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Process Stationarity and Reliability of Trunk Postural Stability

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Abstract

Background—Empirical assessments of torso stability can be estimated from postural variability and nonlinear analyses of seated balance tasks. However, processing methods require sufficient signal duration and test-retest experiments require the assessment must be reliable. Our goal was to characterize the reliability and establish the trial duration for torso stability assessment.

Methods—Kinetic and kinematic data were recorded while subjects maintained a seated posture on a wobbly seat pan. Stability was evaluated from dynamic variability and nonlinear stability analyses. Process stationarity of the measured signals characterized the minimum necessary trial duration. Intra-class correlations measured within-session and between-session reliability.

Findings—Trial duration necessary to achieve process stationarity was 30.2 seconds. Shorter time to stationarity was observed with measures that included multi-dimensional movement behavior. Summary statistics of movement variability demonstrated moderate intra-session reliability, ICC = 0.64 (range 0.38 – 0.87). Inter-session reliability for movement variance was moderate, ICC = 0.42 (range 0.22 – 0.64). Nonlinear stability measures typically performed better than estimates of variability with inter-session reliability as high as ICC = 0.83. Process stationarity and reliability were improved in more difficult balance conditions.

Interpretation—To adequately capture torso dynamics during the stability assessment the trial duration should be at least 30 seconds. Moderate to excellent test-retest reliability can be achieved in intra-session analyses, but more repeated measurements are required for inter-session comparisons. Stability diffusion exponents, H_5 , and the Lyapunov exponents provide excellent measures for intra-session analyses, while H_5 provides excellent inter-session comparisons of torso stability.

Keywords

Low-Back; Stability; Process Stationarity; Reliability

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Introduction

Spinal instability is a significant risk factor of low-back disorders (Nachemson A. 1985). Current trends in clinical rehabilitation attempt to define torso stability and improve dynamic lumbar stabilization (Richardson et al. 2002; Saal J.A. and Saal J.S. 1989). Therefore, reliable measures of torso stability are required in both clinical and research environments. However, empirical assessments of stabilizing neuromuscular control of the torso have only recently become available. Radebold et al. (2001) had patients with low-back pain maintain seated balance on a wobbly chair by means of torso movement. Stability was quantified by summary statistics of movement variability and by nonlinear time-series analyses of movement response recorded during the task (Cholewicki et al. 2000). However, the minimum trial duration necessary to reliably measure the stability is unknown.

The minimum trial duration can be established from the time necessary to achieve process stationarity. A process is considered stationary if its statistical properties do not change over time. Brief transient movements in postural control can influence the mean and variance of a signal if the signal duration is short. Therefore, measurements of standing postural control demonstrate that it is a non-stationarity process in the short-term (Newell et al. 1997). This severely limits repeatability of stability measurements. Carroll and Freedman (1993) reported that stationarity occurred only for trial durations in excess of 15–20 seconds in standing postural control tests. We are aware of no reports to find the stationarity and minimum trial duration requirements for measurement of torso stability.

Reliability quantifies whether experimental results remain consistent over repeated tests under identical conditions (Carmines and Zeller 1979). Tracking therapeutic progress or research involving test-retest experimental designs require a reliable biomechanical assessment. Hence, intra-class correlation (ICC) measures have been reported for quiet standing postural control to document intra-session reliability (Lafond et al. 2004) and inter-session reliability (Birmingham 2000). Note however, that inter-session reliability can only be achieved if individual trial duration achieves process stationarity and is influenced by the number of trials collected during a session (Portney and Watkins 2000). To date, few studies have assessed the reliability of torso stability.

The goals of this study were to: 1) determine minimum test duration necessary for process stationarity of torso stability assessment, and 2) estimate the intra-session and inter-session reliability of stability measures recorded from seated postural torso movement. To address these goals, kinetic and kinematic data were recorded while subjects maintained an upright seated posture without a seat-back support. The stabilizing control of the task was challenged by conditions wherein the seat pan of the chair was free to wobble using methods modified from Cholewicki (Cholewicki et al. 2000). Because the seat-pan was mechanically unstable, dynamic neuromuscular response from the torso musculature was necessary to maintain upright seated balance. Stability was characterized from signal variance as well as nonlinear stability analyses of the task.

