A New Approach to Gait Variability Quantification using Cyclograms

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Abstract: Human gait is cyclic movement and its properties are not constant. Gait variability is widely assessed by fluctuation in spatio-temporal parameters. Since this method operate on a single parameter of the gait cycle, the cycle signal in its entirety does not affect the result. The objective of this work is to present new gait variability assessment method. In order to quantify the variability of entire gait cycle, we have proposed and tested the method based on synchronized cyclograms. The novel approach showed the ability to assess gait variability. The method is not restricted to gait variability assessment and would be beneficial in different areas of cyclic movement variability analysis.

1 INTRODUCTION

The properties of movement are not constant when one moves repeatedly. There are slight alterations in each individual cycle of movement. Fluctuation in gait parameters from one stride to the next is referred as intra-individual gait variability. Fluctuation can be seen even when there are no environmental or external perturbations (Hausdorff, 2005).

The alternation of gait variability shows gait that is influenced by disease (e.g. Parkinson's disease, dementia, multiple sclerosis) (Blin et al., 1990; Jamour et al., 2012; Kaipust et al., 2012) or healthy ageing (Grabiner et al., 2001). Increased gait variability is related to changes in mobility, higher risk of falls (Brach et al., 2005; Hoskovcová et al., 2015) and subtle alterations in underlying physiology (e.g. cardiovascular changes, mental health) (Hausdorff et al., 1994; Hausdorff et al., 2003). Evidence indicates that gait variability may serve as a quantifiable feature of walking function.

Usually, standard deviation and coefficient of variation of kinematic or spatio-temporal parameters of stride are used to assess gait variability (Blin et al., 1990; Hausdorff et al., 1994; Hausdorff et al., 2003; Grabiner et al., 2001; Brach et al., 2005). Nonlinear methods, e.g. detrended fluctuation analysis and approximate entropy, have also been used to quantify gait variability (Kaipust et al., 2012). The most commonly employed parameters are stride length, stride width, and cycle timing (e.g. duration of various phases) (Blin et al., 1990; Grabiner et al., 2001; Hausdorff et al., 2003; Brach et al., 2005; Kaipust et al., 2012; Hoskovcová et al., 2015). Since these methods operate on a single parameter of the gait cycle, the cycle signal in its entirety does not affect the result. Next, different methods have different requirements on walking distance, e.g. nonlinear methods work better over long walks. However, these methods and specified parameters are more difficult to interpret and use in clinical practice.

While spatio-temporal parameters provide information about discrete time events (features) variability, e.g. the double support phase duration, they do not describe the complete curves i.e. development of a feature. For example, curves may have similar peak values indicating low variablity but different waveforms. Therefore, we present an approach to gait variability quantification that enables the evaluation and comparison of entire stride signals. This comparison is carried out by the continuous symmetry method, namely the method of cyclograms (also called cyclokinograms) (Goswami, 2003). The concept of cyclograms, although known to the biomechanics community, has not been mentioned as a tool for evaluating gait variability. The first mention of a cyclogram (Grieve, 1968) argued that a cyclic process such as walking is better understood if studied with a cyclic

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plot. The method of cyclograms is usually used, but not limited, to symmetry (similarity) assessment of contralateral limbs signals. Our approach is to use the method of cyclograms to assess gait variability via inter-cycle similarity. Intra-individual gait variability is assessed by the comparison of entire consecutive stride signals to each other. It means the similarity of entire stride signals (not only one parameter of the stride) is assessed.

In our case, we will use cyclograms for evaluating gyroscope data, i.e. angular rate of lower limb movements during gait. Cyclograms in conjunction with gyroscope data has not been used before for evaluating gait variability. This new application of gyroscope data and cyclograms can provide new clinical use in the diagnosis of patients.

2 METHODS

2.1 Participants

In the study we included 34 Parkinson disease (PD) patients (24 males, 11 females), mean age 67.2 years (SD 7.9), with mild to moderate PD. The control group included 21 volunteers (13 males, 8 females), mean age 65.5 years (SD 8.4), with no history of neuropsychiatric disorders. All PD patients were evaluated in OFF and ON medication states within the same day. The first examination in clinically defined OFF state was followed by an examination in the ON state after a dose of levodopa equivalent to 150 % of their usual morning dose. The study was approved by the Ethics Committee of the General University Hospital in Prague, Czech Republic, and therefore performed in accordance with the ethical standards established in the 1964 Declaration of Helsinki.

