Trunk Dynamic Stability Assessment for Individuals With and Without Nonspecific Low Back Pain During Repetitive Movement

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Objective: This study aimed to employ nonlinear dynamic approaches to assess trunk dynamic stability with speed, symmetry, and load during repetitive flexion-extension (FE) movements for individuals with and without nonspecific low back pain (NSLBP).

Background: Repetitive trunk FE movement is a typical work-related LBP risk factor contingent on speed, symmetry, and load. Improper settings/adjustments of these control parameters could undermine the dynamic stability of the trunk, hence leading to low back injuries. The underlying stability mechanisms and associated control impairments during such dynamic movements remain elusive.

Method: Thirty-eight male volunteers (19 healthy, 19 NSLBP) enrolled in the current study. All participants performed repetitive trunk FE movements at high/low speeds, in symmetric/asymmetric directions, with/without a wearable loaded vest. Trunk instantaneous rotation angle was computed for each trial to be assessed in terms of local and orbital stability, using maximum finite-time Lyapunov exponents (LyEs) and Floquet multipliers (FMs), respectively.

Results: Both groups demonstrated equivalent competency in terms of trunk control and stability, suggesting functional adaptation strategies may be used by the NSLBP group. Wearing the loaded vest magnified the effects of trunk control impairment for the NSLBP group. The combined presence of high-speed and symmetrical FE movements was associated with least trunk local stability.

Conclusion: Nonlinear dynamic techniques, particularly LyE, are potentially effective for assessing trunk dynamic stability dysfunction for individuals with NSLBP during various activities.

Application: This work can be applied toward the development of quantitative personalized spinal evaluation tools with a wide range of potential occupational and clinical applications.

Keywords: dynamic stability, nonspecific low back pain, repetitive trunk movements, Lyapunov exponent

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INTRODUCTION

Several occupational risk factors have been associated with the cause and aggravation of low back pain (LBP) in work environments. Previous research has identified repetitive trunk flexion-extension (FE) movement as one of the key factors (Marras, 2000; Weiner et al., 2006). This activity, which is dependent on multiple control parameters, including speed, physical load, and symmetry/asymmetry, increases the susceptibility of workers to injuries, particularly LBP, and instigates numerous management challenges within work settings (Frymoyer et al., 1980; Haddas et al., 2019; Hendershot et al., 2011). Research also suggests that the control parameters associated with this activity impact the underlying active, passive, and neuromuscular control subsystems whose contribution regulates the dynamic stability of the trunk (Hoffman & Gabel, 2013). This is demonstrated by how an increase in the speed of the trunk during FE movement leads to reduction in the reaction time for the nervous system and a subsequent increase in trunk angular momentum (de Aquino Nava et al., 2018; Granata & England, 2006). Lifting loads and asymmetrical trunk movements have also been shown to alter trunk muscles' level of activation, co-contraction, and recruitment patterns (de Aquino Nava et al., 2018; Graham et al., 2012; Le et al., 2007). These changes come at a cost of higher levels of control for the neuromuscular system in order to retain trunk trajectories within a certain proximity of its equilibrium state (i.e., to maintain trunk dynamic stability). Consequently, for an overburdened trunk stability system, small neuromuscular control errors may lead to subsequent negative impact on the relative motion between the vertebrae, extreme spinal shearing/compression forces, and tissue damage (Moseley et al., 2003).

Quantitative assessment of trunk dynamic stability can improve the knowledge of the underlying stability mechanisms. Nonlinear dynamic analysis methods, such as the maximum Lyapunov exponent (LyE) and Floquet multipliers (FMs), have provided insight into lower/upper limb stability control during repetitive movements (van Emmerik et al., 2016). Both these methods use the spatiotemporal organization of movement variability to determine the manner in which the neuromotor system maintains stability from one repetition to the next (i.e., movement trajectory). The use of LyE determines whether the repetitive adjacent trajectories move toward (negative exponent) or apart (positive exponent) from each other over *time* and reflects the level of local stability (van Emmerik et al., 2016). The Lyapunov approach can quantify the divergence rate of neighboring trajectories for a short period of one cycle (i.e., the short-term LyE) or for longer period of 4–10 cycles (i.e., the long-term LyE). The FM method, however, evaluates the *orbital stability* of repetitive movements to determine whether neighboring trajectories spiral into a limit cycle in the *phase space*. Both LyE and FM quantify the dynamic stability of proximate trajectories but from different aspects (Dingwell & Kang, 2007; Leonov et al., 1995); therefore, it is common to benefit from both and gain a better understanding of the systems' dynamic stability.

The maximum LyE method has shown more favorable use in the recent literature as a promising method for the assessment of trunk dynamic stability in several groups. This has included healthy individuals, athletes with NSLBP, as well as individuals with experimentally induced LBP. However, a knowledge gap exists, as these investigated populations do not reflect the clinical reality of patients who attend primary care settings (Graham et al., 2014) with an existing history of NSLBP (Ross et al., 2015). In healthy individuals, short-term LyE increases with the speed and symmetry of flexion movements (Granata & England, 2006), as well as with lifting (Graham et al., 2012). In comparative studies between healthy and NSLBP groups of athletes (Graham et al., 2014) and nonathletes (Asgari et al., 2015), there was no significant difference in the short-term trunk dynamic stability (Asgari et al., 2015; Graham et al., 2014). In contrast, the presence of induced LBP significantly impaired the short-term trunk dynamic stability for individuals with no LBP history (Ross et al., 2015). Long-term LyE also demonstrated that individuals with chronic NSLBP have more stable trunk FE movements over long-term periods (Asgari et al., 2015). These studies confirm that the underlying stability mechanisms present in experimental/simulated LBP populations may differ from clinically diagnosed populations and/or athletes. These differences are potentially quantifiable and warrant further investigation.

