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Short communication

Ensuring accurate estimates of step width variability during treadmill walking requires more than 400 consecutive steps

David M. Desmet, Andrew Sawers, Mark D. Grabiner *

Department of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, IL 60612, United States

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ABSTRACT

Falls to the side are associated with significant morbidity, including increased risk of hip and radius fracture. Although step width variability, as measured by standard deviation, has been hypothesized to be associated with falls to the side, there is little supporting evidence. The extent to which such a relationship could be reliably established, however, is dependent on the accuracy with which step width, and thus step width variability, is measured. It has been reported that 400 consecutive steps are required to accurately estimate step width of young adults during treadmill walking. The degree to which this requirement generalizes to other populations has not been determined. Here, a secondary analysis of step width time series data from 19 middle-age women during treadmill walking revealed that 400 steps were insufficient to accurately estimate step width or step width variability for the majority of the women sampled. Patterns observed in the data suggest the potential influence of confounding factors including acclimatization to the task and fatigue during the protocol. The results suggest that the minimum number of steps previously reported as necessary to accurately assess step width and step width variability of young adults during treadmill walking is not valid for middle-age women. Furthermore, the results point to the potential value of reproducing and/or extending the original experiment that established 400 consecutive steps as necessary to accurately estimate step kinematics among young adults.

1. Introduction

Falls are among the leading causes of fatal and non-fatal injuries in the United States (Kochanek et al., 2016; CDC, 2017). It was reported that up to 20% of middle-age adults had fallen in the previous year (Nitz and Choy, 2008), and annual fall rate increases to nearly 50% among adults age 85 years and older (Iinattiniemi et al., 2009). Falls to the side are particularly harmful. Over 95% of hip fractures result from a fall, a majority of which are falls to the side (Hayes et al., 1993; Parkkari et al., 1999). Compared to falls in other directions, falls to the side increase risk of hip fracture six-fold (Greenspan et al., 1994), and this risk increases 30-fold if impact occurs directly at the hip (Nevitt and Cummings, 1993). Hip fracture patients demonstrate increased risk of mortality, the hazard ratio of which ranges from 2.12 in the first post-fracture year to 1.79 at eight and more years (Katsoulis et al., 2017). In addition, hip fracture patients often experience long-term limitations with mobility. Between 40 and 60% of hip fracture patients may not regain their pre-fracture mobility and up to 20% are institutionalized within a year of the injury (Dyer et al., 2016).

Exercise-based fall prevention programs are demonstrably effective at reducing fall risk and rate of falling. On average, group-based multicomponent exercise training, home-based multicomponent exercise training and Tai Chi decrease fall risk and rate of falling by 19% and 29%, respectively (Gillespie et al., 2012). However, these metrics, which correspond to all-cause falls, convey no information about the specific types of falls that these interventions affect, such as falls to the side. Furthermore, the reduction in fall risk attributable to these interventions, while significant, may be well below the maximum possible reduction (Visintin et al., 1998; Grabiner et al., 2014). By identifying and targeting biomarkers specific to trip-related falls, a recent intervention implementing trip-specific perturbation training resulted in an almost 50% reduction in trip-related fall-rate (Rosenblatt et al., 2013). Using the same principles derived from the specificity of training hypothesis, it may be possible to develop task-specific interventions to reduce falls in other directions, including falls to the side.

Applying the specificity of training hypothesis to the issue of laterally-directed falls depends upon the identification of modifiable characteristics that are causally related to laterally-directed

* Corresponding author at: Department of Kinesiology and Nutrition, University of Illinois at Chicago, 1919 W Taylor Street, Chicago, IL 60612, United States.

E-mail address: grabiner@uic.edu (M.D. Grabiner).

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fall risk. As the maintenance of mediolateral balance during gait relies, to some extent, upon accurate lateral foot placement (Kuo, 1999; MacKinnon and Winter, 1993; Townsend, 1985), the frontal plane distance between the feet during double support (i.e. step width) has long been hypothesized to be one such characteristic (Guimaraes and Isaacs, 1980). Despite long-term interest, prospectively-derived evidence of a relationship between step width, step width variability (hereafter used to reflect standard deviation) and falls is limited. Narrow step width, but not step width variability, was reported to be prospectively predictive of falls to the side by older adults, although the relationships between step width and falls in other directions were not significant (Ko et al., 2007). In contrast, step width variability, but not step width, was reported to be prospectively predictive of all-cause falls (Maki, 1997). Despite the strong prospective design of these studies, they do not lead to a conclusion related to the capacity of step width and/or step width variability to predict falls.

