Human Movement Science 54 (2017) 339–346

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

Local dynamic stability of the spine and its coordinated lower joints during repetitive Lifting: Effects of fatigue and chronic low back pain

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A R T I C L E I N F O

Keywords:
Fatigue
Chronic low back pain
Nonlinear dynamics
Local dynamic stability
Lyapunov exponent

A B S T R A C T

The nonlinear Lyapunov exponent (LyE) has been proven effective for evaluating the local stability of human movement and exploring the effects of load, speed and direction of individuals with and without nonspecific chronic low back pain (CLBP). The purpose of this study was to examine spinal and lower joint stability and response to fatigue of individuals with and without CLBP while performing lifting-lowering movements. Fourteen healthy individuals and 14 patients with nonspecific CLBP were recruited to perform lifting movement repeatedly while holding two equally-sized dumbbells in their hands. The participants continued lifting until they reported their highest level of fatigue. Kinematic data for the spine and its coordinated lower joints were recorded during the task (more than 40 lifting cycles on average). The first and last 20 cycles of each cyclic time series were defined as early- and late-fatigue conditions, respectively. The maximum LyE was estimated to quantify the local dynamic stability of the angular displacement time series of the spine, hip, knee and ankle on different anatomical planes in both the early- and late-fatigue conditions. The results revealed that local stability of the spine and hip was affected by fatigue. Spinal stability decreased as fatigue increased on the sagittal plane ($p < 0.05$). The hip exhibited a similar affectation (destabilization under fatigue) on all anatomical planes. Patients with CLBP showed more stable hip movement on the frontal and transverse planes ($p < 0.05$). These results suggested that lifting/progressive fatigue could increase the risk of injury to the spine and hip. These findings indicate that patients with CLBP applied different control strategies for the hip; thus, spinal control stability should be evaluated together with the stability of the lower joints.

1. Introduction

Chronic low back pain (CLBP) is a global health concern with a strong societal and economic impact (Hoy et al., 2012, 2014; Mehrdad, Shams-Hosseini, Aghdaei, & Yosefian, 2016). It can influence motor functioning of the spine and other joints (Harris-Hayes, Sahrmann, & Van Dillen, 2009; Shum, Crosbie, & Lee, 2007; Wong & Lee, 2004). Motor function can also be influenced by lifting-induced fatigue (Granata, Slota, & Wilson, 2004; Kahlaee, Bahrpeyma, & Esteki, 2012) through altered muscle recruitment and co-contraction patterns (Potvin & O'brien, 1998). While several current trends in occupational life include repetitive movement over

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http://dx.doi.org/10.1016/j.humov.2017.06.007
Received 26 November 2016; Received in revised form 29 May 2017; Accepted 25 June 2017
Available online 30 June 2017
0167-9457/

long periods of time (Srinivasan & Mathiassen, 2012), fatigue is the unavoidable short-term outcome of such repetitions. Fatigue alters muscle timing and reflex responses to movement control (Herrmann, Madigan, Davidson, & Granata, 2006) by increasing the myoelectric and electromechanical time delay (Hortobagyi, Lambert, & Kroll, 1991). Fatigue could impair an individual's ability to stabilize the spine and its coordinated lower joints during repetitive lifting tasks (Granata & Gottipati, 2008).

To reduce the effects of pain and fatigue, motor variability as a cycle-to-cycle variation through changes in kinematics or muscle activation has been reported (Hodges, Moseley, Gabrielsson, & Gandevia, 2003). Motor variability alters the strategies of movement organization in response to perturbation. Such inherent variability of human motor control during repetitive movement enables quantitative analysis on the time-dependent behavior of the system. This can be kinematic variance about target equilibrium trajectories in the form of divergence/convergence on reconstructed stable dynamics (attractors) (Dingwell & Marin, 2006; Granata & England, 2006).

The Lyapunov exponent is a nonlinear system that has been effectively applied in several studies to quantify local dynamic stability of human movement during repetitive tasks such as lifting (Asgari et al., 2015; Graham, Sadler, & Stevenson, 2012). This approach is capable of evaluating the effect of the control parameters, such as the rate of movement, symmetric and asymmetric conditions of flexion-extension (Granata & England, 2006) and fatigue-induced changes (Asgari et al., 2015; Gates & Dingwell, 2010; Granata & Gottipati, 2008) on local dynamic stability.