An extensive literature search indicated that no comprehensive studies to date have investigated trunk control of local and orbital stability in clinically diagnosed NSLBP patients, in association with occupational risk factors. The only similar study (Asgari et al., 2015) solely considered the effect of speed in a small NSLBP population. Most existing studies have predominantly treated trunk dynamic stability as a *single-input control system*, hence exploring only one control parameter at the time such as speed (Asgari et al., 2015) or symmetry (Ross et al., 2015). On the other hand, real-life occupational settings include working tasks with multiple control parameters. This suggests that trunk dynamic stability would be better investigated as a *multi-input control system,* reflecting human neuromuscular physiology and allowing interaction effects of the various control parameters, including speed, symmetry, and load, to be considered simultaneously.

The aims of the current study were twofold: first, to examine how speed, symmetry, external load, and their interactions affect both the local and orbital components of trunk dynamic stability during repetitive FE movements; and second, to investigate whether healthy and NSLBP individuals employ different control strategies to achieve the local/orbital trunk dynamic stability. Based on the literature, we postulate that trunk dynamic stability decreases with increasing speed, applied external load, and symmetric movements. We also hypothesize that individuals with NSLBP exhibit less dynamically stable movements as compared to healthy controls.

METHODS

Participants

Nineteen healthy male volunteers (mean age: 27.45 ± 5.11 years, mean BMI: 23.57 ± 3.53) free of LBP symptoms during the previous year, and nineteen male volunteers (mean age: 30.22 ± 6.17 years, mean BMI: 23.94 ± 3.33) with chronic NSLBP participated in this study, as detailed in Mokhtarinia et. al. (Mokhtarinia et al., 2016). The presence of NSLBP was defined as back pain lasting for more than 3 months, with no attribution to specific pathologies, including inflammation, tumor, osteoporosis, infection, fracture, or any other red flag indicators (Airaksinen et al., 2006). The participants were diagnosed by an orthopedic specialist and assessed by an experienced physical therapist to ensure they meet the inclusion criteria. The pain intensity level was evaluated using a 10-score Visual Analog Scale (VAS) anchored at "0 = No Pain" and "10 = Worst Pain" (Chiarotto et al., 2019). Only participants with pain levels <3 were included. This was as a precaution related to individual participant safety under the ethics requirements for the designated high-demand tasks in the experimental protocol. Informed consent forms were collected from all volunteers, and the Ethics Approval was confirmed by the local review committee (IR.USWR.REC.1396.352).

Procedures

Each participant performed eight different tasks of repetitive trunk FE movements. These consisted of FE movements with high and low speeds, in symmetric and asymmetric planes, and with and without load. Symmetric movements were continuously executed in the sagittal plane, during which the participant was instructed to follow two targets. The lower target was positioned at 50 cm in front of the participant's knees at the patella level (Figure 1). The upper target was placed on a wall in front of the participant at shoulder height, so it could

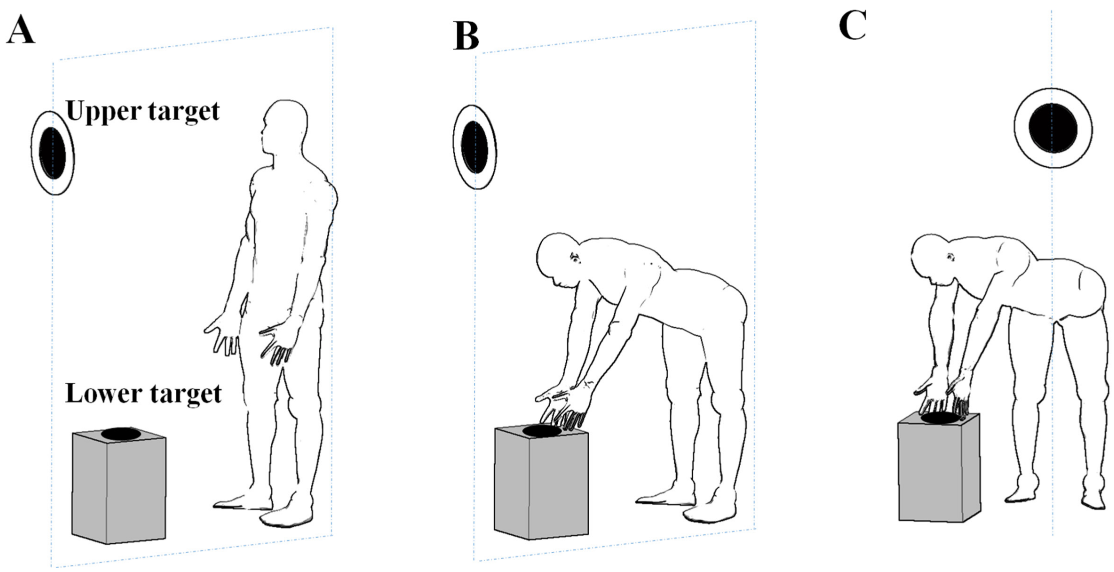

Figure 1. Schematic representation for (A) trunk upright position of both symmetric and asymmetric trials at full extension; (B) symmetric trial at full flexion; (C) asymmetric trial at full flexion.