2.2 Data Acquisition

Xbus Master (Xsens Technologies B.V.), a lightweight (330g) portable device using motion tracking units (MTx) for orientation and acceleration measurement of body segments, was used for the measurement of segment movements. The MTx unit with an embedded accelerometer and gyroscope is an accurate inertial measurement unit measuring drift-free 3-D orientation and 3-D acceleration. Kinematic data was recorded from 3 gyro-accelerometers with a data sampling rate of 100 Hz. The gyro-accelerometer units were symmetrically attached on the lateral shank of each lower leg, 4 cm above the ankle joint; and the chest, 2 cm below the sternal notch. They were calibrated according to manufacturer instructions.

All subjects accomplished an extended Timed Up & Go Test (ETUG) (Wall et al., 2000). Each subject was observed and measured while he/she rose from a chair during the ETUG, walked 7 meters, turned, walked back, and sat down again. Two repeated collections of ETUG were recorded for each subject (i.e. patients and healthy subjects). One of two ETUG trial's accomplishments was randomly selected and processed.

The MTx unit of the chest was utilized in identification subcomponents of ETUG (see subsection Method of Data Processing). Two MTx units, lower leg units, were used to process all three angular rate signals in the particular axes. Besides, we evaluated the magnitude of the angular rate vector

$$\|\omega\| = \sqrt{\omega^2_{vertical} + \omega^2_{horizontal} + \omega^2_{sagittal}} \quad (1)$$

This was done in order to eliminate incorrect placement of the measurement units.

2.3 Method of Data Processing

Before further processing, the raw angular rate signal was low-pass filtered with a zero-phase second-order Butterworth filter with a 60 Hz corner frequency. The ETUG subcomponents, namely sit-to-stand, gait, turn, and turn-to-sit, were automatically identified, see (Salarian et al., 2010). The gait cycles of the steady gait components were determined by automatic identification (Salarian et al., 2010). All preprocessing and analysis was carried out offline using the MatLab (MatLab R2010b, Mathworks, Inc., Natick, MA, USA) programming environment.

The GaitRite instrumented walkway (7.0 m long and 0.6 m wide) and a video camera were used as the references for the TUG subcomponents and gait characteristics to verify implementation of implemented algorithms (not published). Previous studies have verified that the GaitRite is a valid and reliable method for measuring mean gait characteristics in older adults (Menz et al., 2004). During each trial, the video camera recorded at 25 frames per second and was used to determine total step count over the complete trial.

The signals of both lower limbs were used. Gait cycles signals were time-normalized to the same length, see Figure 1. The inter-cycle comparisons via the cyclogram method were done. It can be assumed that lower variability in gait cycles is demonstrated by their high level of similarity (low level of dissimilarity). It is possible to use two options to achieve inter-cycle comparison. The first is to compare each gait cycle to the consecutive one. In this way we get $n-1$

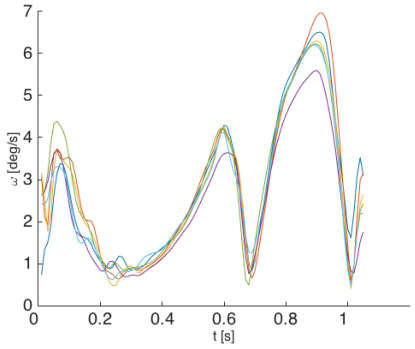

Figure 1: Example of six gait cycles from subject no. 1 (PD OFF). ω - magnitude of angular rate, t-time.

comparisons from n gait cycles. The second option is to compare each gait cycle with all other cycles. In this way we get

$$\frac{n!}{2!(n-2)!} \quad (2)$$

comparison from n gait cycles. The disadvantage of the first option is that the same amount of change (e.g. same level of dissimilarity) between all consecutive cycles does not adequately reflect the real variability, e.g. dissimilarity between first and last cycle. Thus, we employed the second option. Then, the median of all inter-cycles comparisons was computed. According to the assumption, the higher value of dissimilarity represents the greater variability of gait.

