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Development of a new approach to quantifying stepping stability using ensemble empirical mode decomposition

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ABSTRACT

Everyday walking is often interrupted by obstacles and changes in the environment that make gait a highly non-stationary process. This study introduces a novel measure, termed the step stability index (SSI), to quantify stepping stability under non-stationary walking conditions among older adults. This index is based on the ensemble empirical mode decomposition method. We hypothesized that a higher SSI would indicate a more stable gait pattern and could be used to assess fall risk. Accelerometer-derived signals (vertical direction) were analyzed from 39 older adults with a history of 2 or more falls in the past year (i.e., fallers) and 42 older adults who reported no falls in the previous year (i.e., controls) under three walking conditions: baseline walk with and without a harness, and obstacle course with a harness. In each condition, the subjects wore a small, light-weight sensor (i.e., a 3 dimensional accelerometer) on their lower back. The SSI was significantly higher ($p \leq 0.05$) in the controls than in the fallers in all three walking conditions. The SSI was significantly ($p < 0.0001$) lower for both the controls and the fallers during obstacle walking compared with baseline walking. This finding is consistent with a less stable step pattern during obstacle negotiation walking. The SSI was correlated with conventional clinical measures of mobility and fall risk (the correlation coefficient, r, ranged from 0.27 to 0.73, $p < 0.05$). These initial findings suggest that the SSI, an index based on the ensemble empirical mode decomposition, may be helpful for quantifying gait stability and fall risk during the challenges of everyday walking.
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1. Introduction

Decreased stability of the stepping pattern has been associated with fall risk among older adults [1–3]. A number of metrics have been used to quantify "stepping stability." These include indices that reflect step-to-step variability [4–6], the harmonic ratio of gait smoothness [7], local dynamic stability [8], and step and stride degrees of regularity, which are based on autocorrelation functions [9–11]. However, the analytical and computational approaches underlying these methods are generally not readily applicable when the gait time series is not stationary. The time series generated by a stationary process has a joint probability distribution that does not change when shifted in time or space. Walking, in contrast, is often interrupted by obstacles and changes in the environment that render the gait pattern into a non-stationary process.

The ensemble empirical mode decomposition (EEMD) technique is a new computational tool that has been applied to the analysis of nonlinear and non-stationary data [12]. We speculated that the EEMD might be helpful in quantifying stepping stability in non-stationary time series derived from walking, since the EEMD method decomposes non-stationary signals into components with

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different characteristic cycle lengths (or frequency ranges). Specifically, we hypothesized that the energy, as measured by the standard deviation, of the component at the step frequency would be higher than the energy of higher frequency components that likely relate to subtle unsteadiness of stepping [13–15]. We applied the EEMD technique to continuous gait signals to develop a step stability index (SSI). The SSI was defined as the ratio of the energy of the dominant component in a fully step cycle to the energy of faster (higher frequency) components. Our assumption, therefore, is that higher step stability index (SSI) values will reflect a more stable gait pattern.

The goal of the present work is to develop a method of quantifying stepping or gait stability among older adults, based on measurements of a single body-fixed sensor, e.g., an accelerometer, worn on the lower back, and to begin to evaluate the algorithm on data collected in the laboratory during usual-walking and while subjects negotiated obstacles, a condition in which interruptions and, therefore, non-stationarities are commonplace.

2. Materials and methods

2.1. Subjects

81 community living older adults were studied. Subjects were included in this study if they were between the ages of 65–90 years of age, had no clinically diagnosed gait or balance disorders, and scored above 24 points on the Mini Mental State Examination. Subjects were classified as fallers and controls based on their self-report of previous falls. If subjects reported two or more falls in the past year, they were considered as fallers; otherwise they were classified as controls [16,17]. This study was approved by the human studies committee of the Tel Aviv Sourasky Medical Center and all subjects provided informed written consent prior to participating in the study.

2.2. Protocol

2.2.1. Clinical tests

The study participants completed a number of functional performance-based assessments of postural control, mobility and fall risk such as the dynamic gait index (DGI) [18], the berg balance scale (BBS) [19], the timed up and go test (TUG) [20] and the four square step test FSST) [21]. In addition, the activities-specific balance confidence scale (ABC) [22], a measure related to fear of falling, and the geriatric depression scale (GDS) [23] were administered to help characterize the study cohorts.

