Using Gait Parameters to Recognize Various Stages of Parkinson's Disease

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***Abstract*— Monitoring gait patterns seamlessly and continuously over time provides valuable information that could help physicians diagnose diseases in the early stages. Currently, traditional gait measurement approaches do not support continuous monitoring of gait and focus on collecting limited data points in controlled lab environments. However, with advancements in wireless technology, movement patterns can be recorded using small portable wearable devices. Parkinson's disease (PD) is a progressively disabling neurodegenerative disorder that is affecting gait and posture and consequently leads to higher risk of falling. Several research studies have looked into changes in the gait parameters of PD patients compared to healthy adults. However, there are only few studies with the focus on gait assessment of PD patients in the early stages as compared to patterns associated with patients at advanced stages. In addition, the number of gait-related studies in this domain using accelerometers on ankle is very limited. Knowing which body location could serve as a target place for accelerometers to provide accurate information is a necessary step toward the health assessment of PD patients. The purpose of this study was to evaluate the gait parameters of patients with mild or moderate PD using accelerometers on ankles. A number of gait parameters, including average stride time, stride time variability, stride time symmetry, and oscillation of acceleration in the mediolateral (ML) direction were calculated and compared between PD patients and healthy elderlies. Preliminary results indicate that features extracted from accelerometers on ankles can be effective in differentiating between healthy elderlies and PD patients at mid-stages of disease but less so at earlier stages of disease.**

Keywords-Gait patterns; Parkinson's Disease; early diagnosis; preventive healthcare; wearble devices; data analystics.

I. INTRODUCTION

Strategies based on gait analysis have been used in clinical research to identify parameters associated with normal and abnormal gait to evaluate consequent changes after operations or after receiving treatments. Monitoring gait patterns seamlessly and continuously could provide a valuable source of information to help healthcare providers diagnose diseases in the early stages. It would also help physicians to assess treatment options and recommend best treatments, potentially without the need for frequent visits by patients to healthcare centers. Currently, traditional gait measurement approaches are based on collected gait data in laboratory setting, which does not support the concept of continuous monitoring. In addition, individuals are likely to do their best when asked to perform a set of actions in laboratory settings, resulting in different gait measurements as compared to those collected during normal daily life. Portability and affordability of wearable sensors along with improved accuracy and capability of monitoring gait during daily activities make them highly effective devices for capturing gait patterns and consequently continuous clinical gait analysis [1]. Therefore, wearable gait monitoring devices such as accelerometers have recently emerged as viable options for clinical gait assessment.

Gait abnormality is a common issue in patients with nervous system problems, including patients with Parkinson's disease (PD). PD is a neurological condition decreasing the dopamine level. This condition leads to muscle function and mobility impairment and consequently leads to higher risk of falling and reduces ability to perform daily functions. Gait abnormalities in PD can be classified into two types: episodic and continuous [2]. Continuous changes refer to changes in the gait patterns that are persistent all the time. Episodic gait changes occur from time to time and includes start hesitation, festination and freezing of gait [3]. Altered gait in PD patients either with or without freezing gait has been reported as an issue affecting these patients' independence and quality of life [2], [4]–[6]. Therefore, it is essential to examine gait characteristics of this population to prevent these undesired situations and help them towards having a better health condition. Understanding how gait parameters change in the PD patients and keeping track of gait abnormalities over time would help physicians to have a better understanding of disease, provide better treatment options and potentially diagnose PD at early stages.

Even though accelerometers are not yet routinely used for measuring gait and posture parameters related to PD, they have already been used to assess several motor complications in PD patients [7]–[9]. Several studies have focused on identifying discriminating gait parameters between healthy population and patients with PD using accelerometers. For example, analysis of step initiation from one accelerometer on the trunk could provide useful information for the characterization of patients in the mild to moderate stages of PD [10]. Okuda et al compared PD patients with healthy younger and healthy older adults, based on their gait components in vertical, ML, and AP directions, using a single accelerometer located at the level of L4. An accelerometer attached to the posterior trunk could reveal postural instability in patients with untreated PD [11]. Although tri-axial accelerometers have been shown to be valuable and reliable

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tools for continuous gait monitoring in patients with PD [12], they have not been extensively tested and used for analyzing gait parameters of this population in the early stages of disease. Moreover, movement quality in patients with PD has been mostly studied using accelerometers attached to the upper body [10]–[12], while in the clinical diagnosis of patients with Parkinson's disease, the ambulatory estimation of lower extremity movement in the gait is necessary [12]. Only few studies have tried accelerometer on ankle to detect various phases of gait [13] and only one study focused on spectral analysis of gait variability using accelerometer on participants' left heel [14]. No studies have been reported on the analysis of gait in the patients with PD using accelerometers on ankles.

