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BIOMECHANICAL EFFECTS OF A HIP ORTHOSIS ON LUMBO-PELVIC COORDINATION

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BIOMECHANICAL EFFECTS OF A HIP ORTHOSIS ON LUMBO-PELVIC COORDINATION

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering in the College of Engineering at the University of Kentucky

By

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ABSTRACT OF THESIS

BIOMECHANICAL EFFECTS OF A HIP ORTHOSIS ON LUMBO-PELVIC COORDINATION

Abnormal lumbar movement has been observed in individuals who have a history of low back pain (LBP). Affected individuals display a reduction in lumbar spine rotation during trunk movement tasks, while pelvic rotation increases to compensate. Reduced lumbar contribution to forward bending is associated with increased compressive forces and increased shearing demand of the task on the lower back. This abnormal lumbo-pelvic coordination (LPC) can persist beyond LBP symptom alleviation and may contribute to further occurrences or more severe cases of LBP. This study serves as a first step in investigating if abnormal LPC can be corrected with a hip orthosis by examining the effects of the device on the LPC of healthy individuals. Twenty participants without presence or history of LBP were recruited to participate in a repeated measures study, completing trunk motion tasks with and without a hip orthosis. In a random order, participants completed forward bending and backward return, lateral bending to the left and right, and axial twisting to the left and right. Thoracic, lumbar, and pelvic rotation along with lumbar-thoracic ratio (LTR) were calculated for each of the movement tasks. Thoracic rotation (total trunk movement) was not significantly altered ($p>0.05$, $F=0.633$) by the application of the hip orthosis. LTR was significantly increased ($p<0.001$, $F=2.96$) with the orthosis by 32%, 22%, 12%, 4%, and 12% for axial twisting left, axial twisting right, lateral bending left, lateral bending right, and forward bending, respectively. This indicates lumbar contributions were increased by physically restricting the pelvis. The effects of a hip orthosis should be further investigated in LBP patients to verify correction of an abnormal LPC.

KEYWORDS: low back pain, lumbo-pelvic coordination, lumbopelvic rhythm, orthosis

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CHAPTER 1. INTRODUCTION

1.1 Low Back Pain

Low back pain (LBP) is a condition that affects up to 38% of individuals each year. (Hoy et al., 2012) Although the clinical course of LBP is favorable for most patients, up to 44% of patients will experience recurrence within 1 year, (Woolf and Pfleger, 2003) and 10-15% will end up developing chronic LBP. (Balagué et al., 2012) The total costs, both direct and indirect, associated with LBP have been suggested to exceed $100 billion annually, (Katz, 2006) and chronic LBP is the leading cause of disability globally. (Maher et al., 2017) Another concern facing individuals with LBP is opioid use. More than half of regular opioid users report back pain and opioid prescriptions for LBP patients in the US have risen in recent years, despite a lack of evidence linking opioid use with improved functional outcomes. (Deyo et al., 2015) A major challenge in the prevention and treatment of LBP is the inability to identify the root cause in each specific case. LBP is most commonly diagnosed as non-specific LBP, with a more specific diagnosis assigned in only 10% of cases. (Krismer and van Tulder, 2007)

Apart from psychosocial factors or history of LBP, possession of a long, stiff, or flat back was found to predispose an individual to LBP. (Adams et al., 1999) Diagnostic tests used by clinicians to identify the source of LBP demonstrate mixed accuracy and usefulness. (Hancock et al., 2007) This has led researchers to examine the biomechanical differences in LBP patients to better understand the presentation of LBP symptoms. Individuals with LBP demonstrate different lower back biomechanics (altered lumbar and pelvis movements) than individuals without LBP. Mayer et al. first proposed a method for examining spinal range of motion noninvasively, compared to x-ray methods which were common at the time, and reported less lumbar contribution from chronic LBP patients during a standing flexion task. (Mayer et al., 1984) The measurement of lumbar flexion relative to pelvic rotation has been frequently examined in LBP patients and is commonly referred to as lumbopelvic rhythm (LPR) or lumbo-pelvic coordination (LPC). Changes in LPC could suggest changes in control and loading of the trunk, which may play a role in development of LBP. (Vazirian et al., 2016b)

1.2 Characterization of LPC

LPC, or LPR, refers to the pattern of lumbar movement relative to pelvic movement, and is usually characterized in one of two ways: the magnitude aspect or the timing aspect. The timing aspect focuses on order and sequence of the lumbar spine and pelvis contributions to the total trunk movement. The magnitude aspect, on the other hand, focuses on the amount of contributions of the lumbar spine and pelvis to the total trunk movement. A detailed review of methods and measures used to characterize the timing and magnitude aspects of LPC can be found in Vazirian et al (2016a). For the purposes of this study, however, a brief review of literature reporting the magnitude aspect of LPC is provided here.

LPC is typically assessed during a trunk forward bending and backward return task. Specifically, the subject starts from a standing upright posture, bends forward in a manner as if one were attempting to reach for their toes, and then returns to the original standing position (Figure 1.1). While there are variations in measurement methods, the main trunk segment movements measured are the pelvis and thorax. Thoracic movement is often assumed as the total range of motion for the trunk, and lumbar flexion is calculated by subtracting pelvic rotation from thoracic rotation (Figure 1.2). The magnitude aspect of LPC is generally characterized using the values of thoracic, lumbar, and pelvic rotations acquired from the position of maximum trunk forward bend posture. Specifically, the ratio of pelvic (or lumbar) rotation over thoracic rotation representing the percent contribution of pelvic (or lumbar spine) rotation to the total trunk movement or the ratio of lumbar spine to pelvic rotations representing lumbo-pelvic ratio are characterized as magnitude aspect of LPC.

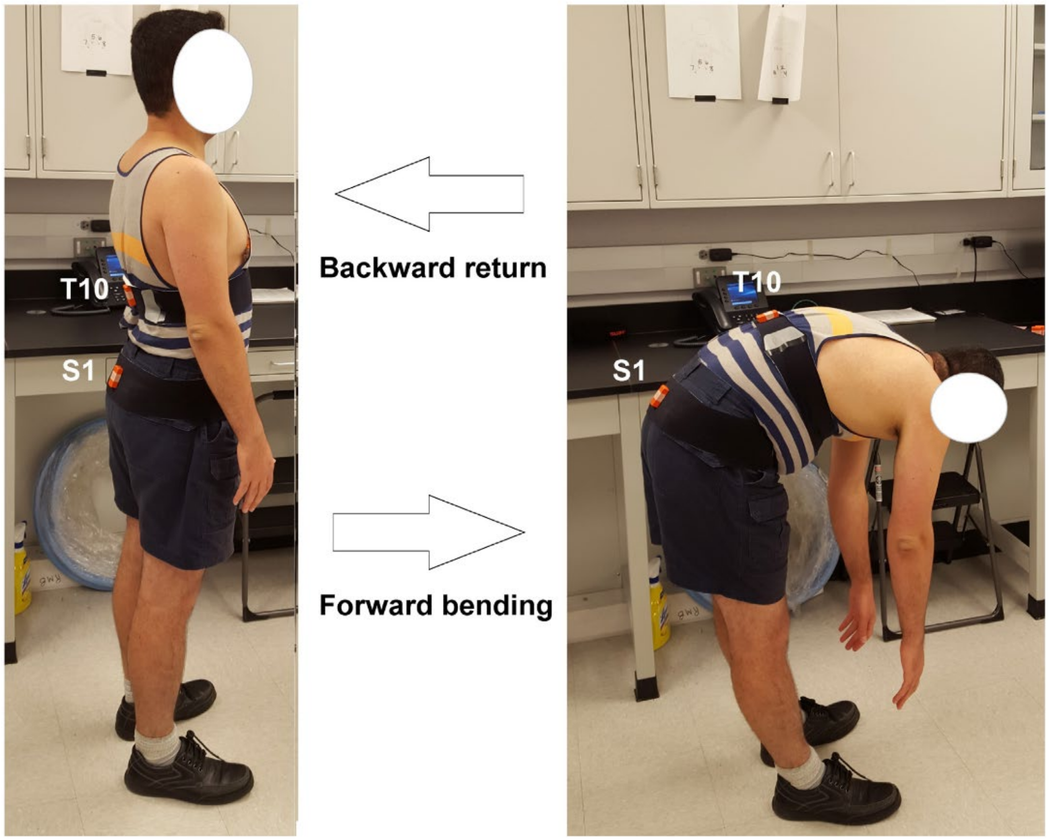

Figure 1.1 Example of standing forward flexion task. Adopted from (Vazirian et al., 2017b)

