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The effects of movement speed on kinematic variability and dynamic stability of the trunk in healthy individuals and low back pain patients

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ABSTRACT

Background: Comparison of the kinematic variability and dynamic stability of the trunk between healthy and low back pain patient groups can contribute to gaining valuable information about the movement patterns and neuromotor strategies involved in various movement tasks.
Methods: Fourteen chronic low back pain patients with mild symptoms and twelve healthy male volunteers performed repeated trunk flexion–extension movements in the sagittal plane at three different speeds: 20 cycles/min, self-selected, and 40 cycles/min. Mean standard deviations, coefficient of variation and variance ratio as variability measures; maximum finite-time Lyapunov exponents and maximum Floquet multipliers as stability measures were computed from trunk kinematics.
Findings: Higher speed significantly reduced the kinematic variability, while it increased short-term Lyapunov exponents. Long-term Lyapunov exponents were higher at self-selected speed and lower in low back pain patients as compared to control volunteers. Floquet multipliers were larger at self-selected speed and during higher pace trunk movements.
Interpretation: Our findings suggest that slower pace flexion–extension trunk movements are associated with more motor variation as well as local and orbital stability, implying less potential risk of injury for the trunk. Individuals with and without low back pain consistently recruited a closed-loop control strategy towards achieving trunk stability. Chronic low back pain patients exhibited more stable trunk movements over long-term periods, indicating probable temporary pain relief functional adaption strategies. These results may be used towards the development of more effective personalized rehabilitation strategies and quantitative spinal analysis tools for low back pain detection, diagnosis and treatment, as well as improvement of workspace and occupational settings.

1. Introduction

Nonspecific low back pain (NLBP) is a major public health and global socioeconomic burden (Bressler et al., 1999; Dagenais et al., 2008; Walker et al., 2004). According to the World Health Organization and the Global Burden of Diseases, Injuries, and Risk Factors Study 2013, low back pain (LBP) is the single leading cause of disability worldwide, occurring in similar proportions in many cultures, and interfering with the quality of life and work performance (http://www.thelancet.com). Several studies have shown that individuals with LBP alter their motor activity and control strategies (e.g. reducing thoracic and pelvic rotations in the transverse plane during walking) to avoid painful movements and postures (Lamoth et al., 2006; Van Den Hoorn et al., 2012). Such adaptive and protective strategies may affect spinal loading and compromise spinal control stability by decreasing damping and increasing the stiffness of trunk. While comforting in the short term, they may lead to further chronic pain (Hodges et al., 2009; Rashedi et al., 2010; Zeinali-Davarani et al., 2008). Despite the increasing knowledge of spinal pathologies, the cause–effect relationship between LBP development and altered movement patterns/stability is not completely known yet (Solomonow, 2012). Low-dimensional quantitative expressions or collective variables (Heriza, 1991) might reveal different aspects of the coordinated movement patterns and help to capture more information on neuromotor control impairments in LBP patients. Towards this goal, a nonlinear system approach may be used to

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elucidate the influence of mechanical conditions on the internal loading and stability control of spine during the performance of various occupational and recreational tasks.

Movement variability which exhibits deterministic behavior, contains important spatiotemporal information (Stergiou and Decker, 2011). Work pace is a relevant occupational factor and a control parameter which has been shown to influence temporal movement strategies during repetitive tasks (Dempsey et al., 2010). Specifically, higher pace has been associated with more variability and errors during repetitive assembly work (Bosch et al., 2011). Gait studies revealed that trunk kinematic variability has the lowest magnitude at preferred speeds compared to lower and higher speeds (Dingwell and Marin, 2006). Increasing motor variability is of interest to ergonomists and biomechanists as an intrinsic factor towards the prevention of musculoskeletal disorders (MSDs) (Srinivasan and Mathiassen, 2012). Conversely, other studies have suggested that reduced coordination variability did not contribute to LBP (Yen et al., 2012). The existing discrepancies partly stem from the disparate experimental protocols and methodologies employed. Measures derived using linear methods (i.e. MeanSD, coefficient of variation (CV) and variance ratio (VR)) do not examine temporal organization of variability. In order to capture and adequately quantify the complexity of neuromotor behavior, time-dependent structural characteristics of movement variability (i.e. stability measures) should be evaluated as well (Khalaf et al., 1999; Stergiou and Decker, 2011).