Since the usage of sensors and accelerometers in the clinical diagnosis of patients is emerging, it is essential to understand which body sites should be targeted to attach the sensors to. We may even realize that for various levels of a disease severity, different body sites could provide different information or one body location is a better target than the other to attach the sensor to. This study aims to assess gait parameters of patients with mild to moderate PD using two accelerometers on both ankles. This study also provides us an insight about the efficacy of attaching accelerometers on ankles for gait assessment of patients with mild or moderate PD.

II. Methodology

A. Participants and Procedure

We used accelerometers-derived data from a publically available data set collected by Barth and colleagues [15]. The experiment was conducted under two protocols: free-walking protocol, and 40-meter walking protocol. In the free-walking protocol, 5 healthy elderlies and 5 patients with PD were asked to walk two minutes around the hospital two times with their comfortable walking speeds. We used the first two minutes for our analysis of the data collected from the free-walking protocol. In the 40-meter walking protocol, 10 healthy elderlies and 10 patients with PD were asked to walk 10 meters four times at their comfortable speed and in an obstacle-free environment. In both protocols data was sampled at 102.4 HZ and collected from subjects' left and right ankles using SHIMMERS. SHIMMER is a validated flexible inertial sensing platform for noninvasive biomedical research and includes one triaxial accelerometer and one gyroscope [16]. X, Y, and Z axes of accelerometer represent signals in the AP, Vertical, and ML directions, respectively. Table I and Table II show subjects' information for free-walking and 40-meter walking protocols, respectively.

The Unified Parkinson's Disease Rating Scale (UPDRS) and Hoehn and Yahr (H&Y) scale are shown for PD patients. UPDRS and H&Y are two scales showing PD symptoms progression. UPDRS III is a part of UPDRS and associated with the motor examination score. As it can be seen in Table I and Table II, PD patients from the free-walking test are in a more progressed level of disease on average compared to PD patients from 40-meter test. Although two protocols' subjects are not the same, having these two datasets including patients with different levels of PD provide us the opportunity to test the efficacy of accelerometers on ankles of patients with PD with a broader range of disease severity.

TABLE I. Subjects' Characteristics - free-walking protocol

	Control	PD
Number of subjects	5	5
Gender (M/F)	3:2	3:2
Age	64 (10)	72 (6.3)
UPDRS III		20.8 (6.1)
H & Y		2.6 (0.5)

TABLE II. Subjects' Characteristics – 40-meter protocol

	Control	PD
Number of subjects	10	10
Gender (M/F)	5:5	5:5
Age	64 ± 8.4	63.8 ± 9.3
UPDRS III		12.7 ± 6.0
H & Y		1.7 ± 0.9

B. Gait Parameters

Data preprocessing and stride segmentation are two necessary steps prior to extracting gait parameters. Both steps were performed as explained in our previous research study [17]. Data from z-axis of gyroscope has been used for step/stride segmentation with the characteristic peak in the middle of swing phase [18], [19]. We implemented the stride segmentation algorithm proposed by Salarian and his colleagues [19] and peaks were identified using the conditions applied in the study by Barth et al. [15]. Using Gold standard data and post processing, we included strides that were missed by the algorithm and removed miss-identified strides. We removed each subject's first and last two strides, thereby eliminating any irregularities associated with the initiation and termination of gait [20]. The diagram in Figure I shows gait parameters we included in our study.

Simple temporal parameters such as average stride time can be recorded using a single accelerometer. Average stride time has been used in evaluation of disease-related gait differences [14], [21]. Thus, we calculated the average stride time for each group in our study and then compared it among the groups.

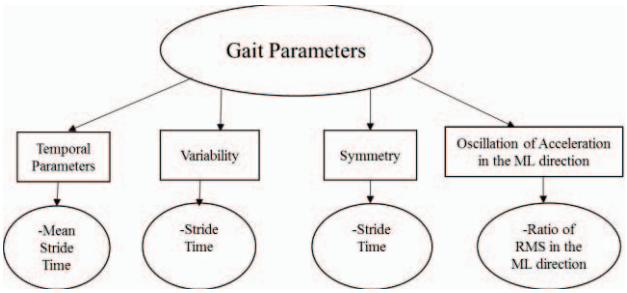

Figure I. Gait parameters and their measurements

Gait variability, defined as stride-to-stride fluctuation has been shown to be sensitive to aging and pathology [21], [22]. There is evidences for increased gait variability in patients with

PD even in the early stages of disease [23]. In our study, variability of stride time was calculated as the within-person coefficient variation (CV) across strides considering both left and right sides.

