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ORIGINAL RESEARCH

Lumbopelvic Kinematics in the Primary and Secondary Planes of Motion During Lateral Bending and Axial Twisting: Age-Related Differences

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OCCUPATIONAL APPLICATIONS Trunk lateral bending and axial twisting are common in the workplace, and are associated with an increase in the risk of low back pain (LBP). We investigated the motions of the lumbar spine and pelvis during these activities, in a laboratory setting, and determined if there are age-related differences. No age-related differences were found in the ranges-of-motion of the lumbar spine or pelvis segment in the primary planes of motion during trunk lateral bending and axial twisting. There were, however, some important differences in coupled motions, outside of the primary planes of trunk motion; where such differences were evident, coupled motions were larger among older individuals. These age-related differences in lumbo-pelvic kinematics, together with earlier evidence of differences in the active and passive mechanical behavior of lower back tissues, imply age-related differences in spinal loads that may contribute to a differential risk of LBP.

TECHNICAL ABSTRACT ***Background:*** Trunk lateral bending and axial twisting are associated with pelvic and lumbar motions that do not occur solely in the frontal and transverse planes, respectively; rather, there are components (coupled motions) in other anatomical planes. ***Purpose:*** We determined if there are age-related differences in the kinematics of the lumbar spine and pelvis in both primary and secondary planes during lateral bending and axial twisting. ***Methods:*** Ranges-of-motion (RoMs) in the lumbar spine and pelvis was measured in primary and secondary planes during trunk lateral bending and axial twisting, and compared between 71 participants in five age groups (aged 20–70 years). RoMs in secondary planes was normalized to values in the primary plane, and are reported as coupled motion ratios (CMRs). ***Results:*** Lumbar CMR in the transverse plane during lateral bending to left, and pelvic CMR in the sagittal plane during the axial twisting to right, were both significantly larger in older age groups. Additionally, lumbar CMR in the sagittal plane during the lateral bending to left, and pelvic RoM in the frontal plane during the lateral bending to both directions, were both larger among males. ***Conclusions:*** The observed age-related differences in lumbo-pelvic kinematics

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during trunk lateral bending and axial twisting likely impose different levels of risk for low back pain due to excessive spinal loads. The underlying sources of the age-related differences found here, particularly given known age-related differences in the active and passive mechanical behavior of lower back tissues, should be investigated in future work, along with their impacts on spinal loads.

KEYWORDS Trunk lateral bending; trunk axial twisting; lumbar spine; pelvis; aging; coupled motion

INTRODUCTION

Low back pain (LBP) is a significant disorder with negative impacts on people's quality of life and the economy (Buchbinder et al., 2013; Deyo, Mirza, & Martin, 2006; Hoy et al., 2014). It has been suggested that excessive spinal loads—stemming from abnormalities in equilibrium and stability of lumbar spine—play an important causal role in LBP development (Adams, Burton, & Bogduk, 2006). Mechanical behaviors of the lower back tissues change with age (Galbusera et al., 2014; Iida, Abumi, Kotani, & Kaneda, 2002; Shao, Rompe, & Schiltenwolf, 2002), which in turn can affect the equilibrium and stability of the lumbar spine and the risk of LBP due to excessive spinal loads. With an increase in the population of older workers (Toossi, 2012), effective management of LBP requires a better understanding of the relationship between aging and changes in aspects of lower-back mechanics that are relevant to equilibrium and stability of the lumbar spine. Such changes include alterations in the active and passive aspects of lower back mechanics, which can be assessed using measures of lumbo-pelvic kinematics, as well as measures of lower back stiffness (i.e., passive, intrinsic, and reflexive stiffnesses).

Addressing the noted need to understand the relationship between aging and lower-back mechanics, we recently completed an exploratory study to determine age-related differences in the active and passive aspects of lower-back mechanics. Specifically, we investigated such differences in terms of lumbo-pelvic kinematics and during responses of the lower back to sudden perturbation and passive stress relaxation tests (Shojaei, Allen-Bryant, & Bazrgari, 2016; Vazirian, Shojaei, Tromp, Nussbaum, & Bazrgari, 2016). Regarding lumbo-pelvic kinematics during trunk forward bending and backward return, we found these to be more in-phase and less variable, and to involve smaller lumbar contributions among older age groups (Vazirian, Shojaei, & Bazrgari, 2017). Other studies have also shown that the range-of-motion (RoM) of the lumbar spine is smaller among older individuals when bending forward in the sagittal plane (Intolo et al., 2009; Kuo, Tully, & Galea, 2009; Song & Qu, 2014). Neither the intrinsic or reflexive responses of the lower-back to sudden perturbations were found to be different between age groups (Shojaei, Nussbaum, & Bazrgari, 2016; Vazirian, Shojaei, Tromp, et al., 2016), whereas responses to passive stress-relaxation tests were found to be larger in older age groups (Shojaei, Allen-Bryant, et al., 2016). More related to changes in spine equilibrium and stability, we also examined age-related differences in lower-back mechanical demands during manual material handling tasks in the sagittal plane, wherein the shearing component on the L5-S1 level was found to be larger in the older age groups (Shojaei, Vazirian, Croft, Nussbaum, & Bazrgari, 2016).

