INVESTIGATION OF THE SUITABILITY OF UTILIZING PERMUTATION ENTROPY TO CHARACTERIZE GAIT DYNAMICS

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ABSTRACT

Permutation entropy (PE) is a natural measure of the complexity of a dynamic system which boasts robustness to noise and computational efficiency. Since its introduction in 2002, PE has served as a valuable tool for assessing nonlinear systems such as speech signals and EEG signals. In this paper, the suitability of utilizing PE as a new method for characterizing walking gait dynamics is explored. Results obtained by analyzing the medial-lateral center of pressure migration of participants during treadmill walking demonstrate that PE shows good preliminary repeatability. PE shows sensitivity to a change in walking conditions; walk alone vs. addition of a concurrent cognitive task. A highly significant age effect in PE (p<0.001) during dual task walking was observed. Analysis revealed no significant age effect on PE for the walk alone condition.

INTRODUCTION

Complexity measures have been widely used to investigate the properties of physical systems [1]. Since Shannon's initial development of the concept of information systems entropy [2], a wide range of different entropy measures have been developed to characterize the complexity of dynamic systems [1,3-7]. In 2002, Brandt and Pompe introduced permutation entropy (PE); a new complexity measure which boasts high computational efficiency, a robustness to noise and invariance with respect to nonlinear monotonous transformations [7]. Since its development, PE has been shown to reliably measure the complexity in a wide range of applications including speech signals [7], EEG signals [1] and classical dynamic systems [1,7]. In this paper, the suitability of utilizing PE to measure gait dynamics is investigated. The suitability of PE as a measure of gait dynamics will be based on its repeatability and its sensitivity to changes in walking conditions.

The ability to assess the quality and stability of an individual's walking gait has been a subject of particular research interest [5-6,8-11]. Its applications in the medical community are far reaching and include identifying aging individuals who may be prone to falls and assessing rehabilitation patients' progress. In recent years, there has been a shift to utilizing nonlinear dynamics tools to analyze walking gaits. Two prominent nonlinear measures are instantaneous Lyapunov exponents (ILEs) [9,10] and maximum floquent multipliers (MaxFm) [8,11]. Although both of these nonlinear analysis tools have shown some initial promise as a means of characterizing walking performance, they each have limitations. The calculation of ILEs is very sensitive to the presence of noise [12]. Furthermore, both ILEs and MaxFm require a long data series to ensure accuracy [11].

Complexity measures offer an alternative approach to the characterization of gait dynamics. In a number of studies, the sample entropy of the center of pressure (COP) migration during quiet stance has shown itself to be a potential indicator of the health of postural balance [13]. Furthermore, both multiscale entropy [5] and control entropy [6] have been applied as a means of characterizing walking gaits.

The impact of dual tasking on walking will be used to assess PE's sensitivity to changes in the gait dynamics. The secondary cognitive task will be based on Useful Field of View (UFOV) assessment techniques. UFOV assessment is a validated, computer-based test that requires visual search mechanisms and the ability to select relevant information and ignore irrelevant information [13]. Studies have found that older adults with slower cognitive speed of processing, as measured by the UFOV test, experienced the greatest mobility loss when dual tasking was introduced [15].

MATHEMATICAL PRELIMINARIES

Permutation Entropy

Entropy measures are an indication of the complexity of a system. Permutation entropy (PE) uses the shapes of neighboring points to assess the complexity of a time series. Therefore, if there are only a few different shapes in the time series and they appear regularly (like a sine wave), the time series will have low PE. Conversely, a time series which contains many different shapes which appear without regularity (white noise, for example) will have high PE.

A brief demonstration of the calculation of PE is presented here [1,7]. Consider the time series defined by X(i)={x(i), i=1,2,…,N} We then consider a subset of neighboring points from this time series, whose length is given by the embedding dimension n: $\{x_i, x_{i+1}, \ldots, x_{i+n-1}\}$. This set of neighboring points is placed in increasing ordered:

$$x_{i+k_1} \leq x_{i+k_2} \leq \cdots \leq x_{i+k_n} \quad (1)$$

Where $0 \leq k_1, k_2, \ldots, k_n \leq n-1$. In the case that neighboring points are equal, entries are order so that $k_j < k_{j+1}$. This ordering process allows us to define a unique permutation type for each shape defined by any n neighboring points. This permutation type is denoted π_i and is given by:

$$\pi_i = [k_1, k_2, \ldots, k_n] \quad (2)$$

Where π_i is one of $n!$ possible permutation types. Let $Q(\pi)$ be the number of occurrences of permutation type π appearing in the time series. We define the relative frequency of each permutation type as:

$$p(\pi) = Q(\pi)/(N-n-1) \quad (3)$$

The PE, h_n, with embedding dimension $n \geq 2$ is then defined as:

$$h_n = -\sum_{i=1}^{n!} p(\pi_i) \ln p(\pi_i) \quad (4)$$

The resulting PE, h_n, features invariance with respect to initial conditions. As a result of this feature, the PE of any set of initial conditions within the same basin of attraction will converge to the same value.