In addition to stride-to-stride fluctuations, gait symmetry is also reported as a significant gait parameter in patients with PD [24]. To measure symmetry of stride time, as in (1), differences between left and right ankle acceleration were calculated using the following equation, in which Fl is the value of the gait parameter F associated with the left ankle and Fr is the value of the same gait parameter associated with the right ankle. Perfect symmetry would have a score of zero.

$$\text{Symmetry} = 1 - \frac{\text{Min}(Fl,Fr)}{Max\ (Fl,Fr)} \quad (1)$$

Root mean square (RMS) of acceleration is a statistical measure of the magnitude of acceleration that has been frequently reported in gait research [25]–[28]. it is suggested to normalize RMS by magnitude of acceleration in three directions [26]. It has been shown that normalizing RMS provided more consistent results across gait analysis research, mostly showing that the normalized RMS of acceleration in the ML direction is significantly higher in people with movement disorder than healthy subjects [25], [26]. In this study, we normalized RMS of acceleration in the ML direction using the following formula proposed by [26] where ML represent the mediolateral direction and $RMSR_{ML}$ is called the ratio of RMS in the ML direction. This measure shows the lower body oscillations in the ML direction.

$$RMSR_{ML} = \frac{RMS_{ML}}{\sqrt{{RMS_{AP}}^2+{RMS_{ML}}^2+{RMS_{Ver}}^2}} \quad (2)$$

Signal Vector Magnitude (SVM), as in (3) is representing intensity. We included SVM as a gait parameter since it is reported as one of the metrics for continuous gait monitoring using accelerometers [29].

$$SVM = \sqrt{X^2 + Y^2 + Z^2} \quad (3)$$

Another gait parameter used in our study was mean of the maximum acceleration per stride in the AP direction.

C. Statistical Analysis

All statistical analyses were performed using SPSS. We used ANOVA ($\alpha = 0.05$) to determine the difference between gait parameters associated with two groups under study. Average stride time was normalized using log transformation for 40-meter walking protocol. Variability and symmetry of stride time were normalized using log transformation for the data from the free-walk protocol. We did not perform homogeneity of variance test since we had equal sample sizes in both protocols.

III. Results

Table III and Table IV show the results of two groups' pairwise comparison regarding all gait parameters mentioned above for the free-walk protocol and 40-meter walk protocol, respectively.

TABLE III. GROUPS' PAIRWISE COMPARISON FOR ALL PARAMETERS FROM THE FREE-WALK PROTOCOL

Parameters	Healthy elderlies vs PD	
	Mean difference	*p-value*
Mean_StrideTime	.53	.621
CV_StrideTime	-.28*	.009
Sym_StrideTime	-.025	.334
$RMSR_{ML}$	.042	.299
SVM	-.210	.119
Mean_MaxAccPerStride_AP	.730*	0.020

TABLE IV. GROUPS' PAIRWISE COMPARISON FOR ALL PARAMETERS FROM THE 40-METER PROTOCOL

Parameters	Healthy elderlies vs PD	
	Mean difference	*p-value*
Mean_StrideTime	.041	.721
CV_StrideTime	-.023	.953
Sym_StrideTime	-.003	.971
$RMSR_{ML}$	-.025	.088
SVM	-.068	.622
Mean_MaxAccPerStride_AP	-.48	.368

As it can be seen in Table III, two gait parameter that are significantly different between healthy elderlies and patients with moderate PD are stride time CV and mean of maximum AP acceleration per stride. Stride time CV is significantly lower in healthy elderlies compared to patients with moderate PD and maximum AP acceleration per stride is significantly higher in healthy group compared to the PD group. Our results for the 40-meter test indicate that there is no statistically significant difference between elderlies and PD patients in the very early stages of disease.

IV. Discussion

The purpose of this study was to examine some of the gait parameters of patients with mild or moderate PD using two accelerometers on both ankles and to examine the efficacy of using data only from accelerometers on ankles to assess gait parameters of this population. Two data sets were selected from a study by Barth et al. [15]. Both data sets included subjects from healthy elderlies and patients with PD. Two data sets were collected under two protocols: free-walk protocol, and 40-meter walk protocol. Although two protocols were not the same, but they were similar since subjects performed a walk on the ground in both protocols. Our PD patients from the free-walk data set had a score of 2.6 H&R on average, while patients from the other data set had a score of 1.7 H&R on average. This indicates that patients in the first data set had more sever PD compared to the second data set. In the free-walk data set, elderlies and patients with PD were not age matched, while elderlies and patients with PD were age-matched in the 40-meter data set.

