INTRODUCTION

Low-Back Disorders (LBDs) are the most prevalent source of musculoskeletal disability and the most common musculoskeletal problem in the United States. LBDs are often attributed to tissue strain from spinal instability. Stability is defined as the ability to maintain intervertebral and global torso equilibrium despite the presence of small mechanical disturbances and/or small neuromuscular control errors. Stability of the spine may be impaired by fatigue of the paraspinal muscles (Granata et al., 2001). This may contribute to the risk of LBDs in industrial manual materials handling tasks. Therefore, the goal of this ongoing study was to assess the change in stability of the torso associated fatiguing trunk extension exertions.

Biomechanical models describe how factors including steady-state muscle recruitment, static spinal posture, and external load contribute to stability of the spine. However, they ignore the role of movement dynamics and neuromuscular response. Empirical estimates of stability are an alternative to biomechanical modeling wherein nonlinear analyses quantify the local stability of repetitive dynamic torso flexion movements (Granata et al., in press). During repetitive dynamic trunk flexion-extension movements it is reasonable to assume that the kinematics of each cycle could be similar to every other cycle, i.e. the target trajectory. Kinematic variance about this target trajectory is the manifestation of stochastic disturbances and control errors. At any given time the kinematic variance can be represented as an \( n \)-dimensional sphere where the volume of the sphere describes the magnitude of the kinematic variance and \( n \) is the number of state variables. Neuromuscular response to the kinematic perturbations will cause the movement dynamics to be attracted toward the target trajectory. Thus, as time progresses the \( n \)-dimensional sphere of kinematic variance evolves into an ellipsoid whose principle axes contract (or expand) at rates described by Lyapunov exponents. The largest Lyapunov exponent, \( \lambda_{\text{Max}} \) quantifies the stability of a dynamic movement task and can be used to assess the effects of fatigue.

METHODS

Five males and five females with no self-reported history of low back pain performed dynamic trunk flexion and extension movements. The task was to touch a target placed near knee level (Thomas et al., 2003) with their hands then return to the upright posture in time with a metronome tone (30 cycles per minute) in a continuously repetitive movement pattern (60 second data trial). 3-D upper-body kinematic data were recorded from electromagnetic motion sensors that were secured with double-sided tape over the vertebral processes of the T10 and S1 (Ascension, Burlington, VT).

Experimental conditions included task asymmetry and fatigue. During the symmetric conditions the subjects touched the target with both hands. During the asymmetric conditions the subjects touched the target with both hands. During the asymmetric trials they were instructed to touch the target with their dominant hand only. After completing the stability assessment the subjects participated in a low-
back fatigue protocol (Davidson et al., *in press*). They performed repeated dynamic trunk extension exertions on a Roman chair. Trunk extension force was recorded from a load cell during maximum voluntary isometric exertion (MVE) each minute during the fatigue protocol. The exercises continued until the MVE force was 60% of the unfatigued value. Immediately following the fatigue protocol, the subjects repeated the stability assessment. All the subjects provided informed consent approved by the Virginia Tech institutional review.

Stability was determined from the measured kinematic data. Maximum finite-time Lyapunov exponents $\lambda_{\text{Max}}$ were calculated from the distance, $d_i(t)$, between kinematic nearest neighbors. Nearest neighbors were found by selecting data points from separate cycles that are closest to each other in the state-space. The maximum Lyapunov exponent, $\lambda_{\text{Max}}$ was approximated as the slope of the linear best-fit line created by the equation,

$$y(t) = \frac{1}{\Delta t} (\ln d_i(t))$$

The time delay for the reconstructed state space was found to be 30 (0.3 sec).

**RESULTS AND DISCUSSION**

To date, preliminary data from 5 of the ten subjects has been completed. No significant gender difference was observed for the number of subjects studied. Embedding dimension represents the number of state-space dimensions necessary to represent the dynamics of the measured system. Movements after fatigue were confined to lower dimensional state space; embedding dimension was 6 after fatigue whereas it was 7 before fatigue, indicating less dynamic complexity. Neuromuscular control of the movement tasks is considered less stable with increased $\lambda_{\text{Max}}$. $\lambda_{\text{Max}}$ of the asymmetric movements were significantly ($p<0.01$) less than those of the symmetric movements, which is consistent with previous studies (Granata et al., *in press*). $\lambda_{\text{Max}}$ of the unfatigued movements were significantly ($p<0.01$) less than those of the fatigued movements, indicating that the system was dynamically less stable when the muscles were fatigued.

**SUMMARY AND CONCLUSIONS**

The maximum Lyapunov exponent $\lambda_{\text{Max}}$ for the trunk movements before the fatigue was found to be less than the $\lambda_{\text{Max}}$ of the fatigued movements. This shows that the local dynamic stability of the torso is impaired by fatigue of the trunk extensor musculature. Further research is warranted to understand the role of this impaired stability behavior in the risk of LBDs associated with fatiguing occupational lifting tasks.

**REFERENCES**

Granata KP. and Wilson SE. (2001). *J.Biomechanics* 16, 650-659

<table>
<thead>
<tr>
<th>Trial type</th>
<th>Before fatigue $\lambda_{\text{Max}}$</th>
<th>After fatigue $\lambda_{\text{Max}}$</th>
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<tr>
<td>Asymmetric</td>
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<td>Symmetric</td>
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<td>1.31 (0.09)</td>
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