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Quantifying Trunk Neuromuscular Control using Seated Balancing and Stability Threshold

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Abstract

Performance during seated balancing is often used to assess trunk neuromuscular control, including evaluating impairments in back pain populations. Balancing in less challenging environments allows for flexibility in control, which may not depend on health status but instead may reflect personal preferences. To make assessment less ambiguous, trunk neuromuscular control should be maximally challenged. Thirty-four healthy subjects balanced on a robotic seat capable of adjusting rotational stiffness. Subjects balanced while rotational stiffness was gradually reduced. The rotational stiffness at which subjects could no longer maintain balance, defined as critical stiffness (k_{crit}), was used to quantify the subjects' trunk neuromuscular control. A higher k_{crit} reflects poorer control, as subjects require a more stable base to balance. Subjects were tested on three days separated by 24 hours to assess test-retest reliability. Anthropometric (height and

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Conflict of Interest Statement

N. Peter Reeves is the founder and president of Sumaq Life LLC. Sumaq Life LLC was formed to both stimulate health-related technological innovation and increase commercialization of government supported research discoveries including technology to improve health outcomes for those suffering low back pain. None of the other authors of this manuscript have any conflicts of interest to disclose.

weight) and demographic (age and sex) influences on k_{Crit} and its reliability were assessed. Height and age did not affect k_{Crit} ; whereas, being heavier ($p<0.001$) and female ($p=0.042$) significantly increased k_{Crit} . Reliability was also affected by anthropometric and demographic factors, highlighting the potential problem of inflated reliability estimates from non-control related attributes. k_{Crit} measurements appear reliable even after removing anthropometric and demographic influences, with adjusted correlations of 0.612 (95%CI: 0.433–0.766) versus unadjusted correlations of 0.880 (95%CI: 0.797–0.932). Besides assessment, trainers and therapists prescribing exercise could use the seated balance task and k_{Crit} to precisely set difficulty level to a percentage of the subject's stability threshold to optimize improvements in trunk neuromuscular control and spine health.

Keywords

Unstable seat; Core stability; Core control; Postural control; Reliability; Sex

1 INTRODUCTION

Most fitness attributes have good indicators for health and performance. For instance, range of motion is used to measure flexibility while the one-repetition maximum is the gold standard to measure strength capacity (American College of Sports Medicine et al., 2018). In addition, fitness indicators are often used to set exercise parameters to maximize training effects. An example is the use of maximal heart rate (HR_{max}) to define training parameters to improve aerobic capacity (e.g., 15 seconds of running at 90–95% HR_{max} followed by 15 seconds of active resting at 70% HR_{max} (Helgerud et al., 2007)). However, for the neuromuscular system, good indicators are lacking, particularly for assessing postural control of the trunk (Borghuis et al., 2008), often referred to as core control or core stability. Moreover, good indicators are needed to adequately prescribe core training and back rehabilitation programs, so that trunk neuromuscular control can be challenged, but not excessively in order to avoid injury or reaggravation of an existing injury.

Postural performance during seated balance tasks have been used as an objective indicator of trunk neuromuscular control (Cholewicki et al., 2000; Lariviere et al., 2013; Lee and Granata, 2008; Reeves et al., 2009a; Reeves et al., 2009b; Silfies et al., 2003; Slota et al., 2008; Sung et al., 2015; van Dieen et al., 2010b; Vanderburg et al., 2006). Seated balance is used to isolate trunk control, minimizing the contributions of the lower extremities. While performing seated balancing, there are a number of control strategies that can be applied. For instance, a person could choose to minimize displacement (i.e., reduce postural sway) or they may choose to minimize energy expenditure (i.e., reduce muscle effort). Further, it is difficult to infer this control intent since it is not readily apparent what control strategy is being optimized by the individual, although some research has been done on this topic (Priess et al., 2015; Ramadan et al., 2019).