Methods

Protocol

A total of 12 healthy adult volunteers participated including 9 males (aged 28.0 (3.1) years, height 178.8 (9.5) cm, mass 80.4 (14.8) kg), and 3 females (aged 25.7 (2.5) years, height 165.7 (4.2) cm, mass 60.4 (3.4) kg). Participants reported no history of low back pain, and provided informed consent approved by the Institutional Review Board at Virginia Tech prior to participation. Each subject was instructed to maintain seated balance on a wobble chair with arms-crossed over their chest with eyes open (Figure 1). The chair had no back rest and the

seat pan pivoted freely in the sagittal and frontal planes. Foot support was attached to the seat-pan to minimize lower limb movement. The torso was free to move independent of the seat pan so as to maintain stability on the wobbly structure. An electromagnetic motion sensor (Ascension Technology, Burlington, VT) recorded seat movement. Reaction forces from beneath the wobble chair were recorded by a force platform (Bertec, Columbus, OH).

The difficulty was modulated by adjusting the rotational stiffness of the seat-pan. Potential energy of the system, including chair and subject, was represented as

$$V = \frac{1}{2} k_{\theta} \theta_s - G(\theta_s, \theta_T) \quad (1)$$

where θ_s is a vector of the two-dimensional (anterior-posterior = x-axis, medial-lateral = y-axis) angle of the seat-pan with respect to horizontal and θ_T is the two-dimensional (2-D) vector of torso angle with respect to vertical. $G(\theta_s, \theta_T)$ is the gravitational potential energy of the body mass and is a function of the instantaneous chair and torso angles. Adjustable springs with rotational stiffness, k_{θ} , applied elastic restorative moment to the seat, i.e. return the seat pan to a horizontal configuration. Rotational stiffness of the seat pan, k_{θ} , was adjusted to achieve robust stability about the base of support of the seat,

$$k_{\theta} + \nabla G = 0, \quad (2)$$

The linearized gradient of gravitational moment $\nabla G = \frac{\partial}{\partial \theta_s} G(\theta_s, \theta_T)$ was recorded in static calibration measurements. Hence, the stability assessment accounted for differences in subject anthropometry intrinsically embedded in ∇G . Experimental conditions included three different robustness of stability conditions (Reeves et al, 2007), i.e. $k_{\theta} = 100\% \nabla G$, $75\% \nabla G$, and $50\% \nabla G$. These represented robust stability ($100\% \nabla G$) and two conditions wherein the biomechanical system is statically less robustly stable ($75\% \nabla G$ and $50\% \nabla G$). To maintain an upright seated posture in these statically less robustly stable conditions, compensatory dynamic torso movement was necessary to correct innate disturbances and/or errors in seat angle.

Data trials of 60 seconds duration were recorded in each experimental condition. Prior to the test protocol, subjects performed three practice trials at $k_{\theta} = 100\% \nabla G$ and $k_{\theta} = 75\% \nabla G$ conditions and five practice trials at $k_{\theta} = 50\% \nabla G$ in order to become accustomed to the procedure. Pilot tests indicated these were sufficient to achieve consistent performance during the experimental tasks. Following acclimation, subjects performed a block of five repeated trials within each experimental condition. One minute of rest was provided between trials. Presentation order of experimental conditions was counter-balanced between subjects to remove any order effects. Identical test protocols were performed during two separate experimental visits with 1 week between visits.

Analysis

Chair angle data and reaction forces and moments were recorded in the sagittal and frontal planes at 100 Hz and filtered using a 10 Hz, low-pass, 4th-order Butterworth filter. The filter cut off frequency was selected to assure sufficient bandwidth to represent torso dynamics; i.e. approximately ten times the natural frequency of the torso (Moorhouse and Granata 2005; Winter et al. 1998). Center-of-pressure (CoP) was calculated by using recorded reaction forces and moments. Both angle and CoP data were re-scaled so that the mean value of each trial was zero. Hence, measured data included nonparametric time-series of kinetic and kinematic performance.