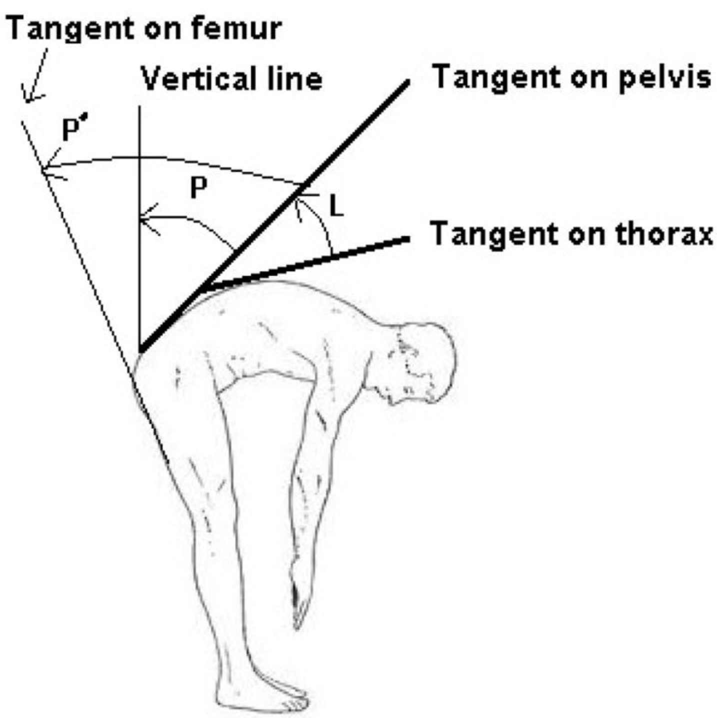

Figure 1.2 Measurements acquired for pelvic rotation (P) and lumbar rotation (L). Adopted from (Vazirian et al., 2016a)

1.3 Abnormal Lumbo-Pelvic Coordination (LPC)

Vazirian et al. have summarized the findings from studies examining LPC in asymptomatic individuals, patients with LBP, and individuals with a history of LBP. Patients with LBP generally have smaller lumbar contributions, and larger pelvic contributions, to trunk movement tasks than asymptomatic individuals with no history of LBP. Additionally, abnormal LPC in individuals who have a history of LBP (with no current symptoms) have also been reported. (Vazirian et al., 2016b)

Using a lumbar monitor, Marras and Wongsam examined trunk angle and velocity during trunk forward bending and hyperextension tasks. They found patients with chronic LBP to have a 25% smaller lumbar contribution during forward bending and backward return when compared to healthy controls. (Marras and Wongsam, 1986) Ahern et al. examined lumbar flexion in chronic LBP patients during a forward bending task. Lumbar flexion was measured using dual goniometers, and patients were found to have an average of 27 degrees compared to 52 degrees in healthy controls. (Ahern et al., 1988) Porter and Wilkinson conducted a study with the sole purpose of comparing relative hip and lumbar motion between men diagnosed with chronic LBP and men without LBP. They reported the chronic LBP patients diverged into two groups at maximum flexion, one of which displayed a larger amount of pelvic rotation with less lumbar flexion. (Porter and Wilkinson, 1997) This abnormal LPC, the reduction of lumbar flexion and increase of pelvic rotation, was also documented in a case study by O’Sullivan, who went on to propose it is a mal-adaptive response where compensations for LBP in turn become a mechanism that drives the disorder. (O'Sullivan, 2005)

Abnormal LPC has also been investigated in non-chronic LBP patients. Paquet et al. found non-chronic LBP patients exhibited smaller lumbar movements compared to healthy individuals during a forward bending task. Pelvis-spine movement interactions, movement velocities, and muscle activation patterns were examined during trunk forward bending. Individuals with LBP demonstrated a lower mean angular displacement of the thoracolumbar (T8-S1) spine than healthy individuals. The LBP patient group was further divided into two subgroups, one with pelvis-spine movement similar to healthy controls and one with abnormal pelvis-spine movement. For the LBP patients with abnormal movement, the duration of their LBP was significantly longer (39 vs 20 days) compared to the LBP patients with normal movement. (Paquet et al., 1994) Shojaei et al. examined lumbo-pelvic kinematics in non-chronic LBP patients and similarly found smaller lumbar flexion during a trunk forward bending task compared to healthy controls. They also reported LBP patients had a smaller lumbar angular velocity, acceleration and deceleration, as well as a higher pelvic rotation. The authors suggest this is likely to be a movement adaptation to reduce demands on the lumbar spine and avoid further aggravation. (Shojaei et al., 2017a)

1.4 Persistence of LPC beyond symptom improvement

Recent studies from our lab suggest that abnormal LPC observed in individuals with LBP can persist or worsen even after significant improvements in pain. In a study examining recovery from an episode of LBP, Ferguson et al. recorded patients' symptoms and functional performance, using a lumbar motion monitor during trunk flexion-extension tasks, and reported trunk movements were not normalized for several weeks after pain had subsided. (Ferguson et al., 2000) Thomas and France further examined lumbar flexion during patients' recoveries from non-chronic LBP, finding that patients engage in fear-avoidance behavior, reducing the motion of the lumbar spine. (Thomas and France, 2008) They discovered patients with a high fear of re-injury displayed reduced lumbar contributions that persisted at 12 weeks following LBP onset.

1.5 Abnormal LPC and LBP recurrence

Retaining an abnormal LPC could be detrimental on the spine and supporting tissues. A biomechanical modeling study by Tafazzol et al. demonstrated a reduction in lumbopelvic ratio (e.g. a decrease in lumbar flexion) would indicate a decrease in passive lumbar contributions to external moments and spinal loads, increasing the compression and shear forces at the L5-S1 vertebral location during a forward flexion task. (Tafazzol et al., 2014) While examining age-related differences in lumbar flexion, Vazirian et al. expanded on this concept stating less lumbar flexion indicates less stretch from spinal supporting tissues, meaning fewer passive contributions from these tissues. The result would be an increase in active contributions leading to higher forces on the lower spine according to the model. (Vazirian et al., 2017a) Shojaei et al. further examined the effects of abnormal LPC as individuals bent forward to lower a small load (4.5 kg) to knee height and returned to standing. LBP patients experienced significantly higher shearing demands on the lower back than healthy controls due to a smaller amount of lumbar flexion. (Shojaei et al., 2018)

As described in the previous section, patients with LBP can retain and continue to display abnormal LPC even after symptoms of pain have been relieved or diminished. (Ferguson et al., 2000; Thomas and France, 2008) In a review conducted by Silva et al., LBP recurrence was found to be as high as 33% within 1 year following an episode of LBP, and that a previous episode of LBP was the only significant predictor for LBP recurrence. (Silva et al., 2017) Given the knowledge previously reported regarding increased loading on the lumbar tissues from an abnormal LPC, and that individuals could retain these movements after an episode of LBP, it is worth investigating if abnormal LPC could play a role in LBP recurrence. Furthermore, as it was discussed in section 1.3, patients with chronic LBP demonstrate similar abnormality in LPC (Ahern et al., 1988; Marras and Wongsam, 1986; O'Sullivan, 2005; Porter and Wilkinson, 1997), giving support to the idea of examining if abnormal LPC can be corrected, and if that correction could play a role in decreasing recurrence of LBP or its transition to chronic stage.

1.6 LPC correction

Exercise programs that include coordination or stabilization have shown effective in reducing chronic LBP. (Searle et al., 2015) Shahvarpour et al. examined what effects an 8-week lumbar stabilization exercise program would have on LPC and flexion-relaxation in LBP patients. (Shahvarpour et al., 2017) LPR was evaluated during a trunk forward bending task performed before and after the 8-week program. While patients reported a decrease in pain after completing the program, there was no significant change in LPR. Patients continued to exhibit a smaller lumbar range of motion and larger pelvic range of motion, when compared to healthy controls. The authors suggested that patients learned to stiffen the lumbar spine during the program and retained the movement pattern after the decrease in pain, which is not necessarily beneficial to the patient.

Mayer et al. examined the effects of a functional restoration program on lumbar flexion-relaxation and lumbar range of motion. (Mayer et al., 2009) Lumbar and pelvic range of motion was measured by physical therapists with inclinometers while participants were at maximum flexion. Out of the 49 LBP patients who completed the program and had not received a spinal surgery, 32 exhibited a normal lumbar range of motion after the treatment, compared to only 13 with a normal lumbar range of motion before treatment began. Patients who achieved normal range of motion reported much lower pain ratings compared to patients who retained abnormal motion patterns. While this study correlates a normal LPC with a reduction in LBP, approximately 35% of these patients were unable to achieve a normal LPC with this treatment method, indicating further interventions are necessary for LPC to be corrected.