The seated balance task has been used to study differences in trunk neuromuscular control between healthy individuals and those afflicted with back pain (Lariviere et al., 2015; Radebold et al., 2001; van Dieen et al., 2010a). Two studies found no difference in seated

postural sway with back pain (Lariviere et al., 2015; van Dieen et al., 2010a), while one study did but only when the task was challenging (Radebold et al., 2001). One explanation for this finding could be that balancing in less challenging environments allows for flexibility in control, which is not dependent on health status but instead personal preferences; whereas, balancing in challenging environments limits control strategies and unmasks neuromuscular impairments, such as delays in control that are often linked to back pain (Radebold et al., 2001; Reeves et al., 2009b). For these reasons, assessment of trunk neuromuscular control that challenges control to its maximum may yield more insight than submaximal assessment and produce less ambiguous interpretations. Previous research investigating the threshold of stability during a seated balance task supports this assertion (Tanaka et al., 2009).

The goal of this paper is to highlight how challenging postural control maximally during seated balancing can be used to quantify trunk neuromuscular control. Rotational stiffness of an unstable seat can be used to adjust postural control demands: as stiffness is reduced the task becomes more challenging. The rotational stiffness at which an individual can no longer maintain balance, defined as critical stiffness, k_{Crit} , delineates the transition from stable to unstable postural control and is used to quantify limits in trunk neuromuscular control. However, for this new indicator of trunk neuromuscular control to be useful in training and rehabilitation, reliability of the method used to define k_{Crit} must be demonstrated. Therefore, this study was performed to determine test-retest reliability of assessing k_{Crit} . A secondary goal of the paper was to evaluate the effects of anthropometrics (weight and height) and demographics (sex and age) on k_{Crit} and its reliability. Based on findings from (Cholewicki et al., 2000), we hypothesized that taller and heavier subjects will have higher k_{Crit} than shorter and lighter subjects. Given that females have a higher prevalence of back pain (Schneider et al., 2006; Wang et al., 2016), we also hypothesized that female subjects will have higher k_{Crit} (i.e., poorer trunk neuromuscular control) than their male counterparts, when other anthropometric and demographic factors are controlled. We also hypothesized that older subjects will have higher k_{Crit} due to the negative effects of aging on postural control (Cofre Lizama et al., 2014). And finally, we hypothesized that reliability estimates will be affected by anthropometric and demographic characteristics, suggesting that traditional estimates of reliability of trunk neuromuscular control may be artificially inflated due to non-control related attributes in the subject pool (Prescott, 2019).

2 METHODS

2.1 Subjects

Thirty-three subjects (13 males and 20 females) completed the study (Table 1). Data was collected as part of a previous study (Ramadan et al., 2017). Subjects had no previous experience with the seated balance test. Assessment of k_{Crit} was conducted first in the larger study. Subjects were in good health with no history of back pain lasting longer than three days or any neurological conditions that could affect balance. Michigan State University Biomedical and Health IRB approved the research protocol (MSU BIRB #16–617). All subjects signed an informed consent form prior to testing.

2.2 Data collection

A custom-made torque-controlled robotic platform was used to assess trunk neuromuscular control during seated balancing (see Ramadan et al. (2017) for more details, Figure 1). The torque-controlled robotic platform was capable of adjusting rotational stiffness in the coronal plane. The subject was fastened to the robotic seat with a lap restraint across their pelvis and was held in place with adjustable side pads. An adjustable footrest supported the subject's lower extremities. During the seated balancing task, the subject balanced on the platform with their arms cross in front of their chest with their eyes closed and was instructed to maintain an upright position with the seat parallel with the floor. The subject initially balanced on the platform with a rotational seat stiffness of 250 Nm/rad. If the subject was successful at keeping the seat angle within $\pm 12^\circ$, the rotational seat stiffness was gradually reduced by 10 Nm/rad increments until the subject could no longer maintain balance. The procedure was repeated again. The lowest stiffness between the two trials was defined as the "coarse" estimate of k_{crit} . This coarse estimate was then used to define the "fine" estimate of k_{crit} by repeating the procedure starting from the coarse estimate +50 Nm/rad and reducing stiffness by 5 Nm/rad increments until the subject could no longer maintain balance. This was repeated three times and the average rotational stiffness was calculated to represent the fine estimate of k_{crit} , which defines the limit in trunk neuromuscular control. Note that a lower rotational stiffness values for k_{crit} represents a less stable base. A person capable of balancing on a less stable base has better trunk neuromuscular control.