Duration of experimental trials necessary for process stationarity was determined from the measured data. First-order stationarity is achieved when the mean is independent of the initial time value,

$$\langle \bar{x}(t) \rangle_{\Delta t} = \langle \bar{x}(t+\tau) \rangle_{\Delta t} \quad (3)$$

where $\bar{x}(t)$ is the average signal over a period from time t to $t+\Delta t$ with $\Delta t = 1, 2, 3, \dots, 60$ seconds. These were calculated from overlapping time epochs with initial time $t = 0, 0.2, 0.4, \dots, 60-\Delta t$ for each trial. Mean and standard deviation of the absolute value of each $\bar{x}(t)$ were computed across all subject trials and time for each independent value of Δt (Figure 2). Sample durations greater than Δt were considered stationarity when the mean value $\langle |\bar{x}(t)| \rangle_{\Delta t}$ was not statistically different than zero by student T-test.

Summary statistics of postural sway are often used as estimates of stability. Variance was characterized by: 1) root-mean-square (RMS) amplitude of the signals, 2) path-length (PATH), and 3) 95% ellipse area (EA) (Prieto et al. 1996). These were computed from the first 40 seconds of each trial. This assured signal duration was sufficient to achieve process stationarity (see results) while avoiding potential transient artifact at the start and end of each data series. The sway variance measures were recorded for kinetic and kinematic data in x-axis, y-axis, and

radial directions, e.g. $\theta_r(t) = \sqrt{\theta_x(t)^2 + \theta_y(t)^2}$.

Nonlinear stability analyses included the stabilogram diffusion analysis (SDA), the Hurst rescaled range analysis (HRRRA), and the maximum finite-time Lyapunov exponent, λ_{Max} . SDA analyses compute variance from the mean squared distances traveled $\langle \Delta d_i^2 \rangle_{\Delta t}$ by the signal in time interval Δt (Collins & De Luca, 1993). The stability diffusion exponent, H , can be computed from the log-log slope of $\langle \Delta d_i^2 \rangle_{\Delta t}$ versus Δt and this exponent demonstrated bi-linear behavior, i.e. short-term and long-term stability exponents. Only the short term exponent, H_S , has been shown to discriminate between subject groups with and without low-back pain (Radebold et al., 2001). Therefore, only the short-term exponent was used in the present analyses.

HRRRA avoids this bilinear effect thereby presenting a single parameter to describe the dynamics of the task (Delignieres et al. 2003). Variance was represented by the mean value R/S across all time segments Δt , $\langle R/S \rangle_{\Delta t}$, where R is the range between the maximum and minimum of each data segment and S is the standard deviation. The Hurst stability exponent, H_H , was computed from the log-log slope of variance versus $\Delta t = 0.01$ to 2 seconds. Values of H_S and H_H closer to 0 indicates that perturbations are likely to be controlled and attracted toward the equilibrium state, whereas values greater than 0.5 indicate a disturbance will continue to grow toward infinity.

Lyapunov exponents quantify the mean rate of divergence with respect to an equilibrium state. The dynamic state at each instant in time was described by a four-dimensional vector including position and velocity in the x-axis and y-axis, $\vec{q}(t) = [\theta_x, \theta_y, \dot{\theta}_x, \dot{\theta}_y]$. For every data point $\vec{q}(t)$ in the time series the mean distance, $d(t)$, to three data points that were nearest to it was calculated (Kantz and Schreiber 2004). Stability was quantified from the rate at which disturbances grow over a finite-time period $\Delta t = 0.01$ to 0.2 seconds, i.e. from $d(t)$ to $d(t+\Delta t)$ averaged over all time samples, t ,

$$\left\langle \frac{d(t+\Delta t)}{d(t)} \right\rangle_t = e^{\lambda_{\text{Max}} \cdot \Delta t} \quad (4)$$

Large values of $\lambda_{\max}$ represent poor stability. Detailed description of these methods is available in Wolf (Wolf et al. 1985) and Rosenstein (Rosenstein et al. 1993).

