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LOWER BACK BIOMECHANICS AT NON-CHRONIC STAGE OF LOW BACK PAIN

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LOWER BACK BIOMECHANICS AT NON-CHRONIC STAGE OF LOW BACK PAIN

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

ABSTRACT OF DISSERTATION

LOWER BACK BIOMECHANICS AT NON-CHRONIC STAGE OF LOW BACK PAIN

Prior studies have reported differences in lower back biomechanics during activities of daily living between individuals with and without chronic low back pain (LBP). Nevertheless, the literature on lower back biomechanics of patients with non-chronic LBP is scant. Therefore, the objective of this study, as the first step towards future prospective studies, was to investigate the lower back biomechanics in patients with non-chronic LBP. Case-control studies were conducted wherein measures of lumbo-pelvic coordination during bending and return tasks as well as measures of mechanical demand on the lower back during lifting tasks in the sagittal plane were investigated between patients with non-chronic LBP and matched asymptomatic individuals. Patients were enrolled into the study at the non-chronic stage of their LBP. We found distinct difference in measures of lumbo-pelvic coordination as well as mechanical demands on the lower back between patients with non-chronic LBP and controls. Reduced lumbar range of flexion and slower task pace as well as the more in-phase and less variable lumbo-pelvic coordination observed in patients with non-chronic low back pain, may be the result of a neuromuscular adaptation to reduce the forces and deformation in the lower back tissues and avoid pain aggravation. Such a neuromuscular adaptation, however, resulted in a larger shearing demand on the lower back. Persistent abnormal lumbo-pelvic coordination might play a role in transition to chronic stage or recurrence of LBP. However, such inferences need to be further investigated using prospective studies as well as clinical trials involving a combination of physical and psychological treatments aimed at correction of lumbo-pelvic coordination.

Keywords: Low back pain; Lumbo-pelvic coordination; Non-chronic; Forward bending and backward return; Lowering and Lifting Task; Lower back mechanical demand

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Acute and chronic low back pain and causal mechanisms

The complexity and multi factorial nature of low back pain (LBP) pose a significant challenge for its management. Despite extensive research, the pathomechanism and risks factors associated with progression of LBP from an acute episode to chronic and/or recurrent LBP is poorly understood (Biering-Sørensen 1982, Hides et al. 2001).The recurrence rate following an acute episode of LBP is very high ranging from~25% to ~55% (Von Korff et al. 1993, Hoy et al. 2010, Melloh et al. 2011, da Silva et al. 2017). Patients with chronic and/or recurrent LBP account for the most of LBP-related disability and total cost (Spengler et al. 1986, Frymoyer and Gordon 1989, Fromoyer et al. 1991). It is, therefore, critically important that risk factors responsible for transition from an acute episode to chronic and/or recurrent LBP are understood, as the efficient management of the first-episode LBP has been suggested to reduce the recurrence rate (Hides et al. 2001).

One likely causal mechanism for occurrence and recurrence of LBP is the direct and/or indirect stimulation of the embedded nerve endings within the lower back tissues by mechanical loads (i.e., forces and deformations). The instantaneous or cumulative forces and deformations of lower back tissues has been suggested to initiate a first episode of LBP. Specifically, the mechanical risk factors (e.g., awkward posture, high loading manual tasks, exposure to vibration and specific sporting activities) can alter lower back mechanical loads beyond injury thresholds and initiate low back injury. Therefore, a developed understanding of differences in the lower back mechanical loads (i.e., forces and deformations) between asymptomatic individuals and those who are at different stages of the lower back problem may help identify and provide early management to patients whose LBP is likely driven by abnormalities in the lower back mechanical loads.

1.2. Studying patients with low back pain using biomechanical methods

Given difficulties associated with direct measurement of lower back mechanical environment, indirect methods, including kinematic-, kinetic-, and electromyography (EMG)-based methods, have been widely used to study abnormalities in the lower back

mechanical environment of patients with chronic LBP. In contrast to research concerning patients with chronic LBP, only a few studies have investigated the lower back mechanical environment in patients with non-chronic LBP.

1.2.1. Kinematic-based methods

The studies implemented kinematic-based method have investigated magnitude aspects of lumbo-pelvic coordination (e.g., pelvic and thoracic rotations, lumbar flexion, lumbo-pelvic/-thoracic ratio), timing aspects of lumbo-pelvic coordination (e.g., continuous relative phase of pelvis and thorax, variability in relative phase of pelvis and thorax), lumbar lordosis/pelvic tilt and thoracic kyphosis, lumbar proprioception, and trunk higher order kinematic.

Patients with chronic LBP

There has been considerable differences in population of earlier studies (e.g., age, gender, BMI, occupation, criteria for inclusion/exclusion of patients with LBP) and heterogeneity in participants of each single study (e.g., differences in participants characteristics, mixing patients with LBP from different subgroups). Nevertheless, the general trend from earlier studies is that patients with chronic LBP, compared to asymptomatic individuals, exhibitsmaller lumbar range of deformation (flexion: 41.6° vs. 50.6°; lateral: 23.3° vs. 28.4°; axial: 22.4° vs. 25.7°) when reaching their trunk range of motion in three planes of motion, poorer lumbar proprioception (position/reposition differences: 5.2° vs. 2.6°), and slower lumbar deformation (i.e., exhibiting smaller peak velocity or acceleration).

Patients with non-chronic LBP

Paquet et al. (1994) reported similar ranges of flexion but smaller peak angular velocity for lumbar and hip between 10 patients with non-chronic LBP and 10 asymptomatic individuals during trunk forward bending and backward return tasks. In another study, Aluko et al. (2011) reported smaller mean and peak angular acceleration of lumbar spine for patients with non-chronic LBP during trunk forward bending and backward return. For a similar task, we have also recently observed that patients with non-chronic LBP perform the task slower but, in contrast to report by Paquet et al (1994), they exhibited smaller lumbar range of flexion as compared to asymptomatic individuals. For spinal posture

during standing, Christie et al. (Christie et al. 1995) reported larger lumbar lordosis for patients with chronic LBP and larger thoracic kyphosis and a forward head position for patients with non-chronic LBP when compared to asymptomatic individuals. During sitting, patients with non-chronic LBP indicated larger thoracic kyphosis compared to asymptomatic individuals. Nakipoglu et al. (Nakipoglu et al. 2008) did not find any differences in the lumbosacral angles of patients with chronic vs. non-chronic LBP using standing and lateral lumbosacral x-rays (Nakipoglu et al. 2008).

1.2.2. EMG-based methods

Patients with chronic LBP

EMG- and kinetic-based methods have been used by researchers to study neuromuscular behavior and lower back loads in patients with chronic LBP. The findings from EMG-based methods have been more in favor of the theory of secondary pain-related trunk neuromuscular adaptation rather than the belief of primary neuromuscular impairment in patients with LBP. In general, earlier studies have reported larger activation/co-activation of trunk muscles and absence of flexion-relation phenomenon in patients with chronic LBP vs. asymptomatic individuals. Kinetic-based methods try to directly estimate the effects of abnormalities in trunk motion and neuromuscular behavior on changes in lower back loads in patients with LBP.

Patients with non-chronic LBP

Goubert et al. (Goubert et al. 2017) investigated the structure and function lower back muscles in patients with continues (all days of a week) chronic, non-continues (~ half days of a week) chronic, and recurrent (recovered from multiple episodes) LBP. They reported higher fat cross-sectional area and lean muscle fat index of the multifidus and erector spinae in continuous chronic LBP compared to the other groups as well as lower metabolic activity of these muscles in patients with recurrent LBP compared to the other two groups. Danneels et al. (2002) compared EMG activity of the multifidus and the iliocostalis lumborum pars thoracis between patients with chronic LBP, non-chronic LBP, and asymptomatic individuals during coordination, stabilization and strength exercises. Specifically, they reported lower EMG activity of the multifidus for patients with chronic LBP compared to asymptomatic individuals during the coordination exercises, no

difference in EMG activity of muscles between the groups during the stabilization exercises, and lower EMG activity of both muscles for patients with chronic LBP versus asymptomatic individuals during strength exercises.

1.2.3. Kinetic-based methods

Patients with chronic LBP

Kinetic-based methods may vary from simple link-segment models (used to estimate mechanical demands on the lower back) to sophisticated detailed models (used to estimate muscle forces and spinal loads as well as stress and strain experienced in lower back tissues). In a few studies investigating lower back loads in patients with chronic LBP there are reports of smaller, similar, or larger lower back loads in patients with chronic LBP vs. asymptomatic individuals (Bazrgari and Xia 2017).

Patients with non-chronic LBP

Using a link-segment model, Shum et al. (2007, 2010) estimated lower back loads in patients with non-chronic LBP during forward bending and backward return as well as sit-to-stand and vice versa tasks. For trunk forward bending and backward return, the moment demand on the lower back was smaller in patients at the end range of trunk bending but was larger at smaller bending angles. For sit-to-stand and vice versa, the moment demand of the task on the lower back in sagittal plane was smaller for patients compared to controls.

1.3. Research gap

To the best of our knowledge the reviewed 8 studies above are the only studies wherein patients with non-chronic LBP were investigated using biomechanical methods. Furthermore, despite the current knowledge about lower back mechanical environment in patients with LBP who are either at chronic or non-chronic stage (i.e., from cross-sectional studies), it remains unclear if and how lower back mechanical environment of patients with non-chronic LBP changes as they recover or progress to chronic stage.

1.4. Objectives and hypotheses

The objectives of this study, as the first step towards future prospective studies, were:

1) To investigate the lower back mechanical environment in patients with non-chronic LBP and age- and gender-matched asymptomatic individuals using measures of magnitude aspects of lumbo-pelvic coordination during trunk forward bending and backward return. We **hypothesized** that in an effort to reduce the forces and deformation in the lower back tissues, and hence avoid pain aggravation due to mechanical stimulation, patients with non-chronic LBP would display an altered lumbo-pelvic coordination (i.e., smaller lumbar range of flexion, smaller thoracic range of rotation and/or larger compensatory pelvic range of rotation, smaller angular velocity, deceleration and acceleration of lumbar flexion) during trunk forward bending and backward return.

2) To investigate the lower back mechanical environment in the same groups using measures of timing aspects of lumbo-pelvic coordination during trunk forward bending and backward return. We **hypothesized** that patients with non-chronic LBP will adopt a protective motor control strategy, resulting in more in-phase and less variable lumbo-pelvic coordination, to reduce the likelihood of painful deformation of spinal tissues under dynamic tasks.

3) To investigate the lower back mechanical environment, using kinetics biomechanical methods, in the same groups through measures of mechanical demand on the lower back during lowering and lifting tasks in the sagittal plane. Considering the assumed smaller thoracic range of rotation and smaller deceleration and acceleration of lumbar flexion in patients with non-chronic LBP, we **hypothesized** that the moment demand on the lower back would be smaller for patients vs. controls. However, since patients are assumed to adopt a larger pelvic rotation, we further hypothesized that the shearing and axial components of the task demand will, respectively, be larger and smaller in patients with non-chronic LBP versus controls.

1.5. Organization of the dissertation

In Chapter 2 magnitude aspects of lumbo-pelvic coordination (objective 1) will be investigated and compared between patients with non-chronic LBP and asymptomatic individuals during forward bending and backward return. In Chapter 3 timing aspects of

lumbo-pelvic coordination (objective 2) using measures of continuous relative phase and its variability will be compared between the same groups and during the same task. The effects of differences in lumbo-pelvic coordination between the two groups on their lower back loads (objective 3) will be investigated in Chapter 4 using a link segment model of lower limbs and pelvis. Chapter 5 will be devoted to the discussion and conclusion drawn from the entire study and the suggestions for future research.

Chapter 2. Comparison of Lumbo-Pelvic Kinematics during Trunk Forward Bending and Backward Return between Patients with Acute Low Back Pain and Asymptomatic Controls

This chapter reproduced from a published manuscript, Shojaei, I., E. G. Salt, Q. Hooker, L.R. Van Dillen and B. Bazrgari (2017). "Comparison of Lumbo-Pelvic Kinematics during Trunk Forward Bending and Backward Return between Patients with Acute Low Back Pain and Asymptomatic Controls" Clinical Biomechanics **41**: 66-71.

2.1. Introduction

Low back pain (LBP) has been suggested to be the leading cause of disability, ahead of 290 other health related conditions(Buchbinder et al. 2013). In the United States ~ 80% of people are affected by LBP at some point during their lifetime; with an estimated annual healthcare expenditure of ~ $100 billion(Hart et al. 1995, Katz 2006). The lack of clarity in mechanisms driving pain presents challenges to the management of LBP. In only ~10% of LBP cases (i.e., specific LBP) the pain can be related to severe spinal pathology such as infection or tumor(Krismer and Van Tulder 2007).

The lower back mechanical environment, specifically forces and deformations experienced by lower back tissues, has an important causal role in occurrence of LBP (Marras 2000, Adams et al. 2006); thus, a developed understanding of differences in the lower back mechanical environment between individuals with and without LBP is imperative to characterize the mechanisms driving various types of LBP. Although studies have been conducted to delineate such differences, there are limitations to these studies. Direct in-vivo assessment of the lower back mechanical environment is not currently possible due to technical limitations, and ethical considerations associated with the use of the existing measurement techniques(Winkelstein et al. 2002, Ledet et al. 2005). Instead, indirect in-vivo measures of the lower back mechanical environment, like trunk kinematics and electromyography of trunk muscles, have been used by researchers(Granata and Marras 1993, Cholewicki et al. 1995, McClure et al. 1997, Wong and Lee 2004, Kim et al. 2013). These indirect measures have also been used by clinicians to assess the patient's status and guide the treatment (Rittweger et al. 2002, Scannell and McGill 2003, Carpes

et al. 2008). Findings from studies involving indirect measures of the lower back mechanical environment, particularly kinematic measures, have considerable variability and are not conclusive. Several studies have reported restrictions on the relative contribution of lumbar flexion to trunk rotation in patients with LBP vs. controls(Porter and Wilkinson 1997, Wong and Lee 2004). In contrast, other studies have found no differences or larger contribution of lumbar flexion to the forward bending in a LBP cohort(McClure et al. 1997). The reason for such inconsistency in results may be in part due to differences in the clinical history, LBP subtypes and personal characteristics of the participants. It has been reported that in only 54% of earlier studies of lumbo-pelvic kinematics were the patient and control groups comparable for age, gender and body mass index (BMI)(Laird et al. 2014). Furthermore, most of prior studies included patients with chronic LBP and it is not clear whether their finding can be generalized to patients with acute LBP. Although only ~ 10 % of patients with acute LBP develop chronic LBP (Andersson 1999, Carey et al. 2000, Waddell 2004, Majid and Truumees 2008), treatment of LBP has been suggested to be more effective before the chronic stage(Waddell and Burton 2001).

The objective of this study was to investigate differences in the lower back mechanical environment, using measures of trunk kinematics, between females with and without acute LBP. Although participants' ages were comparable between the two groups in our study, we included age as an independent variable to further explore any group by age interaction. We included the age-related analysis because of our recent findings of age-related differences in lower back biomechanics (Shojaei et al. 2016, Shojaei et al. 2016, Vazirian et al. 2016). We also investigated the effects of task pace (i.e., fast versus self-selected) on lower back kinematics. We hypothesized that, in an effort to reduce the forces and deformation in the lower back tissues, and hence avoid pain aggravation due to mechanical stimulation, patients with acute LBP would display reduced lumbar range of flexion compared to the asymptomatic controls during the forward bending and backward return task. We further hypothesized that such reduction of lumbar flexion in patients would affect the task performance, reflected in smaller thoracic range of rotation, or/and result in larger compensatory pelvic range of rotation. We similarly hypothesized that patients would make an effort to decrease the forces and deformations in their lower back tissues by adopting a slower pace as compared to asymptomatic controls that would be reflected in smaller values of the maximum angular velocity, deceleration and acceleration

of lumbar flexion. Whether the hypothesized differences between patients and controls would be magnified with aging (i.e., interaction of group and age) was unclear and left as an exploratory objective of this study.

2.2. Methods

2.2.1. Study Design

A case-control study design was used wherein patients with acute LBP (health care provider diagnosed LBP ≤ 3 months) were recruited to complete a set of experimental procedures that had been used in a baseline study involving asymptomatic individuals between 20 and 70 years old(Shojaei et al. 2016, Vazirian et al. 2016). Upon completion of data collection from the patients with LBP, the data from all participants in the baseline study who were gender matched and were within the same age range (i.e., 40-70 years old) were extracted for comparison with the data collected from the patients.

2.2.2. Participants

The patients with acute LBP were referred to the study by their primary physician, whereas the asymptomatic controls were recruited via advertisement. The final sample included a group of 19 asymptomatic subjects (controls) and a group of 19 patients with acute LBP (cases). To minimize the effects of gender on the mechanical behavior of the lower back(Nachemson et al. 1979, Sullivan et al. 1994, Shojaei et al. 2016) and considering that the incidence of LBP is higher among females(Manchikanti 2000), we only recruited female participants in this study and accordingly only used data obtained from females from the baseline study. There were no age, stature, body mass, or BMI differences (Table.1) between the two groups (p=0.05). Exclusion criteria for asymptomatic controls were any history of LBP, self-reported musculoskeletal disorders or other medical conditions that might have substantially influenced the experimental results (Shojaei et al. 2016, Vazirian et al. 2016). All asymptomatic controls also reported engaging in regular, moderate levels of physical activity. Patients with acute LBP (e.g., ≤ 3 months) were excluded if they had significant cognitive impairment, intention to harm themselves or others, or substance abuse (Radloff 1977, Ewing 1984, Brown and Rounds 1995, Borson et al. 2000). All participants in these studies completed an informed consent procedure

approved by the University of Kentucky Institutional Review Board before any screening procedure.