be clearly seen at full trunk extension (Granata & England, 2006). The protocol required the participant to flex their trunk to a point where they could touch the lower target with fully extended arms, and then extend their trunk until they could see the upper target. The asymmetric trials were designed with the lower target moved to the right at a 60° angle relative to the midsagittal plane (Figure 1(C)). The participant was free to move their trunk and pelvis, but not to bend their knees. Two levels of speed, 20 (low) and 40 (high) cycles/min, were selected (Granata & England, 2006). To avoid the effects of fatigue on neuromuscular control stability, the low- and high-speed movement durations were chosen as 90 and 45 s (i.e., 30 repetitions for each), respectively (Dupeyron et al., 2013; Granata & Gottipati, 2008). Each participant was instructed to synchronize their movements via a metronome for each target. To study the effect of load, the participant wore an 8 kg vest which was uniformly loaded to minimize moment of inertia. The order of the tasks/testing conditions was randomized with a 3-min interval between each test. A practice trial was undertaken prior to data collection to familiarize participants with the study protocol.

Kinematic data of the trunk were collected (100 Hz sampling rate) using six cameras as part of a VICON motion tracking system (V460, Oxford Metrics, London, UK). Four single reflective markers were firmly placed over the seventh cervical vertebra (C7), tenth thoracic vertebra (T10), the clavicle, and the sternum based on the literature (Asgari et al., 2015; Chehrehrazi et al., 2017). Equivalent angle–axis representation ($\vec{\theta} = \theta\hat{e}$), describing any arbitrary orientation about an axis ($\hat{e}$) by an angle (θ), was applied in order to compute the trunk instantaneous rotation angle. The instantaneous rotation angle was calculated based on the rotation matrix representation of the thorax (Craig, 2005). The thorax as a segment was defined based on virtual markers calculated from the four actual markers. The kinematic data were processed using the VICON Woltring filter (Woltring, 1986). Further analyses were performed using a custom in-house MATLAB code (Mathworks, Natick, MA).

Data Analysis

Local dynamic stability. The maximum LyEs were computed, based on Rosenstein's algorithm, to measure the local stability of the trunk during FE movements. A "delay embedding method" was used to reconstruct an *n*-dimensional unfolded state-space from the one-dimensional time series of instantaneous rotation angles explained in Section "Procedures" (Figure 2(A), (B), (E); Rosenstein et al., 1993).

$$\bar{X}(t) = \left[x(t),\ x\left(t+T_d\right),\ x\left(t+2T_d\right),\ \ldots x\left(t+(n-1)\,T_d\right)\right] \quad (1)$$

Here, $\bar{X}(t)$ represents the state-space, $x(t)$ is the instantaneous angular time series for the thorax, n is the estimated embedding dimension, and T_d is the constant time delay. T_d was defined as the first minimum point for the average mutual information function (Figure 2(C); Kantz & Schreiber, 2004). Time delays were found to be 0.65 and 0.35 s for the low- and high-speed trunk movements, respectively. Based on the false nearest neighbor method (Kantz & Schreiber, 2004), an embedding dimension $d_E = 6$ was selected (Figure 2(D); Asgari et al., 2015). With trajectories reconstructed, the maximum LyE λ_{max} was estimated as the slope of the line that best fitted the following equation (Rosenstein et al., 1993):

$$y(i) = \frac{1}{\Delta t} < \ln d_j(i) > \quad (2)$$

In this equation, $< \ln d_j(i) >$ represents the average of the natural log of the displacement $d_j(i)$ for initially close neighbors, j, after i time steps Δt. Short-term λ_{max-s} and long-term λ_{max-l} LyEs were computed to describe the responses of trunk dynamic stability control to the infinitesimal inherent perturbations over short- and long-time periods, respectively. λ_{max-s} and λ_{max-l} were the slope of the fitted line over the 0–1 cycle and 4–10 cycles, respectively (Figure 2(F); Dingwell & Marin, 2006; England & Granata, 2007).

Orbital stability. The orbital stability of the trunk was investigated using maximum FM (Hurmuzlu & Basdogan, 1994). This method of defining trunk dynamic stability requires that