Our results show that mean stride time was not significantly different between healthy elderly and patients with PD under

both experimental conditions. This confirms other research studies' results [14], [21].

Mean stride time CV was significantly different between healthy elderlies and patients with moderate PD. This result is consistent with the results of study by Henmi et al. [14] and Hausdorff et al. [21] in which they found significant difference between healthy control and PD groups regarding the variability of stride time. However, mean stride time CV was not significantly different between healthy elderlies and patient with mild PD. This result could be due to the fact that the degree of gait variability is correlated with the level of disease severity [21] or because of the limitation of using accelerometers on ankle in capturing gait abnormalities in the early stages of disease.

There was no significant difference between mean stride time symmetry of elderlies and patients with PDs. However, it does not mean that there is no asymmetry in the classic PD motor symptoms [24], [30].

Evaluation of RMS of acceleration by Okuda et al. [25] showed that RMS of trunk acceleration in the ML direction was significantly higher in patients with PD compared to healthy older adults. Results of our analysis for the ratio of RMS in the ML direction showed no significant difference between two groups. This inconsistency could be the result of having PD patients with a lower degree of disease severity in both data sets compared with the PD patients in the study by Okuda et al. [25]. This can be also due to the limitation of using accelerometers on ankle in capturing gait bilateral oscillations because RMS of trunk acceleration in the ML direction is an indicator of sway, while ankle acceleration in the ML direction cannot be an indicator of sway. In fact, we could have a hypothesis, stating that as PD progresses, bilateral oscillation of lower limb may decrease because of the rigidity issue in this population. However, testing this hypothesis needs further investigation.

No significant difference was found between elderlies and patients with PD regarding SVM, indicating that intensity of walking is not different between two populations under the study.

Maximum AP acceleration per stride was significantly different between elderlies and patients with PD from the free-walk protocol in which patients with PD had a higher H&Y score and they were on average older than the PD patients from the other data set. This could either indicate that as the disease progresses, using accelerometers on ankle could reveal some of the gait abnormalities associated with PD or this difference between two groups could be due to the aging process itself, not the disease progression. Further investigation is needed to evaluate the usage of accelerometers on ankle in older population and patients with PD. In our future works, we will add data from geriatrics group and patients in the advanced stages of PD to find out whether gait deficiencies due to aging and advanced stages of PD can be captured using accelerometers on ankle or not.

Based on our findings we can say that accelerometers on ankles are not able to capture gait abnormalities in the very early stages of PD. However, as the disease progresses, features extracted from accelerometers on ankles can be effective in differentiating between healthy elderlies and PD patients.

Limitations: One of the limitation of this study was having limited data sets which makes it impossible to draw a general conclusion about the results. Second limitation of our study was the lack of having age-matched PD patients with elderlies in the free-walk protocol. We also did not have information about patients' medication condition. Being on or off medication has different impacts on gait and posture of this population. Another limitation of this study was the lack of having the same subjects participating in two mentioned protocols. If we had the same subjects participating in both conditions, we could examine gait parameters of these populations in the free- walking condition as well as in the supervised condition.

V. Conclusions

It has been stablished that changes in human gait reflect changes to well-being. Keeping track of changes in the gait parameters associated with PD patients help healthcare providers to have a better understanding of disease, provide better treatment options and potentially diagnose PD at early stages. The purpose of this study was to identify discriminating gait parameters between healthy elderlies and patients with mild or moderate PD using accelerometers on ankles. A number of gait parameters, including average stride time, stride time variability, stride time symmetry, and oscillation of acceleration in the mediolateral (ML) direction were calculated and compared between patients with PD and healthy elderlies. Our findings showed that using accelerometers on ankles, stride time CV and maximum acceleration in the AP direction per stride were significantly different between healthy elderlies and patients with moderate PD. On the other hand, there was no significant difference between healthy elderlies and patients with mild PD regarding all of the extracted gait parameters. It does not necessarily mean that patients with mild PD does not show any gait deficiencies, but may indicate the limitation of accelerometers on ankles in capturing gait abnormalities in this population. Further gait analysis of PD patients in various development stages using accelerometers on various body sites is needed to be able to generalize the results. Overall, our findings indicate that features extracted from accelerometers on ankles can be effective in differentiating between healthy elderlies and PD patients at mid-stages of disease but less so at earlier stages of disease.

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