METHODS & NONLINEAR ANALYSES FOR MEASURING TORSO STABILITY

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Abstract

Mechanical assessment of torso stability is a valuable tool for identifying individuals at risk for low-back pain. The apparatus challenges stabilizing control of subjects to quantify torso stability. In addition, a method is outlined for calculating the maximum Lyapunov exponent from the measured data. The results showed a significant negative correlation between chair stability and the maximum Lyapunov exponent with good trial repeatability. The method was found to be sensitive to changes in stability and indicates that it may be a useful method to analyze the effect of an intervention such as fatigue, static flexion, or physical therapy, on torso stability.

Introduction

Low back pain is a common condition afflicting more than 80% of the population 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 (Adams and Dolan 1995) that may result from unstable buckling of the vertebral column (Preuss and Fung 2005). Direct measurements of buckling loads often results in destruction of the test specimen. Since direct spinal buckling tests cannot be performed on human subjects, 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 (Radebold et al. 2001). Cholewicki (2000) directed subjects to sit on a wobbly seat with a hemisphere attached to bottom. Task difficulty was modulated by adjusting the radius of curvature upon which the seat pan balanced, effectively altering the restorative moment. Nonlinear time-series analyses of the seat movements were used to estimate stability.

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.

Methods

Experimental Apparatus

The wobble chair is a new seated stability testing apparatus consisting of a seat mounted on a thin, flat seat pan supported by a ball joint (Figure 1a). This allows the seat pan to pivot freely in 2-dimensions about its geometric center. The seat can be adjusted forward and back on the seat pan to assure the subject's center of mass is directly over the pivot point. Steel springs are located to the front, rear, left, and right of the center. The springs were selected such that the free length is equal to the distance from the base to the seat

pan of the wobble chair at the neutral position (Figure 1a). The rotational stiffness can by adjusted by changing the distance from the springs to the central ball joint.
Restorative 2-D moment $\vec{M}$ is,

$$\vec{M} = \vec{\vec{P}}\vec{\theta}_S, \; p = k \cdot d^2$$
$$\begin{Bmatrix} M_{AP} \\ M_{ML} \end{Bmatrix} = \begin{bmatrix} p & 0 \\ 0 & p \end{bmatrix} \begin{Bmatrix} \theta_{AP\_S} \\ \theta_{ML\_S} \end{Bmatrix} \quad (1)$$

where $\vec{\theta}_S$ is the 2-D angle vector of the seat, composed of the anterior-posterior angle θ_{AP_S} and the medial-lateral angle θ_{ML_S}. The proportional gain constant, *p*, is a function of the spring stiffness, *k*, and the distance, *d*. The proportional gain matrix, $\overline{\overline{P}}$, has diagonal elements equal to p. Since the moment is proportional to the square of the spring distance, a larger range of proportional gain can be achieved. Static stability is decreased by reducing the stabilizing restorative moment, i.e. proportional gain provided by the springs. This is achieved by moving the springs closer to the center. The wobble chair's continuous range of gain, $\overline{\overline{P}}$, allows the level of static stability to be normalized to body mass and weight distribution. The gravitational moment, $\vec{M}_g$, about the ball joint can be measured for an individual subject. The gravitational gradient, ∇G, is a measure of the mass and weight distribution of an individual given by,

$$\nabla G = \frac{\partial}{\partial \vec{\theta}_S} \vec{M}_g(\vec{\theta}_S, \vec{\theta}_T) \quad (2)$$

where, $\vec{\theta}_T$ is the 2-D angle to the torso. Neutral stability is achieved when the proportional gain produced by the spring's restorative force is equal to and offsets the gravitational gradient. This condition is defined as a spring setting of 100%. At spring settings greater than 100%, the stabilizing moment generated by the springs is greater than the destabilizing gravitational moment. The system is attracted toward the neutral position and is statically stable. For spring settings less than 100% the destabilizing gravitational moment is greater than the stabilizing spring moment. Upon small perturbations from the neutral position the system is repelled from the neutral position and is unstable. However, it can be demonstrated that a 2 segment under-actuated inverted pendulum is controllable and can be stabilized (Figure 1b). Humans achieve this through voluntary and reflexive neuromuscular control. Stability tests are typically conducted at or below the 100% level, thus requiring neuromuscular control to maintain stability. Testing at prescribed levels of instability (e.g. 100%∇G, 75%∇G, 50%∇G) can be achieved by adjusting the spring location to compensating for anatomical differences in test subjects.