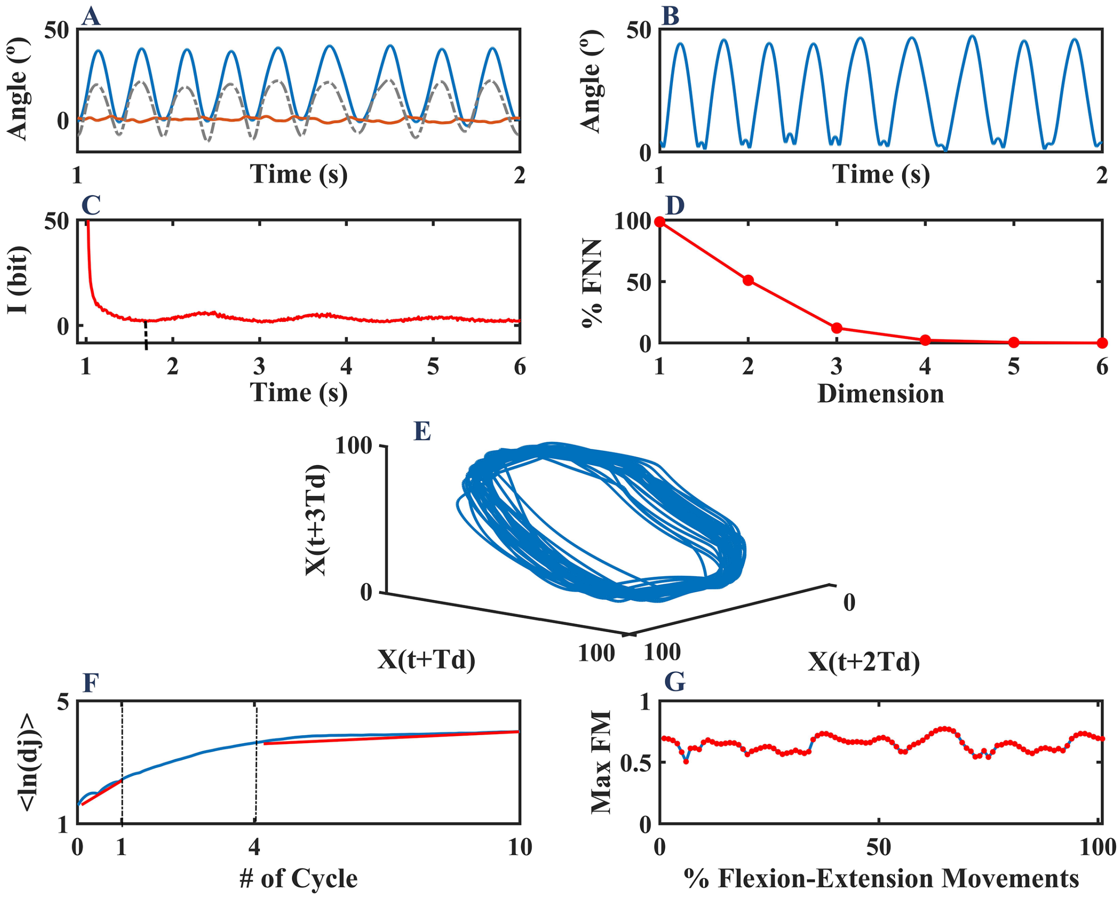

Figure 2. Representative healthy volunteer's data (asymmetric, low speed, load condition). The procedure for reconstructing the state-space and computing maximum LyE and FM: (A) original 3D angular time series of the trunk; (B) equivalent angle for 3D trunk angles shown in Figure 2(A); (C) mutual information function for 1D angular time series graphed in Figure 2(B); (D) false nearest neighbor for the shown 1D angular time series; (E) 3D presentation of the reconstructed state-space with $d_E = 6$ and $T_d = 0.65$ s; (F) λ_{max-s} and λ_{max_l} computed from the embedded state-space; (G) FM obtained at (0%–100%) Poincare sections from the reconstructed state-space. FM = Floquet multiplier; LyE = Lyapunov exponent.

all periodic neighboring trajectories passing at a certain Poincare section remain in the neighborhood of a reference/limit cycle. The Poincare section can be defined as an imaginary hypersurface (from dimension of $n-1$) placed across the flow of repetitive trajectories of the trunk FE. The intersections of the trajectories with the Poincare section define a recurrence map that can quantify the behavior of neighboring trajectories. Therefore, the state-space was divided into 101 Poincare sections from 0% to 100% of the FE trajectories. Floquet theory assumes that the $(k+1)^{\text{th}}$ state of a system is at function (F) of the k^{th} state:

$$X_{k+1} = F\left(X_k\right) \tag{3}$$

k increments from to the number of repetitions of the FE movements. Considering the limit cycle trajectory, that is, the equilibrium state, as the average of all cycles within the state-space, it must satisfy $X^* = F\left(X^*\right)$, where X^* is the intersection point of the limit cycle and the Poincare section. To investigate whether the neighboring trajectories diverge or converge from the limit cycle over time, a first-degree approximation of Eq. (3) about X^* was calculated (Kang & Dingwell, 2009) as follows:

$$\left[X_{k+1} - X_k\right] \cong J\left(X^*\right)\left[X_k - X^*\right] \quad (4)$$

$J\left(X^*\right)$is a $d_E \times d_E$ Jacobian matrix. The maximum Eigenvalue of $J\left(X^*\right)$ is defined as the maximum FM, and if it is <1 (Figure 2(G)), the limit cycle proves stable. Here, we only reported the maximum FM at Poincare sections defined at 25%, 50%, 75%, and 100% of the FE movements, as they all revealed similar information about the trunk orbital stability.

Statistical Analyses

ANOVA analysis with a repeated-measures design was used to assess how asymmetry, speed, load, and their interactions influenced the local and orbital stability of the trunk (α = .05) among healthy controls and NSLBP individuals. The independent variables were speed, load, symmetry (within-subjects), and spinal health condition (between-subjects). The dependent variables were λ_{max-s}, $\lambda_{\max\_l}$, and maximum FM (only at 25%, 50%, 75%, and 100% of the movement cycle). Further *t*-tests and paired-sample *t*-tests were employed whenever significant interactions were found. All statistical analyses were performed using SPSS 20 (IBM Corporation).

