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Full Length Article

Age-related differences in the timing aspect of lumbopelvic rhythm during trunk motion in the sagittal plane

Milad Vazirian, Iman Shojaei, Babak Bazrgari *

F. Joseph Halcomb III, M.D. Department of Biomedical Engineering, University of Kentucky, Lexington, KY, USA

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A B S T R A C T

Forward bending and backward return of the human trunk in the sagittal plane are associated with a specific lumbopelvic rhythm, which consists of magnitude and timing aspects. In this study, the age-related differences in the timing aspect of lumbopelvic rhythm were investigated using the continuous relative phase method. Specifically, the mean absolute relative phase (MARP) between the thoracic and pelvic motions as well as variation in MARP under repetitive motions, denoted by deviation phase (DP), were characterized in sixty participants between 20 and 70 years old. MARP and DP were determined for trunk forward bending and backward return tasks with self-selected slow and fast paces. The MARP and DP were both smaller ($p = 0.003$, $p < 0.001$ respectively) in the older versus younger age participants with no gender-related difference. In fast versus slow pace task, the MARP was smaller ($p < 0.001$) only in forward bending, whereas the DP was smaller ($p < 0.001$) in both the forward bending and backward return. A more in-phase and more stable lumbopelvic rhythm denoted respectively by smaller MARP and DP in older versus younger individuals maybe a neuromuscular strategy to protect the lower back tissues from excessive strain, in order to reduce the risk of injury.

1. Introduction

Frequent trunk bending and return[1] has been suggested to be a risk factor for occupational low back pain (LBP) (Damkot, Pope, Lord, & Frymoyer, 1984; Hoogendoorn et al., 2000; Punnett, Fine, Keyserling, Herrin, & Chaffin, 1991), a disorder which still remains of a high morbidity in industrial societies, and adversely affects the well-being of people and economy (Buchbinder et al., 2013; Hoy et al., 2014). Thus, obtaining a detailed knowledge about the pattern of trunk movement during bending and return is an important step for LBP management. Trunk bending and return result from rotation of the pelvis as well as flexion/extension of the lumbar spine. The patterns of pelvic rotation and lumbar flexion/extension have been studied generally from the magnitude and timing-related perspectives, under the so-called topic of lumbopelvic rhythm (Kim et al., 2013; Phillips, Bazrgari, & Shapiro, 2014; Pries, Dreischarf, Bashkuev, Putzier, & Schmidt, 2015; Silfies, Bhattacharya, Biely, Smith, & Giszter, 2009; Thomas & Gibson, 2007; Vazirian, Van Dillen, & Bazrgari, 2016a; Wong & Lee, 2004), As a magnitude-based measure of lumbopelvic rhythm, the lumbar contribution has been shown to be larger in the early stage,

* Corresponding author at: Department of Biomedical Engineering, University of Kentucky, 514E Robotic and Manufacturing Building, Lexington, KY 40506, USA.

E-mail address: babak.bazrgari@uky.edu (B. Bazrgari).

[1] Bending and return in this manuscript refer to respectively bending forward from the upright standing posture to the trunk flexed posture, and returning backward from the flexed trunk posture to the upright standing posture in the sagittal plane.

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to decrease gradually, and to be minimum in the late stage of bending. Conversely, the return starts with a minimum lumbar contribution which gradually increases throughout the course of return (Vazirian, Shojaei, & Bazrgari, 2016). On the other hand, studies on the timing aspects of lumbopelvic rhythm have shown that the lumbar spine versus pelvis tends to move sooner in the bending, and remains ahead in the phase of motion. However, in the return, the lumbar spine is behind the pelvis in phase, and finishes the motion later (Pal, Milosavljevic, Sole, & Johnson, 2007). An important requirement for application of lumbopelvic rhythm to prevention, treatment, and rehabilitation of LBP is an understanding of the effects of personal differences (e.g., age and gender) on measures of lumbopelvic rhythm (Vazirian, Van Dillen, & Bazrgari, 2016b). In a recent study, we showed that individuals older versus younger than 50 years of age, implemented smaller lumbar contribution during trunk bending and return motion irrespective of gender or pace of motion (Vazirian, Shojaei, et al., 2016). However, no study yet, to our best knowledge, has investigated the age-related differences in the lumbopelvic rhythm from the timing perspective.