2.3 Data analysis

Descriptive statistics were presented with mean, standard deviation, and range for continuous variables, and frequencies and percentages for categorical ones. The log transformation was used for the k_{crit} ($\log k_{\text{crit}}$) outcome variable in order to fulfill the normality assumption. A linear mixed effect model was considered as follows,

$$y_{ij} = \beta X + \theta_2 Z_2 + \theta_3 Z_3 + b_i + \varepsilon_{ij}$$

where y_{ij} is the ($\log k_{\text{crit}}$), β is a vector that captures the effects of the other potential confounding variable such as age, sex, height and weight including an interception; $\theta = (\theta_2, \theta_3)$ estimates the learning effect between sessions two and one and the learning effect between sessions two and three; $b_i \sim N(0, \sigma_{BS}^2)$ is the between-subject variability, and $\varepsilon_{ij} \sim N(0, \sigma_{WS}^2)$ is the within-subject variability.

The intraclass correlation coefficient, denoted as $ICC(3,1)$, is defined as

$$ICC(3,1) = \frac{\sigma_{BS}^2}{\sigma_{BS}^2 + \sigma_{WS}^2}$$

and assesses the proportion of the total variance that is attributed to the variance between subjects on a given session after adjusting for other factors (Chen et al., 2018; Liljequist et

al., 2019). A high ICC suggests that most of the variance in the seated balance test is attributed to between-subject differences and not within-subject variability.

To assess the within-subject variability, conditioning on other factors, a standard error of measurement (SEM) was used, where SEM is quantified as

$$SEM = \sigma_T \sqrt{1 - ICC(3,1)}$$

where σ_T represent the total variability ($\sigma_T = \sigma_{BW} + \sigma_{WS}$).

Three different estimates of ICC, and their associated 95% confidence intervals, were computed: (1) a single measurement, consistency, 2-way mixed effect model based on an ANOVA approach that used only subjects that completed all three sessions; (2) a linear mixed effect model with only sessions as fixed effect and a random effect for individuals that included all observations; and (3) a multivariate linear mixed effect model that, in addition to sessions, included height, weight, sex, and age. In addition, standard error measurement were estimated to assess the reliability within individual subjects (Weir, 2005).

All tests were two-tailed and a 5% significance level was used. Statistical analyses were performed using STATA version 15.0 (STATA Corp., 2017).

3 RESULTS

One female subject (age 21 years old, height 165.5 cm, weight 137.7 kg) was not able to balance on the robotic platform, even at the highest stiffness level. The remaining 33 subjects completed the testing protocol and did so without any reports of adverse events, suggesting the seated balance task is well tolerated by healthy individuals. Male subjects were younger (29.1 vs. 34.2 years old), taller (177.6 vs. 163.3 cm), and heavier (85.1 vs. 70.8 kg) than female subjects (see Table 1).

3.1 Anthropometric and demographic effects on k_{Crit}

In the multivariate model, age and height were not associated with a change in $\log k_{\text{Crit}}$ (see Table 2). However, sex and weight induced systematic error as men obtained 0.156 (95%CI: 0.006–0.306, p-value = 0.042) lower $\log k_{\text{Crit}}$ than women, and a one-kilogram increment in weight was associated with a 0.02 (95%CI: 0.016–0.250, p-value < 0.001) increment in $\log k_{\text{Crit}}$, respectively

3.2 Learning effect

Mean values of k_{Crit} decreased between sessions, with the largest change occurring after the first day (Figure 2). After adjusting for sex, age, height and weight, the expected mean difference in $\log k_{\text{Crit}}$ between Session I and II was 0.139 (95%CI: 0.090–0.188, $p < 0.001$) and between Session II and III was 0.062 (95%CI: 0.012–0.112, $p = 0.015$).

3.3 Test-retest reliability and standard error of measurement of k_{Crit}

Conditioning on a given session, the proportion of the total variance attributed to between-subject variability, via an ANOVA 2-way mixed-effect model, was 0.89 (95%CI: 0.80–0.94,

n=30) and was similar when considering a linear mixed effect model (0.88, 95%CI: 0.80–0.93, n=33) (see Table 3). On the other hand, further conditioning for demographic and anthropometric measurements such as sex, age, height, and weight, resulted in an estimated ICC of 0.61 (95%CI: 0.43–0.77, n=33). SEM was consistent amongst the three ICC models, ranging from 0.099–0.103. This result suggests that 95% of repeated measurements on the same individual in the first session will be between 4.3 and 4.7 if her/his true value is 4.5 log k_{Crit} .

