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DETERMINING THE THRESHOLD OF STABILITY DURING UNSTABLE SITTING

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INTRODUCTION

Diverse parameters have been developed to quantify spinal stability or system robustness. Kinematic variability (KV) has commonly been used based on the assumption that more robust systems will be able to more effectively reduce system variability. Some of these KV parameters include displacement, standard deviation, RMS area and path velocity of the center of mass (COM) or center of pressure (COP). In addition, stability diffusion analysis and Lyapunov exponents have been used to quantify stability, where lower diffusion or divergence rates indicate a more stable system.

All of these existing methods evaluate system performance at a fixed level of task difficulty. Herein, an alternative approach is introduced in which task difficulty is explicitly manipulated. The basic premise is that increasing task difficulty will have two effects. First, KV of the system will increase, indicating that the participant will explore a larger region of state space. Second, the size of the basin of stability (stable region of state space) will decrease, reducing the area of stable system behavior. When KV goes beyond the boundary of the basin of stability, the system will exhibit unstable behavior. Based on this premise, a new metric is introduced, the threshold of stability (ToS). ToS is defined as the maximum task difficulty at which stability can be maintained, and is found by increasing task difficulty until KV lies just within the boundary of the basin of stability.

METHODS

The wobble chair (Figure 1a) is an unstable seat apparatus used to evaluate spinal stability based on the apparatus developed by Cholewicki et al. (2000) and used in several subsequent studies [1-3]. The seat pivots on a central low-friction ball joint, and adjustable springs are positioned at the front, back, left and right of center. Moving these springs closer to the center decreases the restorative moment applied to the seat, thereby increasing task difficulty.

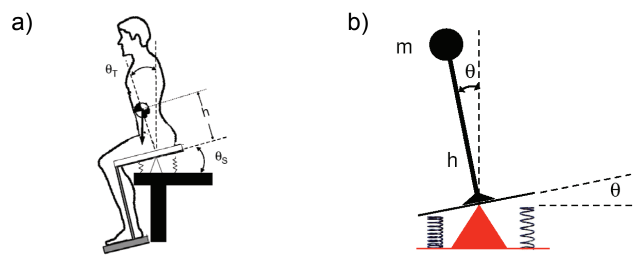

Figure 1: Experimental configuration and simplified model

A simple inverted pendulum model (Figure 1b) was developed in MATLAB® to represent motion of the seated balance test apparatus (Figure 1a) in the sagittal plane. It included a concentrated body mass (*m*) and a massless segment length (*h*). Stabilizing springs with a spring constant *k* are located a distance *d* from the pivot point. Task difficulty is increased by reducing the distance of the springs from the central pivot point. The model also included a limited gain proportional-derivative controller to simulate neuromuscular control. Random disturbances were modeled as perturbation energy, *E (0.1 J)*. Combining these components yields the governing differential equation:

$$\ddot{\theta} = \frac{mgh\sin\theta - kd^2\sin\theta - C(\theta,\dot{\theta}) + E}{mh^2} \quad (1)$$

where, θ, $\dot{\theta}$, $\ddot{\theta}$, and g are the rotation angle, angular velocity, angular acceleration, and acceleration of gravity, respectively. Gravity, springs, and the proportional component of the controller all contribute

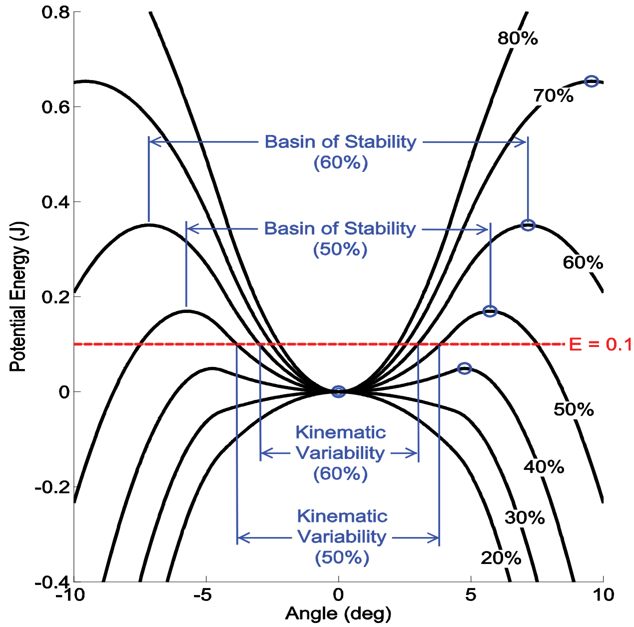

Figure 2: Effective Potential Function (V_{eff})

to the potential energy of the system. These components can be combined to generate an effective potential energy function,

$$V_{eff} = -mgh(\cos\theta - 1) + kd^2(\cos\theta - 1) + \begin{cases} \frac{1}{2} G_p \theta^2 & if \quad |\theta| < \theta_{cr} \\ \frac{1}{2} G_p \theta_{cr}^2 + T_{p\max}(|\theta| - \theta_{cr}) & otherwise \end{cases} \qquad (2)$$

where, G_d is the derivative gain constant, $\theta_{cr} = T_{pmax}/G_p$ is the smallest angle at which the maximum gain is achieved, G_p is the proportional gain constant, and T_{pmax} is the maximum value of proportional torque.