Generally the timing aspect of lumbopelvic rhythm has been studied using three different methods: (1) critical points method wherein a time difference is calculated between different event times (e.g., events like onset, termination, maximum displacement, or maximum velocity) of lumbar and pelvic motion (Pal et al., 2007; Thomas & Gibson, 2007), (2) cross-correlation method in which the lumbar and pelvic motion are cross-correlated by determining a time lag (phase) that is associated with the maximum correlation between the temporal variations of both lumbar and pelvic motion during the task (Lee & Wong, 2002; Wong & Lee, 2004), and (3) continuous relative phase (CRP) method wherein the difference between the phase angles of lumbar and pelvic motions at each time instant is obtained from their phase planes (Hu, Ning, & Nussbaum, 2014; Silfies et al., 2009; Zhou, Ning, & Fathallah, 2015). The CRP method is essentially a dynamical system approach and as compared to the other two methods can provide insight related to the stability of trunk motion in addition to the timing aspects of the lumbopelvic rhythm (Stergiou, Jensen, Bates, Scholten, & Tzetzis, 2001). Therefore, the objective of this study was set to find the age-related differences in the timing aspects of lumbopelvic rhythm using the CRP method. Using this method, it has been shown that LBP patients have a more in-phase and less variable (i.e., more stable) lumbopelvic rhythm in the sagittal plane (Mokhtarinia, Sanjari, Chehrehrazi, Kahrizi, & Parnianpour, 2016; Seay, Van Emmerik, & Hamill, 2011; Selles, Wagenaar, Smit, & Wuisman, 2001). Considering this phenomenon as a protective strategy adopted to prevent the spinal segments from potentially harmful movements relative to each other (van Dieen, Selen, & Cholewicki, 2003), and on the other hand, since the aging is associated with tissues degeneration and impaired functioning of spinal segments (Hoy et al., 2014), it may be speculated that such a protective strategy is also adopted in the elderly. Therefore, it was hypothesized that the older versus younger participants to have a more in-phase and less variable lumbopelvic pattern.

2. Methods

2.1. Study Design and Participants

Sixty individuals were recruited to form five equal-sized and gender-balanced age groups, in order to participate in a cross-sectional study. Each age group represented a working decade of life between 20 and 70 years. To increase the chances for capturing any potential between-group differences in our outcome measures, especially between the adjacent age groups, two years were cut off from each side of the age range of each group, resulting in the age groups of 22–28, 32–38, 42–48, 52–58 and 62–68 year-old. All volunteers consented to participate by completing a procedure approved by the Institutional Review Board of the University of Kentucky. They were then further screened for the following exclusion criteria: 1) back pain during the last year, 2) spinal deformity, surgery or any other musculoskeletal abnormality in the trunk, 3) a history of work in physically demanding occupations (e.g., occupations involving frequent lifting, twisting, bending, driving), and 4) body mass index <20 or >30. Such exclusion criteria were adopted to minimize any confounding effects on the outcome measures due to any back pain history (Seay et al., 2011; Selles et al., 2001) or exposure to LBP risk factors associated with physically demanding occupations (Hu et al., 2014). There were no significant differences in stature ($p = 0.917$) or body mass ($p = 0.234$) between the age groups as determined using univariate analysis of variance (ANOVA) (see Table 1).

2.2. Testing procedure

Two magnetic inertial motion trackers (MT) (Xsens MTw, Xsens Technologies, Enschede, Netherlands) were strapped around the participants' thorax at the level of T10 (Bazrgari et al., 2011; Hendershot et al., 2011; Shojaei, Vazirian, Croft, Nussbaum, & Bazrgari, 2016), and pelvis at the level of S1 to measure the thoracic and pelvic rotations. The three-dimensional orientation of the MTs as rotation matrices, at the sampling rate of 50 Hz were recorded by a computer, after a Kalman filter was utilized to minimize any potential effect of noise on the data (Xsens., 2012) (see Fig. 1).