Characterizing the relationship between step width, step width variability, and cause-specific or direction-specific fall-risk depends upon accurate estimates of step width and step width variability. For young, healthy adults walking on a treadmill, 400 consecutive steps were reported as necessary to establish an accurate and reliable, subject-specific measure of step width and step width variability (Owings and Grabiner, 2003). Beyond 400 steps, and in the absence of potentially confounding variables such as fatigue, it was assumed that increasing the number of steps would only minimally affect the estimate. We are unaware of published evidence detailing the extent to which the use of 400 consecutive steps can be generalized to other populations. Therefore, the purpose of the present analysis was to determine if 400 consecutive steps during treadmill walking were sufficient to establish accurate estimates of step width and step width variability for middle-age women.

2. Methods

2.1. Data collection

The present study was a secondary analysis of step width time series collected from 19 healthy middle-age women (56.6 ± 3.8 years) who served as a control group in a previous study (Pater et al., 2016). Following the acquisition of informed, written consent, and based on the assumption that 400 steps were sufficient to acquire an accurate estimate of step width (Owings and Grabiner, 2003), each woman walked on a microprocessor controlled, stepper motor-driven, dual belt treadmill (ActiveStep, Lebannon, NH) for ten minutes at a self-selected speed. An eight-camera motion capture system (Motion Analysis Co., Santa Rosa, CA) operating at 120 Hz tracked the three-dimensional positions of 22 reflective markers, a subset of which were used to extract step width time series using custom software (Matlab, Mathworks, Natick, MA). The left and right feet were represented as rigid segments defined by markers placed on the shoes over the second metatarsophalangeal joints and the heels. Step width was calculated as the frontal plane distance between the midpoints of the foot segments at midstance during two consecutive stance phases.

2.2. Data analysis

All step width time series were truncated to 422 steps, which was the largest number of steps common to all participants during the ten-minute walking trial. Running mean and associated running standard deviation functions were calculated from the step width time series of each participant. Estimates of step width and step width variability were considered accurate when "the slope of the running function approaches zero" (Owings and Grabiner, 2003). To assess the extent to which the slope of each running function approached zero in the present analysis, a linear regression was applied to the final 25% of each step width and step width variability running function (Owings and Grabiner, 2003; Fig. 1). The regression coefficient (i.e., slope) from each running function was determined for all 19 women, and the margins of error of the regression coefficients were subsequently computed ($\alpha = 0.05$). The criterion for accuracy of step width and step width variability was considered to have been met for those participants whose regression coefficient fell within the margin of error.

For each participant who met the criterion for accuracy for step width and step width variability, the number of steps required to meet this criterion was then determined. To do so, we remained consistent with the methodology used to establish the original requirement of 400 consecutive steps (Owings and Grabiner, 2003). The mean and standard deviation of the final 25% of steps in the time series were calculated and a 50-point sliding window was then used to iteratively (point-by-point) progress through each running function beginning at the first point in the time series. The first point of the first window for which all 50 points fell within ± 3 standard deviations of the mean was used to represent the minimum number of steps required to meet the criterion for accuracy (Owings and Grabiner, 2003; Fig. 1).

3. Results

Four-hundred consecutive steps of treadmill walking were not sufficient to establish accurate estimates of step width or step width variability for the majority of the healthy middle-age women sampled. Only five of the 19 participants (26.3%) met the criterion for accuracy for step width (Fig. 2a). Only nine participants (47.4%) met the criterion for accuracy for step width variability (Fig. 2b).

Notably, those women who met the criterion for accuracy did so with fewer than the expected 400 steps. For these women, the number of steps (mean ± SD) required to accurately estimate step width and step width variability was 256 ± 59 steps and 281 ± 48 steps, respectively.

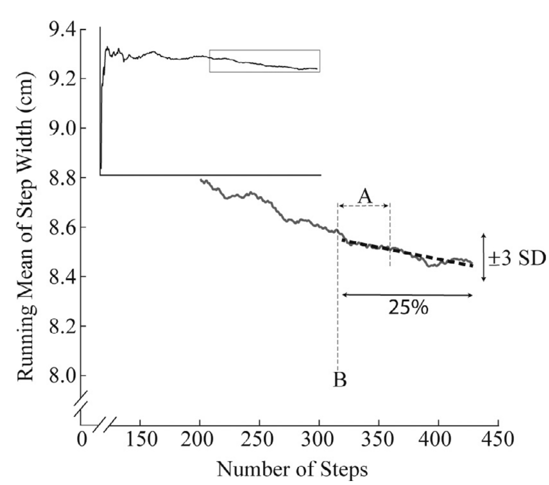

Fig. 1. The insert depicts the complete step width time series, with the final 222 steps presented in the body of the figure. A linear regression was applied to the final 25% of each time series (dashed line) from which the regression coefficient (slope) was determined. If the slope was within the margin of error computed from all of the time series, a 50-point sliding window, starting at the first step, progressed point-by-point through the time series (A) until a window was established in which all 50 points fell within three standard deviations of the mean value of the final 25% of steps. The first point of this window was recorded as the required number of steps to reach an accurate value for that subject and function (B).