Table 2-1: Mean (SD) participants characteristics

Group	Controls	Patients	*t*-value	p-values
Age (years)	56 (9)	58 (9)	0.723	0.474
Stature (m)	1.64 (5)	1.63 (7)	-0.592	0.557
Body mass (kg)	70(12)	76(17)	1.553	0.130
BMI	25.7(4.1)	27.5(4.6)	1.608	0.117

2.2.3. Experimental Procedures

Participants completed two trunk forward bending and backward return tasks while standing on the center of a force platform (AMTI, Watertown, MA). During the first task participants were instructed to stand in an upright posture for five seconds, bend forward using a self-selected pace to reach their maximum trunk rotation (without excessively aggravating their LBP), hold their maximum trunk rotation for 5 seconds, extend back up to the original upright position, and stand again in an upright posture for five seconds. For the second task, participants performed the same task but as fast as possible and without a pause at the maximum trunk rotation. Prior to the conduct of these tasks, the desired method of performing them, wherein knees were kept extended throughout the tasks and arms were hanged in front at full flexed posture, was demonstrated to participants by one of research personnel. All participants completed the task with a self-selected pace prior to the task with a fast pace. Each task was repeated three times. During these tasks, trunk kinematics were tracked using wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands) attached superficial to the T10 and the S1 spinous process(Shojaei et al. 2016). The sampling rate of the inertial units was 50 Hz. Sensors placed on the T10 and the S1 were assumed to measure rotations of pelvis and thorax as rigid bodies whereas the difference between these two rotations (i.e., relative rotation of thorax with respect to the pelvis) was considered to represent lumbar flexion/extension as a joint.

2.2.4. Data analysis

The Xsens MTw™ system is a miniature wireless inertial measurement unit system incorporating 3D accelerometers, gyroscopes, magnetometers, and a barometer. We have tested the accuracy of our sensors and the reliability of using the Xsens system in our lab by a unique testing fixture (Shojaei et al. 2016) which enables us to generate known rotation with <1 deg accuracy. The mean (SD) accuracy of our sensors is 0.5 (0.3) deg and the reliability of using the Xsens system in our lab, quantified using intra class correlation coefficients, is excellent (i.e., ~1.000). Using the rotation matrices extracted from the IMUs, rotation quaternions (a rotation about a unit vector n through an angle α for each IMU) were obtained and used to calculate the pelvic and thoracic rotations in the sagittal plane(Roetenberg et al. 2009). The initial standing posture was regarded as the reference posture. At each time point, lumbar flexion was calculated from the difference between the thoracic and pelvic rotations (Fig. 1 and Fig. 2). Angular velocity and acceleration of the lumbar spine during the fast paced tasks were obtained using a successive numerical differentiation procedure (Fig. 3). To remove high-frequency noise, specifically amplified by differentiating, the kinematic raw data were filtered at 6Hz using a fourth order, bidirectional, Butterworth filter(Winter 2009, Kristianslund et al. 2012).

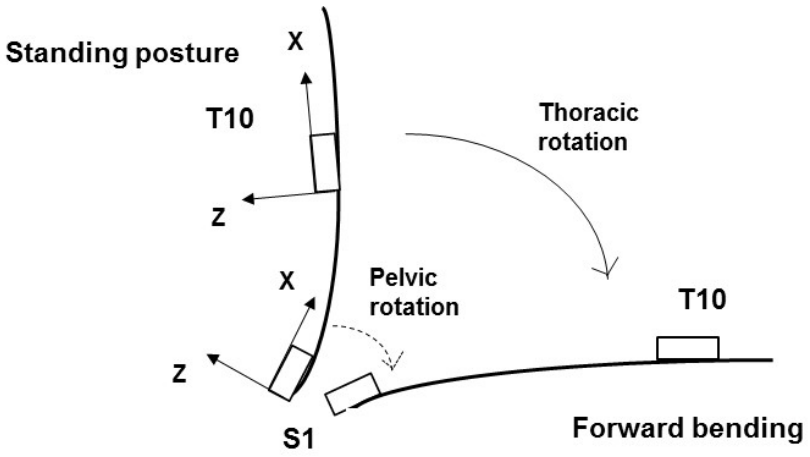
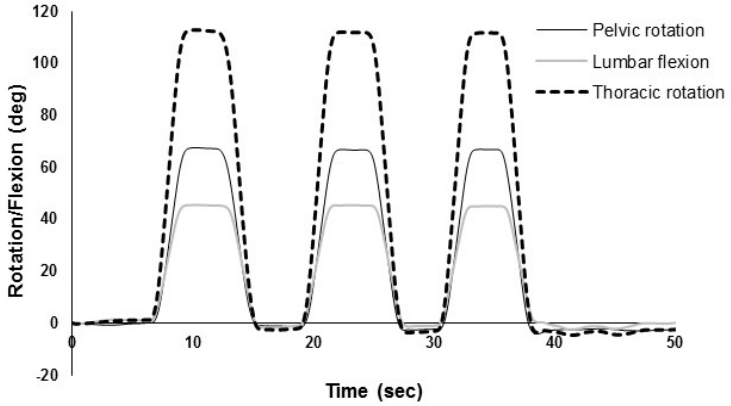


Figure 2-1: Definition of the pelvic and thoracic rotations as well as the local coordinate system of IMUs. Y axis is normal to the plane (the right-hand rule). Lumbar flexion is the difference between the thoracic and pelvic rotations.

2.2.5. Statistical analysis

For each task, pelvic and thoracic ranges of rotation as well as lumbar range of flexion were extracted for statistical analyses. Specifically, range of rotation/flexion was considered to be the maximum recorded rotation/flexion with respect to its value at reference posture. The peak values of angular velocity, acceleration (i.e., increase in absolute value of velocity), and deceleration (i.e., decrease in absolute value of velocity) of the lumbar spine during the forward bending and backward return phases of the task with fast pace also were extracted for statistical analyses. For each variable, the mean value across the three trials was used. All statistical procedures were conducted in SPSS (IBM SPSS Statistics 22, Armonk, NY, USA), and in all cases a p value smaller than 0.05 was considered as statistically significant. One set of mixed-model analysis of variance (ANOVA) tests were conducted on the dependent variables of pelvic and thoracic range of rotations and lumbar range of flexion. The between subjects factors were group (with and without LBP) and age. The within subjects factor was motion pace (self-selected and fast). To be consistent with our earlier baseline study, the age factor was considered to have three levels each related to a decade of life between 40 and 70 years (i.e., 40-50, 50-60, 60-70). A second set of mixed-model ANOVA tests were conducted to test for the effects of group, age, and motion phase on peak values of lumbar angular velocity, angular



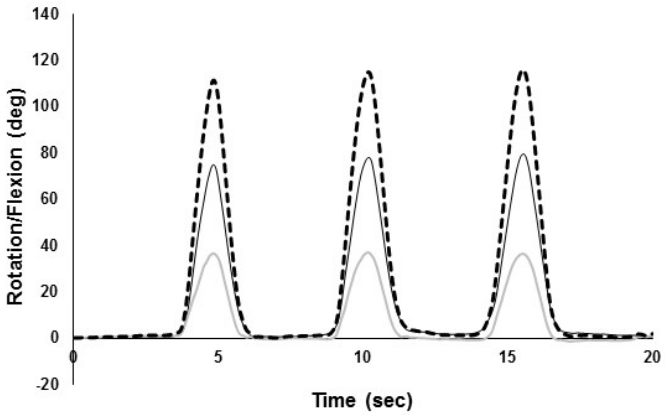


Figure 2-2: Typical examples of pelvic and thoracic rotations as well as lumbar flexion for the tasks with a self-selected pace (top) and a fast pace (bottom).

acceleration, and deceleration during the as fast as possible condition. The between subjects factors were group and age. The within subjects factor was motion phase (forward bending or backward return). Significant ANOVA tests were followed by post hoc tests using Tukey's procedure.

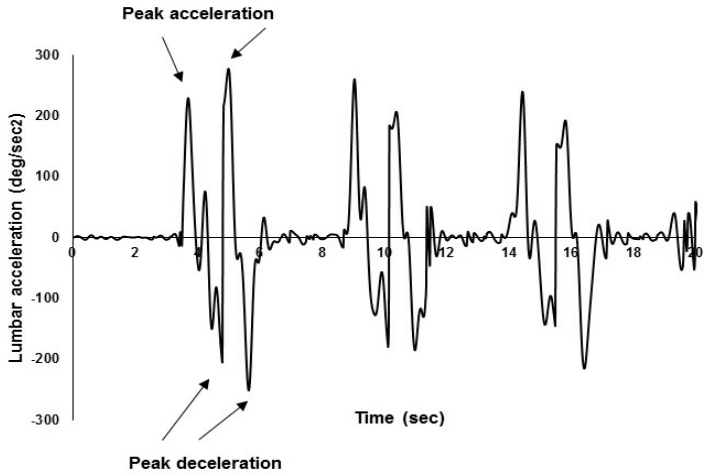


Figure 2-3: Typical examples of lumbar angular velocity (top) and acceleration (bottom). To facilitate automatic extraction of maximum values for lumbar acceleration (i.e., increase in absolute value of velocity) and deceleration (i.e., decrease in absolute value of velocity), the second derivative of lumbar flexion (i.e., containing acceleration and deceleration) was obtained through the numerical differentiation of the absolute values (i.e., positive only) of lumbar angular velocity.

2.3. Results

Thoracic range of rotation:

While there were no significant differences (Table. 2) in the thoracic range of rotation between patients (104.6°(13.6°)) and controls (99.1°(13.4°)), the thoracic range of rotation was larger during tasks with fast (105.3°(12.9°)) vs. self-selected (98.4°(13.7°)) paces. Furthermore, there was no age-related difference (Table. 2) in thoracic range of rotation (40-50: 99.7°(12.7°); 50-60: 108.0°(11.2°); 60-70: 97.4°(14.6°)). There was also no significant interaction effects of independent variables on the thoracic range of rotation (Table. 2).

Table 2-2: Summary of statistics for the effects of group (with and without LBP), motion pace (self-selected and fast) and age (40-50, 50-60, and 60-70) on pelvic and thoracic ranges of rotation and lumbar range of flexion.

		Thoracic Rotation	Pelvic Rotation	Lumbar Flexion
Group	*F*	1.40	17.34	10.69
	p	0.246	**<0.001**	**0.003**
Pace	*F*	24.87	61.67	4.97
	p	**<0.001**	**<0.001**	**0.033**
Age	*F*	2.43	3.70	3.58
	p	0.104	**0.036**	**0.039**
Group X Pace	*F*	0.18	0.01	0.91
	p	0.672	0.918	0.346
Group X Age	*F*	0.36	0.15	0.41
	p	0.700	0.861	0.666
Age X Pace	*F*	0.84	0.24	1.19
	p	0.442	0.789	0.317
Group X Age X Pace	*F*	0.84	0.37	1.57
	p	0.441	0.691	0.223

Boldface indicates a significant effect

Pelvic range of rotation:

Pelvic range of rotation was larger in patients (61.6° (12°)) vs. controls (43.4° (14.5°)) and was larger in tasks with fast (56.7° (15.2°)) vs. self-selected (48.3° (16°)) pace (Table. 2). The effect of age also was significant (Table. 2) such that pelvic range of rotation was larger in the two older groups compared to the younger group (Fig. 4). There was no significant interaction effects of independent variables on the pelvic range of rotation (Table. 2).

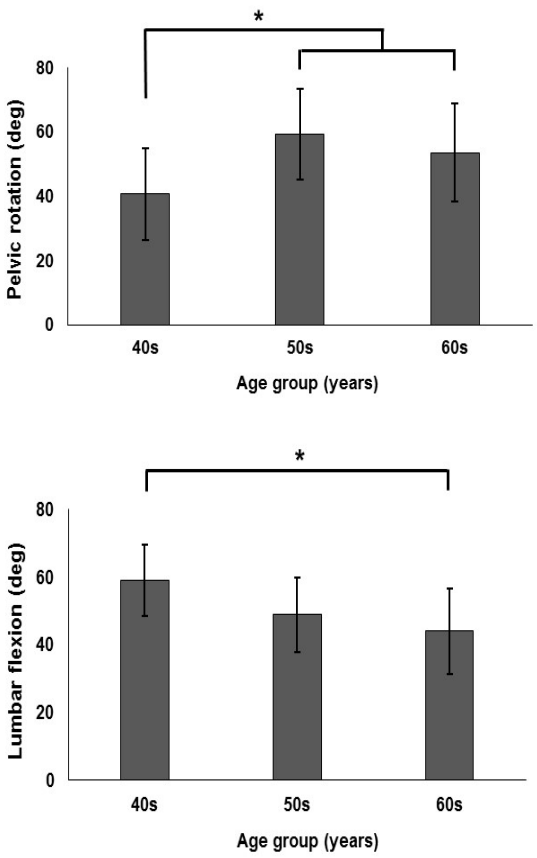


Figure 2-4: Age-related differences in pelvic range of rotation (top), and lumbar range of flexion (bottom). Error bars indicate standard deviations.

Lumbar range of flexion:

Lumbar range of flexion was smaller in patients (43° (11.2°)) vs. controls (55.7° (11.3°)) and was smaller during tasks with a fast (48.6° (13.3°)) vs. self-selected (50.1° (12.5°)) pace (Table. 2). The effect of age on lumbar range of flexion was significant with a smaller range of flexion in the oldest vs. youngest group (Table. 2 and Fig. 4).

Lumbar angular velocity, acceleration, and deceleration during the task with fast pace:

Peak angular velocity of lumbar flexion was higher in controls (94.7 deg/sec (25.9 deg/sec)) than in patients (65.5 deg/sec (31 deg/sec)) and was higher during the forward bending (84.7 deg/sec (33 deg/sec)) vs. backward return (78 deg/sec (28 deg/sec)) phase of the motion (Table. 3). There was a significant three-way interaction of group X motion phase X age on lumbar angular deceleration (Table. 3). Specifically, during the forward

bending phase, the effect of group was significant (F=9.5, p=0.009) on peak lumbar deceleration of individuals in the 60-70 year old group such that the deceleration was larger in controls (259.8 deg/sec^2 (89.2 deg/sec^2)) than patients (137.4 deg/sec^2 (55.2 deg/sec^2)) (Fig. 5). Moreover, during thebackward return phase, the effect of group was significant (F=22.5, p<0.000) on peak lumbar deceleration of individuals in the 50-60 year old group such that the deceleration was larger in controls (291.4 deg/sec^2 (69.3 deg/sec^2)) than patients (140.2 deg/sec^2 (38.3 deg/sec^2)) (Fig. 5). Similarly, there was a significant (Table. 3) interaction of group X motion phase X age on the lumbar angular acceleration. Specifically, for the forward bending phase of the motion, the effect of group was significant (F=5.56, p=0.036) for individuals in the 60-70 year old group with larger lumbar acceleration in controls (213.2 deg/sec^2 (73.9 deg/sec^2)) vs. patients (132.2 deg/sec^2 (53.0 deg/sec^2)) (Fig. 5). Furthermore, for the backward return phase of the motion, the effect of group was significant (F=8.95, p=0.011) for individuals in the 50-60 years old group with larger lumbar acceleration in controls (265.3 deg/sec^2 (79.0 deg/sec^2)) vs. patients (148.0 deg/sec^2 (67.7 deg/sec^2)) (Fig. 5).

Table 2-3: Summary of statistics for the effects of group (with and without LBP), motion phase (forward bending and backward return) and age (40-50, 50-60, and 60-70) on the maximum values of lumbar velocity, deceleration, and acceleration.

