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Multiscale and Shannon entropies during gait as fall risk predictors—A prospective study

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ABSTRACT

Although entropy-based measurements of gait dynamics are becoming widely used tools for fall risk assessment, their relationship to fall occurrence is still unclear. The aim of this study was hence to compare fallers and non-fallers in terms of gait dynamics assessed by the multiscale and Shannon entropy. This study included 139 participants, aged 60–80 years, divided into two groups according to fall occurrence during a 6-month prospective observation (38 fallers, 101 non-fallers). The methodology involved the use of the Tinetti balance assessment tool (TBAT) and 5 min of overground walking with 3D accelerometers located near the L5 vertebra and shanks. We analyzed 150 strides for gait complexity, an index of complexity (CI), computed from multiscale entropy (MSE) and Shannon entropy (ShE) derived from the recurrence quantification analysis. We found no significant differences between groups in MSE and CI. The TBAT total score was significantly higher in non-fallers ($P = 0.033$), however, both groups showed low risk of falls. ShE in the anterior-posterior direction from trunk and in the medial-lateral direction from the shanks were both significantly higher in fallers ($P = 0.020$; $P = 0.024$). ShE was negatively correlated with CI, the shank ShE in the vertical direction was positively correlated with TBAT. Taken together, our findings suggest that MSE is not able to distinguish between highly functional groups, whereas Shannon entropy seems to be sufficient in fall risk prediction.

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1. Introduction

Although entropy-based measures are widely used for gait assessment, their relationship to fall risk remains still unclear. During dynamic conditions, approximate entropy [1] and sample entropy [2] are used to assess the complexity and regularity of a system [3]. Because these two measures provide only one scale of information about the system, Costa et al. [4,5] introduced multiscale entropy (MSE), sample entropy computed for several scales.

MSE is a relatively new approach in locomotor assessment; therefore, its use in scientific studies is limited. For fall risk assessment during quiet stance, Kang et al. [6] used MSE to distinguish between elderly individuals with different degrees of frailty. According to their results, non-frail elderly showed higher center of pressure movement complexity than pre-frail and frail groups. Additionally, the complexity decreased with increased difficulty of a given task (i.e., from quiet stance to a dual task).

Bisi et al. [7] recently used the MSE method to assess toddler gait. Toddlers are frequent fallers; therefore, their risk of falling is considerably higher compared to that of adults. Toddler gait was compared to gait of the young and elderly adults in order to investigate if MSE could be used to distinguish between toddlers and young adults and elderly and young adults. They reported that MSE computed from trunk acceleration in vertical (V) and anterior-posterior (AP) direction in toddlers is significantly higher than that obtained in young adults. Moreover, MSE in V direction was significantly higher for elderly group compared to young adults indicating less stable gait. According to Bisi et al. [7], variables which are able to distinguish toddlers and young adults should have more promising ability to distinguish elderly fallers and non-fallers.

Another study by Bisi and Stagni [8] investigated the development and decline of gait in terms of complexity in several age groups ranging from toddlers (13 months) to elderly (84 years old). Their results showed that MSE computed from the trunk V and AP accelerations generally decreased from childhood to adulthood

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and increased from adulthood to the old age. This trend could suggest possible indication of maturation of gait which could be described by gait complexity.

Direct fall risk studies on an elderly population involving MSE were conducted by Riva et al. [9] and Ihlen et al. [10]. In both studies, the elderly were divided according to a retrospective fall history report and MSE was computed from trunk acceleration. Riva et al. [9] clearly showed a relationship with fall history for MSE in AP direction with scale factors 2 and 3. According to the results of their study, higher complexity of gait is related to fall history. On the other hand, Ihnel et al. [10] investigated daily life walking episodes with two MSE derived variables – refined composite multiscale entropy (RCME) and refined multiscale permutation entropy (RMPE). Their results are in contrast with the above-mentioned work [9] and showed higher complexity from trunk accelerations in elderly non-fallers for both RCME and RPME in medial-lateral (ML) direction and in AP and V directions for RCME. RMPE in V direction showed high values for fallers. Authors explain that their results could be influenced by walking condition with different regulation of gait in controlled (lab) and uncontrolled (daily life) environment.

Another advanced approach in gait analysis is recurrence quantification analysis (RQA), which provides an insight to time series behavior by quantifying deterministic structures and non-stationarity [11]. Variables derived from RQA seem to be effective in distinguishing between toddlers and young adults [7], elderly fallers and non-fallers [9] or healthy adults and individuals with unilateral vestibular hypofunction [12]. A possible entropy measure derived from RQA is Shannon entropy (ShE), which is considered a complexity measure of a deterministic structure [13]. While this index is still not extensively used to describe gait, several studies reported results of ShE in static conditions [11,14–16]. Their results appear to be quite contradictory showing higher ShE values for younger adults compared to elderly [15] but simultaneously higher ShE for elderly fallers compared to elderly non-fallers [16].