Larivière et al. examined the effects of different lumbar belt designs on LPR, to determine if lumbar belts may be a viable treatment option for individuals with

LBP. (Lariviere et al., 2014) Understandably, wearing a lumbar belt results in a decrease in both lumbar and thoracic range of motion during a flexion task. They suggested that wearing a lumbar belt may be beneficial to combat injury associated with progressive creep of the passive tissues in the lumbar spine due to repetitive lumbar flexion. Additionally, they recommended more investigations should be conducted with lumbar belt use and identification of patients that may benefit. While a lumbar belt may be useful for individuals with a lumbar spine injury, it would not be effective at correcting abnormal LPC. Based on the results provided from Larivière et al., a lumbar belt would reduce lumbar contributions, resulting in further abnormalities in LPC. If a lumbar belt is desired to reduce the risk of re-injury, examinations should be conducted to ensure the patient does not retain abnormal LPC beyond application of the belt. Furthermore, if the purpose of the belt is to reduce lumbar flexion, research indicates LBP patients can adopt this LPC without the use of a lumbar belt which calls into question the need of such a device.

1.7 Correction of LPC via physical restriction of hip joint

As opposed to a lumbar orthosis/belt, a hip orthosis that restricts/reduces hip rotation is more likely to shift LPC of patients toward normal patterns by encouraging an increase in lumbar contributions. Rather than focusing on strengthening targeted muscle groups as in an exercise program, restricting the pelvis could assist the patient in overall movement training to adopt correct LPC. Our goal is to verify whether abnormal LPC of patients with LBP can be corrected using a hip orthosis. As a first step, the effects of a hip orthosis on LPC of healthy individuals were investigated in this master’s thesis. The effects of wearing a hip orthosis on LPC were examined during several trunk motion tests: forward bending and backward return, lateral bending, and axial twisting. Although healthy individuals are not expected to display abnormal LPC, it was hypothesized that the hip orthosis will alter LPC by reducing pelvic motion and increasing lumbar contributions to total trunk motion. If successful, this will serve as justification for examining LBP patients for similar effects with the hip orthosis.

CHAPTER 2. METHODS

2.1 Study Design and Participants

A repeated measures study design was used to evaluate the effects of a hip orthosis on LPC across a set of 3 tasks: 1) forward bending and backward return, 2) lateral bending to the left and to the right, and 3) axial twisting to the left and to the right. Twenty healthy participants (11 M, 9 F; summarized in Table 1) were recruited to complete the 3 tasks in a random order with and without the orthosis. Exclusion criteria included presence or history of low back pain and presence of musculoskeletal or neuromuscular disorders that could affect LPC. All participants completed an informed consent procedure and a screening process approved by the University of Kentucky Institutional Review Board before any measurements were obtained.

Table 2.1 Groups compared using two-sample t-Test

Participant Demographics (SD)			
	M	**F**	**p-values**
Age	22.8 (2.7)	22.6 (3.9)	0.873
Height (cm)	176.6 (6.9)	166.5 (3.7)	0.001
Weight (kg)	82.2 (14.6)	74.1 (18.2)	0.323

2.2 Experimental Procedures

Participants were initially instrumented using wireless, tri-axial inertial measurement units (IMUs; Xsens Technologies, Enschede, Netherlands) placed superficially over the T10 (thorax) and S1 (pelvis) vertebrae to obtain trunk kinematics. The IMUs were assumed to measure the rotations of the thorax and pelvis as rigid bodies. The difference between the two rotations was considered to represent lumbar rotation as a joint. Once the IMUs were placed on the participant, their position was not disturbed in order to maintain accuracy across tasks and conditions.

Each participant then completed the trunk movement tasks with and without wearing a hip orthosis. The starting condition (i.e., with and without orthosis) and task (i.e., forward bending and backward return, lateral bending to the left and right, and axial twisting to the left and right) order were randomized for each participant. Tasks were first demonstrated by research personnel and movement cues were given by computer program. Participants would hear an auditory tone to begin movement, reach their maximum range of motion, hold at their maximum range of motion until hearing another tone to return to standing position. The return cue was given 5 to 8 seconds after the starting cue for each repetition of each task. For all tasks, participants began in an upright standing position with their arms crossed against their chest. For the forward bending and backward return task, participants were instructed to keep their knees straight while bending forward to maximum trunk flexion, holding at maximum trunk flexion posture until hearing the cue to return to standing. For lateral bending to the left and to the right, participants were instructed to bend sideways to the left first, holding at maximum range of motion until receiving the cue to return to standing. Participants then paused at neutral standing posture until hearing the auditory cue to start the bend to the right. They would similarly bend to their maximum lateral bending posture and hold at maximum range of motion before returning to standing. Participants continued with the task, alternating sides for each repetition. The axial twisting to the left and to the right were done similar to lateral bending to the left and to the right except that participant twisted instead of bending their trunk. For the forward bending and backward return task, participants completed a total of 6 repetitions for each condition (with and without orthosis). For the axial twisting and lateral bending tasks, participants completed a total of 8 repetitions (4 to either side) for each condition.

The hip orthosis used to constrain pelvic contribution to trunk motion during the experiments was a compression wrap (BodyMate, CA, USA) that attaches to the individual via hook and loop fasteners around the waist and each thigh (Figure 3). It was constructed of flexible, neoprene material and was a universal fit (the same orthosis was used for all participants).

Figure 2.1 Hip Orthosis (BodyMate, CA, USA)

2.3 Data Collection and Analysis

MT Manager (Xsens Technologies, Enschede, Netherlands) was used to obtain three-dimensional orientation data from the IMUs. Kinematics data was sampled at a rate of 60 Hz and then passed through a Kalman filter to minimize noise on the data. IMU data was then further analyzed using custom scripts in Matlab (MathWorks, MA, USA). Rotation matrices from the IMUs were used to calculate rotations of the thorax and pelvis in the primary plane of motion for each task (e.g. sagittal plane for trunk forward bending and backward return). At each time point, lumbar rotation was calculated as the difference between thoracic and pelvic rotation. The following measures were extracted for subsequent analyses: 1 – thoracic rotation; 2 – pelvic rotation; 3 – lumbar rotation; 4 – Lumbar-thoracic ratio. For thoracic, pelvic, and lumbar rotation, the range of motion for individual repetitions of the task were averaged to find a single value for each measure for the respective task. Lumbar-thoracic ratio (LTR) was calculated by dividing lumbar rotation by thoracic rotation. Thoracic rotation was considered to represent maximum trunk range of motion. LTR (presented as a percentage) is representative of the lumbar contribution to total thoracic rotation (total range of motion of the task).

$$LTR = \frac{Lumbar\ Rotation}{Thoracic\ Rotation} = \frac{Thoracic\ Rotation - Pelvic\ Rotation}{Thoracic\ Rotation} \times 100\%$$

2.4 Statistical Analysis

For each task, thoracic rotation, pelvic rotation, lumbar rotation, and LTR were extracted for statistical analysis. As thoracic rotation provides the total range of motion for the task, this variable indicates the effect of the orthosis on total task performance. Pelvic rotation and lumbar rotation give information on the magnitude of movement that occurred through these segments under the different conditions. In the event of a difference in total range of motion between conditions (with and without orthosis), LTR provides the lumbar *contribution* to total range of motion whereas lumbar rotation (or pelvic rotation) may not provide a clear picture. For axial twisting and lateral bending the effects of the orthosis on these variables was analyzed separately for the left and right directions, due to non-uniformity in participant movements. Two-way repeated measures ANOVA tests were used to investigate the effects of tasks (with five levels) and condition (with two levels) on dependent variables (thoracic rotation, pelvic rotation, lumbar rotation, and LTR). Statistical procedures were conducted in Excel (Microsoft, WA, USA) with a p-value of less than 0.05 indicating statistical significance.

CHAPTER 3. RESULTS

3.1 Summary of statistics

The summary of statistical analyses related to the effects of condition (with and without orthosis) and task (axial bending to the left and right, lateral bending to the left and right, and forward bending) on the dependent variables (thoracic rotation, pelvic rotation, lumbar rotation, and LTR) are presented in Table 2.1. There were no significant interactions between the task and condition for any of the dependent variables.