		Lumbar Velocity	Lumbar Deceleration	Lumbar Acceleration
Group	*F*	7.08	6.84	2.88
	p	**0.012**	**0.014**	0.100
Age	*F*	1.89	1.50	1.13
	p	0.168	0.238	0.337
Motion phase	*F*	8.81	13.19	2.69
	p	**0.006**	**0.001**	0.111
Group X Age	*F*	0.30	0.34	0.56
	p	0.741	0.714	0.575
Group XMotion phase	*F*	1.49	2.04	9.76
	p	0.231	0.163	**0.004**
Age XMotion phase	*F*	2.83	1.95	4.64
	p	0.074	0.159	**0.017**
Group X Age X Motion phase	*F*	2.86	6.86	4.37
	p	0.072	**0.003**	**0.021**

Boldface indicates a significant effect

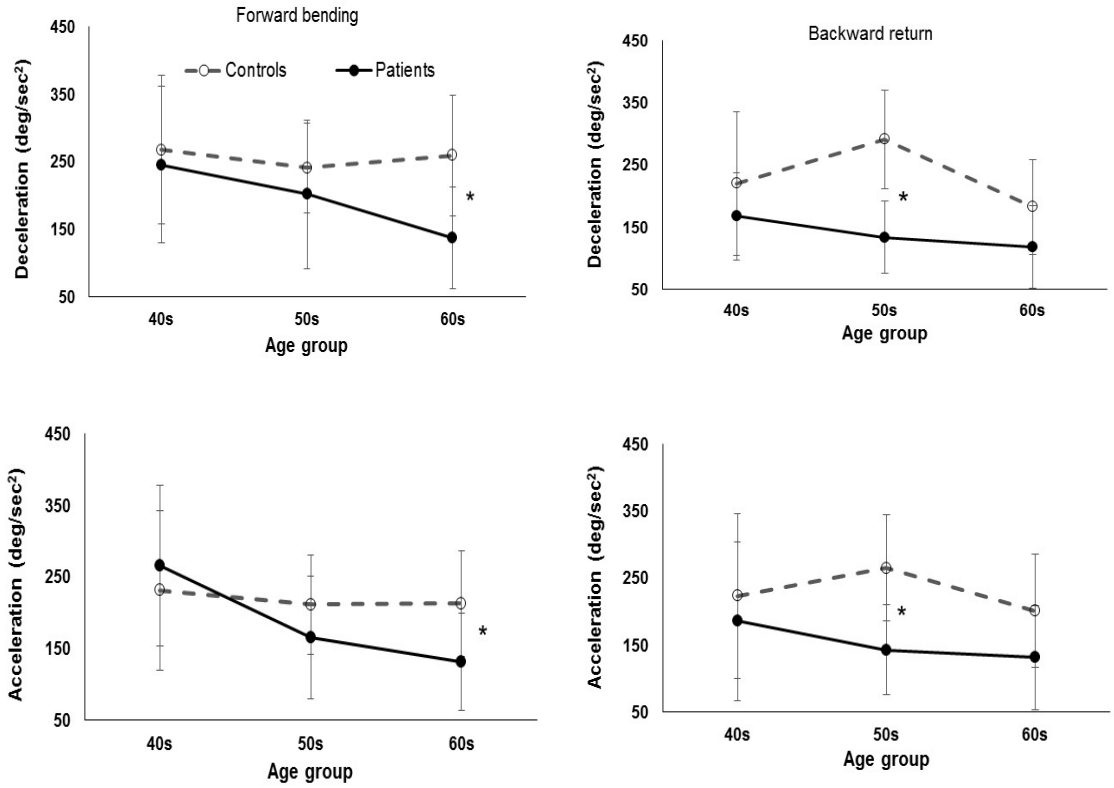


Figure 2-5: The age X group X motion phase interactions in peak lumbar angular deceleration (i.e., decrease in absolute value of velocity) and acceleration (i.e., increase in absolute value of velocity). Error bars indicate standard deviations.

2.4. Discussion

The purpose of this study was to investigate differences in the lower back mechanical environment, using measures of trunk kinematics, between a group of asymptomatic controls and a group of patients with acute LBP. The thoracic range of rotation was similar in both groups. However, the contribution of pelvic rotation and lumbar flexion to range of thoracic rotation was, respectively, larger and smaller among patients compared to controls. These findings confirmed our first hypothesis. Furthermore, as we hypothesized, patients adopted a slower pace compared to asymptomatic controls which was reflected in smaller values of the maximum angular velocity, deceleration and acceleration of lumbar flexion. While the main effect of age was significant on lumbo-pelvic kinematics with smaller pelvic rotation and larger lumbar flexion in younger vs. older population, there

was not any interaction effect of group X age on lumbo-pelvic kinematics indicating that aging similarly affects individuals with and without acute LBP.

A fair number of studies have investigated the effects of LBP on lumbo-pelvic kinematics, however, only a few have included patients with acute LBP (Wong and Lee 2004). Our finding of smaller lumbar range of flexion in patients with acute LBP is consistent with those reported by Wong and Lee (2004). However, due to different methods of measurement between the two studies, we were not able to compare pelvis range of rotation, though, they reported smaller hip flexion (vs. larger pelvis rotation in our study) in patients with acute LBP(Wong and Lee 2004). Considering a population with comparable personal characteristics and accounting for the effects of age and motion pace, our findings demonstrated clear differences (Table. 2) in lumbo-pelvic kinematics between individuals with and without acute LBP. In studies with a more heterogeneous sample where the confounding variables are not considered in the analysis, it is not clear whether the reported differences in kinematics were purely due to LBP or other variables such as personal or task characteristics (Sullivan et al. 1994, McGregor and Hughes 2000, Intolo et al. 2009, Shojaei et al. 2016). Therefore, our findings might have better isolated and highlighted the likely LBP-related differences in lower back kinematics.

The smaller contribution of lumbar flexion to thoracic rotation, adopted by patients with acute LBP, may be an attempt to reduce tension in posterior elements of the ligamentous spine (posterior longitudinal ligaments, posterior aspect of annulus fibrosus, and facet capsule) that have embedded pain sensitive nerve endings (Adams et al. 2006). These results are also consistent with the reported persistent activation of the lumbar erector spinae muscles and the absence of flexion-relaxation phenomenon among patients with LBP which has been suggested to be an attempt to stabilize injured spinal structures and protect them from further injury (Colloca and Hinrichs 2005). In other word, smaller lumbar flexion is associated with smaller passive contribution of lower back tissues to spine equilibrium; a difference in contribution that should be offset by increase in active muscle contribution.

The smaller lumbar contribution in patients with LBP compared to controls did not affect the task performance; both groups displayed a similar amount of thoracic rotation. The similar amount of thoracic movement was the result of using more pelvic rotation by patient with LBP compared to the controls. Large pelvic rotations impose higher shearing demands on the lower back (Shojaei et al. 2016) and are also associated with projection of a larger shearing component of internal muscle forces on the spine (Arjmand and Shirazi-Adl 2005). Therefore, an increased level of contact force on facet joints of the lumbar spine could be the negative cost of the adopted posture displayed by patients with acute LBP.

Earlier studies on lumbo-pelvic kinematics during forward bending and backward return mostly have been conducted under stationary conditions (imaging studies) (Jensen et al., 1994; Pearcy et al., 1984) or slow and self-selected paces (McClure et al. 1997, Wong and Lee 2004, Kim et al. 2013). Including a faster motion pace enabled us to better delineate differences in biomechanics between people with acute LBP and asymptomatic controls. Specifically, while the thoracic rotation increased in the fast vs. self-selected pace, the lumbar flexion decreased. Such posture adoption is probably a safer strategy for reducing stress in the lower back tissues because of the viscoelastic behavior and the inertial demand of fast tasks(Bazrgari et al. 2008).

Higher order lumbo-pelvic kinematics have been suggested to be reliable objective measures of the trunk motion (Kroemer et al. 1990, Aluko et al. 2011)and can well distinguish patients with chronic LBP from asymptomatic controls(Marras et al. 1993). Similar to the study by Marras et al. (1993), where much larger difference was found in lumbar angular acceleration than angular velocity and flexion between patients with chronic LBP and controls (i.e., 5 degree, 49 deg/sec, and 251 deg/sec^2 differences in the respective values of lumbar flexion, lumbar angular velocity, and lumbar angular acceleration), greater differences in angular acceleration were found in the present study (i.e., 12.7 deg, 29.2 deg/sec, and >81 deg/sec^2 differences in the respective values of lumbar flexion, lumbar angular velocity, and lumbar angular acceleration.

Although we didn't control for inter subject variability such as pain level, LBP related disability, fear of movement, and general health status, lumbo-pelvic kinematics were clearly different between LBP patients and asymptomatic controls. However, it remains unclear whether such kinematic differences are the cause or consequence of LBP. Such a research question can be addressed in future studies through conducting longitudinal studies. The observed kinematic differences suggest likely differences in lower back biomechanics between people with acute LBP and people without LBP, however, a better understanding can be achieved regarding altered neuromuscular strategy using model based estimations of trunk muscle forces and spinal loads (Shojaei et al. 2016). Finally, our results on age-related differences in lumbo-pelvic kinematics were consistent with our earlier findings, however, the potential inferential errors due to small sample size should be kept in mind when interpreting these results.

Chapter 3. Timing and Magnitude of Lumbar Spine Contribution to Trunk Forward Bending and Backward Return in Patients with Acute Low Back Pain

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3.1. Introduction

Lumbo-pelvic coordination during trunk forward bending and backward return is often assessed by clinicians to better identify biomechanical abnormalities in patients with low back pain (LBP) (Esola et al. 1996, Hestœk and Leboeuf-Yde 2000, Whittaker 2007). Alterations in lumbo-pelvic coordination denote changes in neuromuscular control of trunk motion as well as changes in the load sharing between passive and active components of the lower back (Davis et al. 1965, Farfan 1975, Davis and Jorgensen 2005, Hashemirad et al. 2010). Both neuromuscular control and load sharing have been recognized to play a role in LBP development (van Dieën and Nussbaum 2000, Panjabi 2003, Leinonen 2004, Hashemirad et al. 2009, Abouhossein et al. 2011, Dubois et al. 2011). The assessment of lumbo-pelvic coordination may simply involve evaluation of the relative contributions of lumbar flexion and pelvic rotation to trunk motion at the end range of forward bending or may include more in-depth evaluation of timing and magnitude of such relative contributions throughout the course of motion (Lariviere et al. 2000, Silfies et al. 2009, Kim et al. 2013, Pries et al. 2015, Mokhtarinia et al. 2016).

In asymptomatic individuals, the lumbar contribution to forward bending has been reported to be dominant in the early stage of trunk motion, whereas pelvis contribution increases toward the end of motion and is dominant at the late stage of motion (Esola et al. 1996, Lee and Wong 2002, Pal et al. 2007, Tafazzol et al. 2014, Vazirian et al. 2016, Vazirian et al. 2017, Vazirian et al. 2017). Conversely, backward return starts with a small lumbar contribution that gradually increases toward the end of motion (McClure et al. 1997, Granata and Sanford 2000, Lee and Wong 2002, Pal et al. 2007). In terms of timing of motion, it has been reported that in forward bending, lumbar motion tends to start sooner

than pelvic motion and lumbar motion remains ahead of pelvic motion throughout the forward bending. In the backward return lumbar motion remains behind pelvic motion (Pal et al. 2007, Thomas and Gibson 2007). Compared to asymptomatic individuals, lumbo-pelvic coordination in patients with LBP is generally more in-phase and less variable and involves smaller lumbar contribution to the trunk motion (Selles et al. 2001, Seay et al. 2011, Mokhtarinia et al. 2016). There are, however, some exceptions to such general trend of observed differences in the literature which could be due to heterogeneity of LBP (e.g., different subtypes of LBP), differences in patient's personal characteristics, and difference in performing forward bending and backward return (e.g., pace of task, presence of load, etc.) (Granata and Sanford 2000, Van Wingerden et al. 2008, Silfies et al. 2009, Kim et al. 2013, Vazirian et al. 2016). Kim et al. (2013), for instance, observed larger lumbar contribution to the trunk motion in a subgroup of patient with LBP who were identified to have "lumbar flexion with rotation syndrome". Silfies et al. (2009) reported a less in-phase and more variable lumbo-pelvic coordination in patients with LBP compared to asymptomatic controls under a reaching task. Despite considerable research related to lumbo-pelvic coordination, most of prior studies included patients with chronic LBP and it is not clear whether their findings can be generalized to include also patients with acute LBP. Due to the simplicity of the assessment, an evaluation of lumbo-pelvic coordination in clinical practice could prove useful to identify biomechanical etiologies for LBP and to direct patient treatment; thus a further understanding of this construct in acute LBP is needed.

Authors of the present study have recently reported the differences in lumbo-pelvic coordination between patients with acute LBP and asymptomatic controls by calculation of the relative contributions of lumbar and pelvis to trunk motion at the end point of forward bending. Compared to asymptomatic controls, patients with LBP implemented smaller lumbar flexion and larger pelvic rotation when bending from standing posture to the end point of forward bending. These results clearly distinguished patients from asymptomatic controls in discrete end points, however, they don't offer any information related to potential differences in lumbo-pelvic coordination throughout the trunk forward bending and backward motion. Further characterization of lumbo-pelvic coordination throughout the entire task cycle could provide more in-depth information about the impact of acute LBP on timing and magnitude aspects of lumbo-pelvic coordination (Selles et al. 2001, Pal et al. 2007, Thomas and Gibson 2007, Mokhtarinia et al. 2016, Vazirian et al. 2016). In

other words, potential biomechanical abnormalities in the lower back of patients with LBP, particularly due to neuromuscular impairments, could be better identified by assessment of lumbo-pelvic coordination throughout the entire task. Therefore, the objective of this study was to investigate differences in timing and magnitude aspects of lumbo-pelvic coordination between patients with acute LBP and asymptomatic controls during forward bending and backward return. Lumbar contribution to the trunk rotation was investigated at each quartile of forward bending and backward return as the magnitude aspect of lumbo-pelvic coordination. The timing aspect of lumbo-pelvic coordination was investigated using the continuous relative phase method (Lamb and Stöckl 2014). We hypothesized that patients with acute LBP would display a more in-phase and less variable lumbo-pelvic coordination that involves a reduced lumbar contribution to the trunk motion compared to the asymptomatic controls during the entire period of the forward bending and backward return task.

3.2. Methods

3.2.1. Study Design and Participants

A case-control study design was used wherein 19 female patients (aged 40-70 years old) with acute LBP (health care provider-diagnosed LBP ≤ 3 months) completed a set of trunk forward bending and backward return tasks. Data for 19 asymptomatic female controls (aged 40-70 years old) were extracted from an earlier study (Vazirian et al. 2017, Vazirian et al. 2017). All participants completed an informed consent procedure approved by the University of Kentucky Institutional Review Board before participation. Age, stature, body mass, and body mass index (BMI) for the two groups were comparable (Table.1). Asymptomatic controls with any history of LBP or musculoskeletal disorders were excluded (Shojaei et al. 2016, Vazirian et al. 2017). Patients with acute LBP were excluded if they had any significant cognitive impairment, intention to harm themselves or others, or substance abuse.

Table 3-1: Mean (SD) participants characteristics

Group	Controls	Patients	*t*-value	p-values
Age (years)	56 (9)	58 (9)	0.723	0.474
Stature (m)	1.64 (5)	1.63 (7)	-0.592	0.557
Body mass (kg)	70(12)	76(17)	1.553	0.130
BMI	25.7(4.1)	27.5(4.6)	1.608	0.117

3.2.2. Experimental Procedures

Two wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands) were attached superficial to the T10 and the S1 spinous process of participants to collect kinematics of thorax and pelvis as rigid bodies (50 Hz). A Kalman filter was used to minimize any potential effect of noise on the data. Each participant completed two trunk forward bending and backward return tasks in the sagittal plane; one at a preferred pace and the other at a fast pace. During the task with preferred pace, participants stood in an upright posture for 5 seconds, bent forward using a preferred pace to reach their maximum trunk rotation, held their maximum trunk rotation for 5 seconds, returned back to the initial upright position, and stood again for 5 seconds. During the task with fast pace, participants performed the same task but with their fastest possible pace and without a pause at the maximum trunk rotation. Each task pace was repeated three times, and participants completed the task with the preferred pace prior to the task with the fast pace.

3.2.3. Data analysis

Using the kinematics data collected with the IMUs, pelvic and thoracic rotations were found with respect to the standing posture. At each time instant, flexion/extension of lumbar spine (i.e., as a deformable segment between thorax and pelvis) was calculated as the difference between the pelvic and thoracic rotations. To calculate the lumbar contribution, the forward bending and the backward return of each task was divided into quarters of equal thoracic rotation. The ratio of range of lumbar flexion/extension over the range of thoracic rotation was then calculated for each quartile. Lumbar contribution in each quartile of forward bending and backward return task was finally calculated as the

average of the above ratio for the same quartile across the three repetitions of the task. The thoracic and pelvic rotation data were also used to calculate the continuous relative phase between thorax and pelvis by initially generating the phase planes of pelvic and thoracic rotations according to (Lamb and Stöckl 2014), and then subtracting the pelvic phase angle from the thoracic phase angle at each instant of the task. To characterize the timing aspect of lumbo-pelvic coordination, two measures from the continuous relative phase (CRP) curve of forward bending and backward return were extracted: 1) the mean absolute relative phase (MARP), and 2) the deviation phase (DP) (Stergiou et al. 2001). Briefly, the mean and standard deviation of the absolute value of relative phase for each percentile of trunk forward bending and backward return across the three repetitions of each task were initially obtained. Subsequently, the average of the calculated mean and standard deviation values over the entire forward bending and backward return were respectively calculated as MARP and DP values. By definition, MARP values closer to 0 represent a more ‘‘in-phase’’ lumbo-pelvic coordination (i.e., more synchronous movement of segments) whereas values closer to π radians represent a more ‘‘out-of-phase’’ lumbo-pelvic coordination (i.e., less synchronous movement of segments). Moreover, a smaller DP represents a lumbo-pelvic coordination with less trial-to-trial variability (i.e., a more stable motion pattern).