METHODOLOGY

In order to assess the viability of using permutation entropy (PE) to characterize changes in gait dynamics, two participant groups were recruited; healthy younger adults in their 3rd decade and healthy older adults in their 7th decade. Measurements for each participant were taken in two different configurations; normal walking at 0.9 m/s (baseline) and walking at 0.9 m/s while performing a secondary cognitive task (dual-tasking). By calculating and comparing the PE of the medial-lateral center of pressure migration during both walking conditions, the sensitivity of PE to changes in gait dynamics can be assessed. Furthermore, the PE of the two different participant groups can be compared to see if PE is sensitivity to changes in gait caused by aging.

Participants

Two groups (n=30 per group) were recruited: (a) active healthy young adults (mean age 25 years, SD 3.2) and (b) healthy, community-dwelling older adults (mean age 63 years, SD 4.4). Participants were excluded if they had a history of falls or had a diagnosis of any of the following conditions: (a) muscular-skeletal injuries or disease (e.g. rheumatoid arthritis, advanced hip/knee osteoporosis or arthroplasty) (b) neurological disorders (e.g. stroke, multiple sclerosis, ALS, brain tumor, Parkinson's disease, Vestibular disorders, or (c) any recent medical illness that would affect their balance or ability to walk without aids for a period of at least six minutes.

Test Protocol

Participants were positioned on the treadmill 100 cm away from a 76 cm (30-inch) monitor at the start of walking. The monitor was connected to a computer running the instrumented game (see Figure 1(A) for picture of the set-up). Participants were given instructions and allowed to play the cognitive computer task in standing to become familiar with the task. Participants walked on a level treadmill at a speed of 0.9 m/s under the following conditions: (a) walk alone, (b) walking while performing the cognitive game task. The order of single and dual task conditions was randomized to minimize potential order effect.

The participants involved in the study were subjected to two different trials. The first trial was regular (baseline) walking at 0.9 m/s for 4 minutes. The second trial consisted of walking at 0.9 m/s while playing the cognitive game (dual tasking). Duration of the dual-task trial was 2 minutes. Although the trials had different lengths, PE was calculated over equal window sizes to eliminate the impact of data length.

In order to assess the test-retest reliability of PE measurements, the older adult participants were tested on two different occasions, separated by a week.

Equipment

A standard treadmill was used with handrails and an over-head harness to provide safety while conducting assessments. A treadmill pressure mat (Vista Medical, Winnipeg, MB) was fitted underneath the belt of the treadmill. The pressure mat consisted of an array of 512 pizo-resistive sensors (with an area of 2.8 cm^2) which were enclosed in a Teflon skin and sampled at approximately 30Hz (subject to inconsistencies in hard drive write speed). This allowed the collection of calibrated foot-ground forces from each individual sensor. Center of pressure migration during the trial was then calculated using the pressure mat data. Figure 1(B) shows a sample of the pressure data collected during the trials.

Interaction with the secondary cognitive task was achieved with an inexpensive commercially-available wireless computer mouse. The computer mouse is small and equipped with inertial sensors. The motion mouse was secured with Velcro to a headband. This method allowed head rotation (left-right and/or up-down) to be used as the computer input device. With this simple method, seamless, responsive and high fidelity hands-free interaction with any computer application (custom or commercial exercise/ brain fitness game) was made possible. Visually guided head movements are among the most natural and therefore can easily be performed with minimal instruction.

Secondary Cognitive Task

The secondary cognitive task consisted of playing a game, the objective of which was to move a paddle and interact with falling objects. Objects appeared every 2 seconds at random locations on the display. The objects fell for 1.5 seconds, after which time the participant's paddle either successfully intercepted and caught the target as it reached the bottom of the screen, or the participant missed the target.

The test game generated a logged game file to record (at 80 Hz) the following signals associated with actions performed by the participant with respect to game play events: (a) time index and coordinates of each game object and (b) position coordinates of the game paddle. Furthermore, overall game-play statistics such as success rate and average reaction time were recorded. These overall game-play statistics were recorded in standing and during the dual-tasking condition. This allowed for the impact of dual-tasking on the participant's game scores to be assessed.