RESULTS

The mean and standard deviation values of the dependent variables for healthy and NSLBP groups during different testing conditions are detailed in Table 1.

The short-term LyE, $\lambda_{\max\_s}$, significantly differed with the main effects of symmetry and speed, but not load (Table 2, Figure 3). The results demonstrated that higher speed and symmetrical FE movements were associated with greater positive short-term LyE. Pairwise comparisons indicated that wearing the loaded vest decreased the short-term LyE for NSLBP patients, while the load and no-load conditions were similar for healthy controls (Figure 4). $\lambda_{\max\_s}$ was similar for both groups, but was significantly impacted by their interaction with load (Figure 4(A)). A significant speed by symmetry interaction was also found for $\lambda_{\max\_s}$ (Figure 4(B)), where the difference of $\lambda_{\max\_s}$, between high- and low-speed movements, tended to be greater for sagittally symmetric FE movements.

The results of the within-subject effects of speed, symmetry, and load on the local and orbital stability between the healthy and NSLBP groups (Table 2) revealed that the speed effect was significant on $\lambda_{\max\_l}$, such that higher speed FE movements were associated with higher values of $\lambda_{\max\_l}$. No significant effect was seen for the maximum FM at the defined Poincare sections at 25%, 50%, 75%, and 100% of FE cycles. All computed maximum FMs were less than unity indicating that the FE movements for the trunk had orbital stability. Positive short-term LyEs were seen for all participants, suggesting local instability of the trajectories during different testing conditions, in line with previous studies (Granata & England, 2006; Granata & Gottipati, 2008). However, almost all participants exhibited negative long-term LyE.

DISCUSSION

In this study, we hypothesized that high-speed movements of the trunk are associated with larger LyE, as compared to low-speed movements. Our findings confirmed that while $\lambda_{\max\_s}$ and $\lambda_{\max\_l}$ significantly increased with the speed of FE movements, this was not the case for the maximum FM. As we anticipated, $\lambda_{\max\_s}$ varied significantly with the symmetry/asymmetry of trunk movements where asymmetrical movements had lower $\lambda_{\max\_s}$. The significant speed by symmetry interaction indicated that the increase of $\lambda_{\max\_s}$ with speed is higher for sagittal symmetrical movements than asymmetric movements. Contrary to our hypothesis regarding the effect of load, no significant effect was observed for the load versus no-load condition. However, the significant group by load interaction suggested that trunk dynamic stability system response was different for healthy and NSLBP groups during load conditions.

Consistent with previous findings (Dingwell & Marin, 2006; Granata & England, 2006), $\lambda_{\max\_s}$ increased with the speed of FE. This suggests

TABLE 1: Mean ± SD of the Short- and Long-Term LyEs, and Maximum FMs in Each Testing Condition and Group

		Symmetric				Asymmetric			
		Low Speed		High Speed		Low Speed		High Speed	
		No-Load	Load	No-Load	Load	No-Load	Load	No-Load	Load
λ_{max_s}	Healthy	0.36 ± .05	0.38 ± .04	0.68 ± .07	0.68 ± .12	0.34 ± .06	0.36 ± .05	0.63 ± .07	0.61 ± .10
	NSLBP	0.38 ± .05	0.37 ± .05	0.75 ± .09	0.68 ± .06	0.37 ± .06	0.34 ± .05	0.64 ± .10	0.63 ± .09
λ_{max_l}	Healthy	0.00 ± .02	0.00 ± .02	0.01 ± .02	0.01 ± .03	0.00 ± .02	0.00 ± .02	0.01 ± .03	0.01 ± .04
	NSLBP	0.00 ± .01	0.00 ± .02	0.00 ± .04	0.00 ± .04	0.00 ± .01	0.00 ± .01	0.00 ± .04	0.00 ± .04
FM 25%	Healthy	0.65 ± .12	0.64 ± .13	0.66 ± .07	0.67 ± .09	0.63 ± .12	0.63 ± .10	0.66 ± .10	0.65 ± .11
	NSLBP	0.68 ± .11	0.66 ± .07	0.64 ± .11	0.67 ± .09	0.66 ± .12	0.62 ± .10	0.64 ± .09	0.65 ± .11
FM 50%	Healthy	0.70 ± .09	0.68 ± .13	0.68 ± .07	0.68 ± .10	0.66 ± .12	0.62 ± .10	0.65 ± .10	0.63 ± .15
	NSLBP	0.67 ± .11	0.66 ± .13	0.66 ± .08	0.67 ± .07	0.67 ± .14	0.60 ± .10	0.67 ± .10	0.68 ± .11
FM 75%	Healthy	0.67 ± .09	0.68 ± .09	0.67 ± .09	0.69 ± .10	0.67 ± .12	0.64 ± .10	0.66 ± .11	0.66 ± .13
	NSLBP	0.68 ± .12	0.67 ± .10	0.65 ± .08	0.65 ± .10	0.67 ± .14	0.63 ± .11	0.68 ± .10	0.67 ± .12
FM 100%	Healthy	0.66 ± .11	0.66 ± .11	0.67 ± .10	0.68 ± .10	0.62 ± .10	0.65 ± .10	0.63 ± .13	0.64 ± .14
	NSLBP	0.65 ± .12	0.67 ± .12	0.67 ± .06	0.62 ± .08	0.67 ± .14	0.65 ± .10	0.67 ± .11	0.67 ± .14

Note. LyE = Lyapunov exponent; FM = Floquet multiplier; NSLBP = nonspecific low back pain.