Table 3.1 Results from two-way ANOVA; p-value < 0.05 and F > 1 indicate significance

	p-Values			F		
Variable	Condition	Task	Interaction	Condition	Task	Interaction
Thoracic Rotation	0.118	**< 0.001**	0.882	0.633	**48.6**	0.121
Pelvic Rotation	**< 0.001**	**< 0.001**	0.427	**3.28**	**51.6**	0.399
Lumbar Rotation	0.265	**< 0.001**	0.882	0.322	**25.0**	0.121
LTR	**< 0.001**	**< 0.001**	0.878	**2.96**	**68.1**	0.124

3.2 Thoracic Rotation

There were no significant differences in thoracic rotation for axial twisting to the left (51° (13°) vs 49° (12°)), axial twisting to the right (54° (13°) vs 48° (11°)), lateral bending to the left (27° (5.4°) vs 27° (6.7°)), lateral bending to the right (28° (7.5°) vs 26° (5.5°)), or forward bending (80° (20°) vs 76° (18°)) between normal and orthosis conditions. There were, however, significant differences in all measures of thoracic rotation between the tasks of axial twisting, lateral bending, and forward bending. (Figure 3.1)

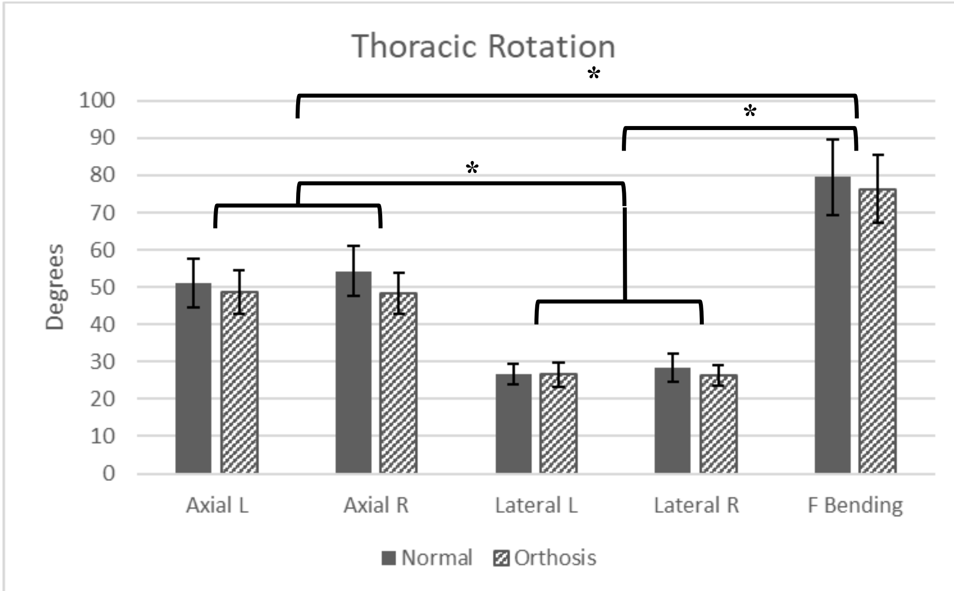

Figure 3.1 Effects of Orthosis on Thoracic Rotation. Error bars indicate standard deviations.

3.3 Pelvic Rotation

The orthosis did cause a significant reduction (normal vs orthosis) in pelvic rotation for axial twisting to the left (40° (12°) vs 33° (9.0°)), axial twisting to the right (41° (8.9°) vs 35° (9.9°)), lateral bending to the left (6.4° (2.9°) vs 4.5° (2.3°)), lateral bending to the right (6.8° (2.6°) vs 5.5° (2.5°)), and forward bending (38° (14°) vs 30° (16°)). In addition, there were significant differences in pelvic rotation between the tasks of axial twisting, lateral bending, and forward bending. (Figure 3.2)

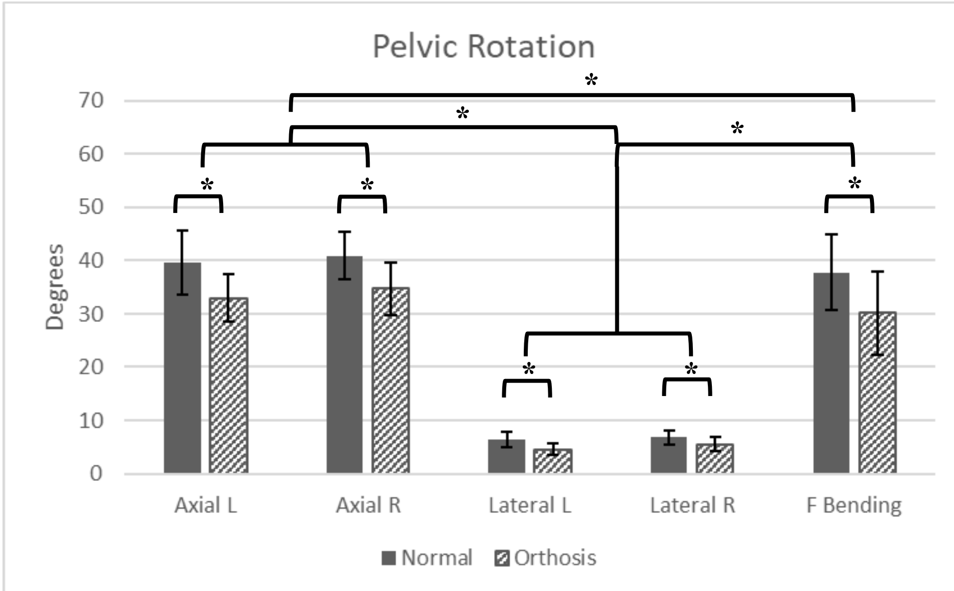

Figure 3.2 Effects of Orthosis on Pelvic Rotation. Error bars indicate standard deviations.

3.4 Lumbar Rotation

There were no significant differences in lumbar rotation (normal vs orthosis) for axial twisting to the left (12° (6.3°) vs 15° (6.8°)), axial twisting to the right (13° (9.0°) vs 14° (8.0°)), lateral bending to the left (20° (4.6°) vs 22° (6.0°)), lateral bending to the right (22° (7.3°) vs 21° (5.6°)), or forward bending (42° (17°) vs 45° (18°)). There were significant differences in lumbar rotation between the tasks of axial twisting, lateral bending, and forward bending. (Figure 3.3)

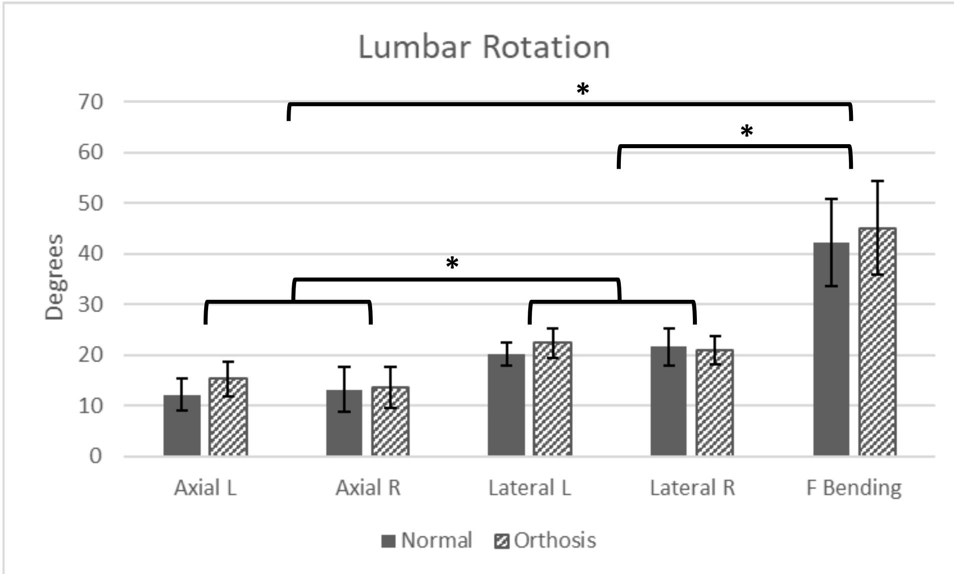

Figure 3.3 Effects of Orthosis on Lumbar Rotation. Error bars indicate standard deviations.