Each participant completed two sessions of data collection with at least 48 h in between. In order to minimize the diurnal and occupational effects on the results, all data collection sessions were held in the morning. Each session included two trunk bending-return (BR) tests with slow and fast paces. In the slow BR test, the participants bent their trunk from an upright standing posture to their full-bent posture. Participant were instructed to pause for five seconds at their full-bent posture, guided by an examiner, and then returned backward to the upright standing posture. The fast BR test was similar, except that participants performed the bending and return as fast as possible without a pause at the full-bent posture. Slow

Table 1
Participants' anthropometry. Each age group included six male and six female participants. Summary values are means (SDs). No significant differences in stature (p = 0.917) or body mass (p = 0.234) between the five age groups were indicated by ANOVA.

Age groups (years)	22–28	32–38	42–48	52–58	62–68
Stature (cm)	173 (8)	172 (6)	173 (9)	172 (12)	172 (11)
Body mass (kg)	73 (10)	76 (12)	79 (15)	78 (12)	73 (167)

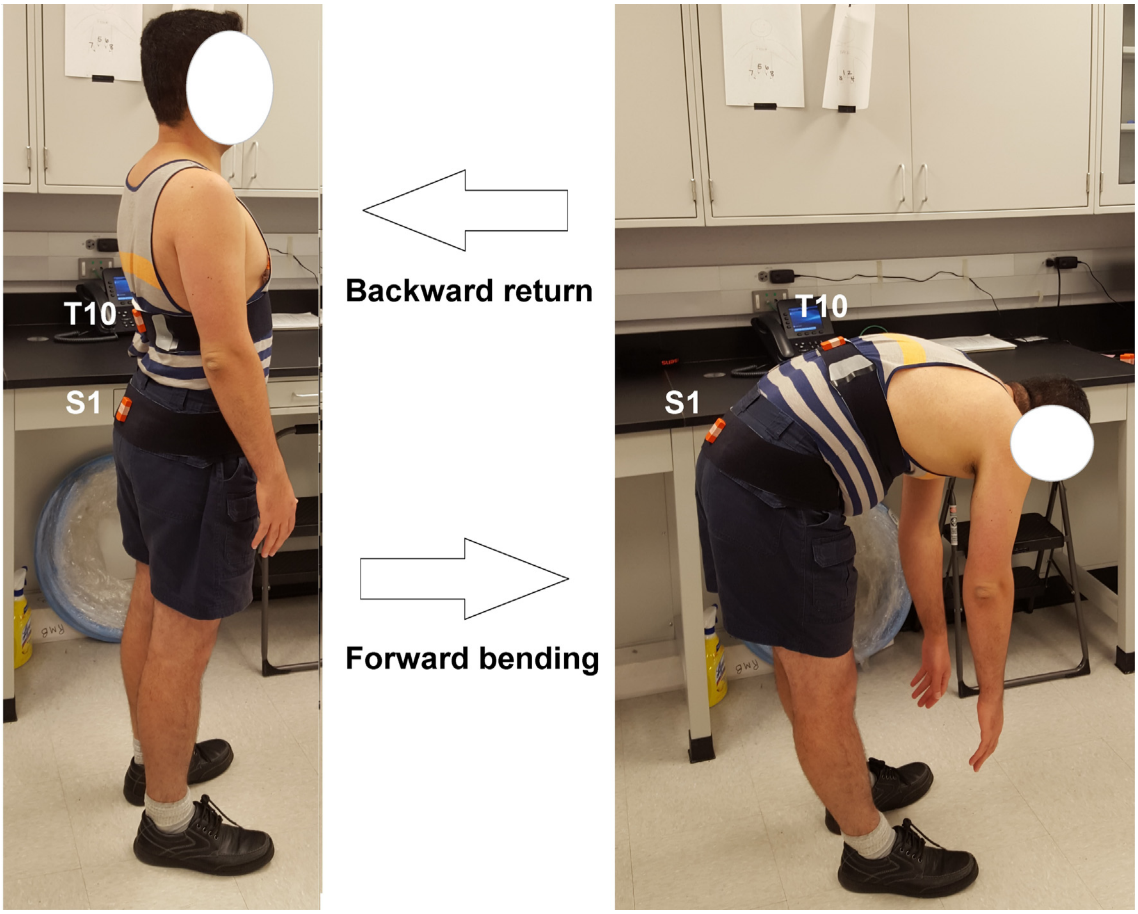

Fig. 1. Motion trackers mounted on a participant at the T10 and S1 spinal levels.