All of these earlier studies were concerned about aspects of lower back mechanics that were characterized during functional tasks and tests done only in the sagittal plane. As a continuation to these studies, findings are presented here on age-related differences in lumbo-pelvic kinematics during lateral bending and axial twisting of the trunk. In contrast to trunk forward bending and backward return, trunk lateral bending and axial twisting are associated with lumbo-pelvic motion in the primary anatomical plane of trunk motion (i.e., primary kinematics) along with motions in the other two secondary anatomical planes (i.e., coupled kinematics). These coupled lumbo-pelvic motions make trunk motion more asymmetric, which increases spinal loads (Kim & Zhang, 2017) and risk of LBP. Therefore, the objective of this study was to determine if there are age-related differences in the magnitudes of lumbo-pelvic kinematics, both in the primary and secondary planes of trunk motion,

TABLE 1 **Mean (SD) characteristics of participants.**

Age range (years)	22–28	32–38	42–48	52–58	62–68
Number and Gender	11 M, 8 F	7 M, 7 F	6 M, 6 F	6 M, 7 F	6 M, 7 F
Stature (cm)	172.1 (7.7)	170.2 (6.2)	173.3 (8.7)	171.5 (11.7)	171.1 (10.4)
Body mass (kg)	69.7 (10.2)	73.0 (12.9)	79.4 (14.5)	78.7 (11.9)	72.1 (16.1)

M: Male, F: Female.

during lateral bending and axial twisting of trunk. In our study of lumbo-pelvic kinematics during sagittal trunk motions, both a smaller lumbar RoM and a larger pelvic RoM were observed among older groups and among females versus males (Vazirian, Shojaei, Agarwal, & Bazrgari, 2017). Therefore, it was hypothesized that the same age- and gender-related differences would be found in terms of lumbo-pelvic kinematics in the primary plane of trunk motion during lateral bending and axial twisting of the trunk. Assessing age and gender-related differences in lumbo-pelvic kinematics in the secondary planes of trunk motions (i.e., coupled motions), was an additional exploratory objective of this study for which we did not have an *a priori* hypothesis.

METHODS

Study Design

A cross-sectional study was completed using participants in five age groups spanning 20–70 years of age. Participants completed two experimental sessions separated by at least 48 h, both of which took place in the morning to reduce confounding effects related to diurnal and occupational changes in lower back mechanics. Each experimental session started with instrumenting the participants, and was followed by a series of tests and break periods to evaluate different aspects of lower back mechanics while minimizing fatigue. These tests included trunk maximum voluntary contraction, trunk flexion-relaxation, forward bending and backward return, lateral bending, axial twisting, material handling, sudden perturbation, and passive stress-relaxation. Here, we only report details of methods and the associated results for trunk lateral bending and axial twisting tests. Methods and results for the other tests have been reported elsewhere (Shojaei, Allen-Bryant, et al., 2016; Shojaei, Nussbaum, et al., 2016; Shojaei, Vazirian, et al., 2016; Vazirian, Shojaei, Agarwal, et al., 2017; Vazirian, Shojaei, & Bazrgari, 2017; Vazirian, Shojaei, Tromp, et al., 2016).

Participants

Seventy-one individuals were recruited to form five age groups (Table 1). The age range of each group represented a decade of an individual's working life, minus two years from each end of the decade (e.g., 22–28 years old, etc.) to increase the chance of identifying any potential differences in the outcome measures by excluding individuals with ages near the border of a decade (Table 1). A consenting procedure, approved by the Institutional Review Board of the University of Kentucky, was completed before screening each participant for the following exclusion criteria: 1) LBP in the past year, 2) previous surgery or any musculoskeletal abnormality in the trunk, 3) history of work in physically demanding occupations (e.g., occupations involving frequent lifting, twisting, bending, driving), and 4) body mass index (BMI) < 20 or > 30. These criteria were used to minimize potential confounding effects on the active and passive aspects of lower back mechanics. No significant differences in stature ($p = .932$) or body mass ($p = .196$) existed between the age groups, as indicated by univariate analyses of variance (ANOVAs).