3.5 LTR

The orthosis did cause a significant increase (normal vs orthosis) in LTR for axial twisting to the left (24% (12%) vs 31% (11%)), axial twisting to the right (23% (13%) vs 28% (14%)), lateral bending to the left (76% (10%) vs 85% (7.4%)), lateral bending to the right (76% (10%) vs 79% (12%)), and forward bending (53% (16%) vs 59% (19%)). In addition, there were significant differences in LTR between the tasks of axial twisting, lateral bending, and forward bending. (Figure 3.4)

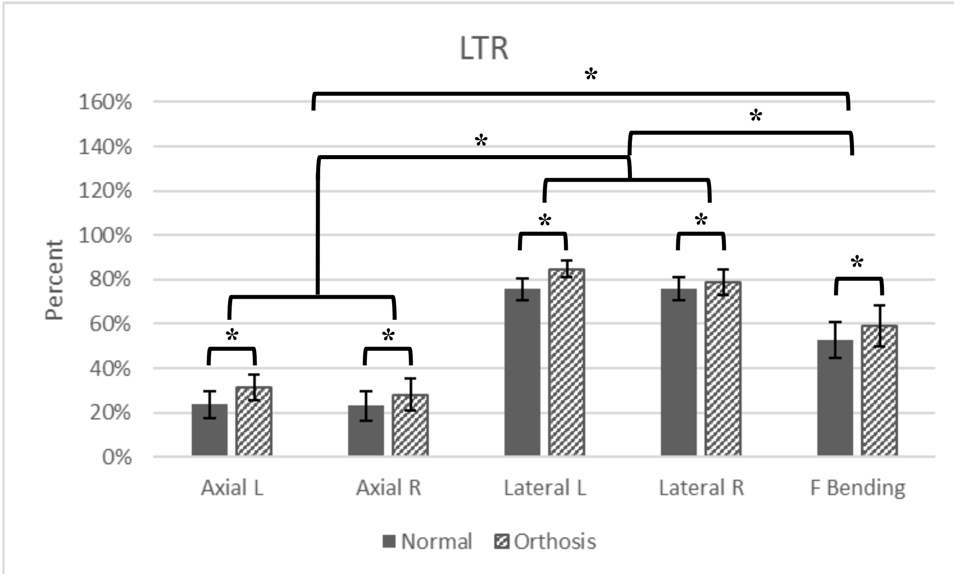

Figure 3.4 Effects of Orthosis on LTR. Error bars indicate standard deviations.

CHAPTER 4. DISCUSSION

4.1 Effects of hip orthosis on LPC

The main objective of this study was to determine if LPC could be altered in a direction that would counter the abnormal LPC often displayed in LBP patients. Specifically, it was hypothesized that physically restricting the hip joint using an orthosis would reduce pelvic rotation and increase lumbar contributions to total range of motion. Significant decreases in pelvic rotation were observed while wearing the hip orthosis for all tasks (axial left: 16.9%, axial right: 15.1%, lateral left: 29.4%, lateral right: 19.3%, forward bending: 20.2%) Orthosis-induced changes in lumbar rotation were not found statistically significant, however LTR values were found significantly larger with versus without the hip orthosis in all tasks (axial left: 31.8%, axial right: 21.5%, lateral left: 11.9%, lateral right: 4.3%, forward bending: 11.9%). This indicates the hip orthosis was effective at shifting LPC in the desired direction by reducing pelvic rotation and increasing lumbar contributions.

Thoracic rotation was analyzed to determine the effect of the orthosis on total task performance. While slight decreases in thoracic rotation were observed, none were statistically significant. This is an important finding, as it indicates the hip orthosis can be used to alter LPC without significantly impacting the individual's ability to complete a movement. We hypothesize this would allow the individual to still complete daily tasks while wearing the hip orthosis, but more examination is needed to confirm.

4.2 LPC correction via physical therapy

Other methodologies, such as physical therapy, have targeted LPC in treatment attempts for LBP. Hoffman et al. examined the effects of a classification-specific physical therapy treatment on pelvic movement compared to a non-specific treatment. (Hoffman et al., 2011) Patients in the specific group received treatment that included directions of lumbopelvic motion associated with LBP symptoms, training to minimize specific directions of lumbopelvic motion with activities of daily living, and a direction-specific exercise program focused on minimizing specific directions of lumbopelvic motion. The non-specific group received treatment including general education regarding neutral spinal alignment, training to maintain neutral spinal alignment, and an exercise program that emphasized increasing strength and flexibility of the trunk and limbs. Participants were instructed to lie prone with one knee flexed to 90°, and either laterally or medially rotate the hip as far as possible then return to starting position. LBP patients from the specific treatment group displayed a significantly smaller amount of pelvic motion when compared to patients from the non-specific group. Lumbar contributions to movement and the standing forward bending task were not examined. This method increases pelvic control and reduces a larger pelvic motion that is found in LBP patients during hip rotation, but it is unclear if this method has any effect on lumbar contribution to trunk movement tasks. Additional investigation of the effects of this treatment on trunk movement tasks could be beneficial. The authors also do not report any effects the treatment options have on alleviation of pain symptoms.

Shahvarpour et al. examined the effects of a lumbar stabilization exercise program on LPC. (Shahvarpour et al., 2017) The lumbar stabilization exercise program is a different treatment plan than what was used by Hoffman et al., with the primary goals including motor control of deep trunk muscles and overloading exercises designed to improve endurance and strength of the paraspinal and abdominal muscles. Pain intensity, disability index, and trunk kinematics during a standing flexion/extension task were recorded. While patients did report a decrease in pain while participating in the exercise program, measurements of LPC did not improve. Patients retained higher amounts of pelvic rotation and lower amounts of lumbar flexion than healthy individuals. The authors suggest these trends could be a goal of the lumbar stabilization exercise program as they are correlated with a reduction in disability, however they propose that patients could have learned to stiffen the lumbar spine during the exercise program and continue to retain this motion after pain and disability diminished, which may not be beneficial to the patient. It is difficult to compare this treatment with the one proposed by Hoffman et al. as measurements of pelvic rotation were obtained from different tasks (prone hip rotation vs. standing forward bending), however lumbar stabilization exercise programs have become a popular treatment option for LBP. (Searle et al., 2015) While this treatment may allow muscles to provide more support to the lumbar spine, it doesn't necessarily teach correct movement patterns. Exercise programs such as this target specific regions and may not be adequate in addressing a larger scale movement deficiency such as one that involves both the pelvis and lumbar spine as in the case of abnormal LPC. This could offer some explanation to a review conducted by Smith et al. that found no significant difference in long-term LBP and disability when treated by stabilization exercises compared to alternative forms of exercise. (Smith et al., 2014)

4.3 Trunk orthoses for movement correction

Other research has examined the effects of external devices on LBP with different motivations. Laraviere et al examined the effects of different lumbar belt designs (Figure 4.1) on LPC in healthy subjects. (Lariviere et al., 2014) Wearing a lumbar belt was found to significantly reduce lumbar range of motion during trunk flexion/extension while leaving pelvic range of motion unaltered. Lumbar belts may be useful when returning to work following a low back injury, in the presence of a low back disorder, or to protect against soft tissue creep-based injuries, due to the applied restriction to lumbar range of motion. Because of this, the authors suggest further examinations be done to determine which types of patients would benefit from lumbar belts, and not to generalize the results across people with back pain.

Figure 4.1 Lumbar belts (Lariviere et al., 2014)

Lumbar orthoses/belts are typically employed to limit lumbar motion and as such are not designed to provide an increase in lumbar contributions to daily tasks. Jegede et al. examined the effects of 3 different types of lumbar orthoses (corset, semi-rigid, and custom; Figure 4.2) on lumbar range of motion in asymptomatic individuals through 15 activities of daily living. (Jegede et al., 2011) They found all 3 orthosis types to cause smaller lumbar range of motion for flexion/extension, lateral bending, and rotation. This somewhat agrees with an earlier study where Cholewicki et al. compared motion restriction and trunk stiffness from 3 thoracolumbosacral orthoses. (Cholewicki et al., 2003) These orthoses were different than those examined by Jegede et al. (thorax-sacral vs lumbar), although lumbar motion across flexion/extension and lateral bending was similarly restricted.