3.2.4. Statistical Analysis

For each task and phase of trunk motion (i.e., forward bending and backward return), the lumbar contribution in each quartile, MARP, and DP were extracted for statistical analyses. All statistical procedures were conducted in SPSS (IBM SPSS Statistics 23, Armonk, NY, USA), and in all cases a *p* value smaller than 0.05 was considered as statistically significant. Mixed-model analysis of variance (ANOVA) tests were conducted on the dependent variables with group (with and without LBP) and age (40-50, 50-60, 60-70) as the between-subjects factors and motion pace (preferred and fast) as the within-subjects factor. Mixed-model ANOVA assumptions were verified, and significant ANOVA tests were followed by post hoc tests using Tukey’s procedure.

3.3. Results

3.3.1. Interaction effects

Forward bending:

The lumbar contribution in the 1st quarter was larger (40-50: F=4.95, p=0.045; 60-70: F=7.90, p=0.016) in the control vs. patient group only during the task with fast pace and for individuals in the 40-50 (40s) and60-70 (60s) year-old age groups (Fig. 1). This lumbar contribution was also larger (F=10.47, p=0.018) in the task with preferred vs. fast pace only for patients in the 60-70 (60s) year-old age group (Fig. 1). Additionally, lumbar contribution in the 4th quarter was larger (F=6.22, p=0.041) in the task with preferred vs. fast pace only for patients in the 50-60 (50s) year-old age group. This lumbar contribution was also larger (F=5.97, p=0.012) in the 60-70 (60s) versus 50-60 (50s) year-old age group only among patients and under task with fast pace (Fig. 2).

Table 3-2: Summary of statistical results for all outcome measures during trunk forward bending and backward return. LC: lumbar contribution. MARP: mean absolute relative phase. DP: deviation phase

Forward Bending												
	LC: 1st quarter		LC: 2nd quarter		LC: 3rd quarter		LC: 4thquarter		MARP		DP	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	15.86	**<0.001**	17.81	**<0.001**	11.36	**0.002**	7.39	**0.011**	5.52	**0.025**	11.94	**0.002**
Pace (P)	0.07	0.787	108.02	**<0.001**	20.80	**<0.001**	6.90	**0.013**	4.99	**0.033**	15.08	**0.001**
Age (A)	2.60	0.090	5.71	**0.008**	3.64	**0.038**	1.67	0.205	1.53	0.233	3.18	0.055
G XP	0.77	0.388	2.32	0.137	0.11	0.739	0.75	0.394	0.60	0.445	2.38	0.133
G XA	0.44	0.651	0.47	0.620	0.58	0.568	0.92	0.411	0.74	0.483	2.78	0.078
A XP	0.41	0.670	0.25	0.779	0.15	0.859	1.14	0.332	0.66	0.524	0.22	0.806
G X A X P	4.09	**0.026**	0.18	0.839	2.37	0.110	4.81	**0.015**	1.02	0.371	2.19	0.129
Backward Return												
	LC: 1st quarter		LC: 2nd quarter		LC: 3rd quarter		LC: 4th quarter		MARP		DP	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	9.59	**0.004**	15.21	**<0.001**	17.58	**<0.001**	12.30	**0.001**	6.60	**0.015**	4.94	**0.034**
Pace (P)	27.15	**<0.001**	44.03	**<0.001**	19.74	**<0.001**	3.41	0.074	1.62	0.213	11.42	**0.002**
Age (A)	3.28	0.051	5.01	**0.013**	4.32	**0.022**	0.76	0.476	0.67	0.519	2.71	0.082
G XP	3.90	0.057	0.43	0.517	0.91	0.347	5.33	**0.028**	0.45	0.506	0.79	0.382
G XA	1.12	0.340	0.35	0.711	0.14	0.870	0.32	0.729	0.07	0.930	0.60	0.557
A XP	1.65	0.208	2.00	0.153	1.20	0.315	2.97	0.066	1.17	0.324	0.56	0.576
G X A X P	3.92	**0.030**	1.30	0.287	1.48	0.244	5.21	**0.011**	2.93	0.068	0.07	0.935

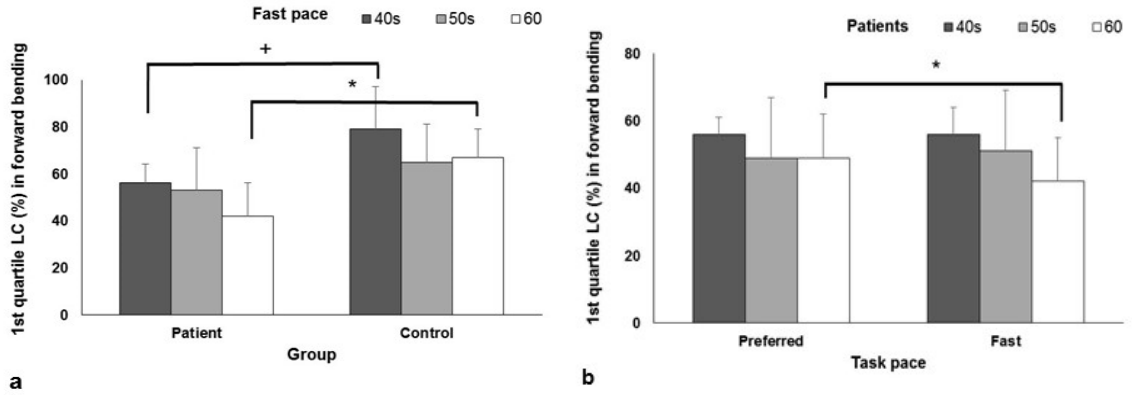


Figure 3-1: The simple main effects of group (a) and task pace (b) on lumbar contribution (LC) were significant in the 1st quarter of forward bending. Error bars indicate positive standard deviations. The symbols * and + indicate significant paired differences.

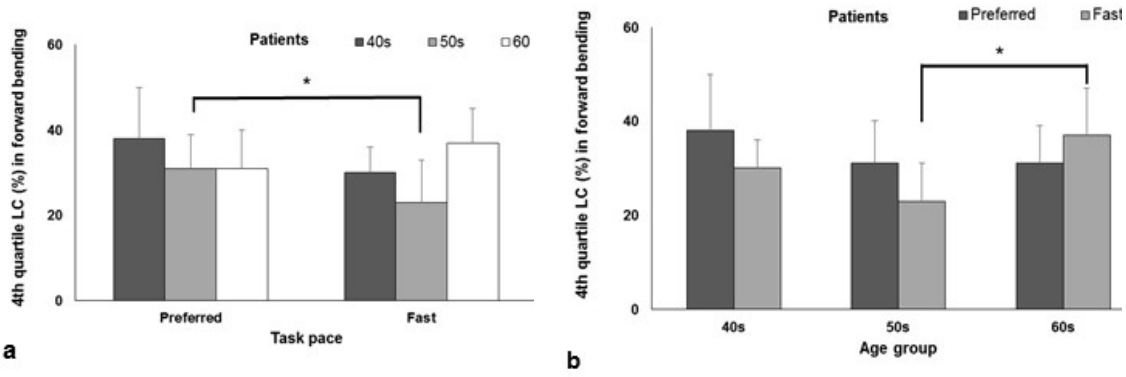


Figure 3-2: The simple main effects of task pace (a) and age (b) on lumbar contribution (LC) were significant in the 4th quarter of forward bending. Error bars indicate positive standard deviations. The symbol * indicates significant paired differences.

Backward return:

The lumbar contribution in the 1st quarter was larger (F=14.71, p=0.012; F=9.37, p=0.022) during the task with preferred vs. fast pace only for controls in the 40-50 (40s) and60-70 (60s) year-old age group (Fig.3). This lumbar contribution was also larger (F=5.01, p=0.020) for controls in the 40-50 (40s) vs. controls in the 50-60 (50s) year-old age group(Fig.3).

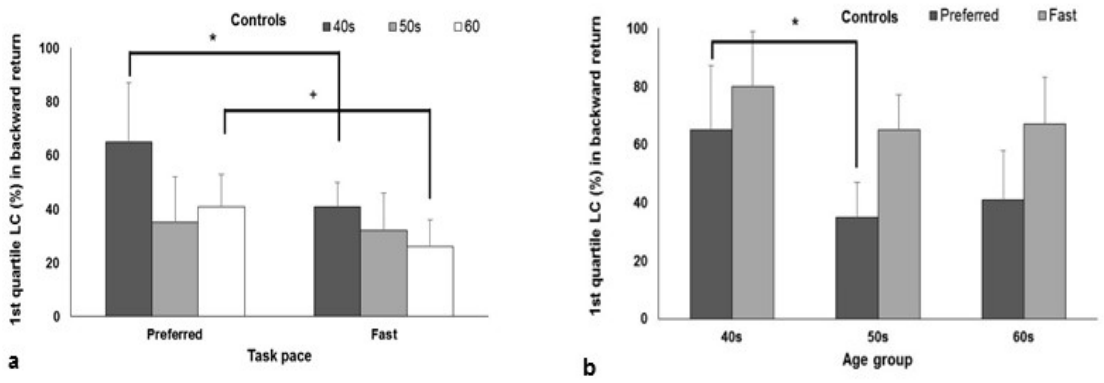
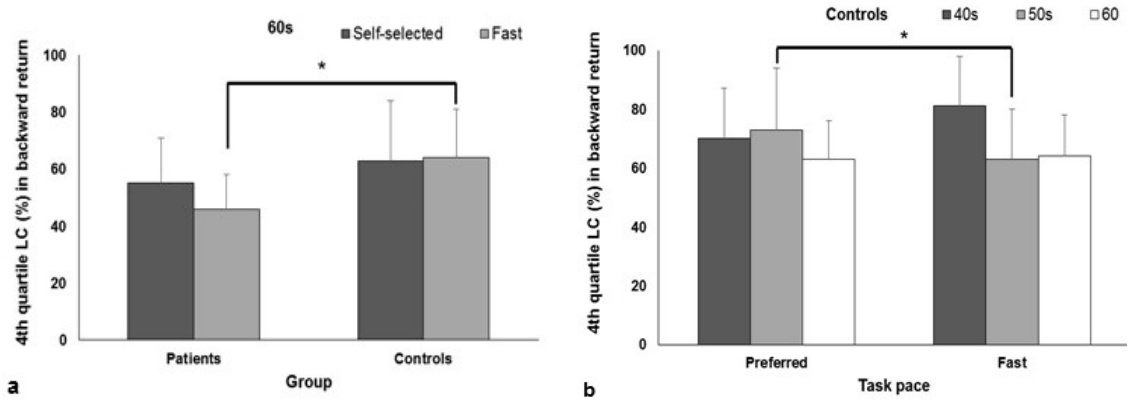


Figure 3-3: The simple main effects of task pace (a) and age (b) on lumbar contribution (LC) were significant in the 1st quarter of backward return. Error bars indicate positive standard deviations. The symbols * and + indicate significant paired differences.

Additionally, the lumbar contribution in the 4th quarter was larger (F=5.12, p=0.043) for controls in the 60-70 (60s) year-old age group vs. patients in the same age group only during the task with fast pace (Fig.4). This lumbar contribution was also larger (F=17.62, p=0.009) in the task with preferred vs. fast pace only for controls in the 50-60 (50s) year-old age group (Fig.4).Furthermore, this lumbar contribution was larger (F=21.26, p=0.004) during the task with preferred vs. fast pace only for patients in the 60-70 (60s) year-old age group (Fig. 4).



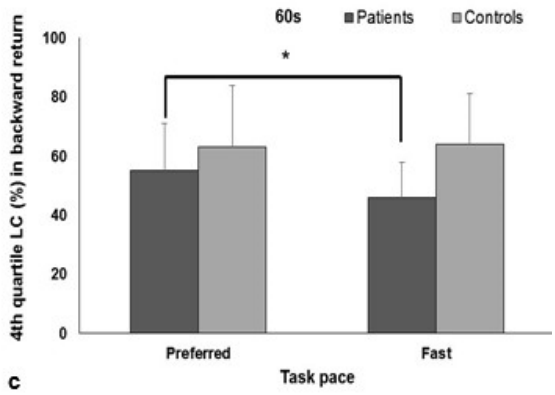


Figure 3-4: The simple main effects of group (a) and task pace (b and c) on lumbar contribution (LC) were significant in the 4th quarter of backward return. Error bars indicate positive standard deviations. The symbol * indicates significant paired differences.

3.3.2. Main effects

Group differences

During forward bending and backward return, the lumbar contribution in the 2nd and 3rd quarters was smaller in the patient group than the control group (Table 2 and Table 3). Furthermore, the MARP and DP were smaller in the patient vs. control group during forward bending and backward return (Table 2 and Table 3).

Table 3-3: Mean (SD) of all outcome measures for different groups, task paces, and ages during trunk forward bending and backward return. MARP: mean absolute relative phase. DP: deviation phase. Post hoc tests results for the effects of age were indicated by lowercase Latin letters (a and b).

Forward Bending								
		Group		Task Pace		Age		
		Patients	*Controls*	*Preferred*	*Fast*	*40-50*	*50-60*	*60-70*
Lumbar contribution (%)	*1st quarter*	49 (14)	70 (17)	60 (18)	60 (19)	73 (19)	56 (16)	55 (16)
	2nd quarter	42 (13)	60 (15)	57 (17)	45 (15)	65 (16)[a]	54 (14)[b]	51 (16)[b]
	3nd quarter	38 (12)	52 (15)	49 (15)	42 (14)	57 (18)[a]	45 (14)[b]	45 (13)[b]
	4nd quarter	31 (10)	41 (14)	38 (13)	34 (13)	43 (14)	34 (11)	36 (14)
MARP (rad)		0.11 (0.14)	0.18 (0.12)	0.16 (0.11)	0.13 (0.10)	0.20 (0.13)	0.14 (0.11)	0.11 (0.07)
DP x 10^3		38 (26)	71 (54)	71 (53)	38 (29)	84 (64)	43 (29)	47 (38)
Backward Return								
		Group		Task Pace		Age		
		Patients	*Controls*	*Preferred*	*Fast*	*40-50*	*50-60*	*60-70*
Lumbar contribution (%)	*1st quarter*	26 (11)	40 (19)	38 (19)	28 (12)	45 (21)	31 (14)	35 (14)
	2nd quarter	36 (11)	52 (15)	49 (17)	40 (13)	58 (16)[a]	44 (14)[b]	44 (14)[b]
	3nd quarter	47 (12)	65 (13)	59 (16)	54 (15)	69 (13)[a]	57 (13)[b]	54 (17)[b]
	4nd quarter	52 (11)	69 (17)	62 (16)	59 (17)	68 (18)	62 (15)	59 (18)
MARP (rad)		0.08 (0.08)	0.22 (0.12)	0.19 (0.12)	0.18 (0.09)	0.22 (0.12)	0.18 (0.10)	0.16 (0.10)
DP x 10^3		39 (23)	60 (45)	63 (46)	36 (22)	70 (48)	40 (26)	45 (38)

The effects of task pace

Lumbar contribution to the trunk rotation was smaller during the 2nd and 3rd quarters of both forward bending and backward return of the task with fast vs. preferred pace (Table 3). MARP during forward bending and DP during both forward bending and backward return were smaller in the task with fast vs. preferred pace (Table 2 and Table 3).

Age-related differences

Lumbar contribution to the trunk rotation during the 2nd and 3rd quarters of both forward bending and backward return was larger in the 40-50 (40s) year-old age group than the other two age groups (Table 3). No age related differences in MARP and DP during forward bending and backward return were found (Table 2 and Table 3).

3.4. Discussion

The purpose of this study was to investigate differences in magnitude and timing aspects of lumbo-pelvic coordination between patients with acute LBP and asymptomatic controls during trunk forward bending and backward return. Lumbar contribution to the trunk motion in the 2nd and 3rd quarters of forward bending and backward return were smaller in patients with acute LBP vs. asymptomatic controls (i.e., partially confirming our hypothesis). Lumbo-pelvic coordination was more in-phase (i.e., denoted by smaller MARP values) and less variable (i.e., denoted by smaller DP values) in patients with acute LBP vs. asymptomatic controls (i.e., confirming our hypothesis).

In our earlier study, lumbar contribution to the trunk motion at the end point of the forward bending was observed to be smaller in patients with acute LBP vs. asymptomatic controls. Our current finding, further suggest that such overall observed difference was due to smaller lumbar contribution in patients with acute LBP in the 2nd and 3rd quarters of forward bending and backward return. To the best of our knowledge, no other study has reported differences in lumbar contribution to trunk motion throughout the forward bending and backward return between patients with acute LBP and asymptomatic controls. However, in studies including patients with chronic LBP and individuals with a history of LBP similarly

smaller lumbar contribution to the trunk motion in all quartiles (Lariviere et al. 2000) as well as in the early stage (Porter and Wilkinson 1997) or middle stage (Esola et al. 1996) of forward bending and backward return have been reported.