and fast paces were self-selected and each of the slow and fast BR test was repeated three times. To minimize any potential measurement variance due to placement of the MT sensors, the examiner recorded the height of MT sensors from the lab floor in the upright standing posture during the first session to be used for placement of the sensors in the second session.

2.3. Data analysis

The rotation matrices collected by MTs were used to find the rotations of the thorax and pelvis with respect to the standing posture. Using the rotation data, phase planes of the thorax and pelvis were generated according to Lamb and Stockl (2014). Briefly, this method involved three steps: 1) the reference point for calculating the rotation for each task was first moved to somewhere between the standing and full-bent postures, so that these two extremes had equal negative and positive values respectively, 2) the Hilbert transform was used to transform each modified rotation signal from step one into an analytic signal, and 3) the phase plane for each rotation signal was then formed by plotting rotation angles versus their Hilbert transform. Finally, the CRP was calculated by subtracting the pelvic phase angle from the thoracic phase angle at each instant of time (Fig. 2).

Two measures, as suggested by Stergiou et al. (2001), were derived from the CRP curve of each BR test to characterize the timing aspect of lumbopelvic rhythm: the mean absolute relative phase (MARP) and the deviation phase (DP). In this

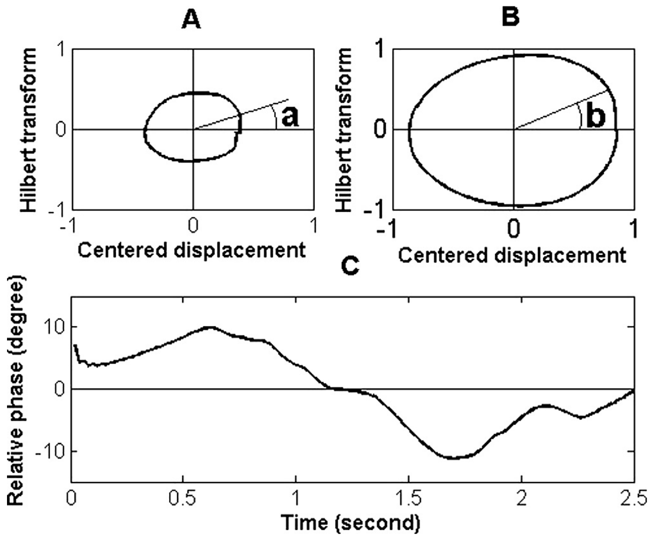

Fig. 2. The phase planes of the pelvis (A) and thorax (B) rotations, and the curve of continuous relative phase (C) for a sample cycle of forward bending-backward return. The angles "a" and "b" respectively represent the phase angles of pelvis and thorax at one second after starting the forward bending.

approach, the absolute value of relative phase for each percentile of trunk bending (return) phase is obtained initially. Subsequently, for each percentile of trunk bending (return) phase a mean and standard deviation value is calculated using corresponding relative phase values from all repetitions of the same test (i.e., three repetitions per session and a total of six repetitions). Finally, the MARP and DP were calculated as the average of the above calculated mean and standard deviation of relative phase over each phase of motion during each test (i.e., bending or return). Based on the definition, MARP values close to 0 indicate a more "in-phase" lumbopelvic rhythm, or segments moving more synchronous, while values closer to π radians indicate a more "out-of-phase" lumbopelvic rhythm, or segments moving less synchronous. On the other hand, a DP closer to 0 indicates a lumbopelvic rhythm with less trial-to-trial variability.