TABLE 2: ANOVA Results: Testing the Within-Subject Effects of Speed, Symmetry, and Load on the Local and Orbital Stability Between Healthy and NSLBP Groups

	ANOVA											
	λ_{max_s}		λ_{max_l}		Max FM							
					25%		50%		75%		100%	
	F Ratio (1, 36)	*p*-Value	*F* Ratio (1, 36)	*p*-Value	*F* Ratio (1, 36)	*p*-Value	*F* Ratio (1, 36)	*p*-Value	*F* Ratio (1, 36)	*p*-Value	*F* Ratio (1, 36)	*p*-Value
Main effects												
Symmetry	21.50	**<.001***	<.001	.99	1.23	.28	3.09	.09	0.75	.39	1.19	.28
Speed	1,304.05	**<.001***	5.65	**.02***	0.54	.47	0.78	.38	0.05	.83	0.09	.76
Load	2.53	.12	0.55	.46	0.13	.73	1.37	.25	0.43	.52	0.01	.93
Group	1.15	.29	0.65	.42	0.07	.80	0.16	.90	0.06	.81	0.25	.62
Interactions												
Symmetry × Speed	9.97	**<.001***	0.97	.33	0.14	.71	1.03	.32	0.78	.38	0.03	.87
Symmetry × Load	0.17	.68	<.001	.99	0.59	.45	1.04	.31	0.74	.40	0.14	.71
Symmetry × Group	0.07	.70	0.43	.51	0.04	.84	1.37	.25	1.73	.12	3.77	.06
Speed × Load	2.41	.13	1.61	.21	1.80	.12	1.98	.17	0.46	.50	0.76	.39
Speed × Group	1.46	.24	2.51	.12	0.94	.34	0.81	.37	0.01	.90	0.08	.77
Load × Group	6.12	**.02***	0.12	.73	<.001	.99	0.02	.90	0.30	.59	0.81	.37

Note. *Indicates *p*-Values <.05. NSLBP = nonspecific low back pain; FM = Floquet multiplier.

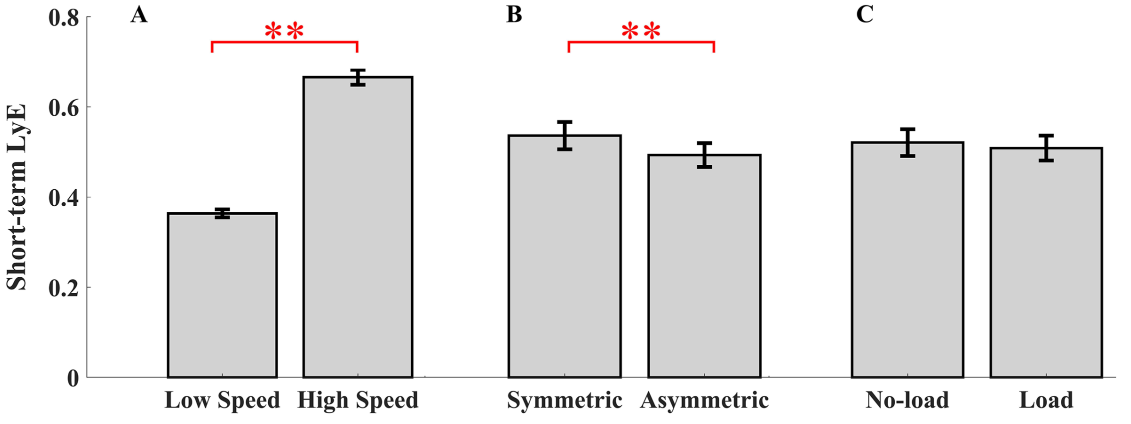

Figure 3. Effects of speed, symmetry, and load on short-term LyE: short-term LyE versus (A) Speed, (B) Symmetry, and (C) Load, for both healthy and NSLBP groups combined. Error bars represent 95% confidence intervals (** indicates $p < .001$). LyE = Lyapunov exponent; NSLBP = nonspecific low back pain.

