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Using relative phase analyses and vector coding to quantify Pelvis-Thorax coordination during lifting—A methodological investigation

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ABSTRACT

Low-back disorder risk can be modulated by pelvis-thorax coordination when lifting. To objectively discriminate between coordination patterns during lifting, the analytical methods used require evaluation. The primary study objective was to determine if continuous relative phase (CRP) and vector coding (VC) analyses can discriminate between lifting techniques that differ based on biomechanical risk criteria. The secondary objective was to determine if normalization/transformation of input segmental angular position and velocity data is required to discriminate between lifting techniques. Sixteen volunteers performed a sagittal lifting task using freestyle (FRE), flexed spine (FLX), and neutral spine (NTL) techniques. CRP and VC analyses were implemented to quantify pelvis-thorax coordination patterns based on time-normalized, phase-normalized, and Hilbert-transformed segmental angular kinematic data. Mean relative phase angles along with thorax-only and in-phase coupling patterns were significantly different between FRE-NTL and FLX-NTL techniques ($p < 0.01$), but not FRE-FLX ($p > 0.44$). This finding was consistent across all relative phase normalization/transformation methods. Therefore, CRP and VC analyses successfully discriminated between different lifting techniques, regardless of the relative phase normalization/transformation method used.

1. Introduction

Repetitive lifting is linked with the reporting of low-back disorders (LBD) (Coenen et al., 2014). In attempt to manage and prevent LBD associated with lifting, the mechanics and control of this fundamental movement have been studied extensively. From the vast literature on the topic, there is evidence that mechanically-induced damage of spine tissues (i.e., low-back injuries) could be the most significant and preventable cause of lifting-related LBD (Marras, 2000), and that low-back injury risk is affected by how spine system components are coordinated when lifting (McGill, 2009). Given these proposed relationships between spinal coordination, mechanical loading, and injury risk, it is conceivable that quantitative measures of spinal coordination could be used effectively as proxies to evaluate LBD prevention strategies. It is also conceivable that objectively quantifying spinal coordination patterns during lifting could spawn novel analytical (mechanistic) lines of inquiry designed to probe underlying causes and consequences of LBD (Beek et al., 1995). However, it is currently unknown if it is valid to use spinal coordination measures for the abovementioned purposes.

Coordination of complex human movement (sub)systems has been operationalized as the spatiotemporal organization of their components into functional behavioral units (Newell, 1985). When defined this way, coordination can be quantified using techniques from systems science (van Emmerik et al., 2016). Continuous relative phase (CRP) and vector coding (VC) are examples of techniques used to study spatiotemporal patterns in time-evolving systems and are thus hypothetically suited to quantify the pattern of relative rotations between the thorax and pelvis segments (i.e., lumbar spine coordination) during repetitive lifting. Indeed, relative phase analyses have been used extensively to study the effects of personal characteristics (Commissaris et al., 2002; Hu and Ning, 2015a, 2015b; McGorry and Hsiang, 1999; van Dieën et al., 1996) and task parameter manipulations (Burgess-Limerick, 1995; Scholz, 1993a, 1993b; Scholz and McMillan, 1995) on lifting technique, and as a means to describe and classify lifting techniques (Burgess-Limerick et al., 1993). To date, there have been no known attempts to use coupling angles (VC) to quantify spinal coordination during lifting, though similar/equivalent quantities (e.g., lumbopelvic ratios) have been used to describe how segments/joints contribute to trunk postures during dynamic activities (Vazirian et al., 2016). Given that coupling angles (VC) may be easier to interpret than relative phase angles (CRP) (Wheat

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and Glazier, 2006), and because VC does not necessarily require that thorax and pelvis segments behave in an oscillatory manner, VC may be preferred in cases where its discriminative capabilities are equal to/greater than those of CRP.

Although CRP and VC analyses of human movement are becoming more prominent, there are several methodological issues that could influence whether it is valid to use these sophisticated analyses to quantify and interpret spinal coordination during repetitive lifting. First, despite the ability of CRP to identify inter- and intra-individual differences in pelvis-thorax coordination patterns during lifting (Seay et al., 2016), the underlying causes and/or effects of these differences are not immediately revealed. Second, there are several methods by which kinematic input signals (i.e., angular displacement and velocity) are handled to quantify relative phase angles. Some authors do not normalize and/or convolve kinematic signals beyond time-normalization of movement cycles (Silfies et al., 2009), while others employ phase-normalization (Burgess-Limerick et al., 1993; Hu and Ning, 2015a, 2015b; Mokhtarinia et al., 2016; Scholz, 1993a, 1993b; Scholz and McMillan, 1995; Scholz et al., 1995; Seay et al., 2016; Zhou et al., 2016) or Hilbert transforms (Lamoth et al., 2009). In studies of lifting mechanics and control, there have been no efforts to investigate the potential implications of normalization/transformation methods on the discriminative capability of CRP analyses. It is thus unknown if recommendations regarding normalization of state space trajectories and specific relative phase angle derivations (c.f., (Hamill et al., 2000; Lamb and Stockl, 2014)) are applicable or necessary for studying lifting-related LBD.