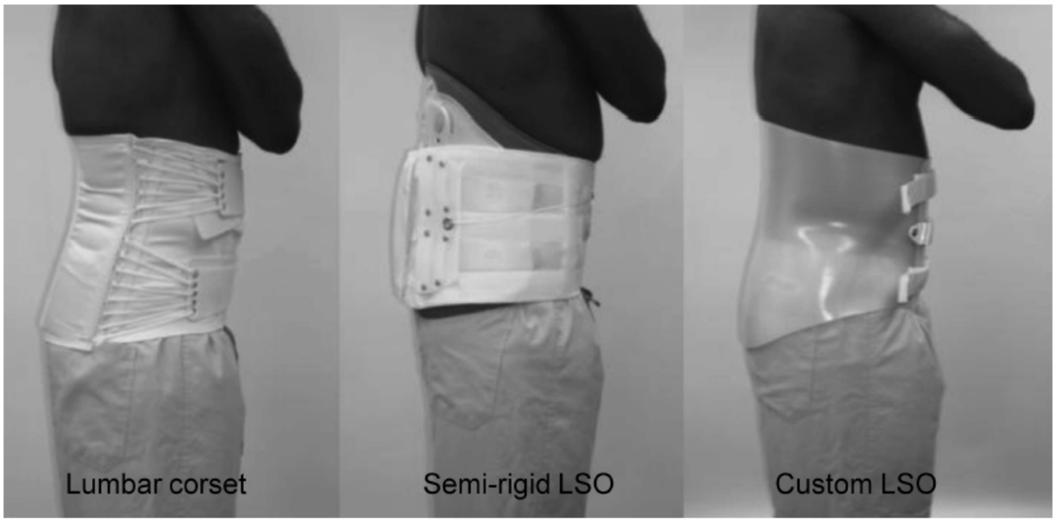

Figure 4.2 Lumbar orthoses (Jegede et al., 2011)

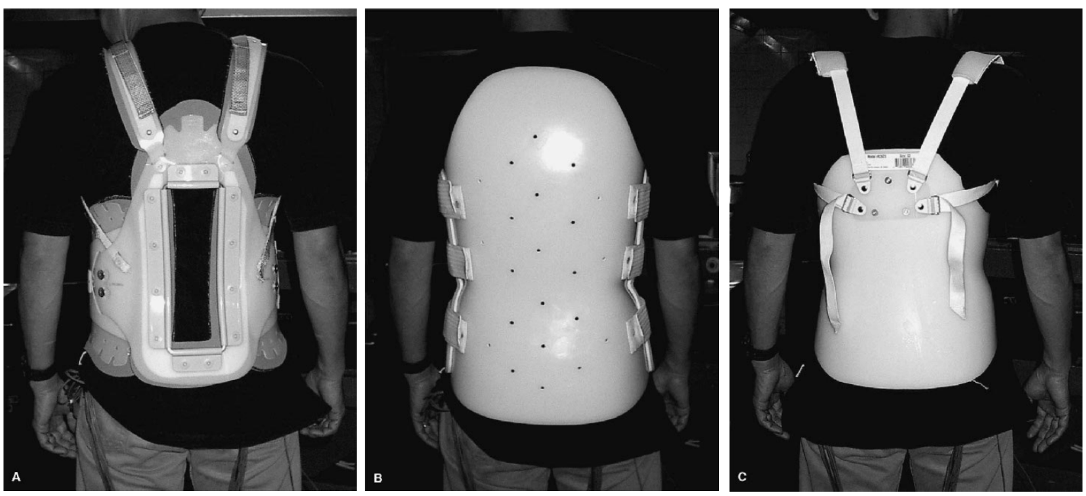

Figure 4.3 Thoracolumbosacral orthoses (Cholewicki et al., 2003)

While lumbar orthoses may help protect against re-injury and soft tissue creep from repetitive motions, they do not address the abnormal LPC which has been observed in LBP patients. Because they reduce lumbar contributions, they would have an adverse effect on LPC. If a lumbar orthosis were used by an individual returning to work or recovering from an injury, it may be beneficial to monitor their movement patterns after use of the belt has ended to ensure they do not retain an abnormal LPC that would increase demands on their lower back.

4.4 Trunk orthoses for pain alleviation

Anders and Hubner examined the effects of an elastic lumbar support belt on trunk muscle function in non-chronic LBP patients. (Anders and Hubner, 2019) Non-chronic LBP were split into two groups (belt vs control) and evaluated over a 3-week period to record pain intensity, functional impairment, and trunk muscle activation while walking. All participants experienced a significant decrease in pain across a 3-week period. Although the belt group showed a higher reduction in pain level compared to baseline, it is difficult to say how much the belt contributed to symptom alleviation as individuals in the control group also saw a significant reduction in pain. Additionally, the impacts of this type of lumbar belt on LPC are unknown as trunk kinematics were not reported from this study.

Morrisette et al. examined the effects of lumbar orthoses (extensible and inextensible) and standard care on LBP management. (Morrisette et al., 2014) They found patients who wore a lumbar orthosis for 2 weeks while also receiving standard care treatment scored better on the Oswestry Disability Index than patients who received the standard care alone. Lumbar orthoses may cause a reduction in pain due to their contribution to reduced trunk muscle activity. (Cholewicki et al., 2007) Cholewicki et al. found participants were able to perform similarly in a seated balance task while wearing a lumbar orthosis and displayed significantly lower EMG signals for thoracic and lumbar erector spinae muscles. The authors suggest this may benefit patients with LBP who exhibit elevated muscular activity.

Different pelvic belt configurations (Figure 4.4) have also been examined for their effect on lumbopelvic pain. (Sawle et al., 2013) It was found that using a pelvic belt to apply pressure towards the site of pain would cause a decrease in pain and improve the function of an active straight leg raise task. Similar to other belts that have been studied, the belt was shown to contribute to pain alleviation, however the effects on LPC are unclear.

Figure 4.4 Pelvic belt configurations (Sawle et al., 2013)

4.5 Other uses for trunk orthoses

Cholewicki et al. examined the effects of a lumbar orthosis (Figure 4.5) on lumbar spine proprioception in healthy individuals. (Cholewicki et al., 2006) Participants wore an orthosis for a minimum of 3 hours daily during periods of activity for 3 weeks. Proprioception was tested by having participants sit in a specially built apparatus which would move the lower body away from a neutral spine position while the upper body was restrained. Participants would either indicate when their spine was moved back into the neutral position (passive) or rotate their lower body back to neutral spine position of one's own accord (active). They found proprioception to be increased in the passive tests after the 3 weeks of use but decreased in the active tests and concluded that no overall proprioceptive benefits could be ascertained. A later study included chronic LBP patients and additionally tested supine and side-lying positions while examining the proprioceptive differences between patients and healthy individuals. (Lee et al., 2010) No difference was found for the passive and active repositioning tasks, but LBP patients performed worse at motion perception. Meaning when the participant's lower body was rotated away from neutral spine position, more travel was required for an LBP patient to notice the difference than for an individual without LBP. Lumbar orthoses did not provide a benefit to these cases, but it does provide information on differences in trunk positioning or movement in individuals with LBP. Additionally, these lumbar orthoses (as with other lumbar belts discussed here) are used to provide stiffness and support to the lumbar region, not to assist in movement or LPC correction as the hip orthosis was examined.

Figure 4.5 Lumbosacral orthosis (Cholewicki et al., 2006)

Newcomer et al. also examined the effects of a lumbar support (Figure 4.6) on proprioception by comparing repositioning error between LBP patients and healthy individuals. (Newcomer et al., 2001) Participants were partially immobilized with a belt around the pelvis and another just above the knees. While standing, participants were instructed to bend to 30%, 60%, and 90% of the maximal ROM in flexion/extension (forward bending and backward return) and lateral bending. An improvement in repositioning error occurred with the lumbar support, but only in flexion, extension, and right lateral bending for LBP patients, and only in left lateral bending for healthy controls. Prior to this, McNair and Heine examined the effects of a neoprene lumbar brace on trunk proprioception in asymptomatic subjects. (McNair and Heine, 1999) Similarly, this study also found significant improvements in proprioception for standing flexion/extension tasks when a lumbar support was applied. Lateral bending was not tested. These studies don't necessarily disagree with the findings later reported by Cholewicki et al. as the testing procedures were different (standing vs sitting). Given the mixed/limited benefits of the lumbar orthoses/supports, there is still room for improvement in treating LBP in these patients.

