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Towards the assessment of local dynamic stability of level-grounded walking in an older population

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ABSTRACT

Local dynamic stability is a critical aspect of stable gait but its assessment for use in clinical settings has not yet been sufficiently evaluated, particularly with respect to inertial sensors applied on the feet and/or trunk. Furthermore, key questions remain as to which state-space reconstruction is most reliable and valid. In this study, we evaluated the reliability as well as the ability of different sensor placement and state-spaces to distinguish between local dynamic stability in young and older adults.

Gait data of 19 older and 20 young subjects were captured with inertial sensors twice within the first day as well as after seven days. 21 different signals (and combinations of signals) were used to span the system's state-space to calculate different measures of local dynamic stability. Our data revealed moderate or high effect sizes in 12 of the 21 old vs. young comparisons. We also observed considerable differences in the reliability of these 12 results, with intra-class correlation coefficients ranging from 0.09 to 0.81. Our results demonstrate that in order to obtain reliable and valid estimates of gait stability λ of walking time series is best evaluated using trunk data or 1-dimensional data from foot sensors.

Introduction

Measures of local dynamic stability (LDS) during walking are able to provide an understanding of an individual's gait stability [1–3]. Such measures are capable of distinguishing between older and younger cohorts [4] with lower levels of LDS associated with a higher risk of falling [2,4]. However, measures of LDS, which can be quantified using the largest Lyapunov Exponents (λ [5]), have mostly been evaluated in young subjects walking on a treadmill [6,7] due to the requirement of collecting multiple strides for its assessment [8]. However, treadmill walking does not represent a physiological activity of daily living and is known to add external constraints, such as acting as a temporal pacemaker, and modifying LDS [9]. The type of walking (i.e. treadmill or overground) should therefore be considered in the protocol design. To ensure clinical relevance, a renewed validation of λ that addresses reliability and validity should be conducted in older people as demanded (but not yet undertaken) in the literature [10,11]. The calculation of λ is based on state-space representations [1], where the representation of a valid state-space could be any vector space containing a sufficient number of independent coordinates defining the state of the system at any instant in time [12]. For example, to calculate λ from a walking time series, state-spaces could be built from anterior–posterior, medial–lateral, and superior–inferior accelerometer signals taken from the hip, knee and ankle joints [1,13], or from trunk position movements in all three directions [14]. Adequate state-spaces could be reconstructed from a single time series using the original dataset and its time delayed copies [15] or e.g. from time series of all angles and angular velocities at that joint [16]. In this case, λ is quantified as exponential rates of divergence of initially neighbouring trajectories in the state-space as they evolve in real time.

Inertial sensors offer feasible options for flexible, mobile, and inexpensive usage in clinical settings. However, a recent test-retest reliability study of young subjects showed that robust inter-day assessment of gait stability is difficult using data from such accelerometer sensors [11]. In their study, gait data captured during outdoor walking was analysed, which had the benefit of allowing accurate capture of magnetometer data for assessing orientation. However, assessment within the constraints of indoor walking where magnetometer data is not necessarily accurate or reliable (which is comparable to clinical settings), might be more appropriate for the analysis of patients suffering from musculoskeletal deficits [17,18].

In order to establish the assessment of λ for overground walking using inertial sensors for clinical use, this study aimed to evaluate multiple state-space definitions (using different signal types) in both

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young and elderly adults. Here, the following state-space reconstructions for evaluating λ were considered in terms of both reliability as well as validity [11,16,19]:

1. differences in the signal dimension (1D vs. 3D) might affect inter-day reliability as different sensor positions affect sensor orientation relative to the segment,
2. signal characteristics are different regarding linear acceleration and angular velocity, and it might be possible to improve reliability through combining these variables for estimation of λ [11], even when the signals stem from the same system, and
3. the reliability and validity of different measures of λ might be sensitive to different segment trajectories (e.g. trunk, foot), but test-retest data are only currently available derived from trunk movements [7,10,11].

The following two research questions were addressed: 1) What is the inter-session and inter-day test-retest reliability of LDS in an older cohort a function of differently reconstructed state-spaces? 2) Are measures of LDS able to distinguish between young and older adults as a function of differently reconstructed state-spaces?

Methods

Subjects

Gait data of 19 healthy older (5 male, 14 female, age: 71 ± 4 years) and 20 healthy young subjects (8 Male, 12 female, age: 26 ± 4 years) were captured twice within the first day and also once after seven days. All participants provided their written informed consent after they were briefed about the research protocol, which complied with the principles of the Declaration of Helsinki and was approved by the board of the ethical committee of Otto von Guericke University, Magdeburg.