While in the current study the patients implemented a more in-phase motion of pelvis and thorax segments compared to asymptomatic controls, Wong and Lee (2004) reported no differences in timing aspects of the lumbo-pelvic coordination between a patient group and a asymptomatic control group. Such inconsistency in the results between the current study and the study by Wong and Lee (2004) could be due to the differences in the personal characteristics of participants (e.g., females ~ 57 years old in the current study vs. males ~ 40 years old in the study by Wong and Lee (2004)), different methods of data analysis (CRP method in the current study vs. Cross-correlation method in the study by Wong and Lee (2004); see Vazirian et al. (2016b) for differences between the two methods) and potential differences in LBP subtypes. In studies including patients with chronic LBP, there are reports of a more in-phase lumbo-pelvic coordination in patients vs. asymptomatic controls during forward bending and backward return (Asgari et al. 2015, Mokhtarinia et al. 2016) as well as during walking and running (Selles et al. 2001, Seay et al. 2011). In contrast, Silfies et al. (2009) and Paquet et al. (1994) reported, respectively, a more out-of-phase and similar lumbo-pelvic coordination in patients vs. asymptomatic controls. Discrepancies in the results of studies concerning patients with chronic LBP may be attributed to the differences in the population studied (e.g., personal characteristics and LBP subtype), differences in the methods of data analysis, and differences in LBP severity at the time of study.

The smaller contribution of lumbar flexion to trunk motion, as seen in patients with acute LBP in the current study, reduces passive contribution of lower back tissues in offsetting the physical demand of the task on the lower back. Such an alteration in lumbar contribution has been suggested to prevent painful deformation in posterior elements of the ligamentous spine (Colloca and Hinrichs 2005). More in-phase and less variable lumbo-pelvic coordination, also known as phase-locked or rigid coordination (Mokhtarinia et al. 2016), is regarded as a protective motor control strategy to reduce the likelihood of painful deformation of spinal tissues under dynamic tasks. Such a strategy, however,

demands higher levels of trunk muscles activation and co-activation which in turn can lead to increased spinal loads and muscle fatigue (Marras et al. 2001, Bazrgari et al. 2008).

The lumbar contribution in the 2nd and 3rd quarters was smaller during the task with fast vs. preferred pace for both forward bending and backward return. Similarly, MARP and DP were found to be smaller during the task with fast pace. These findings are consistent with earlier reports on the effects of task pace on trunk kinematics variability (Asgari et al. 2015). The smaller lumbar contribution and more in-phase lumbo-pelvic coordination is consistent with the strategy to prevent painful deformation and injury (intensified by viscoelastic behavior and inertial demand of fast tasks) given the higher risk of injury under fast trunk motion (Bazrgari et al. 2008).

Better understanding of differences in lumbo-pelvic coordination during trunk forward bending and backward return between individuals with and without LBP is clinically important (White III and Panjabi 1978, Panjabi 2003, Van Hoof et al. 2012). Specifically, quantification of such differences, as done in the present study, may improve the effectiveness of current management paradigm for LBP by positively impacting the diagnosis and treatment stages. More in-depth information about normal and abnormal trunk kinematics during trunk forward bending and backward return can help better match patient pathology with targeted treatments and decide whether a given treatment is moving the patient in the right direction. Additionally, our results indicate that lumbo-pelvic coordination varies with age which also should be considered in the diagnostic process.

Although our findings contribute to the current understanding of the timing and magnitude of lumbar spine contribution to the trunk forward bending and backward return in patients with acute LBP, there are study limitations. First due the use of cross sectional data, we are unable to infer causality. As such we are unable to infer if study findings result in or are consequence to acute LBP. Second, we did not control for inter subject variability such as anthropometric measures, pain level, potential musculoskeletal abnormalities like foot shape abnormalities, flat back, hyper-lordosis as well as LBP-related disability, fear of movement, and general health status. With this being said, there is the possibility of additional unknown factors that affect study outcomes and were not included in our analysis. Third, although we controlled for age and gender-related differences, the

influence of differences in lumbar spine stiffness or mobility between groups on our finding, though perhaps minimal, should not be overlooked. Finally, while studying magnitude and timing aspects of lumbo-pelvic coordination in patients with acute LBP provides some insights into neuromuscular control of trunk motion and load sharing between lower back tissues, quantification of such variables requires detailed model-based studies (Bazrgari et al. 2008, Arjmand et al. 2009) which we plan to conduct in the future.

In summary, the lumbar contribution to trunk motion during the 2nd and 3rd quarters of trunk forward bending and backward return phases of motion as well as MARP and the DP during the entire motion were smaller in the patient vs. the control group. These differences in lumbo-pelvic coordination of individuals with acute versus without acute LBP are likely to be due to a neuromuscular motor control strategy to temporarily reduce the painful deformations in the lumbar tissues.

Chapter 4. Mechanical Demands on the Lower Back in Patients with Non-chronic Low Back Pain during a Symmetric Lowering and Lifting Task

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4.1. Introduction

Low back pain (LBP) is a leading cause of disability with substantial direct and indirect cost (Balagué et al. 2012, Hoy et al. 2014, Maher et al. 2017).Complexity and multidimensional nature of LBP's risk factors pose a significant challenge for risk management strategies aimed at minimizing the level of exposure. Knowledge of the underlying mechanism(s) responsible for the development and/or persistence of LBP may open new avenues for managing this problem, via interventions that specifically target the underlying malfunctioning mechanism(s) rather than simply reducing generic risk factor exposures. Mechanical loads, specifically forces and deformations, in the lower back tissues can instantaneously or cumulatively exceed the tissues' injury/pain threshold and directly or indirectly lead to LBP (Van Dieën et al. 1999, Adams 2004, Adams et al. 2006, Coenen et al. 2014). Therefore, a further understanding of this construct in patients with LBP could provide important insights into this health condition.

Mechanical loads experienced in the lower back tissues are directly related to mechanical equilibrium and stability of the lumbar spine (Kingma et al. 2007, Arjmand et al. 2009). Spine equilibrium requires that forces in the lower back tissues, at a minimum level, to balance the mechanical demand of the task (i.e., due to body weight, external loads, and inertia forces). Forces in the lower back tissues maybe larger than the minimum required force for equilibrium in response to stability requirement of spine (i.e., the capacity to maintain mechanical equilibrium at presence of perturbation). Therefore, spinal loads are the resultant of two sets of forces that balance each other around the spine: 1) body weight, external loads, and inertia forces (i.e., collectively known as the mechanical demands of the task on the lower back) and 2) the active muscle forces as well as the

passive forces in the connective tissues attached to the spine (i.e., collectively known as the internal tissue responses) (Reeves and Cholewicki 2003, Adams et al. 2006, Bazrgari et al. 2008, Bazrgari et al. 2008). Potential injury mechanisms in the lower back due to mechanical loading have been shown in cadaveric studies (Adams 2004, Adams et al. 2006). Lower back tissues can be injured due to excessive loads in the lumbar spine including compression force (e.g., vertebral body damage followed by internal disc disruption), bending moment in the sagittal plane (e.g., posterior ligaments and annulus damage), axial twist and shearing force (e.g., facet joints damage), and combined bending moment and compression force (e.g., annulus and nucleus damage) (Harris and Macnab 1954, Roaf 1960, Osti et al. 1990, Van Dieën et al. 1999, Adams 2004, Adams et al. 2006).

The potential causal mechanism for LBP via excessive mechanical load in lower back tissues (Van Dieën et al. 1999, Adams 2004, Adams et al. 2006, Coenen et al. 2014) has motivated many research to investigate whether exposure to certain physical factors increases mechanical loads in the lower back. For instance, muscle forces and spinal loads under dynamic lifting tasks (Granata et al. 1997, Fathallah et al. 1998), whole body vibrations (Kitazaki and Griffin 1997, Kong and Goel 2003, Bazrgari et al. 2008), sudden forward perturbations (Bazrgari et al. 2009, Shahvarpour et al. 2015), and sudden release loading (Bazrgari et al. 2009) have been estimated for asymptomatic individuals. Though the level and the type of association between exposure to physical factors and occurrence of LBP has been a source of disagreement in the literature (Waddell and Burton 2001, Adams et al. 2006, Roffey et al. 2010, Wai et al. 2010, Maher et al. 2017), collectively these studies suggest increase in mechanical loads under exposure to physical factors. Similarly, investigation of spinal loads in patients with LBP may help verifying whether treatments offered for LBP should also improve the lower back biomechanics.

The published research on spinal loads in patients with LBP has mainly focused on persons with chronic condition. For lifting and lowering tasks from the floor to the hip level, Lariviere et al. (Larivière et al. 2002) did not find any difference in peak moment demand and compression forces on the spine in patients with chronic LBP vs. controls. They used link-segment models to estimate mechanical demands of the task on the lower back and polynomial equations to estimate spinal loads (Larivière et al. 2002). Using a two-

dimensional link-segment model and a single equivalent extensor muscle, Norman et al. (Norman et al. 1998) reported larger peak and mean moments as well as larger compression and shearing forces on the spine of workers with chronic LBP vs. controls during regular work duties on the work site. Marras et al. (Marras et al. 2001) reported larger peak moment and compression as well as larger mean compression and shearing forces on the spine of patients with chronic LBP vs. asymptomatic controls using an EMG-assisted model during lifting tasks in the sagittal plane. Shahvarpour et al. (Shahvarpour et al. 2016) reported similar muscle forces and spinal loads for patients with chronic LBP and asymptomatic controls using a detailed finite element model of spine during unstable sitting on a wobble chair. Notwithstanding the impact of experimental setup and modeling assumptions on findings of earlier studies, it is plausible to postulate differences in lower back loading between patients with chronic LBP and asymptomatic individuals; differences that are task dependent. To our best knowledge, there are only two studies of lower back loading in patients with non-chronic LBP. Using a link-segment model, Shum et al. (Shum et al. 2007, Shum et al. 2010) calculated the lower back moment during trunk forward bending and backward return as well as sit-to-stand and stand-to-sit tasks. The lower back moment was smaller in patients at the end range of trunk forward bending but was larger at smaller bending angles (i.e., 15, 30, and 45 degrees). For sit-to-stand and stand-to-sit activity, the lower back moment was smaller in the main plane of movement (the sagittal plane) but larger in frontal and transverse planes among patients with non-chronic LBP compared to asymptomatic controls. Similar to studies of patients with chronic LBP, differences in lower back loads between patients with non-chronic LBP and asymptomatic individuals appears to be task dependent. The limited number of studies on lower back loading in patient with LBP, particularly those with non-chronic LBP, along with task dependency of change in lower back loading call for further investigation of this important construct in patients with LBP.

The objective of this study was set to investigate differences in mechanical demands of a task involving lowering and lifting a load in the sagittal plane on the lower back between a group of females with non-chronic LBP and a control group of asymptomatic females. Given that for the same two groups of participants, we have observed similar trunk range of rotation but smaller trunk angular acceleration in the patient vs. control group during free trunk forward bending and backward return (Shojaei et al. 2017), we hypothesized

that the moment demand on the lower back would be smaller for patients vs. controls. However, since patients adopted a larger pelvic rotation during the free trunk bending and return (Shojaei et al. 2017), we further hypothesized that the shearing and axial components of the task demand will, respectively, be larger and smaller in patients with non-chronic LBP versus controls (Shojaei et al. 2016).

4.2. Methods

4.2.1. Participants

Nineteen females (aged 40-70 years) with health-care provider diagnosed non-specific LBP were included in this case-control study design to complete a set of experimental procedures that had already been used in a baseline study involving asymptomatic individuals between 20 and 70 years old (Shojaei et al. 2016, Shojaei et al. 2016, Vazirian et al. 2017, Vazirian et al. 2017). Patients were excluded if their LBP had lasted more than 3 months as well as if they had significant cognitive impairment, intention to harm themselves or others, evidence of substance abuse, or did not have access to a telephone (Radloff 1977, Ewing 1984, Brown and Rounds 1995, Borson et al. 2000). Upon completion of data collection from the patient group, the data from female participants in the baseline study who were within the same age range (i.e., 40-70 years old) of the patients in this study were extracted for comparison. Asymptomatic controls were recruited via advertisement and excluded if they had a recent (i.e., during the past year) history of LBP or musculoskeletal disorders (Shojaei et al. 2016, Shojaei et al. 2016, Vazirian et al. 2017, Vazirian et al. 2017). Independent-samples t-tests indicated no differences in age, stature, body mass, or body mass index (BMI) between the two groups (Table 1). Prior to data collection, all participants completed an informed consent procedure approved by the Medical University of Kentucky Institutional Review Board.

Table 4-1: Mean (SD) participant characteristics

	Patients	Controls	t-value	p-values
Age (years)	58 (9)	56 (9)	0.723	0.474
Stature (cm)	163 (7)	164 (5)	-0.592	0.557
Body mass (kg)	76 (17)	70 (12)	1.553	0.13
BMI	27.5 (4.6)	25.7 (4.1)	1.608	0.117
Level of pain*	3.84 (2.09)	--	--	--
Level of disability*	6.16 (4.54)	--	--	--

* The level of pain is based on the pain intensity construct of Wisconsin Brief Pain Inventory (Daut et al. 1983) and the disability is based on Roland Morris Disability Scale (Stroud et al. 2004).

4.2.2. Experimental Procedures

Straps were used to attach wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands) superficial to the T10 vertebral process, sacrum (S1), right thigh (superior to lateral femoral epicondyle), and right shank (superior to lateral malleolus) (Shojaei et al., 2016c)[1]. IMUs placed at the T10 and the S1 levels were assumed to measure rotations of the thorax and pelvis as rigid bodies, while the difference between these rotations was considered to represent lumbar flexion/extension (Shojaei et al. 2016) (Fig 1). During the data collection, participants were instructed to complete one symmetric lowering and lifting task while standing in the center of a force platform (AMTI, Watertown, MA). Participants were asked to lower a 4.5 kg load from an upright posture to their knee height, pause for 5 seconds at this flexed posture, and then extend back to the initial upright standing posture. No more instruction was provided and the task was performed at the participants preferred cadence. The participants completed the task without practice, but if the proper way of performing the task was violated (for example, target height was not achieved) the task was repeated. The kinematics data tracked by IMUs and ground reaction forces collected from the force platform were sampled at the respective rates of 50 and 1000 Hz. Raw kinematics and kinetics data were low-pass

[1]IMUs were attached by student researchers. The first author of this manuscript was present in data collection of all participants and particularly assured the consistency of sensors locations between patients and controls.

filtered (cutoff frequencies of 6Hz and 50Hz, respectively) using a fourth order, bidirectional, Butterworth filter.

4.2.3. Data Analysis

A previously developed linked-segment model of the lower extremities and pelvis was used to estimate the net reaction forces and moments at the lower back (Shojaei et al. 2016). Briefly, the model, developed in MATLAB (The MathWork Inc., Natick, MA, USA, version 8.6), included rigid bodies of seven segments (bilateral feet, shanks, and thighs as well as the pelvis) that were connected using frictionless point-contact joints (Fig. 1).

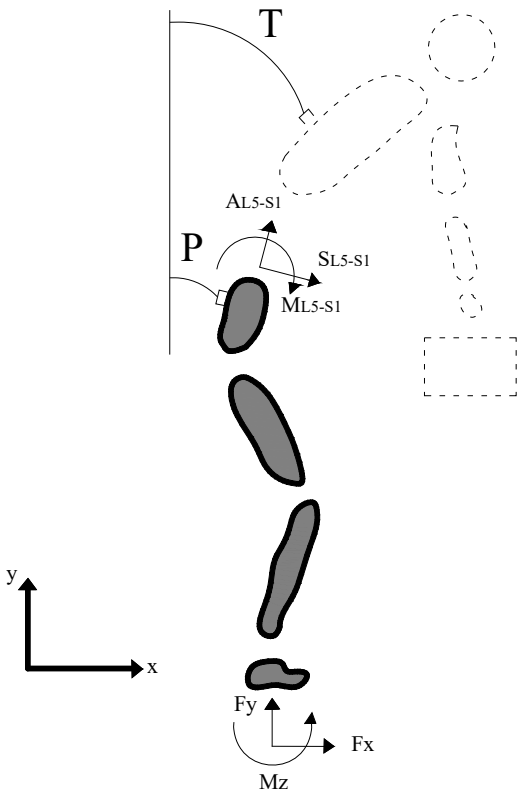
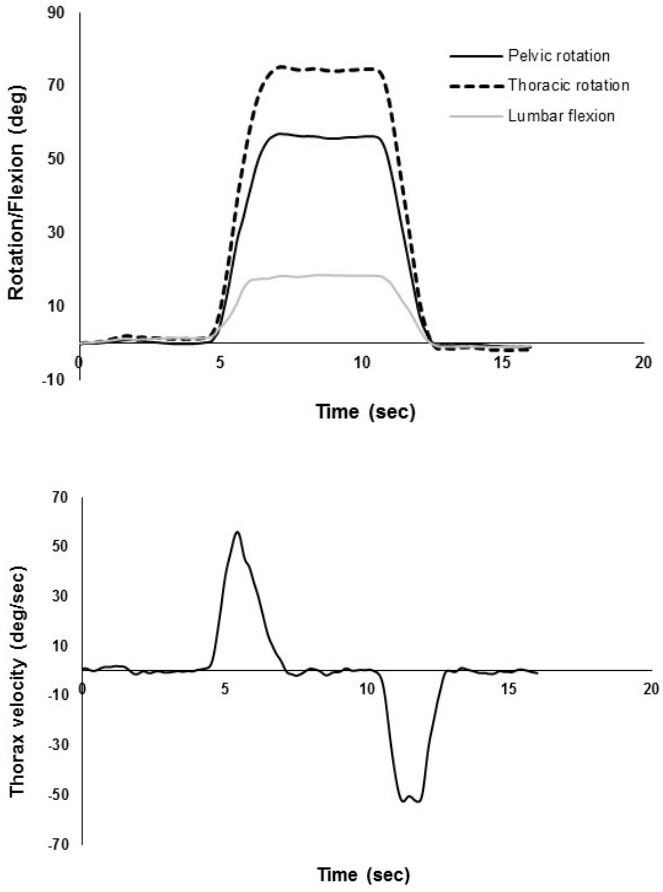


Figure 4-1: Lateral view of the linked-segment model. Pelvic (P) and thoracic (T) rotations are shown in the figure and F_x, F_y and M_z denote ground reaction forces. Segments with solid lines were included in the "bottom-up" inverse dynamics approach. $A_{L5\text{-}S1}$ (axial), $S_{L5\text{-}S1}$ (shearing), and $M_{L5\text{-}S1}$ (moment) represent the mechanical demands of task on the lower back.