To quantify intra-session and inter-session reliability the intraclass correlation coefficient, ICC (2,1) was calculated for each dependent variable, *EA*, *PATH*, *RMS*, *H_S*, *H_H* and $\lambda_{\max}$. The ICC was categorized as follows: excellent (0.75 – 1), moderate (0.4 – 0.74), and poor (0 – 0.39) (Fleiss 1986). Calculations were performed using SPSS (Chicago, IL).

The Spearman-Brown formula (Shrout and Fleiss 1979) was used to estimate the number of trials (*k*) required to obtain a desired reliability ICC* based upon measured estimates of reliability from the current study,

$$k = \frac{ICC^*(1 - ICC)}{ICC(1 - ICC^*)}. \quad (5)$$

The target value ICC*=0.75 was used because it is defined as the threshold for excellent reliability (Fleiss 1986; Portney and Watkins 2000). Average of the values for the difficult conditions $k_0 = 75\% \nabla G$ and $50\% \nabla G$ are reported because the easiest condition $100\% \nabla G$ often demonstrated poor reliability and longer trial duration to stationarity. There were few differences between RMS values calculated from medial-lateral, anterior-posterior and radial components of the data, so the number of trials necessary to achieve ICC*=0.75 was computed from the average RMS reliability estimate. Similarly, results were computed for the mean value of the SDA exponent and the Hurst exponent.

Results

Stationarity

The trial duration necessary for process stationarity was computed from nonparametric kinetic and kinematic data (Table 1). Mean trial duration across all conditions necessary to achieve process stationarity was 30.2 (11.8) seconds. For angle movement and CoP in the anterior-posterior plane the signal mean was not significantly different from zero for trial durations greater than 48 seconds at $100\% \nabla G$. Therefore, process stationarity is observed for trial durations greater than this time. During the difficult balance conditions the data were stationarity at smaller durations, between 30 and 44 seconds. Kinetic and kinematic data showed similar stationarity trial durations thresholds. Signals recorded from the radial direction, i.e. sum of squares of ML and AP components, achieved process stationarity in shorter time duration, 18.2 (7.5) seconds.

Summary statistics

Summary statistics of sway demonstrated moderate to excellent intra-session reliability in most conditions (Table 2). Range (average) of intra-session reliability was 0.38 – 0.87 (0.64). The robust stability condition, $100\% \nabla G$, demonstrated the poorest reliability. Intra-session reliability performance was better in the more difficult conditions. Reliability in the $75\% \nabla G$ and $50\% \nabla G$ conditions were 0.65 – 0.87 (0.70) and 0.65 – 0.80 (0.71) respectively, whereas in the $100\% \nabla G$ it was 0.38 – 0.87 (0.51). Most of the measures of sway variance measures performed equally well, i.e. the reliability of *EA*, *PATH*, and *RMS* summary statistics were similar. Only the kinetic *PATH* estimate of stability variance demonstrated excellent reliability performance at $100\% \nabla G$ while all other metrics except medial-lateral *RMS* and anterior-posterior *RMS* demonstrated moderate reliability in the $100\% \nabla G$. In the $75\% \nabla G$ and $50\% \nabla G$ conditions several parameters showed excellent reliability including *PATH* computed from kinetic data as well as *EA* and *RMS* computed from kinematic data.

Inter-session reliability for sway variance demonstrated poor to moderate reliability, 0.22 – 0.64 (0.42). Performance in the 75% ∇G and 50% ∇G conditions were 0.42 – 0.59 (0.49) and 0.26 – 0.64 (0.47) respectively but 100% ∇G showed poorly repeatable results. Inter-session reliability during 75% ∇G were 0.46 – 0.59 (0.53) and 0.42 – 0.47 (0.45) for the kinematic and kinetic data respectively. Reliability for the 50% ∇G conditions were 0.54 – 0.64 (0.57) and 0.26 – 0.48 (0.37) for the kinematic and kinetic data respectively. Differences between dependent measures of EA, RMS, and PATH were small.