2.4. Statistical analysis

The MARP and DP data were first transformed using the natural logarithm (log) in order to result in a suitable data distribution of values, as necessitated to comply with the assumptions of analysis of variance (ANOVA). Then, a mixed ANOVA was performed on the log transformed MARP and DP values using SPSS 22.0 (SPSS Inc., Chicago IL, USA) to determine the effects of age and gender as between-subject factors, as well as pace and direction (i.e., bending or return) of trunk motion as within subject factors. Tukey post hoc test was used to determine differences between the age groups when appropriate. A *p*-value of 0.05 was set as the maximum to have a significant difference.

3. Results

Summary of statistical analyses is presented in Table 2. Age differences were found to have significant statistical effects on both the MARP and the DP. Specifically, the MARP values were significantly smaller in the two older (i.e., 52–58 and 62–68 years old) versus the two younger (i.e., 22–28 and 32–38 years old) age groups (Fig. 2). The DP values also were significantly smaller in the oldest (i.e., 62–68 years old) versus the three younger (i.e., 22–28, 32–38 and 42–48 years old) age groups (Fig. 3).

The pace and direction factors had a significant interaction for the MARP. Separate three-way ANOVA tests (i.e., using age and gender as two between-subject factors, and pace or direction as one within-subject factor) on the levels of pace and direction (i.e., four tests altogether) showed that the mean MARP value for the fast bending test was significantly smaller ($p < 0.001$) than the three other tests. Finally, the faster versus slower pace was associated with a significantly smaller ($p < 0.001$) DP (Fig. 4).

4. Discussion

As a part of a larger exploratory project on age-related differences in the mechanics of lower back (Shojaei, Allen-Bryant, & Bazrgari, 2016; Shojaei, Vazirian, et al., 2016; Vazirian, Shojaei, et al., 2016; Vazirian, Shojaei, Tromp, Nussbaum, & Bazrgari, 2016), the purpose of this study was to find the age-related differences in the timing aspect of lumbopelvic rhythm using the CRP method during bending and return. The older versus younger age groups were found to have a smaller MARP

Table 2
ANOVA results for the effects of age, gender, motion pace, and direction on mean absolute relative phase (MARP) and deviation phase (DP). Significant effects are denoted by bold fonts.

Source	Mean Absolute Relative Phase			Deviation Phase	
	df	F	Sig.	F	Sig.
Age	4	4.748	**0.003**	6.340	**0.000**
Gender	1	2.864	0.097	1.998	0.164
Pace	1	11.329	**0.001**	29.133	**0.000**
Direction	1	18.081	**0.000**	2.227	0.142
Age * Gender	4	0.610	0.658	1.496	0.218
Pace * Age	4	1.254	0.301	1.919	0.122
Pace * Gender	1	3.149	0.082	0.582	0.449
Direction * Age	4	0.733	0.574	0.478	0.752
Direction * Gender	1	0.241	0.625	1.780	0.188
Pace * Direction	1	13.995	**0.000**	2.384	0.129
Pace * Age * Gender	4	1.206	0.320	0.604	0.661
Direction * Age * Gender	4	0.286	0.885	1.041	0.395
Pace * Direction * Age	4	1.127	0.355	1.622	0.183
Pace * Direction * Gender	1	0.929	0.340	0.185	0.669
Pace * Direction * Age * Gender	4	0.544	0.704	0.407	0.803