Statistical Analysis

Detailed statistical analysis of the results was conducted in order to assess the ability of PE to characterize walking dynamics. The effect of walking condition (within group factor; walk-alone vs. dual-tasking) and age (between group factor; younger vs. older age group) was evaluated using a 2-way repeated-measures analysis of variance (ANOVA). The significance level, or p-value, of the ANOVA was used to assess whether the values of PE were meaningfully different. A p-value of less than 0.05 is required to suggest a meaningful difference, with lower p-values suggesting increasingly more significant differences.

Assessment of test-retest reliability was achieved using the intraclass correlation coefficient (ICC). The ICC assesses how similar two groups are. Values of the ICC range from 0 to 1 where 0 represents two uncorrelated groups and 1 represents perfect correlation.

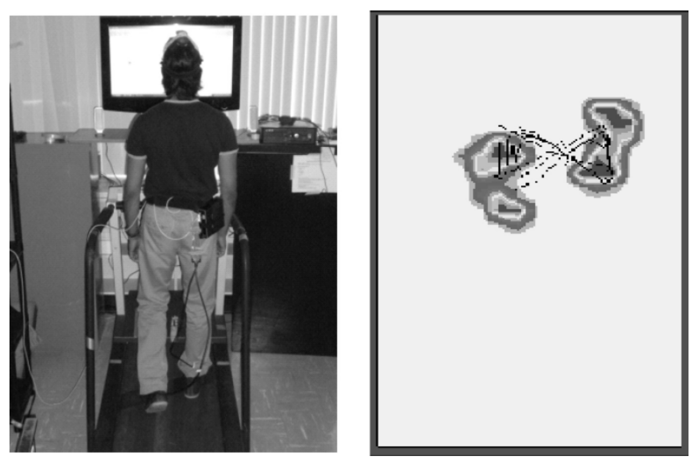

FIGURE 1. (A) INSTRUMENTED PARTICIPANT INTERACTING WITH THE MONITOR DURING A TRIAL (B) READING FROM PRESSURE MAT DURING TESTING

RESULTS AND DISCUSSION

Window Size

Establishing the length of data required to obtain meaningful results is vital. In [16], Staniek demonstrated that PE shows a sensitivity to window size when small window sizes are used. However, once the window size is sufficiently large, PE is almost independent of window size. The region when PE is dependent on window size must be avoided as in this region the measure has not converged to its final value and is not reliable [16].

In order to find the window size after which PE becomes saturated, PE was calculated for windows of increasing size.

Calculations were performed on a 240 second long trial of typical walking and a 120 second long trial in the dual-tasking condition. The mean PE for each window size was calculated across the length of the entire trials. These results are presented in Figure 2. This figure shows the clear saturating effect of increasing the window size. A window size of 1800 samples (corresponding to approximately 60 seconds) was deemed to reduce the error to an acceptable level.

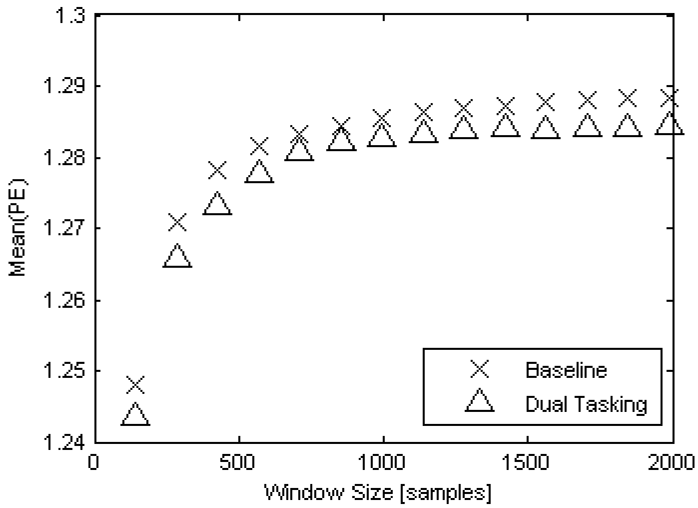

FIGURE 2. EFFECT OF WINDOW SIZE ON PE

Test-Retest Reliability

Assessment of the test-retest reliability of PE measurements was based on the two separate test sessions conducted with the older adult group. The ICC of baseline walking and dual-tasking conditions were 0.79 and 0.81, respectively, which demonstrates strong test-retest reliability.