Nonlinear stability analyses

Reliability of intra-session nonlinear stability results were poor to excellent, 0.26 – 0.93 (0.60) (Table 2). The stability measures showed greater reliability when computing intra-session reliability from the kinetic data than the kinematic data, 0.32 – 0.93 (0.68) and 0.22 – 0.78 (0.51) respectively. The most difficult experimental condition 50% ∇G demonstrated greater intra-session reliability than the easiest 100% ∇G conditions, 0.22 – 0.92 (0.65) and 0.26 – 0.90 (0.53) respectively. The SDA short-term exponent, H_S , demonstrated better intra-session reliability than the Hurst exponent, 0.27 – 0.93 (0.76) and 0.26 – 0.67 (0.46) respectively. The reliability of the Lyapunov method, 0.22 – 0.31 (0.27), was lower than Hurst stability analyses, 0.26 – 0.56 (0.44), from the kinematic data. However, when nonlinear stability measures were computed from the kinetic data the reliability of the SDA, 0.78 – 0.93 (0.86) and Lyapunov exponents, 0.75 – 0.83 (0.78), were excellent in all experimental conditions.

Inter-session reliability computed from the nonlinear stability measures was 0.13 – 0.84 (0.47). Inter-session reliability computed from the nonlinear stability measures was more reliable than sway variance. The nonlinear stability measures were better when computing intra-session reliability from the kinetic data than the kinematic data, 0.22 – 0.84 (0.53) and 0.13 – 0.70 (0.41) respectively. SDA short-term exponent, 0.26 – 0.84 (0.62), showed better than the Hurst exponent, 0.20 – 0.53 (0.36) and Lyapunov analyses, 0.13 – 0.57 (0.36).

The number of trials for desired reliability

Results showed that the average number of trials to achieve a desired reliability was smaller for intra-session reliability, 9 (5.1), than for inter-session reliability, 19 (7.6). Summary statistics had smaller number of trials for the intra-session, 6.3 (0.6), and inter-session, 17.0 (2.6), than nonlinear stability analyses, 11.7 (6.7) and 21.0 (11.3), respectively (Table 3).

Discussion

When the spine is stable under a specified spinal load then small neuromuscular or vertebral movement errors are automatically corrected without tissue damage (McGill and Cholewicki 2001). Conversely, if the spine is unstable then biomechanical forces associated with small errors can cause sudden uncontrolled vertebral movement, i.e. spinal column buckling (Crisco and Panjabi 1992). These buckling movements impose acute strain on intervertebral tissues (Crisco et al. 1992). Repetitive strain of intervertebral discs and ligaments causes passive tissue laxity (Solomonow et al. 1999). Severe passive tissue laxity in the spine can be observed on clinical examination and is often described as a symptom of instability (Frymoyer and Selby 1985). However, it is important to distinguish between instability and subsequent tissue laxity, i.e. tissue laxity is often misnamed clinical instability. Hence, stability is defined as the capacity to maintain equilibrium posture of the spine and torso despite the presence of neuromuscular or kinematic disturbances (Granata and England 2006).

Musculoskeletal stability is measured from the kinematic movement and control forces. The biomechanical system can be considered as a complex nonlinear input-output relation. Input disturbances include neuromuscular errors, external disturbance forces, and kinematic

perturbations. These act on the musculoskeletal mass to cause output movements, i.e. dynamic states that are not equal to the equilibrium state. The neuromuscular system acts to control and attenuate these input disturbances so as to recover movement errors by attraction toward the equilibrium state. Hence, biomechanical measures of sway variability record the disturbance amplitude observed at the output of the system, i.e. RMS amplitude of output variance, PATH as a measure of total disturbance distance, and ellipse area to quantify the size of involuntary multidimensional movement (Prieto et al. 1996). However, variance represented by sway amplitude does not account for the neuron-dynamic mechanisms underlying the variability. Stability is achieved when small disturbances with respect to the equilibrium posture are attenuated and the disturbed state is attracted toward equilibrium. Nonlinear stability assessments including the SDA, Hurst exponent, and Lyapunov exponent record the attenuation of disturbances (Norris et al. 2005). Thus, variability and stability should be considered independently (England and Granata 2006).