Testing Procedure

Five inertial measurement units (IMUs: Xsens MTw, Xsens Technologies, Enschede, Netherlands) were strapped around the head, thorax at the T10 spinal level, pelvis at the level of S1, right thigh, and right ankle of each participant (Figure 1) according to earlier studies (Bazrgari et al., 2011; Hendershot et al., 2011). The spinous processes of S1 and T10 vertebrae, used for the placment of IMUs, were found by palpation in both sessions to enhance the consistency of placements. The accuracy and reliability of IMUs for measurements of trunk motion have been previously reported (Tafazzol, Arjmand, Shirazi-Adl, & Parnianpour, 2014; Yun, Kim, Ahn, Park, & Park, 2015). All IMU sensors were strapped direclty on the body, except for the pelvis, which had to be strapped over clothes. To minimize

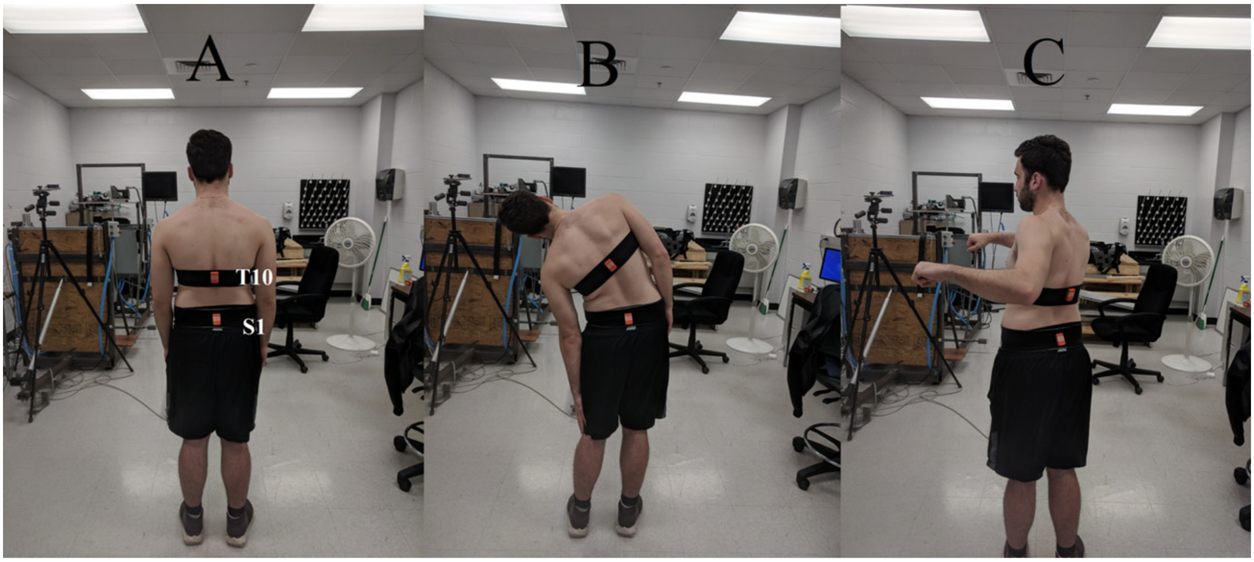

FIGURE 1 **A participant with motion trackers (IMUs) mounted on the spine at the T10 and S1 levels in: (A) upright standing posture, (B) lateral bending, and (C) axial twisting. This figure demonstrates trunk posture and motion tracker locations, but does not show the full instrumentation.**

relative motion between the pelvic sensor and clothes, it was tightly strapped. During testing, three-dimensional kinematics of the IMUs were sampled at 50 Hz.

During each session, participants completed two trials of each of lateral bending and axial twisting motions of the trunk. For both motions, they started from the neutral standing posture, bent/rotated to the left as far as possible without feeling any discomfort, returned to the neutral standing posture, and repeated the same task for the right direction. These motions were performed at the participants' preferred pace, with one minute of rest between each. During the lateral bending motion, the participant arms were in the extended position (see Figure 1(B)), whereas during axial twisting participants maintained a semiabducted shoulder posture with bent elbow to facilitate the twisting (see Figure 1(C)).