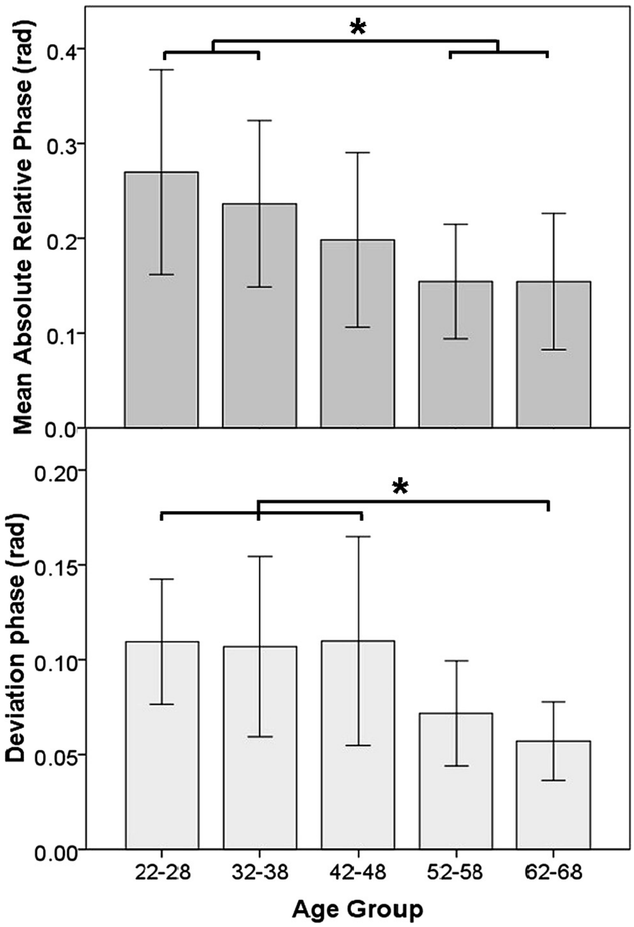

Fig. 3. The effects of age on mean absolute relative phase (MARP) (top) and deviation phase (DP) (bottom). Values are averaged across all motion paces and directions. The error bars and stars indicate the standard deviation and significant difference between age groups respectively.

and DP, suggesting that the lumbar and pelvic motions contribute to the trunk motion with more in-phase and less variable patterns in the older versus younger age groups (i.e., confirming our hypothesis).

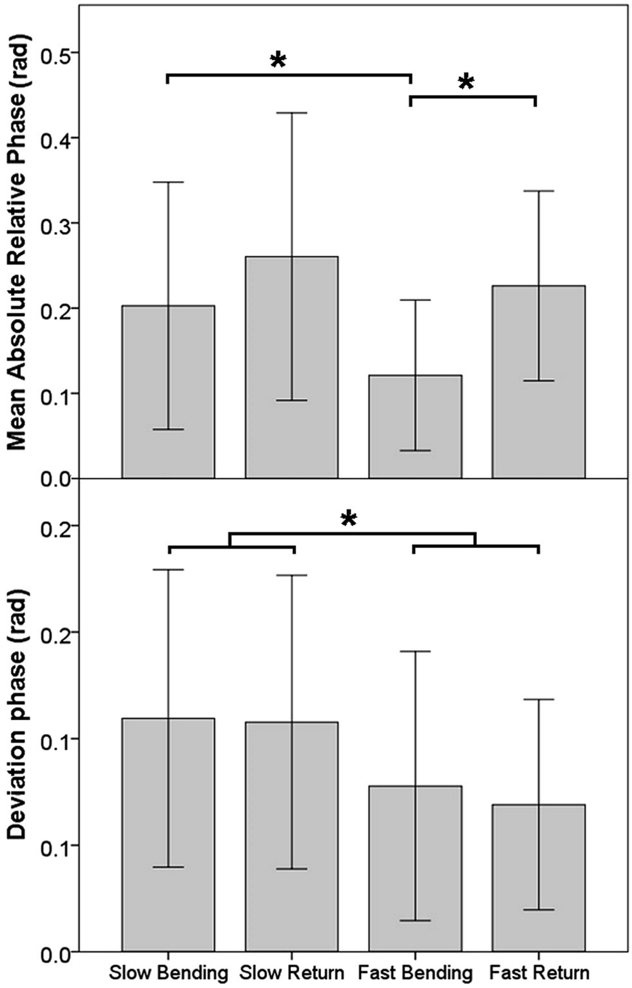

Fig. 4. The interaction between the pace and direction on mean absolute relative phase (MARP) (top) and deviation phase (DP) (bottom). The MARP and DP values are averaged for all the participants. This chart demonstrates that the MARP is smaller in the fast bending than the slow bending and fast return. Also, the DP is smaller in the fast versus slow bending/return tests regardless of motion direction. The error bars and stars indicate the standard deviation and significant difference between groups respectively.