Eight adults from the university and surrounding area participated in the study. The gravitational gradient (∇G), a measure of body mass and distribution, was measured for each subject. Participants were instructed to sit on the wobble chair with arms crossed in front of the body while attempting to maintain an upright balanced posture for 60 seconds. Testing beginning with an initial spring setting of 80% ∇G and was adjusted after each trial using consistent methods. Task difficulty was increased if stability was maintained and decreased if stability was lost. This method was used to determine the maximum task difficulty at which stability could be achieved (i.e. the ToS). Tests were performed with the presence or absence of visual feedback.

Threshold of stability was determined by evaluating the number of passing and failing trials at each spring setting. When both passing and failing trials existed at a given spring setting, the majority result was assigned to that spring setting. If upon completing eight trials a clear separation existed between passing and failing spring settings, testing was concluded. However, if the number of passing and failing trials was equal at a given level, additional trials were performed until a definitive outcome was obtained.

For purposes of comparison with the ToS, the maximum Lyapunov exponent (λ_{max}) was also determined using existing methods [1, 2]. Paired *t*-tests were used to assess the sensitivity of both the ToS and λ_{max} to the manipulation of visual feedback. Since λ_{max} was determined at the ToS, which varied between subjects and visual conditions, an additional analysis of covariance (ANCOVA) was performed (with ToS and visual condition as independent variables). A value of $p< 0.05$ was used as the criterion for significance.

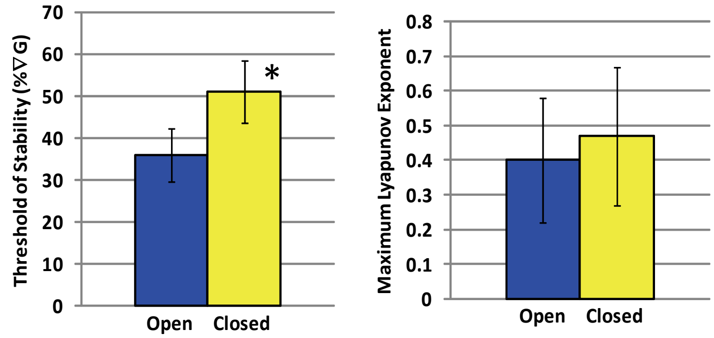

Figure 3: Sensitivity if the ToS and λ_{max} to differences in visual feedback (eyes open vs. closed) during unstable sitting

RESULTS

The effective potential function (V_{eff}) had a basin of stability between ±7.16° and a KV between ±2.99° at a task difficulty of 60%∇G (Figure 2). Increasing task difficulty to 50%∇G increased KV to ±3.84° and decreased the basin of stability to ±5.72°. Increasing perturbation energy, E, increases KV without affecting the basin of stability. If the value of E exceeds the maximum value of V_{eff}, the system is unbounded and may become unstable (eg. 40%∇G).

Removal of visual feedback significantly [3] (t=11.2; p<0.001) increased the ToS by ~15% of ∇G (Figure 3). In contrast, the effect of visual condition on λ_{max} was not significant (t=0.786; p=0.46), with mean (SD) values for eyes open and closed of 0.40 (0.18) and 0.47 (0.20), respectively. The effect of visual feedback condition on λ_{max} was similarly non-significant (p=0.71) in the covariate analysis.

DISCUSSION

In this study the threshold of stability (ToS) was developed and evaluated as an indicator for spinal stability. The theoretical analysis verified the premise that KV increases and the size of the basin of stability decreases with increasing task difficulty. Experimentally, the ToS was shown to be sensitive to differences in visual acuity, a factor known to influence postural stability. Hence, support for the ToS method was provided both theoretically and experimentally. Future applications for the ToS method might include its use as a diagnostic tool for evaluating spinal stability associated with LBP.

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REFERENCES

1. Tanaka, M. L., and Granata, K. P., 2007, "Methods & Nonlinear Analysis for Measuring Torso Stability," Blacksburg, VA.
2. Lee, H., and Granata, K. P., 2008, "Process Stationarity and Reliability of Trunk Postural Stability," Clin Biomech (Bristol, Avon), Vol. 23(6), pp. 735-42.
3. Cholewicki, J., Polzhofer, G. K., and Radebold, A., 2000, "Postural Control of Trunk During Unstable Sitting," J Biomech, Vol. 33(12), pp. 1733-7.