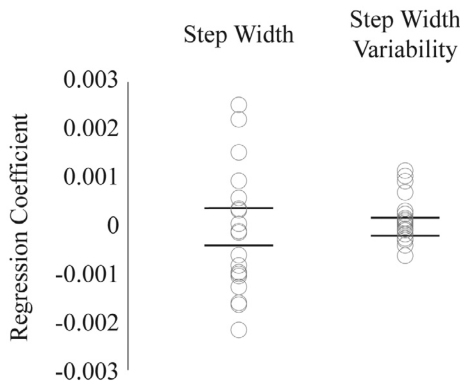

Fig. 2. Regression coefficients calculated from the final 25% of the step width and step width variability running functions for each subject. The subjects with regression coefficients falling within the margin of error (horizontal lines) were determined to have met the criterion for accuracy for that running function.

4. Discussion

The purpose of this study was to determine whether 400 consecutive steps during treadmill walking, a criterion previously established for young adults (Owings and Grabiner, 2003), were sufficient to establish accurate estimates of step width and step width variability for middle-age women. Based on the premise that the accuracy of step kinematic estimates is reflected by the extent to which the slope of the associated running function approaches zero as the number of consecutive steps increases (Owings and Grabiner, 2003), our results indicate that 400 consecutive steps were not sufficient to establish accurate estimates of step width or step width variability for the majority of the women in the present analysis. However, fewer than 400 consecutive steps were required to estimate step width or step width variability for those women who achieved our criterion for accuracy. Notably, the average required number of steps for each variable reported in this study was within one standard deviation of that previously reported for young adults, which was around 200 steps (Owings and Grabiner, 2003).

The step width and step width variability running functions that did not meet our criterion for accuracy included some that continued to increase and others that, after achieving a local maximum, decreased thereafter. Several factors have been reported to influence estimates of step width and thus could have influenced the running functions. Acclimatization to a dual-belt treadmill, for example, has been shown to first result in relatively large step widths that subsequently decrease as the participant presumably becomes more comfortable (Zeni and Higginson, 2010). In the present study, the step width and step width variability running functions that peaked and then decreased would therefore be expected to plateau with more steps if treadmill acclimatization was a contributing factor. This implies that an accurate estimate, as defined, would eventually be obtained. In addition, fatigue has been shown to significantly increase step width in older adults (Helbostad et al., 2007) and could therefore be a factor contributing to the running functions that continued to increase in the present study. The effect on gait kinematics of continued walking in the presence of fatigue has not, to our knowledge, been reported. Accurate estimates of step width may be more difficult to obtain from populations more susceptible to these confounding factors. This complicates the determination of a generalizable minimum number of steps required to accurately estimate step width and step width variability.

The clinical utility of step width and step width variability to identify fall-prone individuals and/or to assess the effectiveness of fall prevention interventions remains unknown. To establish clinical utility, the relationship between step width, step width variability and fall risk must first be determined. However, reliably establishing this relationship depends upon accurate estimates of step width and step width variability, which, based on the present analysis, requires more than 400 consecutive steps among healthy middle-age women. Due to the physical limitations of certain populations and the potential influence of confounding factors, such as fatigue, collecting such a large number of consecutive steps may be impractical. If fewer consecutive steps are available for analysis there would consequently be fewer participants for whom accurate estimates of step width and step width variability are determined. The effect would be increased between-subject variability and larger sample sizes necessary to ensure adequate statistical power to detect within- and between-group differences. However, identifying individuals at risk for laterally-directed falls and assessing the effects of fall prevention programs based on step width and step width variability requires confidence in subject-specific estimates of these parameters. Therefore, further systematic investigation to establish the conditions necessary to accurately estimate step width and step width variability is considered prudent in an effort to determine the clinical utility and limitations of these measures.

In summary, 400 consecutive steps were not sufficient to establish accurate estimates of step width and step width variability among the majority of the middle-age women who participated in this study. Potential value exists in determining the extent to which the previously established criterion of 400 consecutive steps for young adults is reproducible. In light of continued interest in spatial and temporal step kinematics as risk factors and possible biomarkers for falls, it seems prudent to systematically establish the conditions necessary to assure both the accuracy and the reproducibility of these measures across populations for whom fall risk is a concern.

Author contribution

Study Concept and Design: M.D. Grabiner, A. Sawers, D.M. Desmet.

Acquisition of Data: D.M. Desmet.

Analysis and Interpretation of Data: D.M. Desmet, M.D. Grabiner.

Drafting of Manuscript: D.M. Desmet, M.D. Grabiner.

Critical Revision of Manuscript of Important Intellectual Content: M.D. Grabiner, A. Sawers.

Statistical Analysis: D.M. Desmet, M.D. Grabiner.

Study Supervision: M.D. Grabiner.

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Declaration of Competing Interest

The authors declare that there are no conflicts of interest associated with this work.

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