The lumbopelvic rhythm has magnitude and timing aspects, which need to be studied using separate analyses (Vazirian et al., 2016a). Previously, the authors showed for the same sample of participants that the lumbar contribution (as a magnitude-related measure of lumbopelvic rhythm) was smaller in the age groups above the 50 years of age than those below (Vazirian, Shojaei, et al., 2016). Here, it was further shown that not only the older age groups had a smaller lumbar contribution throughout the bending and return, but they tended to have a more in-phase motion of the lumbar spine and pelvis. More in-phase lumbopelvic rhythm in patients with LBP versus control group has been suggested to be a protective neuromuscular strategy adopted to prevent the lumbar spine from large deflections (Mokhtarinia et al., 2016). Adopting a more in-phase motion in older versus younger participants of our study may similarly be a neuromuscular strategy for better protection of the lumbar spine by avoiding large strains (Mokhtarinia et al., 2016; Seay et al., 2011).

Variability of lumbopelvic rhythm, as reflected in our measure of DP, was smaller in the older versus younger age groups. Higher stiffness of lower back in older versus younger individuals, as we have recently reported for the same cohort of participants (Shojaei, Allen-Bryant, et al., 2016), could be in part the reason for such age-related differences in variability of lumbopelvic rhythm during bending and return motion. Differences in neuromuscular control of trunk motion (McGill, Yingling, & Peach, 1999; Quirk & Hubley-Kozey, 2014) may also have a role in age-related differences in variability of lumbopelvic rhythm.

Although lumbar contribution to the trunk motion was reported to be significantly smaller in the females versus males in the same sample of participants (Vazirian, Shojaei, et al., 2016), the results of this study showed that there was no gender-related difference in the MARP and DP. Furthermore, fast versus slow motion paces were reported to be associated with a smaller lumbar contribution to trunk motion (Vazirian, Shojaei, et al., 2016). The MARP and DP were similarly found here to be smaller under the fast versus slow motion. These findings are potentially related to the added mechanical demand on the lower back while performing fast versus slow trunk motions. The inertial load on the spine increases with an increase in the pace of trunk motion. In an earlier modeling study of spine (Bazrgari, Shirazi-Adl, Trottier, & Mathieu, 2008), we reported up to two times larger spinal loads under fast versus slow paces of trunk motion, primarily as a result of the required large muscle forces to offset the increase in mechanical demand of the task. Thus, the more in-phase lumbopelvic rhythm during bending, and also, the less variable lumbopelvic rhythm during the bending and return in the fast versus slow motion may as well be explained as a protective neuromuscular strategy to avoid tissue injury. Increase in mechanical demand of the task due to inclusion of external load has similarly been reported to result in a more in-phase lumbopelvic rhythm (Hu & Ning, 2015; Nelson, Walmsley, & Stevenson, 1995).

On the basis of existing evidence, related to the timing aspect of lumbopelvic rhythm during trunk bending and return, particularly the differences between individuals with and without LBP, as well as the effects of external load, it was speculated that one possible scenario for a more in-phase lumbopelvic rhythm is an attempt to avoid excessive stress and strain in the lower back tissues. However, it is necessary to conduct additional investigation using modeling studies to further support the relationship between the relative phase and spinal loads. Moreover, the method used in this study for calculation of CRP was one of several methods used in the literature (Burgess-Limerick, Abernethy, & Neal, 1993; van Emmerik & Wagenaar, 1996). The adopted method in the present study eliminates the frequency artifacts and provides the relative phase with the highest accuracy, as suggested by Lamb and Stöckl (Lamb & Stockl, 2014). However, the wavelet coherence methods can provide further insight into the dynamics of the lumbopelvic rhythm by investigating the time–frequency dependency of the relative phase (Ihlen, 2014).

In summary, from the timing perspective, the lumbopelvic rhythm under trunk forward bending and backward return, was significantly different between the older and younger age groups while there was no difference between the males and females. Measurement of the lumbopelvic rhythm is often performed in clinic to diagnose potential abnormalities in patients' neuromuscular behavior as well as to monitor treatment progress. Therefore, availability of information related to differences in the normal lumbopelvic rhythm due to personal (e.g., age and gender) and task characteristics (e.g., motion pace, presence of external load) can further enhance the effectiveness of such clinical tool for management of LBP.

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