Stationarity

Duration of trials must be sufficient to fully characterize the movement and control dynamics of the seated balance task. If trial duration is brief then measurements may capture only part of the complex natural oscillations and thereby fail to achieve process stationarity. Results suggest that the seated stability protocol required trial duration of approximately 30 seconds to achieve process stationarity. Although the medial-lateral and anterior posterior data demonstrate similar trial length requirements, the radial direction data achieved stationarity in a shorter time duration, 18 seconds. This difference can be attributed to the coupled dynamics, i.e. movement dynamics in the ML direction can be transferred to AP movement. Whereas one-dimensional measures ignore this interaction, the radial measurements capture the full dynamics of the system (F.Takens 1981). Previously reported measurements of standing postural sway (Carroll and Freedman 1993) observed stationarity within 20 seconds, similar to our radial values. Conversely, power spectral density analyses of postural sway indicate that 120 seconds of data may be necessary to fully characterize the system dynamics (Powell and Dzendolet 1984). This discrepancy may be explained by analysis methods. The signals were determined to be stationary when the mean was not significantly different than zero, i.e. the mean was within 1.67 standard deviations of zero ($P=.05$ 1-tailed t-value with 59 df). Therefore, the signal duration sufficient to achieve process stationarity was influenced by variability between means of individual time segments. Large variance of means will increase the range of mean values that fail to be statistically different than zero. Consequently, large variance of means will allow shorter trials to achieve process stationarity according to this statistical approach. An 18 second trial duration may under-estimates the time necessary to fully characterize the stabilizing dynamics.

The trial duration necessary to achieve process stationarity was shorter in more difficult balancing tasks. We attribute this to two factors. First, sway variance increased with task difficulty, i.e. larger values of RSM, PATH, and EA. As noted above, this variance may artificially reduce the time-duration necessary to achieve process stationarity. Second, more difficult conditions limited the region of stability. However, as the rotational stiffness of the wobbly chair declined the available region of stability collapses. This prohibits large amplitude slow movements and may contribute to shorter time to process stationarity. Zatsiorski and Duarte (2000) describes two components in standing postural data including low-frequency rambling and faster trembling. These are also observed in seated postural movement of the torso (Bennett et al. 2004). This rambling behavior may be associated with the availability of a large biomechanically stable region that can be explored by the neuromuscular controller (Bottaro et al. 2005).

Intrasession reliability

The intraclass correlation coefficient was recorded to document both within-day and between-day reliability of the torso stability assessment. ICC values greater than 0.75 are considered excellent while values less than 0.4 are considered poor (Fleiss 1986; Portney and Watkins 2000). Studies of standing postural sway report moderate to excellent reliability (Birmingham 2000). Similarly, estimates of seated postural sway including signal path length (PATH) and RMS amplitude demonstrated excellent intra-session reliability. Likewise, the stability diffusion exponent, H_S and the Lyapunov exponent, λ_{Max} , calculated from kinetic data demonstrated excellent intra-session reliability. The remaining quantitative measures of sway variability and stability demonstrated moderate reliability, particularly in the 75%VG and 50%VG conditions. The only exception was the Lyapunov exponent computed from the kinematic data. This nonlinear method for calculating the dynamic stability requires much longer data sets (Rosenstein et al. 1993). However, the Lyapunov analyses has the advantage of easier interpretation of state-space attraction toward the equilibrium state; the SDA and Hurst analyses are metrics by which the data are compared to Brownian random-walk, i.e. integral of random signal.