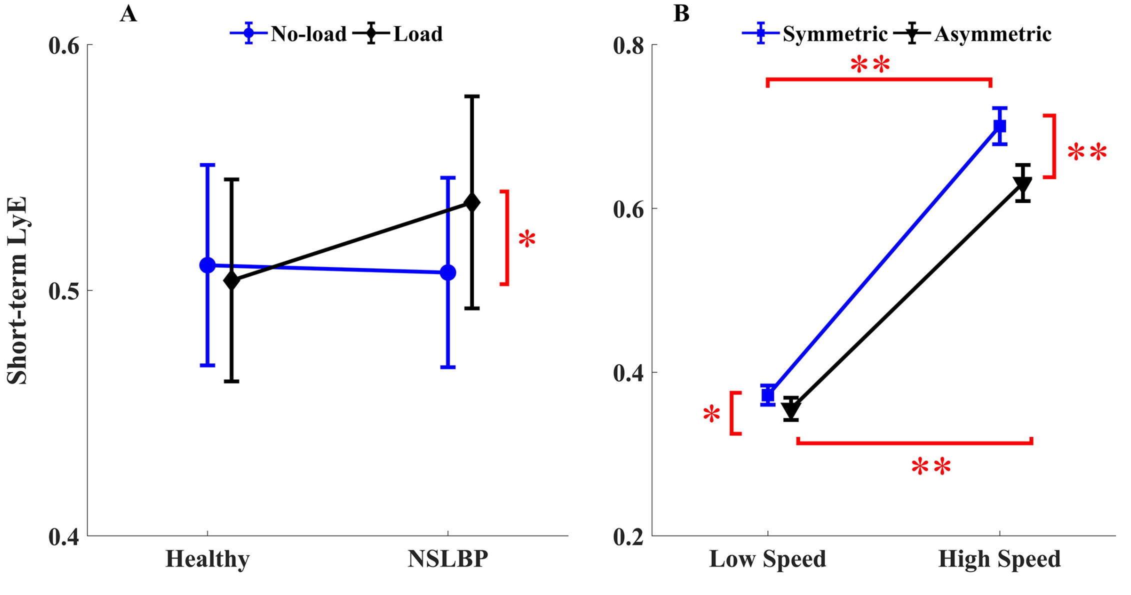

Figure 4. Speed × Symmetry and Load × Group interaction effects on short-term LyE: short-term LyE versus (A) Group, (B) Speed for combined healthy and NSLBP groups. Error bars represent 95% confidence intervals (* and ** indicate $p < .05$ and $p < .001$, respectively). LyE = Lyapunov exponent; NSLBP = nonspecific low back pain.

that speed can undermine the local stability of trunk movements, regardless of the participants' health or LBP status. A positive LyE can be considered as the inability of the trunk control system to sustain trunk dynamic stability in a *particular direction*, when exposed to perturbations. Therefore, rapid repetitive movements can reduce the reaction time required for the neuromuscular control system to attain the desired response time objectives for that particular direction. The angular momentum of the trunk also increases with the movement speed, which can increase the burden on the trunk's system stability control (Granata & England, 2006). It is important to note, however, that local instability in one direction cannot be expanded to global instability for the entire trunk system. Global stability depends solely on the sum of LyEs in all directions/dimensions.

Our findings also confirmed that the trunk FE movements are more locally stable during asymmetrical trials, when compared to the symmetrical trials (Granata & England, 2006). This can be explained by increased trunk muscle co-contraction and activation during asymmetrical movements, which involve the internal and external oblique muscle groups (Cholewicki & McGill, 1996; Granata & Marras, 1993). Higher levels of muscle recruitment most likely increase the neuromuscular system's ability to reproduce trunk FF movements by limiting the kinematic degrees of freedom of the spinal column. Another possible explanation may be the generation of asymmetrical torques and correspondingly larger muscle forces and stiffness, which enhance the dynamic stability of the trunk (Shin et al., 2006). So far, our findings suggest that high-speed symmetric FE movements are more dynamically unstable, while low-speed asymmetric FF movements are more locally stable, hence presenting a lower risk of injury. It should be emphasized, however, that there is no guarantee that more dynamically stable trunk movements are also associated with improved strength and structural stability.

We found that local trunk dynamic stability was similar for the "load" and "no-load" conditions. This finding is in contrast to earlier research, in which the free-load lifting tasks were more unstable in the healthy individuals (Graham et al., 2012). This inconsistency may be due to the differences in the experimental protocol, which included the type of task and the load carrying condition. Previous work, in contrast to this current study, used an experimental protocol where the participants performed a free style lifting task that involved repositioning of a target box from the floor to a table.

An important finding of our study was that NSLBP and healthy individuals applied different trunk control strategies during the load and no-load trials. Wearing a loaded vest contributed to more locally stable trunk movements for the NSLBP patients, while healthy individuals exhibited similar levels of trunk dynamic stability for trials with and without the vest. For trials with the loaded vest, the moment arm and mass of the upper body increase, which leads to a larger postural moment at the trunk level. We suspect these changes most likely have increased the trunk muscle co-activation and stiffness in the participants with NSLBP, more so than in the healthy controls (Larivière et al., 2000; Marras et al., 2001). It should be stated, however, although wearing the loaded vest enhanced the local stability of trunk FE movements, it also increased the spinal muscular demand and stiffness (Marras et al., 2001). Future research should focus on the control parameter of load and its influence on spinal neuromuscular control, especially in LBP populations, to understand the alterations in muscle recruitment and muscular strategies.