Data Analysis

Rotations of thorax and pelvis, as rigid bodies, were obtained from the IMUs attached on them. Rotations of each IMU were recorded in a rotation matrix format during each trial. For every time increment (i.e., 0.02 s), each rotation matrix was converted to the axis-angle rotation vector format (V_i). The projections of these vectors on the three anatomical planes were considered as the incremental (i.e., frame by frame) rotations of the underlying segment around the normal vectors to those planes:

$$r_{i,S} = V_i.N_S,\ r_{i,F} = V_i.N_F,\ r_{i,T} = V_i.N_T\ ,\ i = 1, \dots, n \tag{1}$$

where i is the number of increment; r, V and N denote the incremental rotation, rotation vector, and normal unit vector to an anatomical plane, respectively; and the subscripts S, F, and T denote the sagittal, frontal, and transverse planes, respectively. Finally, the rotation of each segment (R) in a given plane of motion at any time was defined as the sum of incremental rotations around the normal vector of that plane from the beginning to that time:

$$\begin{gathered} R_{i,S} = \sum_{k=1}^{k=i} r_{k,S},\ R_{i,F} = \sum_{k=1}^{k=i} r_{k,F}, \\ R_{i,T} = \sum_{k=1}^{k=i} r_{k,T}\ ,\ i = 1, \dots, n \end{gathered} \tag{2}$$

Lumbar joint rotations[1] (flexion, lateral bending, and axial twisting) were calculated as the differences between the conjugate thoracic and pelvic rotations (Figure 2):

$$\begin{gathered} L_{i,S} = R^T_{i,S} - R^P_{i,S},\ L_{i,F} = R^T_{i,F} - R^P_{i,F}, \\ L_{i,T} = R^T_{i,T} - R^P_{i,T}\ ,\ i = 1, \dots, n \end{gathered} \tag{3}$$

where L denotes the lumbar joint rotation, and the superscripts T and P denote the thorax and pelvis, respectively.

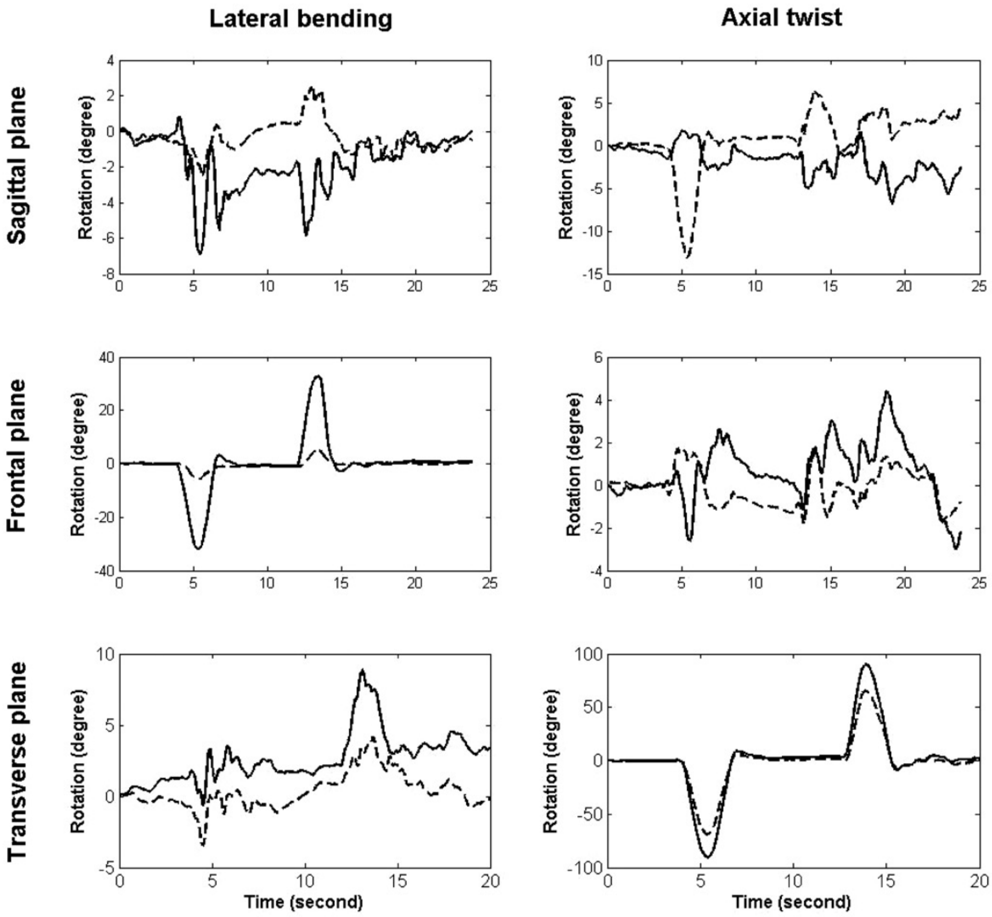

FIGURE 2 Sample rotations of the thoracic (solid line) and pelvic (dashed line) segments during a lateral bending (left column) and an axial twisting (right column) trial, in the sagittal (1st row), frontal (2nd row), and transverse (3rd row) planes.