4 DISCUSSION

The primary goal of this study was to determine if challenging postural control maximally during seated balancing can be used to reliably quantify the limits in trunk neuromuscular control. Results suggest that control can be reliably assessed, but results also show a systematic learning effect as subjects improved seated balance performance over the three testing sessions. Learning mostly occurred between the first and second session. To ensure reliable assessment, a training session should be provided in order to reduce this systematic bias. Lariviere et al. (2013) showed that 4 practice trials of 30 seconds was sufficient to account for learning during seated balancing. Results also indicate that reliability is significantly affected by participant's weight. If the goal is to provide an indicator of an individual's trunk neuromuscular control and not simply differences in body size, it is important to account for anthropometrics, which should also be accounted for when assessing reliability. If anthropometrics are not accounted for, estimates of reliability may be artificially inflated (Prescott, 2019). To clarify, two studies could be conducted to assess reliability, with one study using subjects of the same body size and the second with subjects varying significantly in size. Because anthropometrics, specifically weight, affects seated balance performance (Cholewicki et al., 2000; Lariviere et al., 2013) and given that body size will not change substantially between sessions, the second study with anthropometric heterogeneity will have superior reliability when compared to the study with a homogenous subject pool using the traditional ANOVA approach. Therefore, if the goal is to assess consistency in trunk neuromuscular control and not body size, the linear mixed effect model approach that accounts for anthropometrics is recommended. In addition, accounting for anthropometrics will also require a larger study sample size to produce a narrower confidence interval for the reliability estimate (see Table 3).

Tanaka et al. (2009) were the first to propose assessing limits in trunk neuromuscular control, referred to as threshold of stability, using a seated balancing approach. The threshold of stability measure was found to be more sensitive than other postural sway measures (e.g., Lyapunov exponent), highlighting the potential of assessing limits in trunk neuromuscular control may have as a diagnostic tool for conditions such as low back pain. Results presented in this study support this assertion by also demonstrating the reliability of the approach. However, the utility of the approach as a diagnostic tool still needs to be demonstrated by showing that it is sensitive enough to detect differences between people with and without back pain and before and after treatment. This is the focus of a larger clinical study currently underway.

In our study, sex induced systematic error as females have higher k_{Crit} , suggesting that they have poorer trunk neuromuscular control than males. The k_{Crit} measure has been shown to be related to delays in trunk neuromuscular control (Oomen et al., 2015; Reeves et al., 2009b), with a higher k_{Crit} indicating slower postural control. To avoid back injuries in the presence of sudden, unexpected perturbations, timely postural responses are needed to avoid excessive spine displacement and loading (Reeves et al., 2009b) that could increase injury risk (Cholewicki et al., 2005). If, as suggested by the higher k_{Crit} , females have slower postural control, their protective responses to stabilize the spine could be compromised. Although, delayed trunk muscle reflex responses following postural perturbations increase the risk of future back injuries (Cholewicki et al., 2005), there is no evidence at this point that females are at increased risk of injury due to poorer trunk neuromuscular control. Future prospective studies should investigate this possibility.

In terms of age, the current study provides no evidence that age impairs trunk neuromuscular control. However, it is possible that the subject population was not old enough to identify age-related changes in postural control that are often observed (Cofre Lizama et al., 2014). The younger, fairly narrow age range is one of the limitations with the current study.

Another study limitation is the use of only healthy individuals and not persons with potentially impaired trunk neuromuscular control. Healthy individuals were used for the initial reliability study to ensure that testing was safe before moving to populations at greater risk of injury. There were no reported study-related adverse events, suggesting that healthy individuals can tolerate testing. Future studies should explore the feasibility of assessing k_{Crit} in individuals with back pain.