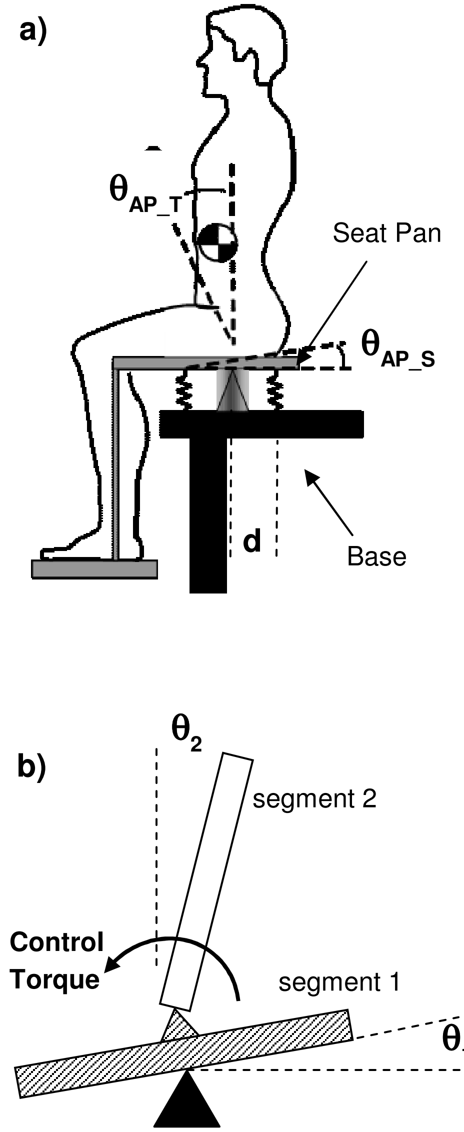

Figure 1: (a) The wobble chair is a new seated stability test apparatus where movement of the lumbar spine is used to maintain balance. (b) Two segment inverted pendulum model.

Experimental Protocol

Twelve human subjects with no history of low back pain participated in the study. Prior to participation all subject were informed of the nature of the study and signed an informed consent form approved by the institutional review board at Virginia Tech. Before stability testing was performed the gravitational gradient for each subject was obtained. The spring distances needed to achieve 100%, 75%, and 50% of the subject's gravitational gradient was calculated. 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 (Motion Star Systems, Ascension Technology Corp, Burlington, VT). 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). By calculating the maximum Lyapunov exponent from data that is averaged over the entire time series the global stability of the system is estimated. The maximum Lyapunov exponent, λ_{max}, quantifies the exponential rate that two points diverge in state space.

$$d(\Delta t) = d(0)e^{\lambda_{\max}\Delta t} \tag{3}$$

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 $d(\Delta t)$. This analysis method is outlined below.

Measured data consisted of a continuous series of data points representing the trajectory over the 60 second trial. From the measured data a time dependent state vector was generated using post-processing software (Matlab, Natick, MA).

$$q(t) = \left[\theta_{AP\_S}(t) \quad \theta_{ML\_S}(t) \quad \dot{\theta}_{AP\_S}(t) \quad \dot{\theta}_{ML\_S}(t)\right] \tag{4}$$

The state vector was filtered at 8 Hz with a seventh order low pass Butterworth filter and down-sampled to 25 Hz prior to analysis. Initially, the first data point in the time series, q(0), was identified as the reference point. A data point was identified that was close to the reference point in state space, but not in time. The nearest neighbor was identified as the point with the smallest Euclidian distance from the reference point in state space. Measures were taken to ensure that each nearest neighbor was not highly correlated with the reference point or with any previously found nearest neighbors. Several investigators have tracked the divergence of a nearest neighbor to find the maximum Lyapunov exponent (England and Granata 2006; Granata and England 2006; Rosenstein et al. 1993; Wolf et al. 1985). In this study the three nearest neighbors were analyzed in order to reduce variability of the results. The above process was repeated with each point in the time series being considered the reference point. The distance between the reference point and each nearest neighbor was calculated as both points evolved over time (Figure 2). The expansion was defined as the relative increase in distance between the two points for some Δt. The mean expansion for a given evolution time was determined by averaging the expansion over all reference points and all nearest neighbors.

$$Mean\ Expansion\ (\Delta t) = \frac{1}{3n}\sum_{i}^{n}\sum_{j}^{3}\frac{d(\Delta t)_{ij}}{d(0)_{ij}} \tag{5}$$

Where, n is the number of points in the time series indexed by i, and j is the index of the nearest neighbor.