Given the above described relationship between rotations of the lumbar joint and the thoracic and pelvic segments, we only report results for rotations of the pelvic segment and lumbar joint. For each direction of motion (i.e., left and right), three measures for each for lumbar joint and pelvic segment rotations were extracted for subsequent statistical analyses: The RoM[2] in the primary plane of motion, and the coupled motion ratios (CMRs) in the two secondary planes of motion. RoM was calculated as the peak value rotation around the vector normal to the primary plane of motion. CMRs in each secondary planes of motion were calculated as the ratio of the peak value of rotation around the vector normal to that plane of motion versus the RoM in the primary plane of motion. CMR values were then converted to absolute values, to prevent the results in each age/gender group from canceling out each other. In other words, the magnitude of CMR is studied here, not the direction of coupled motion.

Statistical Analysis

Dependent variables included the RoMs and CMRs of rotations of the lumbar joint and pelvic segment, whereas the independent variables were age group and gender. The value of a dependent variable for a participant in a given age/gender group was identified as an outlier if it was $\geq$ 1.5 times the interquartile range higher than the third quartile or lower than the first quartile in that group (Tukey, 1977). Accordingly, we identified and eliminated seven outliers. The direction of motion was not considered as an independent variable, both because it was not a factor of interest in the study and because its inclusion would negatively affect statistical power. Thus, the left and right trails were analyzed separately. Separate 2-way analyses of variance (ANOVAs) were conducted in SPSS (IBM SPSS Statistics 22, Armonk, NY, USA) for each dependent variable and direction of motion, and significant age/gender effects were followed by Tukey tests for *post hoc*

TABLE 2 **Summary of statistical results for the outcome measures**

			Lumbar				Pelvis			
			Left		Right		Left		Right	
			F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Lateral Bending	**RoM**	**A**	0.466	.760	1.942	.117	1.879	.127	1.801	.142
		G	1.187	.281	1.255	.267	5.454	**.023**	4.248	**.044**
		A × G	0.480	.750	0.527	.716	0.814	.522	0.369	.829
	CMR-S	**A**	0.101	.982	1.442	.233	0.509	.730	0.443	.777
		G	6.623	**.013**	2.105	.153	1.330	.254	0.581	.449
		A × G	1.456	.228	1.676	.169	0.895	.473	0.857	.496
	CMR-T	**A**	4.642	**.003**	0.709	.589	0.640	.636	1.064	.383
		G	0.024	.879	0.641	.427	0.964	.331	<0.001	.996
		A × G	0.252	.907	0.852	.498	0.367	.831	0.449	.772
Axial Twisting	**RoM**	**A**	1.916	.121	1.195	.323	0.822	.517	1.332	.270
		G	0.503	.481	1.009	.320	0.013	.909	0.147	.703
		A × G	0.609	.658	0.769	.550	1.580	.193	0.670	.616
	CMR-S	**A**	0.810	.524	0.250	.908	1.479	.221	2.754	**.037**
		G	1.067	.306	0.455	.503	1.243	.270	0.006	.938
		A × G	0.174	.951	0.501	.735	0.624	.647	0.800	.531
	CMR-F	**A**	0.802	.529	0.898	.471	1.282	.288	2.840	**.033**
		G	2.550	.116	1.062	.307	1.408	.241	0.167	.684
		A × G	0.907	.466	1.084	.374	0.204	.935	0.272	.895

RoM: range of motion, CMR: Coupled motion ratio, CMR-S: CMR in the sagittal plane, CMR-T: CMR in the transverse plane, CMR-F: CMR in the frontal plane, A: age, G: gender.
Significant effects are denoted using bold font.

comparisons between age/gender groups. A maximum *p* value of .05 was set to accept significance.

RESULTS

A summary of statistical results (i.e., *F* and *p* values) is given in Table 2, whereas the mean values of dependent variables in the different age/gender groups for each motion are provided in Table 3. It is noteworthy that the rows for range of motion (RoM) in Table 3 show actual rotations, while the other rows in that table show ratios. There were no significant age by gender interaction effects on any of the dependent variables. Lumbar CMR in the transverse plane during lateral bending to the left was larger in the 52–58 and 62–68 age groups, compared to the 32–38 age group, by 75% and 92%, respectively. In addition, pelvic CMR in the sagittal plane during axial twisting was larger in the 52–58 age group than the 22–28 age group by 75%. There were no other significant age-related differences (Table 3). RoMs of the pelvis during lateral bending, both to the left and to the right directions, were larger among the male participants by 27% and 26%, respectively. Lumbar CMR in the sagittal plane during lateral bending to the left was also larger among males by 27%. There were no other significant gender-related differences (Table 3).