Using existing regression equations (Winter 2009), anthropometric and inertial properties of each segment were estimated from participant characteristics (i.e., height and mass). Rotation matrices were then extracted from IMUs to calculate angular rotation of segments, whereas angular velocity and acceleration were obtained using a successive numerical differentiation procedure (Fig. 2). The mean (SD) accuracy of IMUs (i.e., rotation measure), when used to measure a known rotation in our lab, was found to be .55 (.32) deg and their reliability of repeated measurements (between-day) quantified using intra-class correlation coefficients was excellent (e.g., 1.000). Linear velocity and acceleration were found using the relationship between linear and angular velocity under the assumption that the position of ankle joint did not



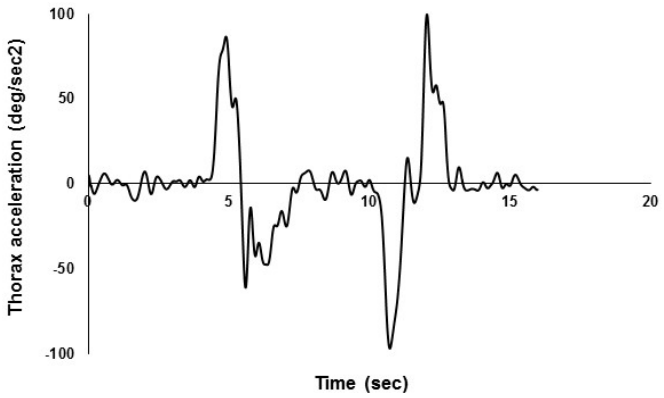


Figure 4-2: A typical example of pelvic and thoracic rotations as well as lumbar flexion (top) during the lowering and lifting task. Thorax angular velocity (middle) and acceleration (bottom) were obtained using a successive numerical differentiation procedure.

change throughout the entire task (Shojaei et al. 2016).Considering the symmetrical nature of the task, equivalent kinematics were assumed for right and left lower extremity limbs. A “bottom-up” inverse dynamics approach (stepwise estimates at the ankle proceeded by knee and hip joints) was used to estimate reaction forces and moments at the lower back which was considered to be the superior level of the pelvis (Freivalds et al. 1984, Song and Qu 2014) (Fig. 1). Projections of the lower back reaction forces perpendicular (axial) and parallel (shearing) to the L5-S1 intervertebral discs were calculated to represent the contribution of task demand to total axial and shearing forces (i.e., task demand plus the response from internal tissues). The standing orientation of the L5-S1 intervertebral disc, with respect to the gravity direction, was considered to be 50 degrees for 40-50 and 50-60 age groups and 54 degrees for the 60-70 age group (Schwab et al. 2006) for both patient and control groups. The axial and shearing demand as well as the moment demand on the lower back throughout the entire task are shown in Fig. 3 for a typical subject. Estimated forces and moments were normalized to individual body mass and body mass*stature, respectively. To be able to present the kinetics measures in a more clinically-meaningful sense, the normalized values were multiplied by the mean body mass and mean body mass*stature across participants (multiplying the measures by a constant value will not affect the results of statistical analyses).

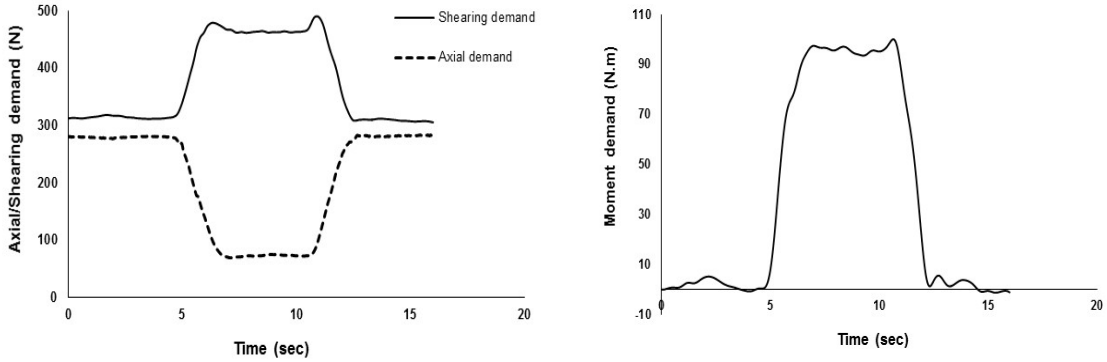


Figure 4-3: A typical example of axial and shearing demand (left) and the moment demand (right) on the lower back throughout the entire lowering and lifting task.

4.2.4. Statistical Analysis

The dependent measures included the axial, shearing, and the moment components of task demand as well as several measures of trunk kinematics. Specifically, for each phase of task, the values of components of task demand at the *time of peak moment component* (TPMC) as well as the peak pelvic and thoracic rotations along with the corresponding values of lumbar flexion were used for statistical analyses. Mixed-model analysis of variance (ANOVA) tests were conducted on the task demand variables with group (with and without LBP) and age (40-50, 50-60, and 60-70) as the between-subjects factors and task phase (lowering and lifting) as the within-subjects factor. Furthermore, univariate ANOVA tests were used to determine effects of group and age and their interaction on the kinematics variables. Mixed-model and univariate ANOVA assumptions were verified, and significant ANOVA tests were followed by post hoc tests using Tukey's procedure. All statistical analyses were performed using SPSS (IBM SMSS Statistics 23, Armonk, NY, USA), and summary values are reported as means (SD). A p value ≤ 0.05 was considered as statistically significant for all measurements.

4.3. Results

4.3.1. Interaction Effects

There was a significant interaction effect of group by age on the shearing component of task demand (Table 2). Specifically, for individuals in 40-50 age group the shearing component was larger (F=7.85, p=0.026) in patients (457.9N ± 23.0N) vs. controls (384.2N ± 31.6N).

4.3.2. Main Effects

Group

There were no differences in the moment component of task demand between patients with non-chronic LBP and asymptomatic controls, whereas the axial component at TPMC was smaller in patients vs. controls (Table 2 and Table 3). Moreover, the patient group adopted a smaller peak thoracic rotation as well as a smaller peak lumbar flexion (Table 2 and Table 3).

Age

There were no age-related differences in any of the kinetics and kinematics outcome measures (Table 2 and Table 3).

Task phase

Larger moment and smaller axial components of task demand at TPMC were observed during lowering vs. lifting phase of the task (Table 2 and Table 3).

Table 4-2: Summary of statistics results for the effects of group (patients with non-chronic LBP and controls), age (40-50, 50-60, and 60-70), and task phase (lowering and lifting) on the components of task demand as well as trunk kinematics for the lowering and lifting task. TPMC: Time of peak moment component.

	Task Demands at TPMC						**Peak Kinematics**					
	Moment		*Shearing*		*Axial*		*Thoracic Rotation*		*Pelvic Rotation*		*Lumbar Flexion*	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	0.06	0.806	6.10	**0.020**	8.10	**0.008**	7.91	**0.009**	3.60	0.068	18.06	**<0.001**
Age (A)	0.21	0.812	1.59	0.222	2.40	0.110	0.10	0.903	2.34	0.114	1.68	0.203
Phase (P)	4.32	**0.047**	3.41	0.076	5.46	**0.027**	-	-	-	-	-	-
G XA	1.48	0.247	3.53	**0.043**	0.11	0.894	2.25	0.124	0.37	0.692	1.14	0.335
G XP	0.75	0.395	0.12	0.737	3.31	0.080	-	-	-	-	-	-
A XP	1.39	0.268	1.58	0.224	2.98	0.068	-	-	-	-	-	-
G X A X P	0.61	0.552	0.10	0.904	0.71	0.501	-	-	-	-	-	-

Boldface indicates significant effect

Table 4-3: Summary of outcome measures including mean (SD) for the effects of group (patients with non-chronic LBP and asymptomatic controls) and age (40-50, 50-60, 60-70), and task phase (lowering and lifting) on the components of task demand as well as trunk kinematics for the lowering and lifting task. TPMC: Time of peak moment component.

		Group		Age			Task Phase	
		Patients	*Controls*	*40-50*	*50-60*	*60-70*	*Lowering*	*Lifting*
Task Demands at TPMC	*Moment(Nm)*	89.5 (19.0)	89.6 (26.6)	88.2 (24.8)	87.4 (20.0)	93.3 (24.8)	91.8 (20.6)	87.3 (25.0)
	Shearing (N)	446.7 (36.0)	415.5 (47.3)	409.8 (56.7)	449.0 (38.1)	429.3 (31.3)	424.1 (42.9)	438.5 (45.0)
	Axial (N)	74.2 (81.9)	159.1 (80.8)	176.3 (77.9)	96.9 (82.3)	88.7 (89.3)	103.4 (89)	127.1 (91.7)
Peak Kinematics	*Thoracic Rotation(°)*	75.2 (10.3)	85.4 (11.3)	81.4 (13.4)	80.9 (7.5)	78.6 (14.7)	-	-
	Pelvic Rotation (°)	42.6 (10.2)	34.0 (11.9)	29.7 (10.1)	42.0 (11.6)	40.9 (10.7)	-	-
	Lumbar Flexion (°)	32.6 (11.0)	51.4 (13.4)	51.6 (16.2)	39.0 (12.4)	37.6 (15.6)	-	-

4.4. Discussion

The purpose of this study was to investigate differences in the mechanical demands of a lowering and lifting task in the sagittal plane on the lower back between a group of females with non-chronic LBP and a group of asymptomatic females. We did not find any differences in the peak moment component of task demand between the patients and controls, however, the shearing (40-50 age group) and axial components of task demand at TPMC were, respectively, larger and smaller in patients vs. controls. These between group differences rejected our hypothesis on moment demand of task, but confirmed our hypothesis on the shearing and the axial components of task demand.

While several studies have investigated the differences in the mechanical demand of physical tasks on the lower back between patients with chronic LBP and controls, only a few studies investigated such differences between patients with non-chronic LBP and controls (Danneels et al. 2002, Shum et al. 2007, Shum et al. 2010). For a trunk forward bending and backward return task, Shum et al. (2010) reported larger moment demand at smaller flexion angle and smaller moment demand at the end range of forward bending between patients with non-chronic LBP and controls. Instead of point-by-point comparison, we compared peak moment demand between the groups which happened to occur at ~ 85% of trunk end range of flexion in both groups. Considering that the transition from larger to smaller differences in the reported differences in moment demand between patients and controls by Shum et al. (2010) occurred somewhere between the mid and the end range of trunk flexion, our results seem to be consistent with their findings. Danneels et al. (2002) reported similar electromyography (EMG) activity of the multifidus and iliocostalis lumborum pars thoracis in patients with non-chronic LBP and controls during coordination and strength exercises (Danneels et al. 2002). Our finding of similar moment mechanical demands on the lower back, though an indication of comparable total internal tissue responses to the task demand in both groups, doesn't suggest comparable active muscle response. Specifically, the observed smaller lumbar flexion in patients (Table 2 to Table 4) suggests a smaller passive contribution of lower back tissues in offsetting the moment demand of task (Shojaei et al. 2016), hence an indication of larger active muscle contribution. Participants were instructed to bend forward with a straightened back (i.e., controlled contribution of passive tissues in offsetting the task demand) in Danneels et al. (2002); an instruction that could be the reason for differences

between our findings and those of Danneels et al. (2002).It is also notable that unlike the findings on similar EMG activity of the muscles in patients with non-chronic LBP vs. controls (Danneels et al. 2002), Danneels et al. (2002) reported lower EMG activity of the muscles in patient with chronic LBP vs. control.

Our hypothesis on smaller moment demand of task in patients was driven by our findings in an earlier study wherein we observed similar peak thorax rotation but smaller peak angular acceleration during free trunk forward bending and backward return in patients vs. controls (Shojaei et al. 2017). Smaller peak thorax rotation also was observed in patients in this study, hence further supporting our hypothesis on moment demand. However, we did not find any differences in the moment demand between the groups. The reason for such lack of difference was that the thoracic rotation as well as the thorax angular acceleration at TPMC were comparable between patients and controls (Table 4).

Table 4-4: Statistics results as well as outcome measures including mean (SD) for the effects of group (LBP patients or asymptomatic controls) on kinematics characteristics of the lowering and lifting task at the time of peak moment component (TPMC).

	Kinematics at TPMC							
	Thoracic Rotation (°)		*Pelvic Rotation (°)*		*Lumbar Flexion (°)*		*Thorax Angular Acceleration (°/s²)*	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group	0.14	0.709	8.84	**0.006**	9.45	**0.005**	0.35	0.562
	Mean (SD)		Mean (SD)		Mean (SD)		Mean (SD)	
Patients	68.8(10.6)		38.7 (10.6)		30.0 (9.8)		92.1 (60.5)	
Controls	69.7 (17.6)		26.9 (11.5)		42.9 (13.7)		82.1 (72.0)	

Furthermore, our hypothesis on larger shearing and smaller axial components of the task demand in patients with non-chronic LBP versus controls was based on our earlier observation of larger pelvic rotation in patients vs. controls during free trunk forward bending and return. In contrast to free motion, peak pelvic rotation was found to be comparable between the groups (Tables 2 and 3) in this study. Nevertheless, our hypothesis was approved as pelvic rotation at TPMC, where the statistical analyses for

the task demands were performed, was larger in patients (Table 4). Additionally, the difference in pelvic rotation between patients and controls was larger (not statistically though) in 40-50 years old age group compared to the other two age groups (i.e., 14.5, 9.2, and 8 degrees in respectively 40-50, 50-60, and 60-70 age groups). Such an age by group difference in pelvic rotation may had a role in the observed differences in shearing demand of the task only in the 40-50 years old age group.

As compared to controls, patients significantly changed their lumbo-pelvic kinematics from the free-style trunk motion to the lowering and lifting task considered in this study. Specifically, patients vs. control adopted a much smaller thorax range of rotation in the lowering and lifting task (i.e., 75.2 vs. 85.4) than in free-style forward bending (104.6 vs. 99.1). Such a reduction in the peak thoracic rotation in patients was achieved by a reduction in the lumbar contribution to the thoracic rotation from 43° to 32.6° (~ 24% reduction), while the reduction in the lumbar contribution to the thoracic rotation in the control group was from 55.7° to 51.4° (~ 8% reduction). The significant reduction of the lumbar contribution under the lowering and lifting task may be an overprotective neuromuscular strategy in patients, for instance, to avoid likely overstretching of pain sensitive tissues in the posterior elements of the ligamentous spine.

We found larger moment demand on the lower back under lowering (91.8 Nm) vs. lifting (87.3 Nm) phase of the task that is consistent with the reports on higher occurrence of musculoskeletal injuries (i.e., 67%) during lowering tasks (Lamonde 1987). However, the literature on differences in mechanical loads on the lower back under lowering vs. lifting tasks is not consistent; there are reports of smaller (De Looze et al. 1993, Larivière et al. 2002), similar (Gagnon and Gagnon 1992), and larger (Davis et al. 1998) mechanical loads on the lower back under lowering vs. lifting tasks. Such inconsistency in the reported mechanical loads can be due to the differences in task characteristics (e.g., the weight of load carried, lift origin and destination) and the lifting technique (e.g., a standardized lifting technique or motion pace vs. a free-style technique).

Our findings contribute to the current understanding of mechanical demands of a sagittally symmetric lowering and lifting task on the lower back in patients with non-chronic, non-specific LBP, however, there are study limitations. We only recruited female patients, therefore, generalizability of the study findings is limited. We did not asked the participants about their level of pain when performing the tasks, therefore, it remains unclear if and how the observed changes in trunk kinematics and the resultant kinetics were affected by their perception of pain during the experiment. Due to lack of reports on incidence and alignment of pelvis in patients with non-chronic LBP and also inconclusive results from the literature (Legaye et al. 1998, Jackson et al. 2000, Hanson et al. 2002, Marty et al. 2002, Jackson et al. 2003) for patients with chronic LBP, same values of sacral orientation were used for both patients and controls when calculating axial and shearing projections of lower back reaction forces. While mechanical demand of physical tasks on the lower back constitutes a small portion of spinal load (i.e., ~ 20%), it directly influences internal muscle responses that constitute the major portion of spinal loads. Studying muscle response and the resultant spinal loads, however, requires detailed model-based studies (Bazrgari et al. 2008, Arjmand et al. 2009) as well as electromyography-based measures of the trunk muscles (Callaghan and McGILL 2001).