Evaluation of spinal mechanical stability at static conditions may not reflect what occurs during dynamic activities. Thus, empirical estimates of stability have been developed as an alternative method. Trunk dynamic stability can be estimated using finite-time Lyapunov exponents (LyEs) (Rosenstein et al., 1993), and Floquet multipliers (FMs) (Hurmuzlu and Basdogan, 1994). These methods consider spatiotemporal organization of kinematic variability (Granata and England, 2006). LyE typically quantifies local stability using the exponential divergence/convergence of trajectories over time with a nearby initial condition (Rosenstein et al., 1993). FM quantifies orbital stability using the tendency of neighboring trajectories to return to the limit cycle orbit (Hilborn, 2000) with the progression of time. Trunk stability depends on the collective functional and mechanical contribution of passive, active and neurocontrol subsystems (Panjabi, 1992). Recent studies have shown that movement pace, direction (Granata and England, 2006), load (Graham et al., 2012; Lee and Nussbaum, 2013) and fatigue (Granata and Gottipati, 2008) influence neuromuscular spinal stability. In addition, research shows that cyclic occupational activities in general affect the passive stiffness and gains of neuromuscular control (Lu et al., 2008; Solomonow, 2012; Wang et al., 1998).

In summary, the frequency, maximum flexion, angular velocity, and repetitive trunk movement are all potential determinants for spinal motor variability and control stability, and to our knowledge, these factors have not been investigated adequately during different movement tasks. Furthermore, the majority of existing studies are based on healthy participants rather than LBP patients. The few studies devoted to LBP patients reveal lower spinal motor variability as compared to healthy subjects during walking (Srinivasan and Mathiassen, 2012). Hence, more studies are needed to substantiate these findings during various movement tasks, particularly for the LBP population.

Therefore, the main objectives of this study are to evaluate whether the varying speed of motion affects the kinematic variability and movement control of the trunk; and secondly to test if LBP patients use altered trunk movement patterns and different neurocontrol strategies as compared to healthy individuals. Based on previous findings, our underlying assumption is that the trunk kinematic variability decreases with speed and during target-directed movements (Jordan et al., 2007; Plamondon and Alimi, 1997; Winter, 1984). It is expected that increasing the speed would decrease the neuromuscular control of trunk stability over short-term intervals (Granata and England, 2006). On the other hand, we hypothesize that the subjects would exhibit more stable movements over long-term intervals based on increased reliance on feedback, especially by LBP patients.

2. Methods

2.1. Participants

Fourteen male volunteers with chronic nonspecific low back pain (NLBP) were recruited from local physical therapy clinics. Twelve healthy volunteer males with no self-reported history of LBP, were recruited from the University of Social Welfare and Rehabilitation Sciences (Table 1). NLBP is a pain that is not attributed to any recognizable pathology (e.g. inflammation, tumor, osteoporosis, infection, fracture, etc.) that lasts a duration of at least 3 months (Airaksinen et al., 2006). Participants were excluded, based on examinations of a physical therapist, one of the authors (HRM), if they had any background surgical intervention on the vertebral column, specific spinal deformities and any neurological, pulmonary, rheumatism and metabolism diseases. Proper ethical approval was obtained and all subjects signed the informed consent form prior to the start of the experiment. Moreover, because of high demanding movement tasks included the experimental protocol, only LBP patients with low pain intensity (score of less than 2 for Visual Analogue Scale (Price et al., 1983)) were recruited.

2.2. Experimental procedure

All subjects were required to execute repeated trunk flexion–extension movements consecutively in the sagittal plane. They were asked to touch a target with their hands located in the sagittal midline, 50 cm anterior to the knee in upright position, while looking at another target placed at shoulder height in the sagittal midline during standing. Specifically, the participants were asked to touch the lower target with extended arms, followed by looking at the upper target with enough extended trunk while their arms were positioned alongside their bodies, and to do this motion repeatedly throughout the duration of each trial. No motor constraints were imposed on the lower extremity joints since movement constraints affect motor control strategies (Granata and Gottipati, 2008). In order to avoid excessive range of motion, subjects were asked not to move their knees or feet. Verbal feedback was given if instructions were violated. Upon data collection, knee angle time series were inspected for possible excessive movements.

The experimental protocol included repetitive movements at three different speeds: 20 cycles/min, self-selected, and 40 cycles/min. Subjects were asked to reach targets synchronously with a metronome in order to establish the movement pace of 20 and 40 cycles/min similar to Granata et al. experiment (Granata and England, 2006). The slow and fast paced trials lasted 90 and 45 s in duration, respectively, in order to obtain a continuous movement pattern having 30 cycles per trial, and to minimize the effects of fatigue (Dupeyron et al., 2013). For the self-selected paced trials, the subjects were asked to perform at least 30 continuous movement cycles at their own pace. They were allowed to perform several practice movements to get comfortable with task prior to the data collection. The order of speed conditions was randomized, with at least a 3 min rest period between trials. Self-selected pace was typically between low pace and high pace flexion–extension movements for all subjects (Table 1).

Table 1
Subject characteristics (means ± SD) and self-selected pace for healthy and LBP patients.

	Healthy (n = 12)	LBP (n = 14)
Age (years)	28.0 ± 4.4	31.5 ± 6.6
Height (cm)	173.8 ± 8.0	177.8 ± 8.6
Body mass (kg)	74.1 ± 11.7	74.8 ± 8.8
BMI	24.5 ± 3.5	23.8 ± 3.4
Self-selected pace (cycles/min)	32 ± 2	30 ± 4