Contrary to our hypothesis, no significant difference was seen for the between-subject effect of group, and λ_{max_s}, λ_{max_l}, and FM were similar for both healthy and NSLBP groups. This suggests the neuromotor system of the NSLBP patients provided trunk dynamic stability with sufficient competency, such that its functional performance could not be differentiated from that found in healthy individuals. A potential reason for the nonsignificant group effect may be due to the low level of pain cutoff in the inclusion criteria for the NSLBP participants (VAS pain <3), where the injury based on this pain level was most likely adequately compensated for by the neuromuscular functional adaptability strategies, that is, the NSLBP group functionally approached the control group (Price et al., 1983). Further potential explanations include the constrained movement speed versus self-selected speed (Asgari et al., 2015), as well as the spatial and temporal constraints during trunk FE movements for both groups. Additional studies are warranted to incorporate participants with higher levels of LBP, as measured on either a

VAS or a numerical rating scale (NRS), and/or potentially differentiating between participants using a regional patient-reported outcome measure (PROM) functional score, rather than pain only. It is well recognized that pain and function are *not* directly associated, especially for low pain levels during preferred parameterization of movement patterns (Mokhtarinia et al., 2018; Weiner et al., 2003). LBP individuals with high VAS or NRS pain scores may still attain high functional scores, and conversely individuals with low VAS pain levels may yield low levels of function, as measured with PROMs (Cuesta-Vargas & Gabel, 2014; Mokhtarinia et al., 2018).

The long-term LyE, a measure of the prediction of dynamic stability over long periods, varied significantly with the speed of the FE movements. Higher speed FE movements had greater $\lambda_{\max\_l}$, which confirmed the increased challenge for the trunk neuro-control system in maintaining trunk stability over long-term periods (Rosenstein et al., 1993). Furthermore, for most participants a negative long-term LyE was obtained, which can be considered as a prediction of dynamic stability in the global sense. Although no statistically significant effect was seen between the groups, the long-term stability intended to be higher for the NSLBP individuals, supporting the theory of trunk stability enhancement due to adopted control strategies (Asgari et al., 2015; Hodges et al., 2009; Zeinali-Davarani et al., 2011). Maximum FM, which is known as a predictive measure over long-term behavior, did not vary significantly by control parameters across all Poincare sections. However, in line with recent studies (Asgari et al., 2015; Dingwell & Kang, 2007), we found all maximum FMs to be less than one unit across the Poincare sections. This suggests that the trunk trajectories exhibited orbital stability in the state-space, regardless of the testing condition or group. It can, therefore, be inferred that all participants in this study had globally stable trunk movements, although they showed locally unstable movements in some directions.

From the dynamic system point of view, the FM determines the extent to which neighboring trajectories move toward a limit cycle in the presence of disturbances (Argyris et al., 1994). Existing biomechanical studies tend to consider an average of all repetitive trajectories as a limit cycle. This, however, may be controversial because motor coordination studies have revealed that the motor control system steers the movement trajectories toward an attractor rather than a limit cycle trajectory (Todorov & Jordan, 2002). It also can be argued that when the reference limit cycle is averaged across all trajectories within a trial, the maximum FM usually tends to be less than unity. Thus, evaluation of the orbital stability using kinematics data by means of FM *may not* always uncover relevant novel information.

Several studies have used the Euclidean norm of Euler angles to reconstruct the state-space and have argued that expansion in one direction compensates contraction in another (Beaudette et al., 2016; Granata & England, 2006). Here, we have used the equivalent angle of rotation instead, because it contains spatiotemporal information based on all three Euler angles (Asgari et al., 2015). Contrary to the Euclidean norm, which is only a mathematical value for the trunk angles in different planes, the equivalent angle is a defined concept in classical physics. However, using the equivalent angle rotation alone can introduce the limitation of ignoring spatiotemporal information about the floating axis. Future studies would benefit from comparing the current representation methods for angular time series in order to establish a standardized method.

One limitation for our study was that the participants were free to use their own lumbopelvic movement patterns without constraining their lower limb movements. There is evidence that constraining the pelvis/lower limbs can influence movement coordination and trunk stability (Larson et al., 2019). We have, therefore, allowed the participants to freely move their pelvis. The movements of the lower joints (i.e., knee and ankle), however, were monitored to ensure that they followed consistent FE patterns, mostly dominated by trunk movements. The study population is also limited to male participants, and hence gender effects on trunk stability could not be elucidated.

CONCLUSION

Our findings revealed that the maximum finite-time LyE was more successful in differentiating control stability strategies associated with different task conditions, as compared to the maximum FM. The Lyapunov stability measure suggested that high-speed and mid-sagittal symmetrical trunk FE movements increase the susceptibility to low back injury. It also indicated that the NSLBP group had greater local stability when wearing the loaded vest. In general, the NSLBP participants demonstrated sufficient competency in terms of trunk dynamic stability, as associated with functional performance, which suggests that more complex functional adaptation strategies were engaged. Future research should enhance the current experimental protocol by including NSLBP participants of both genders with higher pain levels established using PROMs to indicate functional status and not pain alone. Such validated protocols, in combination with nonlinear stability approaches, can be invaluable in addressing ongoing research challenges in a wide range of industrial and clinical applications. The ultimate goal remains to develop effective quantitative tools for the spinal evaluation of NSLBP, toward enhanced personalized diagnosis, rehabilitation, and treatment strategies.

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KEY POINTS

- Trunk dynamic stability was investigated in healthy and NSLBP groups for different levels of speed, symmetry, and load.
- High-speed symmetric FE movements were found to be more dynamically unstable.
- Wearing a loaded vest contributed to more locally stable trunk movements for the NSLBP patients.
- The NSLBP group demonstrated sufficient competency in terms of trunk dynamic stability and control.

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