DISCUSSION

We assessed whether there are age-related differences in lumbo-pelvic kinematics during bilateral trunk lateral bending and axial twisting. No differences in RoMs were found between the five age groups testing; as such there was no support for our first hypothesis that there would be larger rotation of the lumbar joint and smaller rotations of the pelvic segment in the older groups. Moreover, rotations of the pelvic segment were significantly larger among males during lateral bending of the trunk, refuting our initial hypothesis. Finally, wherever age and gender-related differences in CMRs were found, they were larger in the older age groups by at least 75%, and among males versus females by at least 26%.

TABLE 3 **Mean (SD) of the outcome measures**

				Lumbar		Pelvis	
				Left	Right	Left	Right
Lateral Bending	**RoM**	**A**	**22–28**	25.6 (5.8)	24.6 (5.4)	5.3 (2.8)	6.7 (3.2)
			32–38	24.7 (4.3)	25.6 (4.8)	5.8 (2.9)	6.1 (3.4)
			42–48	27.3 (3.7)	25.3 (4.3)	6.1 (3.2)	7.2 (4.4)
			52–58	25.9 (5.1)	23.9 (4.2)	8.2 (3.6)	9.3 (4.2)
			62–68	24.6 (6.7)	20.9 (4.1)	6.5 (3.3)	9.2 (5.8)
		G	**M**	25.0 (5.5)	23.7 (5.0)	7.1 (3.5)	8.6 (4.1)
			F	26.1 (5.0)	24.4 (4.7)	5.6 (2.8)	6.8 (4.3)
	CMR-S	**A**	**22–28**	0.38 (0.16)	0.46 (0.19)	0.79 (0.46)	0.41 (0.20)
			32–38	0.36 (0.20)	0.40 (0.17)	0.68 (0.70)	0.59 (0.46)
			42–48	0.37 (0.22)	0.52 (0.25)	0.61 (0.45)	0.57 (0.52)
			52–58	0.37 (0.18)	0.48 (0.28)	0.76 (0.63)	0.50 (0.47)
			62–68	0.40 (0.16)	0.58 (0.25)	0.93 (0.77)	0.53 (0.49)
		G	**M**	0.42 (0.19)	0.51 (0.26)	0.66 (0.63)	0.47 (0.39)
			F	0.33 (0.15)	0.45 (0.19)	0.87 (0.55)	0.54 (0.44)
	CMR-T	**A**	**22–28**	0.16 (0.06)[a,b]	0.22 (0.11)	1.37 (0.57)	1.06 (0.47)
			32–38	0.12 (0.05)[b]	0.19 (0.10)	0.94 (0.44)	0.90 (0.49)
			42–48	0.15 (0.03)[a,b]	0.19 (0.07)	1.15 (0.91)	1.21 (0.94)
			52–58	0.21 (0.06)[a]	0.21 (0.09)	1.27 (1.04)	1.21 (0.96)
			62–68	0.23 (0.11)[a]	0.25 (0.08)	1.37 (0.81)	0.74 (0.25)
		G	**M**	0.17 (0.07)	0.22 (0.09)	1.16 (0.62)	1.04 (0.71)
			F	0.18 (0.08)	0.20 (0.10)	1.32 (0.87)	1.00 (0.61)
Axial Twisting	**RoM**	**A**	**22–28**	17.1 (4.2)	16.1 (4.4)	51.0 (13.1)	45.7 (10.5)
			32–38	19.8 (5.5)	19.1 (4.6)	47.4 (9.0)	43.5 (6.7)
			42–48	19.0 (2.9)	16.4 (4.0)	44.7 (11.9)	39.4 (10.4)
			52–58	21.5 (4.0)	18.1 (2.4)	48.6 (13)	43.9 (8.6)
			62–68	20.7 (6.6)	17.4 (5.9)	51.3 (10.4)	47.3 (8.3)
		G	**M**	19.0 (4.7)	17.9 (4.8)	48.9 (10.9)	44.4 (8.6)
			F	19.8 (5.3)	16.5 (4.1)	49.0 (12.6)	43.9 (10.2)
	CMR-S	**A**	**22–28**	0.48 (0.26)	0.44 (0.34)	0.15 (0.05)	0.08 (0.02)[b]
			32–38	0.41 (0.28)	0.38 (0.17)	0.13 (0.05)	0.10 (0.05)[a,b]
			42–48	0.32 (0.12)	0.37 (0.13)	0.14 (0.05)	0.10 (0.04)[a,b]
			52–58	0.36 (0.23)	0.37 (0.17)	0.15 (0.07)	0.14 (0.06)[a]
			62–68	0.46 (0.41)	0.37 (0.16)	0.18 (0.07)	0.12 (0.06)[a,b]
		G	**M**	0.38 (0.21)	0.38 (0.26)	0.16 (0.06)	0.10 (0.04)
			F	0.45 (0.33)	0.41 (0.17)	0.15 (0.06)	0.11 (0.06)
	CMR-F	**A**	**22–28**	0.32 (0.19)	0.34 (0.16)	0.05 (0.02)	0.06 (0.03)[a]
			32–38	0.46 (0.42)	0.47 (0.27)	0.07 (0.04)	0.07 (0.03)[a]
			42–48	0.46 (0.48)	0.43 (0.37)	0.05 (0.02)	0.06 (0.03)[a]
			52–58	0.27 (0.14)	0.32 (0.16)	0.05 (0.03)	0.09 (0.04)[a]
			62–68	0.34 (0.20)	0.31 (0.14)	0.07 (0.05)	0.10 (0.06)[a]
		G	**M**	0.42 (0.37)	0.40 (0.26)	0.06 (0.04)	0.08 (0.05)
			F	0.30 (0.19)	0.33 (0.20)	0.05 (0.03)	0.07 (0.04)