To address the abovementioned knowledge gaps and methodological uncertainties, the primary objective of this study was to determine if pelvis-thorax relative phase and coupling angles discriminate between lifting techniques that were experimentally controlled to be distinct based on biomechanical (kinematic and kinetic) LBD risk criteria. A secondary objective was to determine if input signal phase-normalization and Hilbert-transformation is necessary to differentiate between said lifting techniques. As such, this study was effectively designed to assess the validity of relative phase and coupling angles as proxies of lifting-related LBD risk and was not intended to explain potential links between LBD risk and real-life (e.g., occupational) lifting behaviors. For this reason, the lifting techniques were deliberately contrived to provide the boundary conditions required to assess whether spinal coordination measures discriminate between high- and low-risk lifting techniques.

2. Methods

2.1. Participants

A convenience sample comprised of 16 volunteers between the ages of 18–29 years participated (Table 1). The Physical Activity Readiness Questionnaire (PAR-Q) (Binkley et al., 1999; Stratford et al., 2004; Warburton et al., 2011) and Lower Extremity Functional Scale (LEFS) (Binkley et al., 1999; Stratford et al., 2004; Warburton et al., 2011) were administered prior to participation to exclude any individuals whose self-assessment of health status or functional capacity would have exposed them to greater than nominal risk as a result of participation. Exclusion criteria were used to control for potentially confounding effects of age (Pries et al., 2015), low-back pain (Bouriguaet al., 2014; Larivière et al., 2000, 2002; Mokhtarinia et al., 2016), and lower extremity joint dysfunction (Beach et al., 2014; Davis and Seol, 2005) on lifting technique, and were met by scoring greater than 70 (out of 80) on the LEFS and answering ‘no’ to all PAR-Q questions. The University of Toronto’s Office of Research Ethics approved all experimental procedures and supporting documentation used in this study and written consent was obtained from all participants prior to data collection.

Table 1
Characteristics of study participants and the individualized lifting origin heights.

Participant	Sex (M/F)	Body mass (kg)	Height (m)	Lift height (m)
1	F	53.8	1.64	0.36
2	M	99.6	1.89	0.38
3	M	76.1	1.73	0.27
4	F	72.8	1.77	0.28
5	M	83.6	1.87	0.43
6	F	61.5	1.60	0.27
7	F	72.2	1.62	0.40
8	M	75.4	1.81	0.37
9	F	70.1	1.65	0.39
10	F	50.3	1.55	0.28
11	M	68.6	1.75	0.36
12	M	70.1	1.78	0.40
13	M	84.3	1.80	0.37
14	F	76.5	1.56	0.35
15	M	78.3	1.78	0.41
16	F	83.4	1.64	0.36
Mean (SD)		73.5 (11.6)	1.71 (0.1)	0.36 (0.05)

2.2. Procedures

Participants performed bouts of repetitive lifting using a self-selected (i.e. freestyle), neutral spine, and flexed spine technique. Physical constraints were imposed to promote the neutral spine and flexed spine techniques since technique-oriented verbal instructions do not necessarily influence lumbar spine kinematics in the intended manner (Beach et al., 2018). The constraints effectively induced contrived lifting techniques that were representative of theoretical extremes of spinal coordination that could be employed during lifting (to assess the validity of spinal coordination measures) and were not intended to represent techniques that would (or should) be used in *bona fide* occupational settings. A brief description of the task constraints for each lifting bout is provided below:

- FREESTYLE TECHNIQUE (FRE): The freestyle technique was performed with no additional task constraints imposed beyond: load origin and destination; load mass for women (9 kg) and men (10 kg), barbell dimensions (2.5 cm diameter); foot surface boundaries (60 cm × 90 cm); and lifting instructions (described below) (Fig. 1a). These task constraints were consistent for all lifting techniques.
- NEUTRAL SPINE TECHNIQUE (NTL): A carbon steel dowel (mass = 0.6 kg) was fastened to the mid-line of the pelvis and thorax when lifting (Fig. 1b). The dowel was secured to the thoracic region using a non-elastic band and to the pelvis using a non-threaded bushing sleeve that was welded to the pelvic harness. Rigid, localized lumbar support was applied at the approximate L_3 spinal level during upright standing to prevent lumbar flattening. The participant’s head was not secured to the dowel, but they were instructed to maintain head contact with the dowel throughout.
- FLEXED SPINE TECHNIQUE (FLX): An adjustable vertical barrier was placed between the participant and the barbell to prevent knee flexion and ankle dorsiflexion (Fig. 1c). Participants stood with their feet under the barrier and thighs lightly touching the barrier when standing upright. Thigh contact with the barrier was not maintained when lifting, nor did the knees contact the barrier at any point during the lift/lower task. The height of the vertical barrier was adjusted to mid-thigh, but below knuckle-height so that the barbell could clear the barrier.

The barbell origin height was individualized to ensure that participants were capable of lifting with the flexed and neutral spine techniques. Individualization was achieved by initially positioning the barbell at mid-shank height, then instructing participants to lift the