To our knowledge, no prospective studies of MSE and ShE during gait have been conducted to date. The main aim of the present study is to assess differences in MSE and ShE between elderly fallers and non-fallers using a prospective approach. The second aim is to evaluate the relationship between clinical results and entropy measures. The hypotheses for this work are as follows. Based on the in lab results obtained by [7–9], we expect that complexity of the gait is connected to fall occurrence in elderly subjects resulting in higher MSE values for fallers. This relationship should also be related to the results of clinical evaluation with negative correlation suggesting decline in clinical score followed by increase of complexity of the gait. Based on the results of Ramdani et al. [16], we expect similar trends also for ShE.

2. Methods

The study included 139 participants, who were recruited from clubs for the elderly and the University of the Third Age in Olomouc, Czech Republic. The inclusion criteria included the ability to stand and walk without any support and older age, specifically, age of more than 60 years. Participants with musculoskeletal problems, injuries, and surgical interventions that were performed within 2 years before measurement were excluded from the study. All of the participants signed written informed consent forms before examination. The research was approved by an institutional ethics committee (no. 24/2014). Participants completed the Tinetti balance assessment tool [17], and the acceleration of their gait was measured. After baseline measurements, the participants were observed for 6 months to collect fall data. The participants were given a notepad to ensure all of the falls were recorded, and phone calls were made, at a minimum of once every two weeks, to collect the fall data. A fall was defined as “an unexpected event in which the participants come to rest on the ground, floor, or lower level” [18]. Falls related to sports, such as skiing and cycling, and those caused by a great external force were excluded from the analysis. A “faller” was considered a person with at least one fall during the observed period of time.

2.1. Measurements

The Tinetti balance assessment tool (TBAT) was included for clinical examination. The TBAT score was considered in each of the sections (balance and gait) separately and together. Gait was measured over 5 min of walking at a preferred walking speed in a 30 m long indoor corridor. Two well-visible marks were placed on the floor restricting a 25 m long pathway. Participants were instructed to walk straight, maintain a stable pace, and turn around after crossing the marks. Walking speed was defined to be the mean speed of the participant’s walk between the marks and was computed for each interval from the distance and time needed to complete this task. Participants wore comfortable sport shoes during the measurement. 3D accelerometers (sampling rate 296.3 Hz, Trigno wireless system, Delsys Inc., Natick, MA, USA) were attached near the L5 vertebra and on the shanks approximately 15 cm above the malleolus on each limb to record acceleration in V, ML and AP directions. The recording of acceleration started after the initial stride.

2.2. Data analysis

The first 300 samples of the acceleration signal were excluded from the analysis to avoid non-stationarities of the signal caused by sensors’ delayed response. The turnarounds, the last stride before the turnaround and the first stride after the turnaround were removed from the signal before further analysis. Heel strikes were identified using a procedure introduced by Zijlstra and Hof [19], and 150 strides were extracted for further analysis. The signal was analyzed without filtering. Stride time, MSE and ShE were computed for each time series.

MSE was computed for scale factors 1–15 by software available on Physionet [4,5,20]. A number of consecutive data points, m, were set to 2, and the radius was set to 15% of the standard deviation of the time series [5]. The MSE curve was then obtained as a plot of sample entropies as a function of scales. The index of complexity (CI) was computed as an integral of the MSE curve [4].

ShE was computed from the RQA by an algorithm developed by Ouyang [13] in Matlab (R2015b, MathWorks, Inc., Natick, MA, USA). Each time series was normalized to 15,000 data points to obtain approximately 100 data points per stride. The input variables for RQA were determined as follows. Time delays were computed from an average mutual information function at the first minimum. The resulting delays were averaged in each direction giving time delays of 9, 6 and 11 samples for the V, ML and AP directions, respectively, for signals from the shanks. There were time delays of 11, 8 and 10 samples for the V, ML and AP direction, respectively, for trunk acceleration. The embedding dimension was computed from a global false nearest neighbor analysis, which resulted in dimension 6. The Euclidian distance was calculated [12], and the radius was set to 40% [9] for analysis. For the purposes of this work, only ShE was extracted from RQA.

2.3. Statistics

The Kolmogorov-Smirnov test was used to verify the normality of the data distribution. Since some of the data did not have a

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