RoM: range of motion, CMR: Coupled motion ratio, CMR-S: CMR in the sagittal plane, CMR-T: CMR in the transverse plane, CMR-F: CMR in the frontal plane, A: age, G: gender.

Post hoc results for paired comparisons between age-groups, when applicable, are summarized with letter superscripts starting from “a” form groups with different means.

While no age-related differences were found in lumbar joint RoM during lateral bending of the trunk, earlier studies had reported a decreasing trend with age (Dvorak, Vajda, Grob, & Panjabi, 1995; Einkauf, Gohdes, Jensen, & Jewell, 1987; Russell, Pearcy, & Unsworth, 1993; Van Herp, Rowe, Salter, & Paul, 2000). There is, however, considerable variation in reported values of lumbar RoM for different age and gender groups. For example, reported mean values during trunk lateral bending to the left (right) in

20–30 year old men vary from 18 (17) to 35.9 (36.2) degrees (Dvorak et al., 1995; McGregor, McCarthy, & Hughes, 1995; Pearcy, 1985; Russell et al., 1993). Such a variation may be due to differences in study populations, how bending trails were performed (e.g., whether the participants had to bend as far as they could (Pearcy, 1985; Vachalathiti, Crosbie, & Smith, 1995), or to a comfortable limit), measuring system employed (e.g., X-ray (Pearcy, 1985), goniometry (Einkauf et al., 1987), three-dimensional (3D) Space tracking system (Russell et al., 1993), or spinal motion analyzer (McGregor et al., 1995)), and landmarks used to monitor lumbar kinematics (e.g., from the L1 to sacrum (Russell et al., 1993), from the T12 to sacrum (McGill, Yingling, & Peach, 1999), or rotations at C7 (Einkauf et al., 1987)).

In this study, we tried to be consistent across participants in terms of all these factors, except the independent variables of the study. We also used 3D motion trackers (IMUs), which should have provided improved accuracy compared to several previous studies (Tafazzol et al., 2014). However, the current findings on lateral bending to the left and right (25.6 (5.8) and 24.6 (5.4), respectively) are both within the variation range of earlier studies. A lack of age-related differences in lumbar RoM during the axial twisting of the trunk, as found here, is in agreement with most of previous studies (McGill et al., 1999; Russell et al., 1993; Vachalathiti et al., 1995), although some authors have found a decreasing trend with age (McGregor et al., 1995; Van Herp et al., 2000).

As expected from earlier studies, a coupled motion in the transverse plane was observed in rotation of the lumbar joint during lateral bending of trunk. Such a coupling likely results from the active and passive kinematics constraints imposed on the lumbar joints by the lower back tissues. Several *in vitro* studies with cadaveric specimens have shown that the ligamentous lumbar spine undergoes a coupled motion in the transverse plane, even under pure lateral bending moment (Barnes, Stemper, Yogananan, Baisden, & Pintar, 2009; Oxland, Crisco, Panjabi, & Yamamoto, 1992; Panjabi, Yamamoto, Oxland, & Crisco, 1989). Our results indicated an increasing trend with age in the lumbar CMR in the transverse plane during lateral bending to left. The natural degeneration of the ligamentous lumbar spine with age, including damage to the facet joints and a loss of the intervertebral fluid (Podichetty, 2007), might be responsible for this change in coupled axial rotation. Previous studies have suggested that the facets have a restricting role for relative axial rotation of the lumbar joint, and Oxland et al (Oxland et al., 1992) reported that removing the facets from a cadaveric lumbar spine under pure lateral bending moment significantly increased CMR in the transverse plane of the L5-S1 joint. This result was further supported by the finite element modeling studies of Shirazi-Adl (1994), which showed that removal of the facet joints of the L4-L5 motion segment resulted in a substantial increase in axial rotation in that level while the lumbar spine was under lateral bending. Shirazi-Adl's (1994) simulations also demonstrated that a loss of disc fluid in the L4-L5 motion segment resulted in a larger contact force in the facet joint at that level, hence affecting its role in coupling motion of the ligamentous lumbar spine. Thus, our finding of an increase in the lumbar CMR among older versus younger participants might, in part, be due to age-related degeneration in the lumbar spine. However, the role of active contribution of muscles in such age-related differences in CMRs remains unclear.