In summary, we found patients with non-chronic LBP vs. controls adopt distinct trunk kinematics involving less lumbar flexion to perform lifting and lowering task, leading to our observation of differences in the shearing and axial demands of the task on the lower back between the two groups. Although such kinetics differences might have been driven by a neuromuscular effort to minimize lumbar flexion in patients, it directly affects equilibrium and stability of the spine, and hence, the load experienced in the lower back tissues. Regardless of the underlying source of such kinetics differences in patients with LBP, their impact on spine equilibrium and stability and lower back loading should be further investigated. Given the continuity of the spinal column, alterations in mechanical contributions to task demand in one area/component should be compensated by another area/component. The likelihood of further injury and/or structural changes in the lower back tissues that can lead to persistence of LBP increases if the tissue(s) offering compensatory mechanical contributions are not evolved for such response. Furthering knowledge of these biomechanical differences can positively impact the efficiency of present management paradigm for LBP and can help better match patient pathology with

target treatments with the long-term goal of avoiding LBP recurrence and/or progression from a non-chronic to a chronic stage.

Chapter 5. Discussion

5.1. Study objectives

The objectives of this study, as the first step towards future prospective studies, were to investigate the lower back mechanical environment, using kinematics and kinetics biomechanical methods, in patients with non-chronic LBP.

5.1.1. Findings and hypotheses

Measures of magnitude and timing aspects of lumbo-pelvic coordination during trunk forward bending and backward return as well as measures of mechanical demand on the lower back during lowering and lifting tasks in the sagittal plane were investigated between patients with non-chronic LBP and age- and gender-matched asymptomatic individuals.

Magnitude aspects of lumbo-pelvic coordination

The thoracic range of rotation was similar in both groups. However, the contribution of pelvic rotation and lumbar flexion to range of thoracic rotation was, respectively, larger and smaller among patients compared to controls. Furthermore, patients adopted a slower pace compared to asymptomatic controls which was reflected in smaller values of the maximum angular velocity, deceleration and acceleration of lumbar flexion. These findings confirmed our first hypothesis (see 1.4) on magnitude aspects of lumbo-pelvic coordination.

Timing aspects of lumbo-pelvic coordination

Lumbo-pelvic coordination was more in-phase (i.e., denoted by smaller MARP values) and less variable (i.e., denoted by smaller DP values) in patients with non-chronic LBP vs. asymptomatic individuals. These findings confirmed our first hypothesis on timing aspects of lumbo-pelvic coordination.

Mechanical demand on the lower back

We did not find any differences in the peak moment component of task demand between the patients with non-chronic LBP and asymptomatic individuals, however, the shearing and axial components of task demand were, respectively, larger and smaller in patients vs. asymptomatic individuals. Our hypothesis on smaller moment demand of task in

patients was rejected, whereas our hypothesis on the shearing and the axial components of task demand (i.e., respectively, larger and smaller in patients) was confirmed.

5.1.2. Interpretation

Magnitude aspects of lumbo-pelvic coordination

The smaller contribution of lumbar flexion to thoracic rotation, adopted by patients with non-chronic LBP, may be an attempt to reduce tension in posterior elements of the ligamentous spine that have embedded pain sensitive nerve endings (Adams et al. 2006). These results are also consistent with the reported persistent activation of the lumbar erector spinae muscles and the absence of flexion-relaxation phenomenon among patients with LBP which has been suggested to be an attempt to stabilize injured spinal structures and protect them from further injury (Colloca and Hinrichs 2005).

The smaller lumbar contribution in patients with LBP compared to controls did not affect the task performance; both groups displayed a similar amount of thoracic rotation. The similar amount of thoracic movement was the result of using more pelvic rotation by patient with LBP compared to the controls. Large pelvic rotations impose higher shearing demands on the lower back (Shojaei et al. 2016) and are also associated with projection of a larger shearing component of internal muscle forces on the spine (Arjmand and Shirazi-Adl 2005). Therefore, an increased level of contact force on facet joints of the lumbar spine could be the negative cost of the adopted posture displayed by patients with non-chronic LBP.

Higher order lumbo-pelvic kinematics have been suggested to be reliable objective measures of the trunk motion (Kroemer et al. 1990, Aluko et al. 2011) and can well distinguish patients with chronic LBP from asymptomatic controls (Marras et al. 1993). Similar to the study by Marras et al. (1993), where much larger difference was found in lumbar angular acceleration than angular velocity and flexion between patients with chronic LBP and controls (i.e., 5 degree, 49 deg/sec, and 251 deg/sec2 differences in the respective values of lumbar flexion, lumbar angular velocity, and lumbar angular acceleration), greater differences in angular acceleration were found in the present study

(i.e., 12.7 deg, 29.2 deg/sec, and >81 deg/sec2 differences in the respective values of lumbar flexion, lumbar angular velocity, and lumbar angular acceleration.

Timing aspects of lumbo-pelvic coordination

More in-phase and less variable lumbo-pelvic coordination, also known as phase-locked or rigid coordination (Mokhtarinia et al. 2016), is regarded as a protective motor control strategy to reduce the likelihood of painful deformation of spinal tissues under dynamic tasks. Such a strategy, however, demands higher levels of trunk muscles activation and co-activation which in turn can lead to increased spinal loads and muscle fatigue (Bazrgari and Xia 2017). Also, MARP and DP were found to be smaller during the task with fast pace. These findings are consistent with earlier reports on the effects of task pace on trunk kinematics variability (Asgari et al. 2015). The more in-phase lumbo-pelvic coordination is consistent with the strategy to prevent painful deformation and injury (intensified by viscoelastic behavior and inertial demand of fast tasks) given the higher risk of injury under fast trunk motion (Bazrgari et al. 2008).

Mechanical demand on the lower back

Our hypothesis on smaller moment demand of task in patients was driven by our findings in an earlier study wherein we observed similar peak thorax rotation but smaller peak angular acceleration during free trunk forward bending and backward return in patients vs. controls (Shojaei et al. 2017). Smaller peak thorax rotation also was observed in patients in this study, hence further supporting our hypothesis on moment demand. However, we did not find any differences in the moment demand between the groups. The reason for such lack of difference was that the thoracic rotation as well as the thorax angular acceleration at TPMC were comparable between patients and controls (Table 4). Our finding of similar moment mechanical demands on the lower back, though an indication of comparable total internal tissue responses to the task demand in both groups, doesn't suggest comparable active muscle response. Specifically, the observed smaller lumbar flexion in patients (Table 2 to Table 4) suggests a smaller passive contribution of lower back tissues in offsetting the moment demand of task (Shojaei et al. 2016), hence an indication of larger active muscle contribution.

Furthermore, our hypothesis on larger shearing and smaller axial components of the task demand in patients with non-chronic LBP versus controls was based on our earlier observation of larger pelvic rotation in patients vs. controls during free trunk forward bending and return. In contrast to free motion, peak pelvic rotation was found to be comparable between the groups (Tables 2 and 3) in this study. Nevertheless, our hypothesis was approved as pelvic rotation at TPMC, where the statistical analyses for the task demands were performed, was larger in patients (Table 4).

5.1.3. Clinical relevance

Better understanding of differences in lumbo-pelvic coordination during trunk forward bending and backward return between individuals with and without LBP is clinically important (White III and Panjabi 1978, Panjabi 2003, Van Hoof et al. 2012). Specifically, quantification of such differences, as done in this study, may improve the effectiveness of current management paradigm for LBP by positively impacting the diagnosis and treatment stages. More in-depth information about normal and abnormal trunk kinematics during trunk forward bending and backward return can help better match patient pathology with targeted treatments and decide whether a given treatment is moving the patient in the right direction.

We found patients with non-chronic LBP vs. controls adopt distinct trunk kinematics involving less lumbar flexion to perform lifting and lowering task, leading to our observation of differences in the shearing and axial demands of the task on the lower back between the two groups. Although such kinetics differences might have been driven by a neuromuscular effort to minimize lumbar flexion in patients, it directly affects equilibrium and stability of the spine, and hence, the load experienced in the lower back tissues. Given the continuity of the spinal column, alterations in mechanical contributions to task demand in one area/component should be compensated by another area/component. The likelihood of further injury and/or structural changes in the lower back tissues that can lead to persistence of LBP increases if the tissue(s) offering compensatory mechanical contributions are not evolved for such response. Furthering knowledge of these biomechanical differences can positively impact the efficiency of present management paradigm for LBP and can help better match patient pathology with target treatments with

the long-term goal of avoiding LBP recurrence and/or progression from a non-chronic to a chronic stage.

5.2. Study limitations

Our findings should be interpreted with consideration of our study limitations. First, it remains unclear whether observed kinematic and kinetic differences between patients with LBP and asymptomatic individuals are the cause or consequence of LBP. Second, we did not control for inter subject variability such as anthropometric measures, potential musculoskeletal abnormalities like foot shape abnormalities, flat back, hyper-lordosis, fear of movement, and general health status. With this being said, there is the possibility of additional unknown factors that affect study outcomes and were not included in our analysis. Third, although we controlled for age and gender-related differences, the influence of differences in lumbar spine stiffness or mobility between groups on our finding, though perhaps minimal, should not be overlooked. Fourth, while studying magnitude and timing aspects of lumbo-pelvic coordination as well as mechanical demand on the lower back in patients with LBP provides some insights into neuromuscular control of trunk motion and load sharing between lower back tissues, quantification of such variables requires detailed model-based studies (Bazrgari et al. 2008, Arjmand et al. 2009, Shojaei et al. 2016). Finally, while our results raise several intriguing research questions, the relatively small sample of our patient group should be kept in mind.

5.3. Future research

In the present study we investigated the differences in lower back mechanical environment, using kinematics and kinetics biomechanical methods, between patients with non-chronic LBP and asymptomatic controls. We observed abnormalities in lumbo-pelvic coordination of patients with non-chronic LBP when compared to controls. Whether such abnormal lumbo-pelvic coordination persists over time and if it plays a role in transition to chronic stage is unknown. Prospective studies are required to investigate the changes in lower back mechanical environment of patients with non-chronic LBP and to determine differences between those who recover and those who progress to chronic stage.

In the present study, since the patients were recruited after appearance of symptoms, whether the observed abnormal lumbo-pelvic coordination in patients was a consequence of LBP remains unclear. Prospective studies of lower back biomechanics conducted on asymptomatic individuals can provide insights into this research question through longitudinal study of lower back biomechanics in individuals who will end up developing LBP. Specifically, to make such a prospective study practical, investigating individuals involved in demanding occupations (e.g., nurses, truck drivers) with high rates of LBP prevalence is suggested.

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Wong, T. K. and R. Y. Lee (2004). "Effects of low back pain on the relationship between the movements of the lumbar spine and hip." Human movement science **23**(1): 21-34.

Vita

Education

Ph.D., Biomedical Eng	University of Kentucky, Lexington, KY, USA	2013-2018
M.S., Civil (Structural) Eng	University of Tehran, Tehran, Iran	2012
B.S., Civil Eng	Arak University, Arak, Iran	2009

Profile

- ✓ Strong background in computational mechanics and numerical methods including finite element methods, mesh free methods, and boundary element methods (demonstrated in 5 journal papers)
- ✓ Integrated and used a variety of experimental methods including EMG, motion capture, strength testing, force plate, signal processing, and advanced statistics to study human biomechanics (15 journal papers)
- ✓ Proposal writing experience as Co-PI & Co-Investigator
- ✓ Proficient in Abaqus finite element software (4 journal papers)
- ✓ Deep understanding of solid mechanics, structural dynamics, and vibration (4 journal papers)
- ✓ Demonstrated expertise in solving engineering problems using advanced mathematics (4 journal papers)
- ✓ Developed workflow and interface between Matlab & Abaqus to automate/accelerate optimization procedures
- ✓ Developed platform for synchronized data collection from motion trackers, force plates, EMG device, and load cells using National Instruments, Matlab, and Matlab Simulink
- ✓ Simulated/modeled human motion using rigid body and finite element analysis
- ✓ Used neural networks to develop predictive models in engineering problems
- ✓ Used optimization methods to design mechanical and biomechanical systems
- ✓ Created 3-D geometry from CT and MRI image data using segmentation, repairing/filtering, and meshing
- ✓ Designed and performed experimental tests on human subjects to study trunk stability and bending stiffness
- ✓ Demonstrated experience in writing scripts to automate pre-processing, simulations, and post-processing
- ✓ Matlab coding for a variety of kinematics, kinetics, and EMG data analysis
- ✓ Proficient in study design and (bio)statistical analysis using SPSS

Selected Honors & Awards

- ✓ Departmental outstanding graduate student awards in the doctoral category (2016)
- ✓ Dissertation stipend award (2018, $ 3,000)
- ✓ The USEC Inc. Graduate Fellowship (2017, $1,000)
- ✓ *Kentucky Opportunity* PhD Fellowship (2016, $20,000)
- ✓ The American Society of Biomechanics (ASB) Student Travel Award (2016) granted by ASB annually to six outstanding students
- ✓ Eight-time recipient of student travel award (2013-2018), University of Kentucky
- ✓ Ranked 65th among more than 60000 participants in the Nationwide University Master Degree Entrance Exam (2009)

Peer-Reviewed Journal Articles in Biomechanics

1. **I. Shojaei,** C. Suri, B. Bazrgari "The effects of backpack type on lumbo-pelvic coordination during trunk bending and return tasks", *In Press.*
2. **I. Shojaei,** N. Arjmand, J.R. Meakin, B. Bazrgari "A model-based approach for estimation of changes in lumbar segmental kinematics associated with alterations in trunk muscle forces" *Journal of biomechanics,* 2018, *70: 82-87*.
3. **I. Shojaei,** E.G. Salt, Q. Hooker, B. Bazrgari "Mechanical Demands on the Lower Back in Patients with Non-Chronic Low Back Pain during A Symmetric Lowering and Lifting Task" *Journal of biomechanics, 2018, 70: 255-261.*
4. B. Hendershot, **I. Shojaei,** J.C. Acasio, C. Dearth, B. Bazrgari "Walking Speed Differentially Alters Spinal Loads in Persons with Traumatic Lower Limb Amputation" *Journal of biomechanics,* 2018, *70: 249-254*.
5. **I. Shojaei**, E.G. Salt, Q. Hooker, L.R. Van Dillen, B. Bazrgari "Comparison of Lumbo-Pelvic Kinematics during Trunk Forward Bending and Backward Return between Patients with Acute Low Back Pain and Healthy Controls" *Clinical Biomechanics, 2017, 41: 66-71.*

6. **I. Shojaei**, B. Bazrgari "Activity of erector spinae during trunk forward bending and backward return: the effects of age" *Annals of Biomedical Engineering, 2017, 45: 1511-1519.*

7. M. Vazirian, **I. Shojaei**, B. Bazrgari "Age-related Differences in the Timing Aspect of Lumbopelvic Rhythm during Trunk Motion in the Sagittal Plane" *Human Movement Science*, *2017, 51: 1-8.*

8. **I. Shojaei**, M. Vazirian**,** E.G. Salt**,** L.R. Van Dillen, B. Bazrgari "Timing and Magnitude of Lumbar Spine Contribution to Trunk Forward Bending and Backward Return in Patients with Acute Low Back Pain" *Journal of biomechanics, 2017, 53: 71-77.*
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9. M. Vazirian, **I. Shojaei**, A. Agarwal, B. Bazrgari "Lumbar contribution to the trunk forward bending and backward return; age-related differences" *Ergonomics*, *2017, 60: 967-976.*

10. **I. Shojaei**, K. Allen-Bryant, B. Bazrgari "Viscoelastic response of the human lower back to passive flexion; the effects of age" *Annals of Biomedical Engineering, 2016, 44(9): 2817–2826.*

11. **I. Shojaei**, B.D. Hendershot, E.J. Wolf, B. Bazrgari "Persons with unilateral transfemoral amputation experience larger spinal loads during level-ground walking compared to able-bodied individuals" *Clinical Biomechanics, 2016, 32: 157–163.*

12. **I. Shojaei**, M.A. Nussbaum, B. Bazrgari "Age-related differences in trunk muscle reflexive behaviors" *Journal of Biomechanics", 2016, 49 (14), 3147-3152.*

13. **I. Shojaei**, M. Vazirian, E. Croft, M.A. Nussbaum, B. Bazrgari "Age related differences in mechanical demands imposed on the lower back by manual material handling tasks" *Journal of Biomechanics, 2016, 49(6): 896-903.*

14. M. Vazirian, **I. Shojaei**, R.L. Tromp, M.A. Nussbaum, B. Bazrgari "Age-related differences in trunk intrinsic stiffness" *Journal of biomechanics, 2016, 49(6): 926-932.*

15. **I. Shojaei,** N. Arjmand, B. Bazrgari "An optimization-based method for prediction of lumbar spine segmental kinematics from the measurements of thorax and pelvic kinematics" *International journal for numerical methods in biomedical engineering, 2015, 31(12).*

16. **I. Shojaei,** A. Kaveh, H. Rahami, B. Bazrgari "Efficient non-linear analysis and optimal design of biomechanical systems" *Advances in Biomechanics & Applications, 2015, 2(1): 11-27.*

17. M. Vazirian, **I. Shojaei**, B. Bazrgari "Lumbopelvic Kinematics in the Primary and Secondary Planes of Motion during Lateral Bending and Axial Twist: Age-related Differences", *Under Review.*

18. **I. Shojaei**, C. Suri, J. H. van Dieën, B. Bazrgari “Alterations in Trunk Bending Stiffness Following Changes in Stability and Equilibrium Demands of a Static Lifting Task”, *Under Review*.

