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LOCAL DYNAMIC STABILITY OF SPINE MOTOR PATTERNS AND STIFFNESS DURING LIFTING TASKS

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INTRODUCTION

There has been a debate in recent years as to how best to define and quantify spine stability [1,2], with the outcome being that different methods are used without a clear understanding of how they relate to one another. To address this issue, we recently directly compared lumbar spine rotational stiffness (a first approximation of stability) calculated with a quasi-static EMG-driven biomechanical model, to local dynamic spine stability calculated using Lyapunov analyses of kinematic data, during repetitive continuous dynamic lifting under three load and three rate conditions [3]. We found stronger relationships between the two models under conditions in which load was manipulated compared to conditions in which rate was manipulated. A question that may help explain these observed differences is: “how does the CNS control spine motor patterns and stiffness in a time-dependent manner during these repetitive dynamic lifting challenges?” The goal of the present study was thus to reanalyze our data from [3] to assess: 1) the local dynamic stability of spine muscle activations (motor patterns), and 2) the local dynamic stability of spine rotational stiffness, during these dynamic lifting challenges.

METHODS

Twelve healthy males (age: 24.3 ± 2.5 yrs; height: 178.1 ± 5.6 cm; weight: 84.1 ±10.7 kg) with no self-reported history of back pain were recruited to participate in the study.

The full procedure can be found in [3]. Briefly, participants performed five trials of 30 continuous freestyle box lifts, synchronous to a metronome, between separate targets positioned at shoulder and knee height (Figure 1). The five trials, which were block-randomized, consisted of: i) lifting three loads (equivalent of 0%, 5%, and 10% of maximum back strength) at 12/min and ii) lifting the 5% maximum back strength load at three rates (6/min, 12/min, and 18/min). The average 10% load lifted was 8.5 ± 0.71kg.

Trunk muscle activity was monitored using bipolar Ag/AgCl EMG electrodes, affixed unilaterally over seven muscles [4]. Raw EMG signals were bandpass filtered and amplified (AMT-8, Bortec, Calgary, AB, CA) and captured digitally at 2048Hz. Kinematic data were collected at 32Hz (Liberty™, Polhemus, Colchester, VT, USA), synchronous to the EMG, from four body landmarks [3]. After basic processing, EMG signals were normalized to maximum activation, and down-sampled to 32Hz to match the kinematics. 3-D lumbar spine angles were calculated using Euler rotation matrices [5].

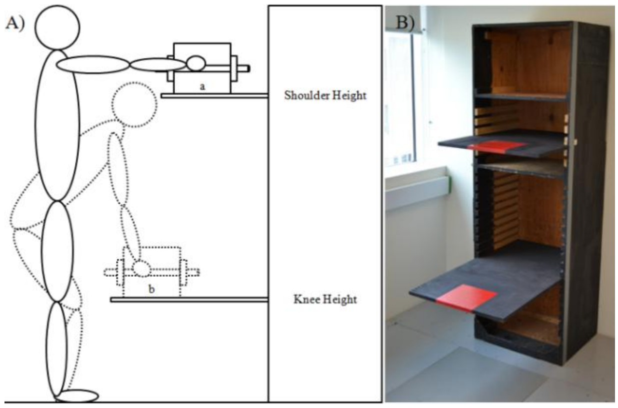

Figure 1: A) Experimental setup used for repetitive lifting between shoulder (a) and knee height (b). B) Each of the 30 lifts consisted of moving from a target at position (a) to a target at position (b) and back, to the beat of a metronome.

Normalized EMG signals as well as the 3-D lumbar spine angles were entered into an anatomically-detailed EMG-driven biomechanical model representing 58 muscle lines of action crossing the L_4/L_5 spinal joint, in order to calculate rotational stiffness about the flexion/extension, lateral bend, and axial twist axes [3,6]. Then, in order to get an estimate of overall spine rotational stiffness, the Euclidean norm of the stiffness about all three axes was calculated.

The local dynamic stability of: 1) spine muscle activations and 2) spine rotational stiffness were assessed using the maximum finite-time Lyapunov exponent, λ_{max}. Because estimates of λ_{max} may be biased by time series length [7], the data from each of the five lifting trials sampled at 32Hz were normalized to 4000 samples prior to further analyses. For the local dynamic stability of spine rotational stiffness, an *n*-dimensional state-space was created using the method of delays [8]. A delay of 16 samples (10% average lift) and an embedding dimension of six were used [3]. For the EMG data, a 6-D state space was created using the combined spine muscle EMG signals and the method of delays, as per above. λ_{max} values were then calculated by analyzing the exponential rate of divergence of initially neighbouring trajectories in each reconstructed state space [9]. The slope was calculated from 0 to 80 samples (0-0.5 lifts), which controls for lifting rate differences across conditions [10].