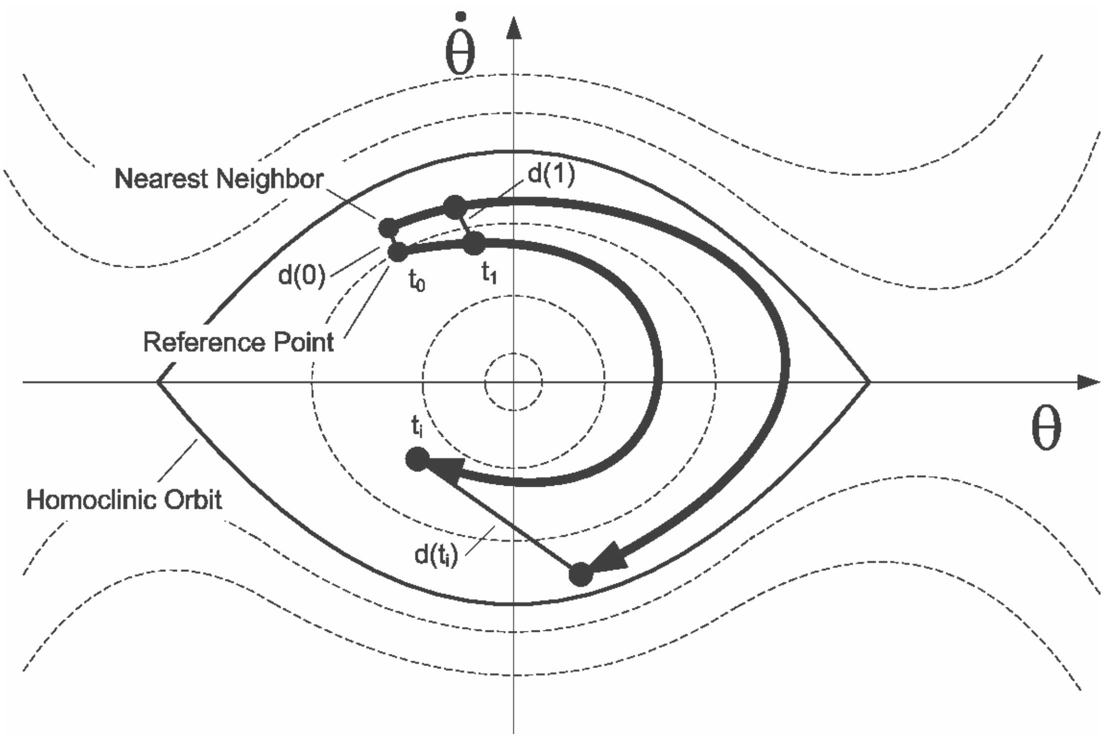

Figure 2: Nearest neighbor to the reference point was found in n-dimensional state space. The distance between these two points is tracked as it evolves over time. The homoclinic orbit indicates the separatrix between stable and unstable regions.

The maximum Lyapunov exponent can be calculated by solving equation 3.

$$\lambda_{\max} = \frac{1}{\Delta t} \ln\left(Mean\ Expansion\ (\Delta t) \right) \tag{6}$$

From the experimental data, the maximum Lyapunov exponent was found by calculating the slope of the natural log of the mean expansion with respect to the evolution time over the range of 0.2 seconds to 0.7 seconds (Figure 3). Evolution times less than 0.2 seconds were excluded from the evaluation because the 8 Hz filter (T =.125 s) removed much of the data in this range. After 0.7 seconds the curve begins to flatten as the points approached full diffusion within state space.