Impact of Dual Tasking on Cognitive Task

There was a significant decrease in success rate of the cognitive task (88% versus 75%; $p<0.01$) while in standing compared to walking. There was also a significant increase ($p<0.01$) in movement response time and in mean residual movement error from standing to walking conditions. This demonstrates that the addition of walking negatively impacted the participants' ability to perform the cognitive task.

Test Sensitivity

The different walking conditions performed by the young and older adults were used to investigate the sensitivity of PE to changes in the gait dynamics. The PE for each participant in the older adult group and the young adult group was calculated for each case. The mean PE with standard error for each case is presented in Figure 3. There was a highly significant ($p<0.001$) decrease in PE from walk-alone to dual-tasking conditions, and a highly significant ($p<0.001$) age effect; the decrease in PE from walk-alone to dual-tasking conditions was significantly greater in the older group compared to the younger group. Post hoc analysis (t-test) revealed no significant age effect on PE for the walk alone condition.

A secondary analysis of the effect of dual-task walking on conventional spatiotemporal gait variables (single-support time, swing time, step time, and step width) was also performed on the data from both groups. An ANOVA revealed a statistically significant effect ($p<0.01$) between walk alone and dual-task walking on the conventional spatiotemporal gait variables (mean and coefficient of variation) in the older adult group. In contrast, there was no statistically significant difference in the young adult group. These findings are consistent with recent studies which show a significant decline in walking performance measures during dual-task walking conditions in older aged adults [15].

Although this research is not at a state where a definitive connection between PE and walking performance can be claimed, the observation that a decrease in complexity accompanies degradation in balance control is not new. Studies on the complexity of standing balance have shown that complexity decreases when constraints like cognitive load, age or disease are placed on postural control [13]. Considering the nature of the adjustments made to balance could offer an explanation for this observation. Frequent and subtle adjustments to balance associated with healthy walking are likely to produce a large variety of different permutation types in the time series, leading to high PE. In contrast to this, large adjustments or stumbles would create simpler features like local extrema in the time series, which consist of relatively few permutation types and would result in a lower value of PE.

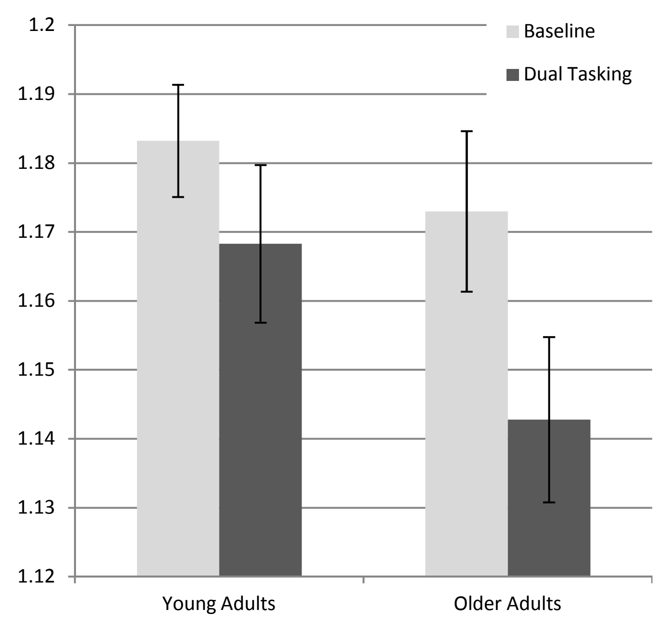

FIGURE 3. MEAN PE OF BOTH PARTICIPANT GROUPS FOR BL WALKING AND DT (WITH STANDARD ERRORS)

CONCLUSIONS

Permutation entropy (PE) is a measure of the complexity of a time series which boasts robustness to noise, computational efficiency and invariance with respect nonlinear monotonous transformations [7]. In this paper, the suitability of using PE to measure gait dynamics was assessed based on repeatability and sensitivity. A preliminary analysis of the test-retest reliability of PE measurements showed strong measurement reliability between different test sessions. A detailed sensitivity analysis to the gait impairment caused by the addition of a secondary cognitive task (dual-task walking) showed that for older participants, PE measures a highly significant difference ($p<0.001$). A similar, but less significant difference ($p=0.03$) was detected in the younger population group.

Future work is to include comparing the findings of PE to that of other measures of complexity (like SampEn and FuzzyEn), further testing the sensitivity of PE to gait changes by studying additional demographics/walking conditions and a study on the impact that changes in conventional spatiotemporal gait variables (single-support time, swing time, step time, and step width) have on the measurement of PE. Although further investigation is needed, PE has thus far demonstrated very favorable properties in characterizing the dynamics of walking.

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