Future work should also address optimizing training using the seated balance task and stability threshold (i.e., k_{Crit}). There is evidence that unstable environments promote the activation of core stabilizing muscles impaired in back pain patients (Hides et al., 1996; Hides et al., 1994; Hodges and Richardson, 1996; Weber et al., 2017). Therefore, the unstable environment created by seated balancing appears well suited as a training modality. In addition, the seated balance task, along with knowledge of the individual's limits in trunk neuromuscular control, could be used to precisely prescribe back training and rehabilitation. Adjusting rotational stiffness can be used to regulate postural stability demands, which in turn can then be used to control trunk muscle activation and spine displacement (Oomen et al., 2015). We suspect that optimal training and rehabilitation parameters exist that nurture spine health, which can be precisely set to the individual's abilities using k_{Crit} .

In conclusion, k_{Crit} appears to reliably quantify limits in trunk neuromuscular control. k_{Crit} also appears to be a suitable indicator of trunk neuromuscular control, being less ambiguous than postural sway parameters (Tanaka et al., 2009). Anthropometric factors, specifically weight, need to be accounted for when quantifying limits in trunk neuromuscular control. In addition, a training session needs to be considered for future experiments. Results suggest that females may have poorer trunk neuromuscular control, which may predispose them to future injury. Age-related changes in trunk neuromuscular control cannot be ruled out given the restricted age range of the study. And finally, the seated balance task along with

measures of stability threshold represents a promising modality to precisely train and rehabilitate trunk neuromuscular control based on the individual's ability.

5 PRACTICAL APPLICATIONS

Trainers and therapists interested in improving core fitness could use the seated balance task along with k_{crit} to reliably assess athletes and patients, and safely train their trunk neuromuscular control by setting postural stability demands and monitoring their progress over time. Such training could help prevent new back pain cases and reoccurrence in back pain patients.

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Figure 1: Robotic platform used to regulate rotational stiffness during seated balancing in the coronal plane. Subject tried to maintain balance as the rotational seat stiffness was gradually reduced. At some critical stiffness, k_{Crit} , subjects could no longer maintain balance, reflecting the stability threshold used to quantify the limit in trunk neuromuscular control.

Figure 2. Distribution of k_{Crit} between testing sessions. Note that a higher k_{Crit} indicates poorer trunk neuromuscular control.

Table 1.

Mean (standard deviation, range) of age, height and weight of subjects who completed the study, separated by sex; and mean (standard deviation, range) of k_{crit} (log scale) for each testing session.

Characteristic	Males (13, 39.4%)	Females (20, 60.6%)
Age (years)	29.1 (11.9, 20–59)	34.2 (11.8, 18–57)
Height (cm)	177.6 (7.4, 167.3–190.9)	163.3 (5.4, 154.2–173.0)
Weight (kg)	85.1 (11.8, 69.3–109.4)	70.8 (12.5, 50.0–98.4)
k_{crit} (Log(Nm/rad))		
Session I	4.71 (0.23, 4.27–5.14)	4.62 (0.34, 4.00–5.27)
Session II	4.59 (0.19, 4.38–5.15)	4.45 (0.33, 3.91–5.11)
Session III	4.49 (0.22, 4.25–4.94)	4.42 (0.34, 3.91–5.11)

Table 2:

Estimated coefficients of the linear mixed model for k_{Crit} on log scale adjusted by sex, age, height, weight, and session.

Variable	Coefficient	Standard Error	95%CI	p-value
Sex (Male)	-0.156	0.077	(-0.306, -0.006)	0.042
Age (years)	-0.001	0.002	(-0.005, 0.004)	0.804
Height (cm)	-0.003	0.005	(-0.011, 0.006)	0.578
Weight (kg)	0.020	0.002	(0.016, 0.025)	< 0.001
Session				
II		Reference		
I - II	0.139	0.025	(0.090, 0.188)	< 0.001
II - III	0.062	0.025	(0.012, 0.112)	0.015

Table 3:

Estimated intraclass correlation coefficients (ICC) and standard error of measurement (SEM).

	Two-way mixed effect ANOVA model ^a (n=30)		Mixed effect model with sessions as fixed effect (n=33)		Mixed effect regression model adjusting for sex, age, height, weight and session (n=33)	
	Estimate	95%CI	Estimate	95%CI	Estimate	95% CI
ICC	0.886	0.803 – 0.940	0.880	0.797 – 0.932	0.612	0.433 – 0.766
SEM	0.103		0.099		0.099	

^a Only for participants who have their three measurements