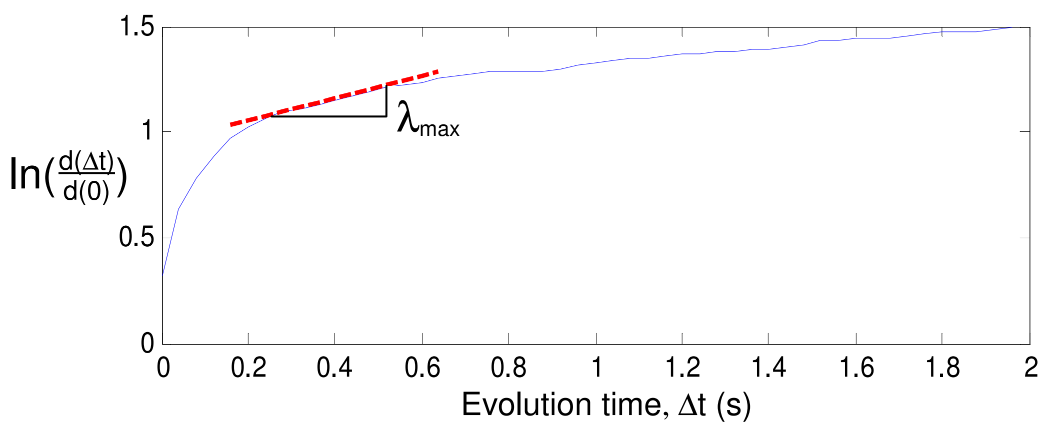

Figure 3: The maximum Lyapunov exponent was determined by calculating the slope of the mean expansion as a function of the evolution time.

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 effect of chair stability on the value of the λ_{max} was found to be significant using a t-test ($t = -9.27$; $p = .0008$). 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%.

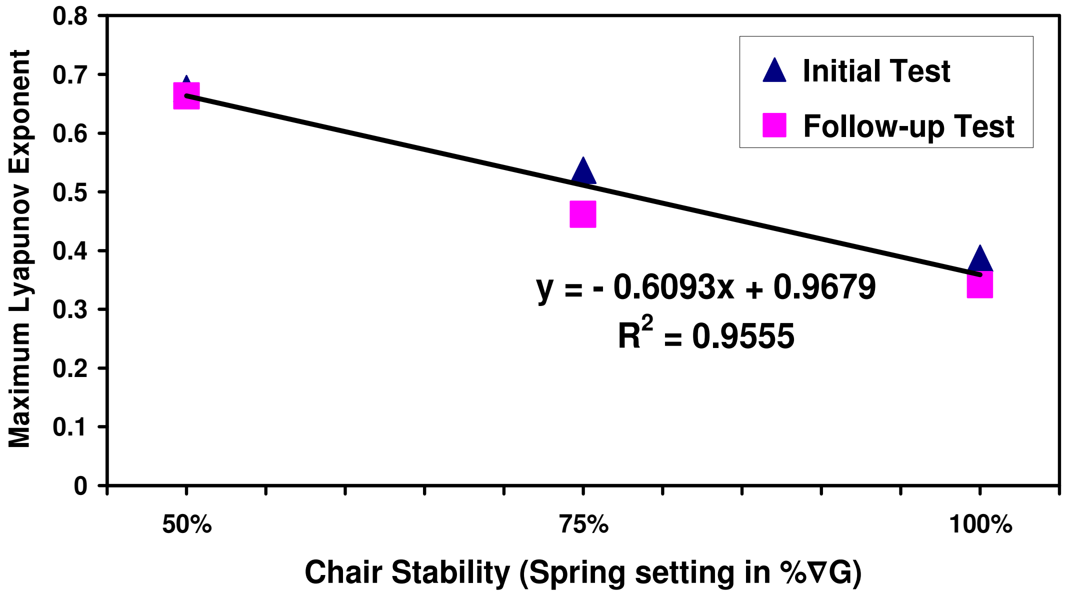

Figure 4: Maximum Lyapunov exponent significantly decreased with increasing chair stability. Results from the initial test and follow-up test one week later differed by less than 10%.

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. The mean value for the maximum Lyapunov exponent was positive which indicates divergent behavior in at least one dimension of state space. However, since stability of the overall system was maintained during the test, the sum of all Lyapunov exponents must be less than or equal to zero.

One limitation of this study was that all stability tests were conducted with fully active neuromuscular control. Since no tests were conducted with disabled or altered control, one cannot separate the contribution of the compensatory neuromuscular control from the uncontrolled dynamics. Thus, it cannot be determined if the compensatory neuromuscular control changes as a function of the task difficulty.

Similar results from the two duplicate test sessions suggest that the method has good repeatability. Test repeatability enables experiments to be conducted that measure changes in stability resulting form an intervention such as fatigue, flexion relaxation, or physical therapy.

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.

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