2.4 Method of Cyclograms

The creation of cyclograms is based on plotting two gait variables vs. each other (Figure 2). In the case of the traditional use of cycles for gait evaluation, two time-series (trajectories) should be identical and a cyclogram should lie on a symmetry line (Kutilek et al., 2014). In our case, the two time-series are time-series of two gait cycles. The symmetry line is a straight line passing through the origin inclined at an angle of 45 degrees. We can also compute the area within the cyclogram, and its orientation to evaluate the rate of asymmetry (Goswami, 2003). We can express mathematically the cyclogram deviation from the cyclogram of an ideal symmetric gait to obtain a quantification of asymmetry. The triplet of geometric properties of cyclograms, namely the area within the cyclogram (S), orientation (α), and moment (J), can be represented by points in 3D space (Figure 3). The ideal point for symmetric gait has the coordinates (0, 45, 0), (Goswami, 2003). The point in the 3D space of the geometric properties of a cyclogram was determined for each measurement. Then, the asymmetry, A, was defined as the distance from the measurement point,

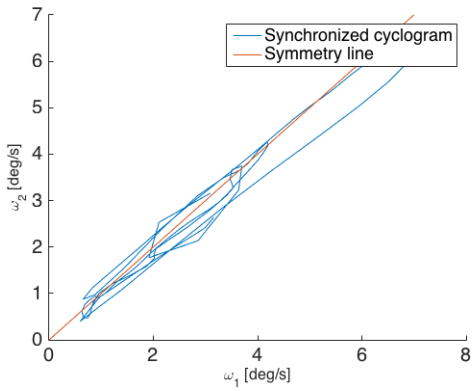

Figure 2: Example of the cyclogram of angular rates of two consecutive gait cycles of subject no. 1. ω_1-magnitude of angular rate of the first gait cycle, ω_2-magnitude of angular rate of the second gait cycle.

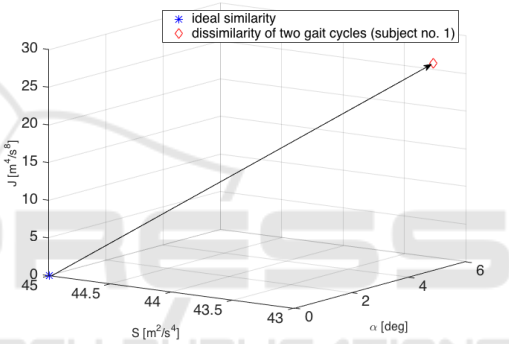

Figure 3: Example of three geometric properties of the cyclogram (subject no. 1). The distance from the point of geometric properties of ideally similar curves (star symbol, [0, 45, 0]) to the point of current cyclogram properties (diamond symbol, [5, 43, 26]) is the quantifier of the curves dissimilarity.

M, and ideal point I:

$$A = \sqrt{(S_M - S_I)^2 + (\alpha_M - \alpha_I)^2 + (J_M - J_I)^2} \quad (3)$$

In our case, the asymmetry, A, is the measure of the dissimilarity of two gait cycles. The higher value of dissimilarity, the higher variability of gait cycles. The indicator of gait variability based on cyclogram characteristics was calculated for the measured movement of the lower limbs of all healthy subjects and PD patients.

2.5 Statistical Analysis

Statistical analysis was performed to examine whether gait variability via the method of cyclograms is able to distinguish a healthy subject from a PD patient. The exclusion criterion was that all gait cycles

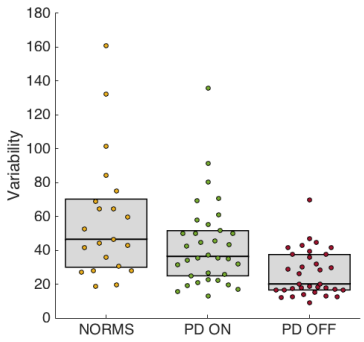

Figure 4: The values of cyclogram-based variability quantifiers for angular rate magnitude.

before turn are detected. Shapiro-Wilk test was used to verify the normality of parameters in each observed dataset. The assumption of normal data distribution in the observed datasets has been rejected (significance level $p = 0.05$). Therefore, nonparametric Wilcoxon signed rank test was used to compare the statisticaly significant differences in gait variability between PD patients in the ON and OFF state. Nonparametric Wilcoxon rank sum test was used to compare PD patient data to norms data. The significance level was set to $p < 0.05$. Statistical analyses and data processing were performed using MATLAB sw (MatLab R2010b, Mathworks, Inc., Natick, MA, USA).