19. M. Vazirian, **I. Shojaei**, B. Bazrgari "The immediate and prolonged effects of military body armor on the relative timing of body segments during toe-touch and two-legged squat tasks", *Under Review*.

20. C. Suri, **I. Shojaei**, B. Bazrgari "The Effects of School Backpack on Spine Biomechanics in Young People during Daily Activities: A Narrative Review of Literature", *Under Review*.

21. **I. Shojaei**, B. D. Hendershot, J. C. Acasio, C. L. Dearth, M. Ballard, B. Bazrgari "Trunk muscle forces and spinal loads in persons with unilateral transfemoral amputation during sit-to-stand and stand-to-sit activities", *Under Review.*

22. **I. Shojaei**, E.G. Salt, B. Bazrgari "A prospective study of lumbo-pelvic coordination in patients with non-chronic low back pain: progression to chronic stage versus symptom recovery", *Under Review.*

23. C. Suri**, I. Shojaei,** B. Bazrgari "The effects of backpack type on lumbo-pelvic coordination during walking and jogging", *Under Review.*

Peer-Reviewed Journal Articles in Computational Mechanics & Optimization

24. **I. Shojaei**, H. Rahami "Vibration analysis of global near-regular mechanical systems" *Journal of Algorithms and Computation, 2017, 49 (2): 113-118.*

25. **I. Shojaei**, A. Kaveh, H. Rahami, R. Shirazi, B. Bazrgari "Analysis and reanalysis of mechanical systems: concept of global near-regularity" *Acta Mechanica, 2017, 228: 1445-1456.*
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26. **I. Shojaei**, A. Kaveh, H. Rahami "Efficient numerical solution of Laplace and Poisson's equations using geometrical transformation and graph products" *Applied Mathematical Modelling, 2016, DOI: 10.1016/j.apm.2016.03.043.*

27. **I. Shojaei**, A. Kaveh, H. Rahami "An efficient finite element solution using a large pre-solved regular element" *Acta Mechanica, 2016, 227(5): 1331-1349.*

28. **I. Shojaei**, H Rahami, A Kaveh "A mesh free method using rectangular pre-solved domains using kronecker products" *Mechanics based design of structures and machines*, *2016, DOI:10.1080/15397734.2016.1146147.*

29. **I. Shojaei**, A. Kaveh, H. Rahami "A numerical method for eigensolution of near-regular structural and mechanical systems" *Periodica Polytechnica Civil Engineering, 2016, 60(2): 247-255.*

30. A. Kaveh, **I. Shojaei,** H. Rahami "New developments in the optimal analysis of regular and near-regular structures: decomposition, graph products, force method" *Acta Mechanica, 2015, 226(3): 665-681*

31. H. Rahami, A. Kaveh and **I. Shojaei** "Swift analysis for size and geometry optimization of structures" *Advances in Structural Engineering*, *2015, 18(3): 365-380.*

32. A. Kaveh, H. Rahami, **I. Shojaei** "An efficient method for seismic analysis of structures" *Engineering Computations, 2015, 32(6).*

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Refereed Conference Proceedings in Biomechanics

1. **I. Shojaei**, M. Ballard, B. Bazrgari "Trunk muscle forces and spinal loads in persons with unilateral transfemoral amputation during sit-to-stand and stand-to-sit activities" *Accepted as oral presentation/talk, 13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

2. A. Elliott-Rosenberger, C Suri, **I. Shojaei**, B. Bazrgari "Diurnal changes of trunk stiffness: sedentary vs. physically active nurses" *13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

3. C. Slade, **I. Shojaei**, C. Suri, B. Bazrgari "Effects of Spinal Fusion Surgery on Lumbo-pelvic Coordination" *13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

4. K. Jackson, C. Suri, **I. Shojaei**, B. Bazrgari "Diurnal changes of lumbo-pelvic coordination: sedentary vs. active nurses" *13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

5. M. Ballard, **I. Shojaei**, B. Bazrgari “Immediate effects of a hip orthosis on lumbo-pelvic coordination” *13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

6. N. P. Baumann, A. K. Johnson, **I. Shojaei**, N. R. Heebner, J. D. Winters, J. P. Abt, B. Bazrgari “Peak Lower Extremity Joint Moments during Squat and Stoop Lifting Techniques” *13th Annual CCTS Spring Conference, Lexington, KY, USA, April 13, 2018.*

7. J. C. Acasio, C. M. Butowicz C. L. Dearth, **I. Shojaei**, B. Bazrgari, B. D. Hendershot “Trunk Muscle Forces and Spinal Loads while Walking in Persons with Lower Limb Amputation both with and without Chronic Low Back Pain” *42th annual meeting of the American Society of Biomechanics, Rochester, Minnesota, USA, August 8-11, 2018.*

8. **I. Shojaei**, B. Hendershot, M. Ballard, B. Bazrgari “Trunk muscle forces and spinal loads during sit-to-stand and stand-to-sit activities: differences between persons with and without unilateral lower limb amputation” *The 15th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (CMBBE), Lisbon, Portugal, March 26-29, 2018.*

9. **I. Shojaei,** E.G. Salt, B. Bazrgari “Trunk kinematics in patients with acute low back pain during flexion-extension tasks” *Accepted as oral presentation/talk*, *The Biomedical Engineering Society (BMES) Annual Meeting, Phoenix, Arizona, USA, October 11-14, 2017.*

10. **I. Shojaei,** B. Bazrgari “Reflexive behaviors of trunk muscles in sudden perturbations: the effects of age” *The Biomedical Engineering Society (BMES) Annual Meeting, Phoenix, Arizona, USA, October 11-14, 2017.*

11. C. Suri, **I. Shojaei,** B. Bazrgari “The effects of backpack type on kinematics of lower back and activity of abdominal muscles during walking and jogging” *The Biomedical Engineering Society (BMES) Annual Meeting, Phoenix, Arizona, USA, October 11-14 , 2017.*

12. **I. Shojaei,** N. Arjmand, J. Meakin, B. Bazrgari “Estimation of changes in lumbar segmental kinematics associated with alterations in trunk neuromuscular strategy” *41th annual meeting of the American Society of Biomechanics*, *Boulder, Colorado, USA, August 8-11, 2017.*

13. **I. Shojaei,** Q. Hooker, E.G. Salt, B. Bazrgari “Estimation of mechanical demands of a lowering and lifting task on the lower back in patients with acute low back pain” *41th annual meeting of the American Society of Biomechanics*, *Boulder, Colorado, USA, August 8-11, 2017.*

14. C. Suri, **I. Shojaei,** B. Bazrgari “Effects of backpack type on lumbar kinematics during daily activities” *Annual Resident Research Day, University of Kentucky, Lexington, KY, USA, May 25, 2017.*

15. **I. Shojaei,** N. Arjmand, J. Meakin, B. Bazrgari "Model-based estimation of changes in lumbar spine kinematics with alterations in trunk neuromuscular strategy" *International conference on "Spine loading and deformation: from loading to recovery", Berlin-Germany*, 2017.

16. **I. Shojaei,** Q. Hooker, E.G. Salt, B. Bazrgari "Mechanical demands of a lowering and lifting task on the lower back of patients with acute low back pain" *International conference on "Spine loading and deformation: from loading to recovery", Berlin-Germany*, 2017.

17. B.D. Hendershot, **I. Shojaei**, B. Bazrgari "Faster walking speeds differentially alter spinal loads in persons with traumatic lower limb amputation", *Berlin-Germany*, 2017.

18. **I. Shojaei,** E.G. Salt, B. Bazrgari "Mechanical demands imposed on the lower back by manual material handling tasks in patients with acute low back pain" *Accepted as oral presentation/talk*, *12th Annual CCTS Spring Conference, Lexington, KY, USA, March 30, 2017.*

19. A. Defosse, C. Suri, **I. Shojaei,** K. Jackson, B. Bazrgari "The effects of backpack type on the activity of rectus abdominis and external oblique when performing different physical activities", *12th Annual CCTS Spring Conference, Lexington, KY, USA, March 30, 2017.*

20. C. Dowling, **I. Shojaei**, C. Suri, B. Bazrgari "Does an ergonomically designed backpack, compared to a normal backpack, impose smaller external loads on the lower back?", *12th Annual CCTS Spring Conference, Lexington, KY, USA, March 30, 2017.*

21. C. Force, C. Suri, **I. Shojaei,** B. Bazrgari "Does Backpack type affect lumbar kinematics while performing physical activities?", *12th Annual CCTS Spring Conference, Lexington, KY, USA, March 30, 2017.*

22. **I. Shojaei,** B. Bazrgari "Spinal loads in people with unilateral lower limb amputation during level-ground walking" *17th seminar in spinal physical therapy, Tehran, Iran, December 28-29, 2016.*

23. **I. Shojaei**, B. Bazrgari "A numerical method for estimating lower back segmental kinematics during sagittal-plane flexion task" *Science in the Age of Experience, Boston, MA, USA, May 23-25, 2016.*

24. **I. Shojaei**, K. Allen-Bryant, B. Bazrgari "How Aging Affects Viscoelastic Response of the Human Lower Back to Passive Flexion" *11th Annual CCTS Spring Conference, Lexington, KY, USA, April 21, 2016.*

25. **I. Shojaei,** C. Suri, B. Bazrgari " Age-Related Differences in Activity of Trunk Extensors during Trunk Flexion-Extension Motion" *40th annual meeting of the American Society of Biomechanics*, *Raleigh, North Carolina, USA, August 2-5, 2016.*

26. **I. Shojaei,** B. Bazrgari " Age-Related Differences in Viscoelastic Behavior of the Lower Back during Passive Flexion Tests" *40th annual meeting of the American Society of Biomechanics*, *Raleigh, North Carolina, USA, August 2-5, 2016.*

27. M. Vazirian, **I. Shojaei,** B. Bazrgari "Trunk Motion in the Sagittal Plane: Timing Aspects; Effects of Age" *Second Annual Postdoctoral Research Symposium, Lexington, KY, USA, June 3, 2016.*

28. M. Vazirian, **I. Shojaei,** B. Bazrgari “Timing Aspect of the Lumbopelvic Rhythm in Forward Bending and Backward Return" *11th Annual CCTS Spring Conference, Lexington, KY, USA, April 21, 2016.*

29. **I. Shojaei,** C. Suri, B. Bazrgari "How Activation of Trunk Muscles Affects Trunk Stiffness" *11th Annual CCTS Spring Conference, Lexington, KY, USA, April 21, 2016.*

30. M. Vazirian, **I. Shojaei,** B. Bazrgari “Age-related Differences in the Relative Timing of Lumbar and Pelvic Contribution to the Trunk Motion in the Sagittal Plane" *40th annual meeting of the American Society of Biomechanics*, *Raleigh, North Carolina, USA, August 2-5, 2016.*

31. **I. Shojaei,** M. Vazirian, EC. Croft, MA. Nussbaum, and B. Bazrgari "Lower Back Biomechanics during Manual Material Handling Task; the Effects of Aging" *Accepted as oral presentation/talk*, *The Biomedical Engineering Society (BMES) Annual Meeting, Tampa, FL, USA, October 7-10, 2015.*

32. M. Vazirian, **I. Shojaei,** RL. Tromp, MA. Nussbaum, and B. Bazrgari "Age-related Alterations in Trunk Intrinsic Stiffness" *Accepted as oral presentation/talk*, *The Biomedical Engineering Society (BMES) Annual Meeting, Tampa, FL, USA, October 7-10, 2015.*

33. M. Vazirian**, I. Shojaei,** A. Agarwal, and B. Bazrgari "The Lumbopelvic Rhythm During Trunk Flexion: The Effects Of Age, Gender And Motion Pace" *39th annual meeting of the American Society of Biomechanics*, *Columbus, Ohio, USA, August 5-8, 2015.*

34. **I. Shojaei,** M. Vazirian, EC. Croft, MA. Nussbaum, and B. Bazrgari "Age-related differences in passive viscoelastic behavior of the lower back" *39th annual meeting of the American Society of Biomechanics, Columbus, Ohio, USA, August 5-8, 2015.*

35. **I. Shojaei,** M. Vazirian, RL. Tromp, and B. Bazrgari "Age-related differences in active and passive mechanical response of lower back tissues and the resultant spinal loads during lifting" *39th annual meeting of the American Society of Biomechanics*, *Columbus, Ohio, USA, August 5-8, 2015.*

36. M. Vazirian, **I. Shojaei,** RL. Tromp, MA. Nussbaum, and B. Bazrgari "Alterations in Lower Back Stiffness with Age” *10th Annual CCTS Spring Conference, to be held in Lexington, KY, USA, March 25, 2015.*

37. **I. Shojaei,** M. Vazirian, EC. Croft, MA. Nussbaum, and B. Bazrgari "How Aging Affects Lower Back Loading During Lifting Tasks" *10th Annual CCTS Spring Conference, Lexington, KY, USA, March 25, 2015.*

38. M. Vazirian, **I. Shojaei,** RL. Tromp, MA. Nussbaum, and B. Bazrgari "Age and Gender Differences in Intrinsic Trunk Stiffness" *International conference on "Spine loading and deformation: from loading to recovery", Berlin-Germany, July 02 – 4, 2015.*

39. **I. Shojaei,** M. Vazirian, EC. Croft, MA. Nussbaum, and B. Bazrgari "Age Related Changes in Mechanical Demands Imposed on the Lower Back by Manual Material Handling Tasks" *International conference on "Spine loading and deformation: from loading to recovery", Berlin-Germany, July 02 – 4, 2015.*

40. **I. Shojaei,** B. Bazrgari "An Analytical Solution For Obtaining The Lumbar Spine Segmental Rotations" *Accepted as oral presentation/talk*, The Biomedical Engineering Society (BMES) *Annual Meeting, San Antonio, TX, USA, 22-26 October 2014.*

Refereed Conference Proceedings in Computational Mechanics and Optimization

41. A. Kaveh, **I. Shojaei** " Advances in Optimal Analysis of Structures: Regular Structures, Near-Regular Structures, Optimal Analysis and Design, and Modal Analysis", *Proceedings of the Twelfth International Conference on Computational Structures Technology, Stirlingshire, Scotland, paper 251: 1-19, 2014.*

Selected Invited Seminars and Presentations

1. Prediction of muscle forces and spinal loads in patients with unilateral lower limb amputation during level-ground walking (2016). Department of Mechanical Engineering, Vanderbilt University, TN, USA.

2. Biomechanics of lower back: the effects of age, amputation, and low back pain (2017). The Henry Ford Hospital Bone & Joint Center, MI, USA.

Mentoring Experience

- ✓ **High school students:** Aurian Vaez, Korbin Jackson, Maya Elias, Ly Sereyratana (2015-present)
- ✓ **Undergraduate students:** Laura Schoettmer, Aaron Defosse, Christopher Dowling, Christopher Force, Zachary Thompson, and Carson Elrod (2015-present)
- ✓ **Graduate student:** Cazmon Suri, Cameron Slade, Andrea Ward, Matt Ballard, and Quenten Hooker (2015-present)

Teaching Experience

1) *Mechanical Modeling of Human Motion* (BME 540), University of Kentucky (Spring 2016, Spring 2017, Spring 2018). Nature of work: Homework grading, office hours, and teaching

2) *Advanced Engineering Mathematic* (2010), University of Tehran, Iran. Nature of work: Homework grading and office hours

3) *Structural Analysis I* and *II* (2009), University of Isfahan, Iran. Nature of work: Principle instructor

Selected Professional Service & Memberships

1) Journal reviewer:
   a. Journal of Biomechanics
   b. Applied Mathematical Modeling
   c. Computers & Structures
   d. Clinical Biomechanics
   e. Ergonomics
   f. Plos One
   g. Human Movement Science
   h. Annual International Conference of the IEEE Engineering in Medicine and Biology Society
   i. 17th seminar in spinal physical therapy, Tehran, Iran, 2016
   j. Journal of Science and Technology Transactions of Civil Engineering (IJSTC)
   k. Arabian Journal for Science and Engineering

2) Vice President of the University of Kentucky BMES Student Chapter (2017)

3) College of Engineering E-Day participation (2013-2018)

4) National Biomechanics Day participation (2016-2018)

5) Memberships
   a. Biomedical Engineering Society (BMES) (2013-present)
   b. American Society of Biomechanics (ASB) (2013-present)
   c. IEEE Engineering in Medicine and Biology Society (2015)