To the best of our knowledge, there is no report regarding age-related differences in the RoM or CMR of the pelvic segment during either trunk lateral bending or axial twisting. Applying a pure twisting moment on the lumbar spine, though, has been shown to cause a coupled motion in the sagittal plane (Panjabi et al., 1989). This implies that a coupled bending moment in the sagittal plane propagates downward in the lumbar spine when it is under axial twisting. Consistently, a coupled motion of the pelvis in the sagittal plane during trunk axial twisting was observed in this study. Additionally, the observed age-related difference in CMR during the axial twisting to the right, wherein CMR was larger among older participants, might similarly be due to age-related differences in passive and active kinematics constraints imposed by the lower back tissues.

Consistent with earlier studies (Dvorak et al., 1995; Vachalathiti et al., 1995), the ranges of motion of the pelvic segment and lumbar joint found here during trunk lateral bending and axial twisting were not different between males and females, except for the pelvic RoM during trunk lateral bending, which was larger among males. Though such a difference is likely due to gender-related differences in mechanical behavior of the lower back tissues, their exact contributions (i.e., active versus passive) remain to be investigated in future.

There are several limitations associated with this study that should be considered when interpreting the results. First, the tasks were performed at a self-selected pace. Thus, the effects of task pace were not investigated, even though it has been suggested to affect lumbo-pelvic kinematics (Vazirian, Van Dillen, & Bazrgari, 2016). In addition, any volunteers who had suffered from LBP more than one year prior to participation were not excluded from the study, leaving the possibility that persistent LBP-related alterations, particularly in the active mechanical behavior of lower back tissues, could have influenced the study results. Further, we conducted data collection in the morning to minimize the effects of diurnal and occupational changes in lower back mechanics. We did not, however, control for the duration between the time that the participants woke up in the morning and the time that they arrived to the lab, nor any physical activities done within that time window. There may be kinematic measurement errors in the data from the IMUs, due to artifacts from skin and clothes movements. Although Yun et al. (2015) demonstrated the reliability of measurements of trunk motion using such devices, the reliability of our measurements using IMUs for the specific tests we conducted remains unknown. Moreover, although the sample size of this study had been determined by prior power analysis using data from pilot studies, power analysis of the current findings revealed that power was below 0.8 for most of outcome measures. A lack of power might have arisen from variabilities in the age and gender groups for which we did not control, such as lower back stiffness (Shojaei, Allen-Bryant, et al., 2016), muscle strength (Vazirian, Shojaei, Tromp, et al., 2016), and how actively participants forced themselves to reach their end range of motion for a given task. Consequently, it is possible that this study might have failed to detect some existing significant effects.

The differences found here in lumbo-pelvic kinematics between the age and gender groups during trunk lateral bending and axial twisting were likely driven by differences in the passive and active contributions of lower back tissues to these motions. In our earlier studies, we were able to delineate the relative roles of active and passive contributions of lower back tissues to observed age and gender-related differences in lumbo-pelvic kinematics during trunk forward bending and backward return, using results from sudden perturbation and passive stress-relaxation tests that were also conducted in the sagittal plane (Shojaei, Allen-Bryant, et al., 2016; Shojaei, Nussbaum, et al., 2016; Shojaei, Vazirian, et al., 2016; Vazirian, Shojaei, Agarwal, et al., 2017; Vazirian, Shojaei, Bazrgari, 2017; Vazirian, Shojaei, Tromp, et al., 2016). Moreover, such age-related differences in lumbo-pelvic kinematics in the sagittal plane were found to be associated with a larger shearing demand on the lower back among older individuals when performing a lowering and lifting task. Therefore, to understand more about the underlying sources of these differences in lumbo-pelvic kinematics during trunk lateral bending and axial twisting, as well as the potential consequences of these differences, such additional tests should be carried out in future work. Given the important role of spinal loads in occupational LBP, and considering the effects of the mechanical behavior of lower back tissues on the spinal loads via their influences on the spinal equilibrium and stability, such research in clearly critical for our aging workforce.

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CONFLICT OF INTEREST

The authors have no conflict of interest to disclose.

NOTES

1. We assumed the lumbar section of spine to act as a single joint between the thoracic and pelvic segments.
2. For simplicity, the range of joint rotation for the lumbar spine is also denoted by RoM throughout this paper.

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