Testing procedure

A wireless inertial motion tracker (MTw, Xsens Technologies B.V., Enschede, The Netherlands; range of measurement of angular velocity: ± 1200 deg/s, range of measurement of acceleration: ± 160 m/s^2) was fixed onto each of the subjects' forefeet and trunk. Among other things, these sensors measure angular velocities and linear accelerations with a sampling rate of 75 Hz. Kinematic data were captured while the subjects twice walked a distance of 130 m (including one turn) in a straight line on a level hallway at their preferred walking speed. This procedure was repeated 1) after 5 min of rest without removing the sensors and 2), after 7 days at the same time of day.

Data analysis

Heel strikes from 100 strides per subject were estimated as described in Hamacher et al. [20] after removing data captured in 2.5 m prior to and after turning. The first step in the calculation of λ was to reconstruct appropriate state-spaces with the aid of time-fixed delayed copies and/or with different signals representing the same movement. In order to explore the influence of different signals (and combinations of signals) used to span the system's state-space on the reliability and validity of λ, we reconstructed 21 state-spaces which were different with respect to 1) data included from the different sensor axes, with the sensor fixed to the body parts in a way to coincide with the anatomical planes in normal standing (anterior–posterior, medial-lateral, and superior-inferior), 2) the trajectories of different segments (trunk vs. foot), and 3) the nature of the data (linear acceleration vs. angular velocity). Subsequently, we created time delayed copies to build an adequate high-dimensional state-space for LDS calculation.

The time delay (used for the time delayed copies) corresponded with the first minimum mutual information for each participant [21], and the number of time delayed copies was calculated using the global false nearest neighbours method [22] where the appropriate number of copies was defined as the number where a manifest plateau began to appear. Both the embedded dimensions and mutual information were calculated for each subject, and the resulting median of all subjects was applied to calculate λ for the whole group for a particular signal combination. In order to ensure comparability of data from older and younger subjects, the same embedded dimensions and mutual information for each signal (signal combination) of the older subjects was also used for the younger subjects.

The second step was to calculate λ by estimating the exponential rates of divergence of initially nearest neighbours as they evolved in real time, which provided a direct measure of the system's sensitivity to extremely small perturbations. Here, we used Rosenstein and co-workers' algorithm for the calculation of λ [5], which was implemented in MATLAB (version 2013a, The MathWorks BV, Natrick, USA).

Approaches to calculate LDS using multiple repetitions of short walking distances have been published previously [23,24]. In the current study, we merged the data of 100 strides of two repetitions of 130 m which included one single turn (turn data removed). The time series were normalized to 10000 samples [18]. The distance of each point in state-space and the correlating nearest neighbour (Euclidean distance) were tracked for data of the same walk. After taking the logarithm of the mean divergence curve, LDS was computed as the slope of the linear fit through 0–0.5 strides for each signal (or combination) and for each subject. LDS was then interpreted such that positive exponents indicated local instability, while larger positive exponents indicated greater sensitivity to perturbations that occurred while walking [5,19].

Statistics

For estimating the inter-session test-retest reliability, we used both trials of the first day. The inter-day test-retest reliability was calculated using data from the first trial of the first day and the trial captured on the second day. Intra-class correlation coefficients (ICC, 2.1; [25]) were calculated (using the IBM SPSS Statistics 20 software suite) where values between 0.0–0.40 were considered poor, from 0.40–0.59 fair, from 0.60–0.74 good, and from 0.75–1.00 excellent [26]. Furthermore, the Bias and Limits of Agreement [27] were assessed to quantify the agreement between test and retest. Hedges' g was calculated to estimate the effect size comparing old vs. young. We use the conventional values as benchmarks considering 0.2, 0.5 and 0.8 to be 'small', 'medium', and 'large' effects, respectively [28]. The precision on the effect sizes and Intra-class correlation coefficients were estimated with 95% confidence intervals.

Results

Our data revealed effect sizes of 0.51 (medium effect) or higher (up to 1.33, large effect) in 12 of the 21 old vs. young state-space comparisons (Table 1). As a result, only λs calculated with these 12 different state-spaces are reported. Substantial differences were observed regarding the test-retest reliability, with ICC-values ranging from 0.09 to 0.81 (Table 1).

Old vs. young comparison

Anterior–posterior vs. medial–lateral vs. and superior–inferior

λ calculated using linear acceleration signals or angular velocity signals in the superior-inferior direction did not reach medium or high effect sizes. Furthermore, we did not find any systematic differences with respect to λ calculated from data stemming from signals regarding anterior–posterior vs. medial–lateral direction.