Previous studies have tended to evaluate trunk control stability exclusively (Graham, Oikawa, & Ross, 2014; Granata & England, 2006; Granata & Gottipati, 2008), although the stability of the human body is a contribution of the coordinated movement of the upper and lower joints. Altered inter-joint motor control patterns, especially spine-hip coordination (Mokhtarinia, Sanjari, Chehrehrazi, Kahrizi, & Parnianpour, 2016; Wong & Lee, 2004), and different types of lumbo-pelvic synergy during active knee flexion and hip lateral movement (Scholtes, Gombatto, & Van Dillen, 2009) were repeatedly reported in the CLBP population (Shum, Crosbie, & Lee, 2005). Nevertheless, the mechanism of fatigue and effect of its interaction with pain on stability of the spine and lower joints in CLBP patients has not been completely established (Granata et al., 2004). Moreover, the experimental protocols in previous studies mostly included spatiotemporal and physical constraints of the lower limbs (Graham et al., 2014). Such constraints can influence motor function by reducing kinematic redundancy. Considering the importance of unchanged kinematic redundancy, preferred parameterization of human movement with no physical constraint on the limbs or joints were associated with optimal motor variability (Stergiou, Harbourne, & Cavanaugh, 2006) and higher long-term stability (Ghomashchi, Esteki, Nasrabadi, Sprott, & BahrPeyma, 2011; Ghomashchi, Esteki, Sprott, & Nasrabadi, 2010; Graham et al., 2014). This approach provides more efficient evaluation of motor variability and neuromuscular adaptation under perturbation. To date, fatigue-related changes on the local dynamic stability of the spine and its coordinated lower joints have not been evaluated in healthy and CLBP populations; this highlights the need for the present study.

The objective of the present study was to evaluate the effects of lifting-induced fatigue on the local dynamic stability of the spine and its coordinated lower joints in individuals with and without CLBP. For this, the local stability of the spine, hip, knee and ankle were quantified using maximum LyE during a lifting-lowering task. It was hypothesized that individuals may adopt more locally-unstable movement in the lower joints in specific directions in order to preserve the local stability of the spine and control pain-related conditions. In addition, a decrease was expected on the stability of joints during fatigue progression.

2. Methods

2.1. Participants

Fourteen healthy men with no self-reported history of CLBP (age = 23.15 (2.04) years, BMI = 22.42 (2.44)) were recruited from the students and staff of Tehran universities. Another group of individuals comprising 14 male patients with nonspecific CLBP (age = 25.33 (3.45) years, BMI = 24.15 (3.02)) also took part in this study. These individuals were identified from the population of persons under treatment at one of four rehabilitation and physiotherapy centers in the city of Tehran. All participants who met the inclusion criteria provided informed consent as approved by the university ethics committee.

Participants with CLBP were eligible to participate if they were 20 or more years of age, had a history of pain and discomfort in the lumbar area without pain referring to the lower limbs and experienced CLBP recurrently for more than three months with no recognized pathology. Exclusion criteria were symptoms for nerve root irritation, vertebral or leg fracture and/or history of surgery, neurological or rheumatic disease and an observable spinal deformity. Healthy individuals then were selected to be matched with the CLBP patients with regard to age, gender, BMI and level of physical activity ($p > 0.05$).

2.2. Protocol

All test trials were conducted at a similar time of day in the ergonomics laboratory of the University of Social Welfare and Rehabilitation Sciences in Tehran. The experimental protocol required participants to lift two equally-sized dumbbells having a combined weight equivalent to 15% of their body weight. The dumbbells were lifted in the hands up waist level while standing upright. The participants were asked to lower the dumbbells to the floor and lift and lower the loads repeatedly. The lifting movement was continued until the participant reported a score of 17 on the Borg scale, which was considered to be the highest-safe level of fatigue and the task stopping point. A score of 17 corresponds to "very difficult" on the Borg scale (Borg, 1985). Considering this highly-demanding task, a score of 17 was established as the wrap-up point for task repetition to prevent subjects, particularly patients, from the risk of possible injury.