Gait & Posture

Doi: http://dx.doi.org/10.1016/j.gaitpost.2016.11.024

A model of free-living gait; a factor analysis in Parkinson's disease

Rosie Morris, Aodhán Hickey, Silvia Del Din, Alan Godfrey, Sue Lord, Lynn Rochester

Institute of Neuroscience/Newcastle University Institute of Ageing, Clinical Ageing Research Unit, Campus for Ageing and Vitality Newcastle University, Newcastle upon Tyne, United Kingdom

*Correspondence to:

Lynn Rochester PhD

Professor of Human Movement Science

Institute of Neuroscience,

Newcastle University Institute for Aging,

Newcastle University

Newcastle upon Tyne

NE4 5PL

Email: lynn.rochester@ncl.ac.uk

Tel: (+44) 0191 208 1291

Email: lynn.rochester@newcastle.ac.uk

Word Count: Abstract: 254

Article (Excluding abstract): 1317

Figures: 1

Tables: 2

Supplementary Figures: 1

Abstract

Introduction

Gait is a marker of global health, cognition and falls risk. Gait is complex, comprised of multiple characteristics sensitive to survival, age and pathology. Due to covariance amongst characteristics, conceptual gait models have been established to reduce redundancy and aid interpretation. Previous models have been derived from laboratory gait assessments which are costly in equipment and time. Body-worn monitors (BWM) allow for free-living, low-cost and continuous gait measurement and produce similar covariant gait characteristics. A BWM gait model from both controlled and free-living measurement has not yet been established, limiting utility.

Methods

103 control and 67 PD participants completed a controlled laboratory assessment; walking for two minutes around a circuit wearing a BWM. 89 control and 58 PD participants were assessed in free-living, completing normal activities for 7 days wearing a BWM. Fourteen gait characteristics were derived from the BWM, selected according to a previous model. Principle component analysis derived factor loadings of gait characteristics.

Results

Four gait domains were derived for both groups and conditions; pace, rhythm, variability and asymmetry. Domains totalled 84.84% and 88.43% of variance for

controlled and 90.00% and 93.03% of variance in free-living environments for control and PD participants respectively. Gait characteristic loading was unambiguous for all characteristics apart from gait variability which demonstrated cross-loading for both groups and environments. The model was highly congruent with the original model.

Conclusions

The conceptual gait models remained stable using a BWM in controlled and free-living environments. The model became more discrete supporting utility of the gait model for free-living gait.

Keywords: gait, free-living, Parkinson's disease, principle component analysis

1. Introduction

Gait is a marker of global health, cognition and falls risk [1, 2]. Gait is complex and multifactorial and whilst gait speed is widely used to reflect global performance and is sensitive to pathology and ageing it is not specific. Gait is comprised of multiple characteristics which if measured discretely can further discriminate gait alterations in response to neuropathological changes and ageing. Thus, measurement of gait characteristics over and above gait speed is critical in order to discern pathology and specific features of disease [3]. However, covariance amongst gait characteristics is high and in a bid to eliminate redundancy and ease interpretation, conceptual gait models have been developed [4-7]. Our earlier model identified five domains comprising 16 gait characteristics derived from GaitRite™ [4] (**Figure 1A**). Subsequently the model has been used to demonstrate associations of gait with age, gender and cognition [4, 8].

Traditionally, gait assessments have been undertaken in the laboratory which is costly in equipment and time. Accelerometer-based body worn monitors (BWM) provide a portable and affordable solution for assessment of discrete gait characteristics. BWM allow for prolonged data capture which is essential for fluctuating pathologies such as Parkinson's disease (PD). In addition, data can be collected in habitual environments reducing the influence of Hawthorne effect [9].

To date neither laboratory nor free-living gait characteristics derived from BWM have been applied to a conceptual framework, limiting their utility. Differences occur in gait metrics when comparing GaitRite™ with BWM as the latter measures continuous motion and the former discrete events (separate foot-falls). As a result, BWM

demonstrate increased sensitivity to asymmetry and variability characteristics [10]. In addition, BWM derive 14 of 16 characteristics due to limitations measuring step width and step width variability with single tri-axial accelerometers [10]. Thus, we hypothesise that free-living characteristics will load differently onto a conceptual gait model. Our aims were to i) explore a gait model using BWM in controlled and free-living environments in older adults and PD and ii) compare to our previous GaitRite™ derived model.

2. Methods

2.1 Participants

Subjects with newly diagnosed idiopathic PD were recruited from ICICLE-Gait, a nested study within ICICLE-PD (Incidence of cognitive impairment in cohorts of longitudinal evaluation-PD) between June 2009 and December 2011. Idiopathic PD was diagnosed according to UK PD brain bank criteria. Exclusion criteria included; memory impairment (≤24 Mini Mental State Examination [MMSE]), dementia with Lewy bodies, Parkinson's plus syndromes, poor English and inability to consent. PD participants were tested three years post diagnosis. Age matched controls were recruited from community sources that were >60 years, walked independently and had no significant cognitive impairment, mood or movement disorder. Full details of the recruitment process can be found in [11]. The study was approved by Newcastle and North Tyneside research and ethics committee.

2.2 Clinical Assessment

Age, sex and body mass index (BMI) were recorded for all participants. Disease severity was measured using the Unified Parkinson's disease rating scale (UPDRS).

PD participants were assessed ‘on’ medication for controlled conditions, defined as within 1 hour of medication intake.