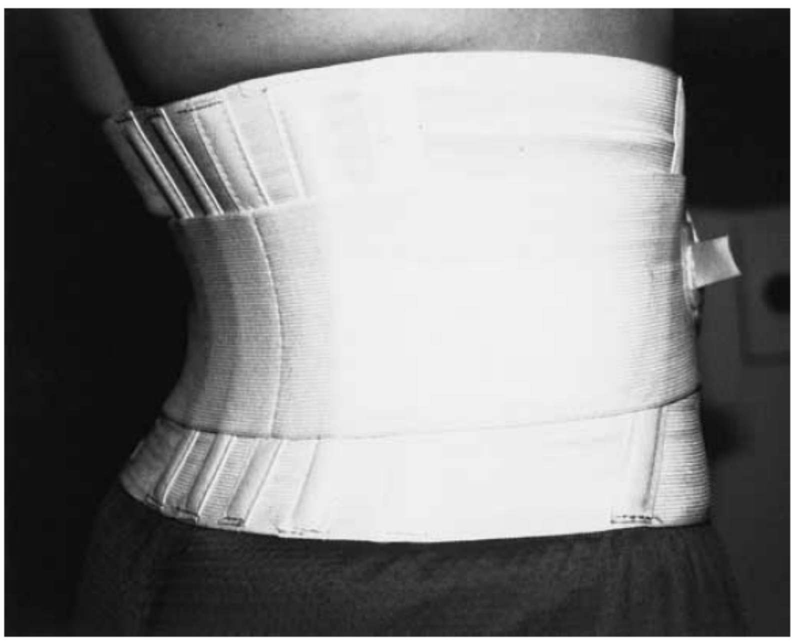

Figure 4.6 Lumbar support (Newcomer et al., 2001)

A dorso-lumbar rigid casting was applied to runners to examine the effects of reduced trunk motion on muscle activity and stride length. (Morley and Traum, 2018) The authors found increased electromyographic activity in the erector spinae and quadriceps femoris with an increased number of steps (due to reduced stride length) required to maintain the same pace as uninhibited running. This study was an extension of a previous one in which Morley and Traum detailed the differences in ground reaction forces while running as a result of dorso-lumbar motion restriction. (Morley and Traum, 2016) While these studies don't provide direct information regarding LBP patients, they demonstrate that reductions in trunk movement (which exists in certain LBP patients) can decrease or alter the performance of other tasks that an individual may partake in, giving further motivation to understanding and correcting abnormal LPC.

Mokhtarinia et al. examined the effects of a newly designed "Tehran Back Belt" (Figure 4.7) on spine muscle activity in healthy individuals during a sitting task. (Mokhtarinia et al., 2019) This orthosis includes a waist belt, two thigh supports, and elastic straps which attach the waist belt to the thigh supports to transfer spinal loading. The design was inspired by other orthoses used by individuals in sitting tasks. Participants completed a simulated sitting task for 35 minutes with and without the belt applied. Over 90% of participants in this study found the device easy to use and comfortable. The activity of the longissimus, rectus abdominis and internal oblique muscle groups saw significant reductions with the device applied, while no difference was found in the activity of the iliocostalis, multifidus, or external oblique muscle groups. The authors conclude the belt could be beneficial in easing spinal loading in sitting postures but acknowledge that more research is required to examine the effects on lumbar lordosis and kinematic changes. This device has similar features to the hip orthosis we tested (waist belt, thigh supports, linkage between the waist and thighs) but it was designed for a different purpose: to reduce stress on the lower back by transferring it to the thighs. Kinematic data from trunk movement tasks with this device would provide more information on the possible changes in LPC.

Figure 4.7 "Tehran Back Belt" (Mokhtarinia et al., 2019)

4.6 Limitations

Certain limitations of this study should be considered when examining these results. First, this study examined only healthy individuals with no recent history of LBP. While orthosis-induced changes were consistent with our hypothesis, the fact that these individuals had no symptoms of LBP cannot be overlooked. Testing the orthosis on individuals with LBP would likely encounter other obstacles not present here (e.g. fear-avoidance behavior). Second, this study population could be viewed as young (18-28 years) and not representative of the LBP population. Other studies have reported smaller lumbar contributions in older individuals (Vazirian et al., 2017a) and a larger resistance to passive deformation of the lumbar spine. (Shojaei et al., 2016) Because of this, further investigations should be conducted involving the application(s) of a hip orthosis to older individuals. Additionally, this study does not address the effects of the hip orthosis on the timing aspect of LPC. Other studies have investigated differences in the timing aspect between LBP patients and healthy individuals. (Shojaei et al., 2017a; Shojaei et al., 2017b; Vazirian et al., 2017b) The hip orthosis produced the desired effects on the magnitude of LPC, yet if the timing is not addressed it is possible that individuals could revert to an abnormal LPC after removal of the orthosis.

4.7 Conclusion

This study confirms our hypothesis that a hip orthosis can be used to increase lumbar contributions to trunk movement tasks by physically restricting pelvic motion in healthy individuals. To the best of our knowledge, no other study has examined the possibility of using a hip orthosis with the goal of altering or correcting LPC. Trunk orthoses used in LBP research usually exist in the form of a lumbar belt or support. Restraining and supporting the lower back may be an effective short-term LBP solution by reducing trunk muscle activity and preventing repetitive motion injuries, however the reduction in lumbar contributions is detrimental to LPC. Similarly, other trunk orthoses and treatment plans show promising results for pain relief but are not effective at correcting LPC. Given the high recurrence of LBP, if these devices or treatments do not address abnormalities in LPC then the possibility of LBP recurrence due to abnormal LPC remains. Using an orthosis such as the one examined here could assist in reducing such recurrences.

4.8 Future Work

This study provides knowledge of how a hip orthosis may be used to alter LPC in healthy individuals. Given the results provided here, the logical next step is to test the effects of a hip orthosis on LPC in patients with a history of LBP or abnormal LPC. If a hip orthosis could correct abnormal LPC in LBP patients, further investigations can be conducted into the possible connections between LPC correction and LBP recurrence. The hip orthosis could be a tool used by therapists to assist in retraining correct movement patterns in patients with abnormal LPC. Review of current literature indicates that orthoses such as this are not commonly used in physical therapy treatments. This is understandable, as a therapist's goal would likely be to correct a movement deficiency to a point where an external device is not needed. However, given that many current techniques have not successfully corrected abnormal LPC, it is worth examining this device's role as a movement training tool. Furthermore, if a definite link between abnormal LPC and LBP recurrence is proven, then individuals could be screened for abnormal LPC in a prevention effort. There is research describing the correlation between abnormal LPC and LBP patients, but as no causative link has been identified, it is still unknown if LPC correction can lead to a reduction in LBP occurrences.

REFERENCES

Adams, A.M., Mannion, F.A., Dolan, F.P., 1999. Personal Risk Factors for First-Time Low Back Pain. Spine 24, 2497-2497.

Ahern, D.K., Follick, M.J., Council, J.R., Laser-Wolston, N., Litchman, H., 1988. Comparison of lumbar paravertebral EMG patterns in chronic low back pain patients and non-patient controls. Pain 34, 153-160.

Anders, C., Hubner, A., 2019. Influence of elastic lumbar support belts on trunk muscle function in patients with non-specific acute lumbar back pain. PloS one 14, e0211042.

Balagué, F., Mannion, A.F., Pellisé, F., Cedraschi, C., 2012. Non-specific low back pain. The Lancet 379, 482-491.

Cholewicki, J., Peter Reeves, N., Everding, V.Q., Morrisette, D.C., 2007. Lumbosacral orthoses reduce trunk muscle activity in a postural control task. Journal of Biomechanics 40, 1731-1736.

Cholewicki, J., Shah, K.R., McGill, K.C., 2006. The Effects of a 3-Week Use of Lumbosacral Orthoses on Proprioception in the Lumbar Spine. Journal of Orthopaedic & Sports Physical Therapy 36, 225--231.

Cholewicki, P.J., Alvi, P.K., Silfies, P.S., Bartolomei, P.J., 2003. Comparison of Motion Restriction and Trunk Stiffness Provided by Three Thoracolumbosacral Orthoses (TLSOs). Journal of Spinal Disorders & Techniques 16, 461-468.

Deyo, R.A., Von Korff, M., Duhrkoop, D., 2015. Opioids for low back pain. BMJ : British Medical Journal 350, g6380.

Ferguson, S.A., Marras, W.S., Gupta, P., 2000. Longitudinal quantitative measures of the natural course of low back pain recovery. Spine 25, 1950-1956.

Hancock, M.J., Maher, C.G., Latimer, J., Spindler, M.F., McAuley, J.H., Laslett, M., Bogduk, N., 2007. Systematic review of tests to identify the disc, SIJ or facet joint as the source of low back pain. European Spine Journal 16, 1539-1550.

Hoffman, S.L., Johnson, M.B., Zou, D., Harris-Hayes, M., Van Dillen, L.R., 2011. Effect of classification-specific treatment on lumbopelvic motion during hip rotation in people with low back pain. Manual Therapy 16, 344-350.