Intersession reliability

Inter-session reliability is typically poorer than intra-session reliability. Estimates of kinetic and kinematic sway variability demonstrated moderate inter-session reliability, 0.42 averaged across dependent measures. Nonlinear stability estimates similarly demonstrated moderate reliability on average, 0.47. However, averaged inter-session reliability was improved in the difficult experimental conditions, 75%VG and 50%VG. More difficult conditions required tighter neuromuscular control for success in the experimental task. Therefore, these challenging tasks permitted less day-to-day variability thereby providing results with greater repeatability. Reliability in difficult conditions may also be related to shorter duration to achieve stationarity in these conditions. If the stationarity duration is considered a sample of the dynamic system, then the difficult conditions were able to acquire the full set of dynamics, occasionally multiple dynamic sampled within a 40 second time-series signal whereas the 100%VG recorded at most merely one time-sample of the full dynamic set. This suggests that longer trial durations may achieve improved test-retest reliability. There were few differences between dependent measures of seated sway variance. However, nonlinear stability analyses by methods of the SDA demonstrated greater reliability than the Hurst Exponent. Collins and DeLuca (1993) attribute these short-term SDA exponents to open-loop biomechanical effects that may be dominated by involuntary response dynamics. The short-term exponents were separated from the remaining diffusion data by an inflection in the response curve (see Figure 2 in Cholewicki et al. (2000)). In our data the critical time duration representing the upper bound of H_S was 0.67 (0.21) seconds. Therefore, voluntary movement influence the SDA and Lyapunov stability estimates less than the Hurst diffusion exponent. The long-term SDA and Hurst exponents are influence by voluntary effects that may contribute within-session and between-session variability in these parameters.

Kinetic and kinematic data

There were very few differences in sway results computed from kinetic and kinematic data. The CoP recorded under the wobbly seat was a mechanical consequence of seat rotations against the steel springs. Thus, the kinetic and kinematic data must be highly correlated and stability results should be similar. Unfortunately, these analyses overlook the control forces imparted by the torso, and the inertial load of the seat assembly. These effects behave as a mechanical low pass filter, i.e. movement can be estimated from the convolution of the control forces and the mechanical filtering effects (Moorhouse and Granata 2005). This filtering behavior can limit the performance of nonlinear analyses as noted by poorer reliability of

nonlinear stability measures computed from kinematic data than computed from kinetic data because of filtering high frequencies. Therefore, the measured data are an adequate representation of the stabilizing control of this dynamic system, but stability estimates from kinematic data should take care to retain high frequency content in the signal.

The number of trials for desired reliability

Results of estimating the number of trials required to obtain a desired reliability ICC* suggest that several measures of stability can be used successfully for intra-session reliability. The number of trials to achieve excellent inter-session reliability is typically large for most dependent measures, but eight trials is sufficient for the nonlinear SDA. However, results are limited to interpretation of healthy subjects. Future studies should quantify repeatability using subjects with low-back pain.

In conclusion, trial duration and number of repeated trials necessary to evaluate torso stability were estimated from a dynamic seated task modified from a protocol by Cholewicki (Cholewicki et al. 2000). Process stationarity indicated that trial duration in excess of 30 seconds is recommended. If analyses include nonlinear stability estimates using the Lyapunov exponent, then longer trials are recommended. Excellent test-retest reliability can be achieved in intra-session analyses, but when studies require inter-session comparisons we recommend eight repeated trials per session. Summary statistics and nonlinear stability measures showed various reliability scores through test conditions. We recommend measures which showed excellent reliability scores when studies required the unstable seated test. Longer trial duration may reduce the number of required trials. Using trials of less than one minute, the stability diffusion exponent H_S proposed by Collins (Collins and DeLuca 1993) and the Lyapunov exponent (Rosenstein et al. 1993) are excellent measures for intra-session analyses and the stability diffusion exponent H_S is an excellent measure for inter-session comparisons of torso stability.