2.2.2. Ambulatory assessment

Subjects walked for 1 min under three different conditions: (1) baseline, usual walk; (2) baseline, usual walk with a harness; and (3) an obstacle course walk with a harness, while negotiating obstacles including boxes and other items that required stepping over or walking on an uneven surface. Subjects wore a small, light-weight sensor (DynaPort hybrid, McRoberts) on a belt on their lower back. The dimensions of the sensor are 87 × 45 × 14 mm; it weighs 74 g. The DynaPort hybrid includes a triaxial accelerometer (sensor range and resolution are: ±6 g and ±1 mg, respectively) and a triaxial gyroscope (sensor range and resolution are: ±100°/s and ±0.006°/s, respectively). The signals were recorded on a secure digital (SD) card at a sample frequency of 100 Hz, and later transferred to a personal computer for further analysis using MATLAB, the Mathworks software. Since the vertical acceleration axis has previously been shown to give the most information on the gait cycle [24], 1 min of the acceleration signal on this axis was analyzed in this initial study.

2.3. SSI: a new metric for quantifying stepping stability

2.3.1. Ensemble empirical mode decomposition (EEMD)

The EEMD method is a noise-assisted enhancement of the EMD method proposed by Huang et al. [12,25]. EMD and EEMD are adaptive decomposition methods based on the local characteristic time scale of the data, which is applicable to nonlinear and non-stationary processes. These decompositions have the advantage of automatically identifying the intrinsic time scales of the data without any assumptions regarding signal stationarity. An example of the EEMD decomposition of a raw acceleration signal is shown in Fig. 1; the modes were ordered according to decreasing frequency.

2.3.2. Definition of step stability index (SSI)

Each acceleration signal in the vertical direction was decomposed into a series of intrinsic mode functions (IMFs) using the EEMD method. The number of IMFs depends on the length of the original data. One minute recordings, sampled at 100 Hz, yield time series with 6000 data points. The EEMD method decomposes signals of this length into 8 IMFs. Based on visual inspection of the dynamic patterns of the original signal and of the IMFs, we inferred that the 4th IMF, denoted as IMF4, captured the dominant oscillatory patterns at step frequency, while IMF1, IMF2 and IMF3 captured the higher frequency fluctuations within each step. Fig. 2 shows raw acceleration signals in the vertical direction, recorded under baseline walk and the obstacle negotiation, and the dominant oscillatory and faster modulation components obtained using EEMD. The components were normalized by dividing each component by the standard deviation of the raw signal to minimize the influence of individual subject differences.

As noted, we hypothesized that a "smooth" step should have more "energy" in key components of the step cycle itself and less "energy" within each step. That is, subjects who walk with a more stable gait pattern would have relatively high energy in IMF4 and low energy in IMF1, IMF2 and IMF3. We calculated the standard deviation (SD) to quantify the "energy" of each IMF. The new step stability index (SSI) was defined as:

$$\mathrm{SSI} = \frac{\text{SD of IMF4}}{\text{SD of IMF1} + \text{SD of IMF2} + \text{SD of IMF3}}$$

2.4. Statistical analysis

Outcome measures were compared between the groups using the Mann Whitney test. Wilcoxon signed rank tests were used for

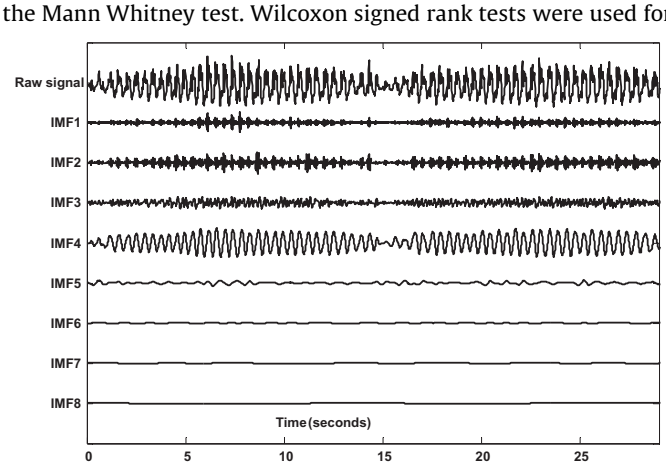

Fig. 1. Example of a segment of an acceleration signal in the vertical direction (baseline walking) from a control subject along with the intrinsic mode functions (IMF 1–8) derived using the EEMD method. The IMFs were ordered according to decreasing frequency content.

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