3 RESULTS

The gait variability assessment via method of cyclograms revealed a significant difference between the control group and PD ON in the variability of the angular rate about the sagittal-axis ($p < 0.01$). The statistically significant difference between the control group and PD OFF has been proven in the variability of the angular rate about the sagittal-axis ($p < 0.01$) and magnitude ($p < 0.01$). The variability about the vertical-axis ($p < 0.01$) and the magnitude of the angular rate ($p < 0.01$) delivered a significant difference between PD ON and PD OFF. The variability about the horizontal-axis did not exhibit a statistically significant difference in any of the evaluated cases. For detailed statistical evaluation see Table 1. The distribution of values of the new variability quantifier is shown in Figure 4.

4 DISCUSSION

We tested and verified a new method of gait variability assessment that is derived from the geometric properties of cyclograms. To our knowledge, this is the first report of the use of symmetry quantification techniques to evaluate stride-to-stride fluctuations.

The results obtained by this novel approach showed a discriminative ability between evaluated subjects groups. Hausdorff et al. (Hausdorff et al., 1998) revealed increased gait variability in PD. Our results are not inconsistent with his findings. In contrast to their work dealing with relative changes in gait parameter variability, our work focused on absolute change in gait cycle variability. Normalization can be included in signal preprocessing to achieve relative change in gait variability. Moreover, they analysed the gait cycle timing while our work deals with rotational properties of gait. Our results confirm that medication has an effect on gait variability in PD as was also mentioned in a previous study (Bryant et al., 2016).

The advantage of our approach to gait variability assessment is the analysis of an entire gait cycle unlike the calculation of coefficients, which are mainly used for quantification of a gait cycle at a specific time. Thus, this method can be employed on any gait signal regardless of precisely predefined events, e.g. double support phase. The other advantage of this method is the uniform approach to gait variability in all movement direction and thus, the possiblity of comparing the impact of a disease or pathology on movement in different directions can be applied. The analysis of variability in various movement directions can reveal new knowledge and clinical interpretations.

Another potential of this method is that it is a general approach to signal variability analysis that can be employed in other areas of cyclic movement analysis, e.g. finger tapping test, stairs ascending/descending, stand-to-sit-to-stand tests.

Different methods quantify different aspects of gait variability and work with various spans of gait signal length, e.g. number of gait cycles. By intra-subject signal normalization to the same length when utilized method of cyclograms the result is unaffected by gait cycle duration. Next, the selection of an appropriate method for specified research or clinical aim is crucial in gait variability assessment (Chau et al., 2005). Therefore, this new approach to gait variability assessment is not a replacement of existing methods but is complimentary.

There are limitations to our study. The most important one is that the sample of the subjects probably is not representative of the larger population. However, to verify the ability of the proposed method to assess gait variability in this preliminary study, a sam-

Table 1: Statistical evaluation of variability via similarity measures. * differences significant at the Holm-Bonferroni-corrected level of $p < 0.05$ (for 4 tests performed).

	Norms vs PD ON	Norms vs PD OFF	PD ON vs PD OFF
$\omega_{vertical}$	0.45	0.26	$< 0.01*$
$\omega_{horizontal}$	0.90	0.33	0.12
$\omega_{sagittal}$	$< 0.01*$	$< 0.01*$	0.05
$\|\omega\|$	0.03	$< 0.01*$	$< 0.01*$

ple of subjects is sufficient. A second limitation in this study is the number of measurements made of each subject. Some patients had stability problems, as is common in these patients, therefore only a limited number of instrumented tests could be performed to ensure that patients remained in a stable motor state.

5 CONCLUSIONS

This paper introduced and tested a new method of stride-to-stride fluctuation using synchronized cyclograms. The variability indicator is based on similarity assessment of gait cycles. We can designate that this method is suitable for the evaluation of gait variability in practice. The proposed method is not limited to gait variability assessment and would be beneficial in different areas of cyclic movement variability analysis. The quantitative analysis of wave form may bring new knowledge of the variability with respect to movement disorders.

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