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Figure 1. Subjects balanced on a wobble chair adapted from methods of Cholewicki (Cholewicki, Polzhofer, and Radebold 2000). Adjustable springs with equivalent rotational stiffness, k_θ , applied elastic restorative moment to the seat, i.e. return the seat pan to a horizontal configuration. Rotational stiffness of the seat pan, k_θ , was modulate the difficulty of the task.

Figure 2. Stationarity test result. After the first 18 seconds the time averaged value of ensemble averaged data is not different from zero ($P > 0.05$).

Table 1

Stationarity. Results indicate the minimum trial duration (seconds) necessary to achieve process stationarity during the torso stability protocol. Kinetic data represent analyses of the normalized reaction moment time-series signals. Kinematic data represent analyses of chair seat-pan angle time-series.

		Task Difficulty		
		100%VG	75%VG	50%VG
Kinetic	AP	47	43	30
	ML	39	32	23
	r	29	15	11
Kinematic	AP	48	44	30
	ML	40	34	24
	r	26	16	12

AP anterior-posterior; ML medial-lateral direction; r radial direction $r = \sqrt{AP^2 + ML^2}$

Table 2

Reliability ICC(2,1) coefficients for seated sway summary statistics of variance and for nonlinear stability measures from kinetic and kinematic data. Coefficients greater than 0.75 are considered excellent reproducibility of stability assessment.

			Intra-Session			Inter-Session		
			100%VG	75%VG	50%VG	100%VG	75%VG	50%VG
Summary statistics	Kinetic	EA	0.51	0.69	0.68	0.35	0.42	0.36
		PATH	0.87	0.87	0.76	0.26	0.43	0.28
		RMS AP	0.42	0.68	0.65	0.25	0.47	0.48
		RMS ML	0.45	0.70	0.67	0.28	0.45	0.26
		RMS R	0.42	0.68	0.65	0.25	0.47	0.48
	Kinematic	EA	0.52	0.76	0.75	0.32	0.59	0.55
		PATH	0.63	0.60	0.73	0.40	0.46	0.54
		RMS AP	0.38	0.77	0.65	0.22	0.47	0.55
		RMS ML	0.48	0.57	0.79	0.29	0.48	0.56
		RMS R	0.44	0.60	0.80	0.31	0.54	0.64
Nonlinear stability measures	Kinetic	H _H AP	0.36	0.48	0.58	0.40	0.22	0.41
		H _H ML	0.42	0.62	0.67	0.47	0.45	0.53
		H _H R	0.33	0.32	0.49	0.43	0.27	0.37
		H _S AP	0.82	0.80	0.85	0.61	0.66	0.50
		H _S ML	0.90	0.93	0.90	0.84	0.83	0.75
		H _S R	0.78	0.86	0.92	0.65	0.72	0.65
		λ_{Max}	0.83	0.76	0.75	0.57	0.55	0.36
	Kinematic	H _H AP	0.26	0.43	0.50	0.31	0.20	0.38
		H _H ML	0.40	0.46	0.53	0.34	0.34	0.46
		H _H R	0.56	0.36	0.42	0.32	0.33	0.30
		H _S AP	0.27	0.70	0.71	0.26	0.65	0.60
		H _S ML	0.66	0.75	0.75	0.37	0.70	0.63
		H _S R	0.51	0.78	0.78	0.45	0.62	0.70
		λ_{Max}	0.31	0.29	0.22	0.19	0.35	0.13

EA sway ellipse area; PATH sway path length; RMS sway amplitude

AP anterior-posterior; ML medial-lateral direction; $r = \sqrt{AP^2 + ML^2}$ Values highlighted in bold indicate excellent reliability ICC > 0.75. Poor reliability is ICC < 0.40

Table 3

Number of recommended trials necessary per session. Results are based on the Spearman-Brown prophecy formula sufficient to achieve ICC = 0.75.

	EA	PATH	RMS	H _{II}	H _S	λ_{Max}
Intra-Session	6	6	7	16	4	15
Inter-Session	16	20	15	27	8	28