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Nonlinear Analysis of Low Back Stability

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INTRODUCTION

Most people (80%) will experience low back pain some time during their lifetime (Kelsey and White 1980; Reeves et al. 2005). The human spine consists of a column of vertebrae separated by discs and surrounded by ligamentous and muscular tissue. Damage can occur when the tissues of the spine are exposed to excessive strain that may result from unstable buckling of the vertebral column (Preuss and Fung 2005). Since direct spinal buckling tests cannot be performed on human subjects without inducing injury, a method to non-destructively evaluate spinal column buckling was sought. When the spinal column is able to maintain a stable upright configuration buckling is unlikely. Thus, torso stability may be used as an indicator of risk. Previous research has shown that stability of the torso is a valuable tool for identifying individuals at risk of low-back pain. Cholewicki (2000) directed subjects to sit on a wobbly seat with a hemisphere attached to bottom.

The experimental design in the current study modified the earlier methods to modulate the mechanical static stability of the wobbly seat then observe the time-domain stabilizing performance of a human subject while sitting on this device. In addition, the analysis method was expanded to compute stability through Lyapunov analyses of the measured data.

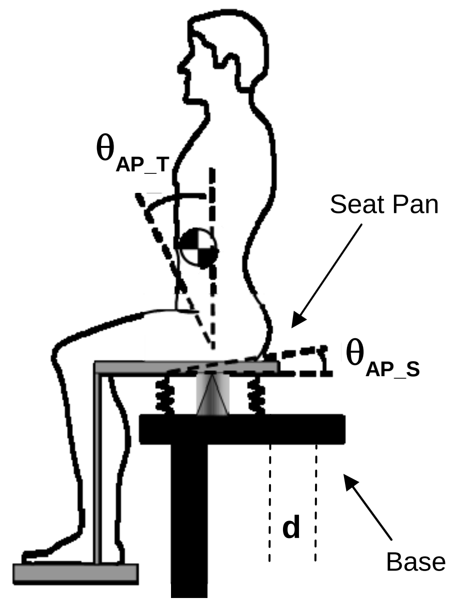

Figure 1: The wobble chair is a new seated stability test apparatus where movement of the lumbar spine is used to maintain balance.

Experimental Protocol

Twelve human subjects with no history of low back pain participated in the study. During experimental stability measurement the subjects were instructed to sit on the wobble chair and with his/her arms crossed over the chest and attempt to maintain an upright posture for 60 seconds. Seat angles and torso angles were recorded at 100 Hz in two dimensions with 6 degree of freedom electromagnetic sensors. The subject was able to use small dynamic movements of the torso to keep the seat at a level position. Each subject was tested at all three spring settings. The order of the spring setting was randomized to avoid confounding between difficulty and trial order. Subjects performed five practice trials prior to executing five duplicate trials at each setting.

Lyapunov Stability Analyses

The maximum Lyapunov exponent is a measure of local stability. Large exponents indicate rapid divergence of two points that are initially close in state space (Figure 2). The maximum Lyapunov exponent, λ_{max}, quantifies the exponential rate that two points diverge in state space.

$$d(\Delta t) = d(0)e^{\lambda_{max}\Delta t}$$

Where d(0) is the initial Euclidian distance in state space between two points in the time series. The evolution time, Δt, is the amount of time that has elapsed as the trajectories of the two points are tracked forward in time. The Euclidian distance between the two points at an evolution time, Δt, is given by $d(\Delta t)$.

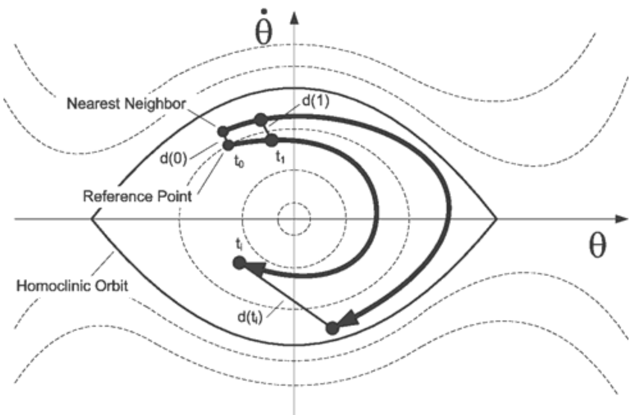

Figure 2: Phase plot demonstrates divergence of two points. The distance between the two points is tracked over time to obtain the maximum Lyapunov exponent.

Results

The resulting values for the maximum Lyapunov exponent were found to be negatively correlated with chair stability, i.e. spring setting (Figure 4). The results fit well to the linear regression model accounting for more than 95% of the variability over the range evaluated. The values for λ_{max} are shown for the initial test and the follow-up test conducted one week later. On average, week to week results differed by less than 10%.

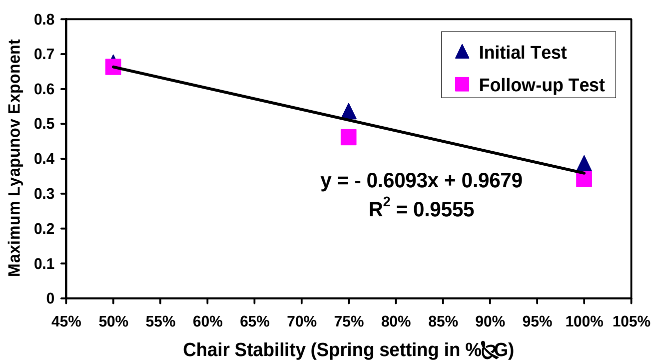

Figure 4: Maximum Lyapunov exponent significantly decreased with increasing chair stability. Results from the initial test and follow-up test one week later differed by less than 10%.

Discussion

The negative correlation between the maximum Lyapunov exponent and chair stability was expected. Higher mean divergence rates associated with large values of λ_{max} should occur at the more difficult spring settings. This is because the potential function is shallower with smaller gradients. Thus, random perturbations inherent in the system lead to larger motions and higher divergence rates.

Summary and Conclusions

The apparatus allows for empirical measurement of torso dynamic stability over a continuously adjustable range of static stability and instability. Adjustments can be made to compensate for anatomical differences in subjects allowing tests to be conducted at a specified static stability level. A method for conducting Lyapunov stability analysis on the experimental data was developed that tracked the divergence of nearest neighbors for all points in the time series. The results showed a significant negative correlation between chair stability and the maximum Lyapunov exponent with good repeatability. This method was found to be sensitive to changes in stability and indicates that it may be a useful method to analyze the differences in stability resulting from an intervention.

Acknowledgements

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