Journal of Biomechanics 45 (2012) 129–133

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The discriminant capabilities of stability measures, trunk kinematics, and step kinematics in classifying successful and failed compensatory stepping responses by young adults

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ARTICLE INFO

Article history:
Accepted 20 September 2011

Keywords:
Falls
Balance
Margin of stability
Time to boundary
Posture

ABSTRACT

This study evaluated the discriminant capability of stability measures, trunk kinematics, and step kinematics to classify successful and failed compensatory stepping responses. In addition, the shared variance between stability measures, step kinematics, and trunk kinematics is reported. The stability measures included the anteroposterior distance (d) between the body center of mass and the stepping limb toe, the margin of stability (MOS), as well as time-to-boundary considering velocity (TTB_v), velocity and acceleration (TTB_a), and MOS (TTB_{MOS}). Kinematic measures included trunk flexion angle and angular velocity, step length, and the time after disturbance onset of recovery step completion. Fourteen young adults stood on a treadmill that delivered surface accelerations necessitating multiple forward compensatory steps. Thirteen subjects fell from an initial disturbance, but recovered from a second, identical disturbance. Trunk flexion velocity at completion of the first recovery step and trunk flexion angle at completion of the second step had the greatest overall classification of all measures (92.3%). TTB_v and TTB_a at completion of both steps had the greatest classification accuracy of all stability measures (80.8%). The length of the first recovery step ($r \leq 0.70$) and trunk flexion angle at completion of the second recovery step ($r \leq -0.54$) had the largest correlations with stability measures. Although TTB_v and TTB_a demonstrated somewhat smaller discriminant capabilities than trunk kinematics, the small correlations between these stability measures and trunk kinematics ($|r| \leq 0.52$) suggest that they reflect two important, yet different, aspects of a compensatory stepping response.

1. Introduction

Falls are the leading cause of injury death and nonfatal injuries for adults aged 65 years and older (CDC–WISQARS (Web-based Injury Statistics Query and Reporting System), 2011). Therefore, the methods and measures that best quantify fall risk and that inform appropriate clinical interventions will beneficially service this growing population. A promising method for determining fall risk may be to evaluate an individual's compensatory stepping response. For example, the need for multiple compensatory steps in response to lateral waist pulls prospectively predicted falls in older adults (Hilliard et al., 2008). Also, control of lateral body motion in response to forward waist pulls of up to 22.5 cm retrospectively distinguished older adult fallers from non-fallers (Rogers et al., 2001). Compensatory stepping in response to larger forward disturbances may also be a useful assessment of fall risk. Following treadmill-delivered disturbances that necessitated many steps, the short, delayed initial steps and large trunk flexion angles and angular velocities of failed responses mimicked the kinematics of trip-induced falls (Owings et al., 2001; Pavol et al., 2001). These similarities suggest that an assessment of the response to large treadmill disturbances is pertinent to trip-related falls, a prevalent cause of falling in older adults (Berg et al., 1997). For this evaluative method to be effective, the most appropriate quantitative outcome measures must be identified. To the best of our knowledge, the measures of the stepping response that best discriminate falls from recoveries, and, therefore, best reflect the effectiveness of the response, have not been thoroughly investigated. Identifying these measures may help determine the most appropriate measures to consider when assessing fall risk from successful compensatory stepping responses, as evaluating fall risk merely by the ability to avoid a fall may not be feasible, sufficient, or desirable.

Whether in response to laboratory-induced trips (Pavol et al., 2001) or treadmill-delivered disturbances (Owings et al., 2001), the ability to both arrest and reverse trunk flexion and perform an appropriate initial recovery step are important components of a successful response. Although trunk and step kinematic measures

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doi:10.1016/j.jbiomech.2011.09.022

may differ significantly between falls and recoveries, they may not individually reflect the overall effectiveness of the stepping response. Most likely, a stepping response requires a sufficiently long and timely step *as well as* the arrest/reversal of trunk flexion in order to maintain stability. It is possible that a kinematic measure that is influenced by both step *and* trunk kinematics may offer a sensitive representation of the effectiveness of the stepping response. Previously established measures of stability, or continuous, quantitative estimates of an individual's state of balance, have considered the position of the whole body center of mass (COM) and its time derivatives relative to the base of support. During a stepping response, the boundary of the base of support is influenced by step kinematics. The anteroposterior position and velocity of the COM is considerably influenced by trunk kinematics, as the trunk comprises nearly 50% of total body weight (Winter, 2005). Since restoration of balance is the objective of a compensatory stepping response, a quantitative estimate of stability may better represent the effectiveness of each step than step or trunk kinematics alone.

During quasi-static situations, the distance (d) between the vertical projection of the COM and the boundary of the base of support has been suggested to reflect direction-specific stability (Shumway-Cook and Woollacott, 1995; Winter., 1995). However, this definition may not sufficiently characterize stability during dynamic conditions. Inclusion of the horizontal velocity of the COM when evaluating stability introduces the future position of the COM to the calculation (Pai and Patton, 1997). Accordingly, a measure that considered COM velocity better explained the necessity of a forward step than the measure d in response to a translating surface (Pai et al., 2000).

The margin of stability (*MOS*) considers both the position and the velocity of the COM relative to the base of support in its calculations (Hof et al., 2005). Previous research has suggested that the *MOS* established with a compensatory step reflects the necessity to take an additional step. After a release from a forward-leaning position, older adults who recovered in a single step demonstrated a larger *MOS* with the initial step than older adults who required a second step (Arampatzis et al., 2008). In addition, young adults establish a larger *MOS* with a compensatory step than older adults (Karamanidis et al., 2008). Such differences observed between age groups suggest a potential utility of the measure in evaluating fall risk from a stepping response.

