
Mentor: Dr. Michael B. Pohl, PhD

2018-2021 Washington University School of Medicine  
St. Louis, Missouri  
Master of Science in Clinical Investigation  
Mentor: Dr. Linda Van Dillen, PT, PhD, FAPTA

2017-2021 Washington University  
St. Louis, Missouri  
Doctor of Philosophy in Movement Science  
Mentor: Dr. Linda Van Dillen, PT, PhD, FAPTA
ACADEMIC POSITIONS/EMPLOYMENT:

2014-2015  Supplemental Instructor
            Department of Mathematics
            Quincy University, Quincy, IL
            Supervisor: Dr. Ping Ye, PhD

2015-2017  Research Coordinator I
            Department of Biomedical Engineering/College of Nursing
            University of Kentucky, Lexington, Kentucky
            Supervisor: Dr. Elizabeth G. Salt, PhD, RN, APRN

2018-2020  Predoctoral Trainee and Research Assistant
            Clinical Research Training Center
            Washington University School of Medicine, St. Louis, Missouri
            Supervisor: Dr. Jay Piccirillo, MD, FACS

2017-Present Precorator Trainee and Research Assistant
        Department of Physical Therapy
        Washington University, St. Louis, Missouri
        Supervisor: Dr. Linda Van Dillen, PT, PhD, FAPTA

RESEARCH SUPPORT:

2015-2017  Role: Research Coordinator I
            Title: “The Effects of a Cognitive Treatment for Acute Low Back Pain”
            Source: National Institute of Health
            Grant #: UL1 TR001998
            Principal Investigator: Dr. Elizabeth G. Salt, PhD
            Funding: $20,500

2017-2018  Role: Predoctoral Trainee and Research Assistant
            Title: “Doctoral Training in Movement Science”
            Source: National Institute of Health
            Grant #: T32 HD007434
            Principal Investigator: Dr. Catherine Lang, PT, PhD
            Funding: $209,422 (direct costs funding year; one of 3 trainees supported
            by the award)

2018-2020  Role: Co-Investigator
            Title: “The Effects of Structural Hip Joint Alterations on Low Back Pain
            Presentation”
            Source: Program of Physical Therapy Research Division
            Funding: $2,000.00
2018-2020  Role: Predoctoral Trainee and Research Assistant  
Title: “Predoctoral Training in Clinical Investigation”  
Source: National Institute of Health  
Grant #: TL1 TR002344  
Principal Investigator: Dr. Jay Piccirillo, MD, FACS  
Funding: $733,803 (direct costs current funding year; one of several trainees supported by the award)

2019-Present  Role: Co-Investigator  
Title: “Impact of Hip Structure and Function on the Clinical Presentation of Low Back Pain”  
Source: American Physical Therapy Association  
Grant #: P19-03313  
Principal Investigator: Dr. Linda R. Van Dillen, PT, PhD, FAPTA  
Funding: $38,894.00

HONORS and AWARDS:

2011-2013  Presidential Academic Scholarship, Illinois Central College  
2013-2015  Presidential Academic Scholarship, Quincy University  
2015  Magna Cum Laude, Quincy University  
2017  Predoctoral Research Travel Award, University of Kentucky  
2019  Burroughs-Wellcome Fund Travel Award  
2019  Distinguished Abstract Travel Award, Musculoskeletal Research Center, Washington University School of Medicine  
2019  Finalist for the David Winter Young Investigator Award, International Society of Biomechanics

PROFESSIONAL SOCIETIES and ORGANIZATIONS:

2016-present  American Society of Biomechanics  
2018-present  Association for Clinical and Translational Science

TEACHING TITLES and RESPONSIBILITIES:

2014-2015  Algebra 1; Supplemental Instructor  
2018-2019  Kinesiology 1; Teaching Assistant  
2018-2019  Kinesiology 1; Invited Lecturer

BIBLIOGRAPHY:

Peer-Reviewed Manuscripts – Published/In Press


**Conference Presentations and Proceedings**


12. **Hooker QL**, Roles KM, Lanier VM, Van Dillen LR. Consistent Differences in Lumbar Alignment between Chronic Low Back Pain Subgroups During Functional and Clinical Sitting Tests. *14th Annual Research Training Symposium-Washington University School of Medicine*, 2019, October 8, St Louis, MO, USA. [Podium]