Hoy, D., Bain, C., Williams, G., March, L., Brooks, P., Blyth, F., Woolf, A., Vos, T., Buchbinder, R., 2012. A systematic review of the global prevalence of low back pain. Arthritis & Rheumatism 64, 2028-2037.

Jegede, K.A., Miller, C.P., Bible, J.E., Whang, P.G., Grauer, J.N., 2011. The Effects of Three Different Types of Orthoses on the Range of Motion of the Lumbar Spine During 15 Activities of Daily Living. Spine. 36, 2346--2353.

Katz, J.N., 2006. Lumbar disc disorders and low-back pain: socioeconomic factors and consequences. The Journal of bone and joint surgery. American volume 88 Suppl 2, 21.

Krismer, M., van Tulder, M., 2007. Low back pain (non-specific). Best Practice & Research Clinical Rheumatology 21, 77-91.

Lariviere, C., Caron, J.M., Preuss, R., Mecheri, H., 2014. The effect of different lumbar belt designs on the lumbopelvic rhythm in healthy subjects. BMC musculoskeletal disorders 15, 307.

Lee, A.S., Cholewicki, J., Reeves, N.P., Zazulak, B.T., Mysliwiec, L.W., 2010. Comparison of Trunk Proprioception Between Patients With Low Back Pain and Healthy Controls. Archives of Physical Medicine and Rehabilitation 91, 1327-1331.

Maher, C., Underwood, M., Buchbinder, R., 2017. Non-specific low back pain. The Lancet 389, 736-747.

Marras, W.S., Wongsam, P.E., 1986. Flexibility and velocity of the normal and impaired lumbar spine. Archives of physical medicine and rehabilitation 67, 213-217.

Mayer, G.T., Neblett, J.R., Brede, J.E., Gatchel, J.R., 2009. The Quantified Lumbar Flexion-Relaxation Phenomenon Is a Useful Measurement of Improvement in a Functional Restoration Program. Spine 34, 2458-2465.

Mayer, G.T., Tencer, F.A., Kristoferson, F.S., Mooney, F.V., 1984. Use of Noninvasive Techniques for Quantification of Spinal Range-of-Motion in Normal Subjects and Chronic Low-Back Dysfunction Patients. Spine 9, 588-595.

McNair, P.J., Heine, P.J., 1999. Trunk proprioception: Enhancement through lumbar bracing. Archives of Physical Medicine and Rehabilitation 80, 96-99.

Mokhtarinia, H., Ghamary, J., Maleki-Ghahfarokhi, A., Asgari, M., Gabel, C.P., Parnianpour, M., 2019. The new "Tehran Back Belt": Design then testing during a simulated sitting task improved biomechanical spine muscle activity. Health promotion perspectives 9, 115-122.

Morley, J.J., Traum, E., 2016. The effects of dorso-lumbar motion restriction on the ground reaction force components during running. Journal of bodywork and movement therapies 20, 432-440.

Morley, J.J., Traum, E., 2018. The effects of dorso-lumbar motion restriction on EMG activity of selected muscles during running. Journal of bodywork and movement therapies 22, 166-177.

Morrisette, D.C., Cholewicki, J., Logan, S., Seif, G., McGowan, S., 2014. A randomized clinical trial comparing extensible and inextensible lumbosacral orthoses and standard care alone in the management of lower back pain. Spine 39, 1733-1742.

Newcomer, K., Laskowski, E.R., Yu, B., Johnson, J.C., An, K.-N., 2001. The effects of a lumbar support on repositioning error in subjects with low back pain. Archives of Physical Medicine and Rehabilitation 82, 906-910.

O'Sullivan, P., 2005. Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. Man Ther 10, 242-255.

Paquet, L.N., Malouin, L.F., Richards, L.C., 1994. Hip-Spine Movement Interaction and Muscle Activation Patterns During Sagittal Trunk Movements in Low Back Pain Patients. Spine 19, 596-603.

Porter, L.J., Wilkinson, L.A., 1997. Lumbar-Hip Flexion Motion: A Comparative Study Between Asymptomatic and Chronic Low Back Pain in 18- to 36-year-old Men. Spine 22, 1508-1513.

Sawle, L., Freeman, J., Marsden, J., Matthews, M.J., 2013. Exploring the effect of pelvic belt configurations upon athletic lumbopelvic pain. Prosthetics and Orthotics International 37, 124-131.

Searle, A., Spink, M., Ho, A., Chuter, V., 2015. Exercise interventions for the treatment of chronic low back pain: a systematic review and meta-analysis of randomised controlled trials. Clinical Rehabilitation 29, 1155-1167.

Shahvarpour, A., Henry, S.M., Preuss, R., Mecheri, H., LariviГЁre, C., 2017. The effect of an 8-week stabilization exercise program on the lumbopelvic rhythm and flexion-relaxation phenomenon. Clinical Biomechanics 48, 1-8.

Shojaei, I., Allen-Bryant, K., Bazrgari, B., 2016. Viscoelastic Response of the Human Lower Back to Passive Flexion: The Effects of Age. Annals of Biomedical Engineering 44, 2817-2826.

Shojaei, I., Salt, E.G., Hooker, Q., Bazrgari, B., 2018. Mechanical demands on the lower back in patients with non-chronic low back pain during a symmetric lowering and lifting task. Journal of biomechanics 70, 255-261.

Shojaei, I., Salt, E.G., Hooker, Q., Van Dillen, L.R., Bazrgari, B., 2017a. Comparison of lumbo-pelvic kinematics during trunk forward bending and backward return between patients with acute low back pain and asymptomatic controls. Clinical biomechanics (Bristol, Avon) 41, 66-71.

Shojaei, I., Vazirian, M., Salt, E.G., Van Dillen, L.R., Bazrgari, B., 2017b. Timing and magnitude of lumbar spine contribution to trunk forward bending and backward return in patients with acute low back pain. Journal of Biomechanics 53, 71-77.

Silva, T.d., Mills, K., Brown, B.T., Herbert, R.D., Maher, C.G., Hancock, M.J., 2017. Risk of Recurrence of Low Back Pain: A Systematic Review. Journal of Orthopaedic & Sports Physical Therapy 47, 305-313.

Smith, B.E., Littlewood, C., May, S., 2014. An update of stabilisation exercises for low back pain: a systematic review with meta-analysis. BMC musculoskeletal disorders 15, 416.

Tafazzol, A., Arjmand, N., Shirazi-Adl, A., Parnianpour, M., 2014. Lumbopelvic rhythm during forward and backward sagittal trunk rotations: Combined in vivo measurement with inertial tracking device and biomechanical modeling. Clinical Biomechanics 29, 7-13.

Thomas, J.S., France, C.R., 2008. The relationship between pain-related fear and lumbar flexion during natural recovery from low back pain. European Spine Journal 17, 97-103.

Vazirian, M., Shojaei, I., Agarwal, A., Bazrgari, B., 2017a. Lumbar contribution to the trunk forward bending and backward return; age-related differences. Ergonomics 60, 967-976.

Vazirian, M., Shojaei, I., Bazrgari, B., 2017b. Age-related differences in the timing aspect of lumbopelvic rhythm during trunk motion in the sagittal plane. Human movement science 51, 1-8.

Vazirian, M., Van Dillen, L., Bazrgari, B., 2016a. Lumbopelvic rhythm during trunk motion in the sagittal plane: A review of the kinematic measurement methods and characterization approaches. Phys Ther Rehabil 3, 5.

Vazirian, M., Van Dillen, L.R., Bazrgari, B., 2016b. Lumbopelvic rhythm in the sagittal plane: A review of the effects of participants and task characteristics. International Musculoskeletal Medicine 38, 51-58.

Woolf, A.D., Pfleger, B., 2003. Burden of major musculoskeletal conditions. Bulletin of the World Health Organization 81, 646-656.

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M. Gilliam, M. Ballard, S. Sunderam, B. Bazrgari "Alterations in Lumbo-Pelvic Coordination from the Application of a Hip Orthosis" *Oral presentation, 14th Annual CCTS Spring Conference, Lexington, KY, USA, April 15, 2019*

S. Thomas, C. Schildt, M. Ballard, E. Powell, Y. Rajamanickam, S. Salles, L. Sawaki, S. Sunderam "A Brain-Computer Interface for Motor Rehabilitation after Spinal Cord Injury" *14th Annual CCTS Spring Conference, Lexington, KY, USA, April 15, 2019*

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