Separate repeated-measures ANOVAs were used to assess the effect of load and lifting rate on each dependent variable (SPSS 20, IBM Corporation, Armonk, NY, USA).

RESULTS AND DISCUSSION

With an increase in the load lifted at a constant rate there was a non-significant trend for decreased local dynamic stability of muscle activations and spine rotational stiffness (increased maximum Lyapunov exponents) (Table 1). This finding indicates that with an increase in load, even though muscular activity and spine rotational stiffness are increased due to augmented muscular and moment demands [11], it is slightly more difficult to continuously match task demands and maintain stable and consistent stiffness and EMG profiles. However, since the differences in dynamic stability of spine rotational stiffness were not statistically significant, this may explain why moderate to strong correlations between the spine rotational stiffness and dynamic kinematic stability estimates were observed in [3]. Stiffness was higher, but the local dynamic stability of spine muscle EMG and stiffness was not significantly altered; resulting in similar kinematic dynamic spine stability values.

With an increase in lifting rate with a constant load there was a large significant decrease in the local dynamic stability of muscle activations and spine rotational stiffness (significant increase in maximum Lyapunov exponents; $p \leq 0.001$ for all measures) (Table 2). Therefore, under the changing rate condition, even though rotational stiffness was higher due to increased muscle activity [3], it was much harder to maintain stable muscular activity and stiffness trajectories and profiles. Thus, it appears that under this condition, even though overall stiffness is higher, there may be a greater chance of having an instantaneous event where stiffness requirements do not match external demands. This might also explain why weak linear relationships between the rotational stiffness and local dynamic kinematic stability measures were observed in our previous work [3]. Although stiffness was higher (more stable), it is likely that there were time-dependent difficulties in modulating muscle activity and forces with increased speed [1], which reduced the dynamic stability of stiffness and resulted in similar local dynamic kinematic stability responses across rates [3].

CONCLUSIONS

In conclusion, we found that the local dynamic stability of muscle activations and spine rotational stiffness non-significantly decreased with an increase in load, but significantly decreased with an increase in lifting rate. Thus, as demand increased, control of spine muscle activation and spine stiffness was reduced. These findings suggest that in addition to the total amount of rotational stiffness (mechanical stability), it is also important to consider how the CNS controls stiffness in a time-dependent manner to continuously meet task demands when assessing injury risk. The findings from this study also help explain our earlier findings [3], and show that Lyapunov analyses of kinematic data do capture information regarding the mechanical effect of spine stiffness (i.e. the amount of stiffness) as well as the time-dependent (local dynamic) stability of these stiffness profiles. Furthermore, running these Lyapunov analyses on the stiffness and muscular activity data provides important information into how the CNS controls motor patterns and subsequently spine rotational stiffness over time, and provides an effective way of addressing some of the limitations associated with different approaches to modeling spine stability; thus moving us closer towards a multi-factorial description of spine stability and control.

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Table 1: Maximum finite-time Lyapunov exponent differences between the three load conditions (0%, 5%, and 10% maximum back strength at 12 lifts per minute) and the results from the repeated-measures ANOVAs. *Note: higher Lyapunov exponent values indicate decreased local dynamic stability.*

	Mean (Standard Deviation) Results						**ANOVA Results**		
	0%		**5%**		**10%**		***F*-ratio**	***p*-value**	**$\eta 2$**
Euclidean Norm Stiffness Stability	0.748	(0.13)	0.778	(0.10)	0.838	(0.10)	2.076	0.176	0.293
Spine EMG Stability	0.777	(0.14)	0.815	(0.08)	0.847	(0.08)	2.261	0.155	0.311

Table 2: Maximum finite-time Lyapunov exponent differences between the three rate conditions (6/min, 12/min, and 18/min at 5% maximum back strength load) and the results from the repeated-measures ANOVAs. *Note: higher Lyapunov exponent values indicate decreased local dynamic stability.*

	Mean (Standard Deviation) Results						**ANOVA Results**		
	6/min		**12/min**		**18/min**		***F*-ratio**	***p*-value**	**$\eta 2$**
Euclidean Norm Stiffness Stability	0.705	(0.07)	0.778	(0.10)	0.851	(0.11)	15.733	***0.001***	0.759
Spine EMG Stability	0.696	(0.09)	0.815	(0.08)	0.891	(0.05)	38.429	***<0.001***	0.885

Bolded values indicate a significant difference at $p<0.05$.