Time-to-boundary measures, which are also referred to as time-to-contact, estimate the elapsed time at which, given the current state of the COM and base of support, the COM would reach the vertical projection of the edge of the base of support. Time-to-boundary can be estimated using the *MOS* or the COM position, velocity, and/or acceleration. After a forward waist pull, time-to-boundary calculated from transverse plane COM position and velocity predicted whether a subject would initiate a compensatory step, but was less successful in predicting a second step (Schulz et al., 2006). In response to a weighted pendulum impact, forward steps were more accurately predicted by time-to-boundary estimates that considered anteroposterior velocity and acceleration (TTB_a) than estimates based on only anteroposterior velocity (TTB_v) or time-to-boundary based on *MOS* (TTB_{MOS}). The inclusion of COM acceleration improved the measure's ability to predict a compensatory step compared to measures that did not include acceleration (Hasson et al., 2008).

To the best of our knowledge, previous studies have not evaluated the aforementioned measures of stability when directly comparing failed anterior compensatory stepping responses, of which a fall is the outcome, to successful responses. A meaningful measure that is indicative of stability, therefore reflecting the effectiveness of the stepping response, should discriminate outcomes. Furthermore, the discriminant capabilities of these measures have not been evaluated concurrently with that of trunk and step kinematic measures.

The primary purpose of this study was to evaluate the discriminant capability of stability measures, step kinematics, and trunk kinematics in classifying successful and failed compensatory stepping responses. Stability measures included d, *MOS*, TTB_v, TTB_a, and TTB_{MOS} at the instant of compensatory step completion. Step kinematic measures included the length and time after the disturbance onset of each step. Trunk kinematic measures included trunk flexion angle and angular velocity at compensatory step completion. We predicted that TTB_a would have the most accurate outcome classification based on its unique consideration of COM and base of support acceleration. The secondary purpose of this study was to determine the relationships between stability measures, step kinematics, and trunk kinematics. We expected that step kinematics and trunk kinematics would significantly correlate with measures of stability.

2. Methods

Seven men and seven women (age: 22 ± 2.7 years, height: 177.4 ± 10.3 cm, mass: 81.0 ± 11.4 kg) who did not self-report neurological or musculoskeletal injuries or disorders participated in this study. The study was approved by the University of Illinois at Chicago Institutional Review Board and subjects provided written, informed consent. Subjects stood on a microprocessor-controlled, stepper motor-driven treadmill (ActiveStep^{TM}, Simbex, Lebanon, NH) having a belt 0.51 m wide and 1.37 m long. Posteriorly directed treadmill belt accelerations required the subjects to perform a compensatory stepping response consisting of multiple, anteriorly directed steps. A ceiling-mounted safety harness protected subjects from contacting the treadmill with their knees and hands in the event of a failed recovery. All subjects were given an initial postural disturbance, having a saw-tooth velocity profile (0.5 s acceleration phase of 6.5 m/s^2 followed by a deceleration phase of -0.375 m/s^2). The peak velocity of this disturbance was 3.25 m/s and the total displacement was 14.9 m. The acceleration phase ended at approximately the same time as the completion of the first compensatory step. The deceleration value was chosen to allow for a gradual deceleration that did not noticeably assist in recovery from the disturbance. Subjects were instructed to "react however you need to avoid falling." After the initial disturbance, thirteen postural disturbances were delivered, the initial accelerations of which ranged from 3.0 to 6.25 m/s^2, and then decreased back to 3.0 m/s^2 (Fig. 1). Finally, subjects were exposed to the initial disturbance a second time.

This series of disturbances separating the initial and last trials was designed with two intended purposes. First, to increase the likelihood that subjects would recover from the initial disturbance when given it a second time and second, to create a misleading expectation of disturbance magnitude that would allow the second delivery of the initial disturbance to have an unexpected magnitude.

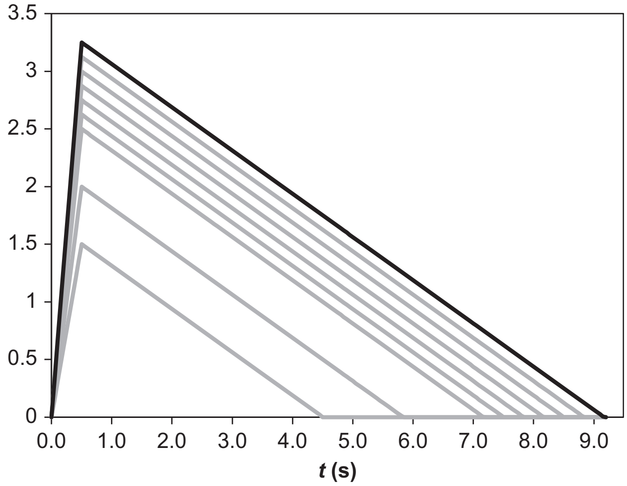

Fig. 1. Velocity profiles of the treadmill belt. The initial postural disturbance (black line) consisted of a 0.5 s acceleration phase of 6.5 m/s^2, peaking at a velocity of 3.25 m/s, followed by a deceleration phase of -0.375 m/s^2. The initial postural disturbance was repeated for the last disturbance delivered to subjects. Thirteen postural disturbances (gray lines), the initial acceleration of which ranged from 3.0–6.25 m/s^2, were delivered between the initial and last disturbances. Within this series, the magnitude of the disturbances initially increased from 3.0 m/s^2 to 6.25 m/s^2, and then decreased back to 3.0 m/s^2.