2.3 Gait Assessment

Participants were asked to wear a single BWM (AX3; Axivity, York, UK; 100Hz, ±8g) located at the fifth lumbar vertebra. During controlled assessment, participants walked for two minutes around a 25m circuit at preferred pace in a laboratory (see **Supplementary Figure 1**). The BWM was attached with a hydrogel adhesive (PALStickies, PAL Technologies, Glasgow, UK) and Hypafix (BSN Medical Limited, Hull, UK). For free-living assessment, participants wore the BWM continuously for 7 days [12].

2.4 Data Processing

Recorded signals were stored locally on the sensor’s internal memory and downloaded on assessment completion. Raw acceleration data for controlled and free-living assessments were analysed using a bespoke MATLAB® (Version 2015a) program, see [10] and [13] for further details of controlled and free-living data processing respectively. 14 previously validated spatiotemporal gait characteristics [10] were quantified (**Figure 1**).

2.5 Statistical analysis

Free-living data were screened so full 7 day data were included in the analysis only. Data were inspected for outliers with histograms and boxplots. Student t-tests and Chi-squared tests were used to compare demographic data. Principle component analysis (PCA) was conducted to identify independent gait domains in controlled and free-living environments. A varimax rotation was applied to derive orthogonal factor scores with the minimum eigenvalue for extraction set at 1. Items which met a

minimum loading of 0.6 were considered significant. Loading value was increased from previous work due fewer participants [5, 14].

3. Results

3.1 Participants

PD and control participants were matched for age (69.8±9.7, and 72.3±6.7 years respectively, p=.07) and BMI (27.2±5.1 and 27.2±5.6, p=1.00 respectively). The PD group had significantly fewer females than controls (46M & 21F, versus 49M & 54F, p<.01). PD participants presented with a mean (SD) UPDRS score of 37.2±12.0.

3.2 Controlled conditions

103 control and 67 PD participants completed laboratory based assessment. The mean total number of steps performed by PD and control participants was 226 ± 22 and 237 ± 23 respectively.

Fourteen gait characteristics were entered into the PCA yielding four factors (pace, variability, rhythm and asymmetry) and accounted for 84.84% and 88.43% of variance for control and PD participants respectively. All item loadings were >0.6 except for step length asymmetry in both groups with cross-loading evident for variability in controls (**Table 1, Figure 1B**).

3.3 Free-living conditions

Ninety-nine controls and 64 PD participants completed free-living assessment. Ten controls and six PD participants did not wear the BWM for the amount of time specified and were removed from analysis. Thus, a total of 89 controls and 58 PD participants were included.

The mean total number of steps per day completed by PD and control participants were 11899 ± 5183 and 13434 ± 4393 respectively. Fourteen gait characteristics were entered into the PCA yielding four factors in both groups (pace, variability, rhythm and asymmetry) and accounted for 90.00% and 93.03% of total variance for control and PD, respectively. All item loadings were >0.6 with cross-loading evident for variability in both groups (**Table 2, Figure 1C**).

4. Discussion

This is the first study to our knowledge to explore conceptual gait models with BWM from controlled and free-living gait characteristics. Furthermore, the models remained stable compared to our previously published model derived from GaitRite™ data [4].

When creating our model, four discrete gait domains were identified under both conditions; showing that the domains are not protocol dependent. Unexpectedly, step length asymmetry loaded onto pace for controls. Previously, gait domains appear more discrete in pathological cohorts than healthy older adults [5]; this complements our findings and demonstrates the impact of PD on gait. Interestingly, step length asymmetry loaded onto the asymmetry domain in free-living for both groups. BWM are more sensitive at detecting characteristics of asymmetry [10] but in addition, perhaps due to environment complexity, asymmetry increased in free-living [13] thereby emphasising it.

We were unable to replicate the postural control domain, which in the earlier model was expressed by three gait characteristics (step width, step width variability and step length asymmetry). The first two cannot be measured using our BWM, and their

omission altered the factor loading for step length asymmetry. This is a limitation as postural control is a critical aspect of gait. Future algorithm development is underway for measurement of these characteristics with BWM. However, BWM's do provide a nuanced approach to postural control measurement [15] which could be used in addition to our gait model for simplistic clinical interpretation.

Although loading of variability characteristics demonstrated instability compared to other domains, in contrast to our previous model, characteristics loaded to one domain. Reasons may be twofold: similarly to asymmetry, BWM analysis appears to be more sensitive to variability characteristics compared to GaitRite [10] and; measures of variability become more accurate with increased step count [16].

This work shows stability of our gait model when using BWM derived characteristics. This is an important finding to inform future clinical research with progression of gait assessment into free-living.

Conflicts of interest statement

There are no conflicts of interest to report.

Acknowledgements

ICICLE-GAIT is supported by the National Institute for Health Research (NIHR) Newcastle Biomedical Research Unit based at Newcastle upon Tyne Hospitals NHS Foundation Trust and Newcastle University. ICICLE-PD is supported by Parkinson's UK. The research was also supported by the NIHR Newcastle Biomedical Research Centre and Newcastle CRF Infrastructure funding. The views expressed are solely those of the authors.

Figure 1. Conceptual gait models derived **A**) previously using a pressure-sensor walkway in the laboratory **B**) with BWM in controlled conditions and **C**) with BWM in the free-living environment. (*C*)= control only, (*P*)= PD only.

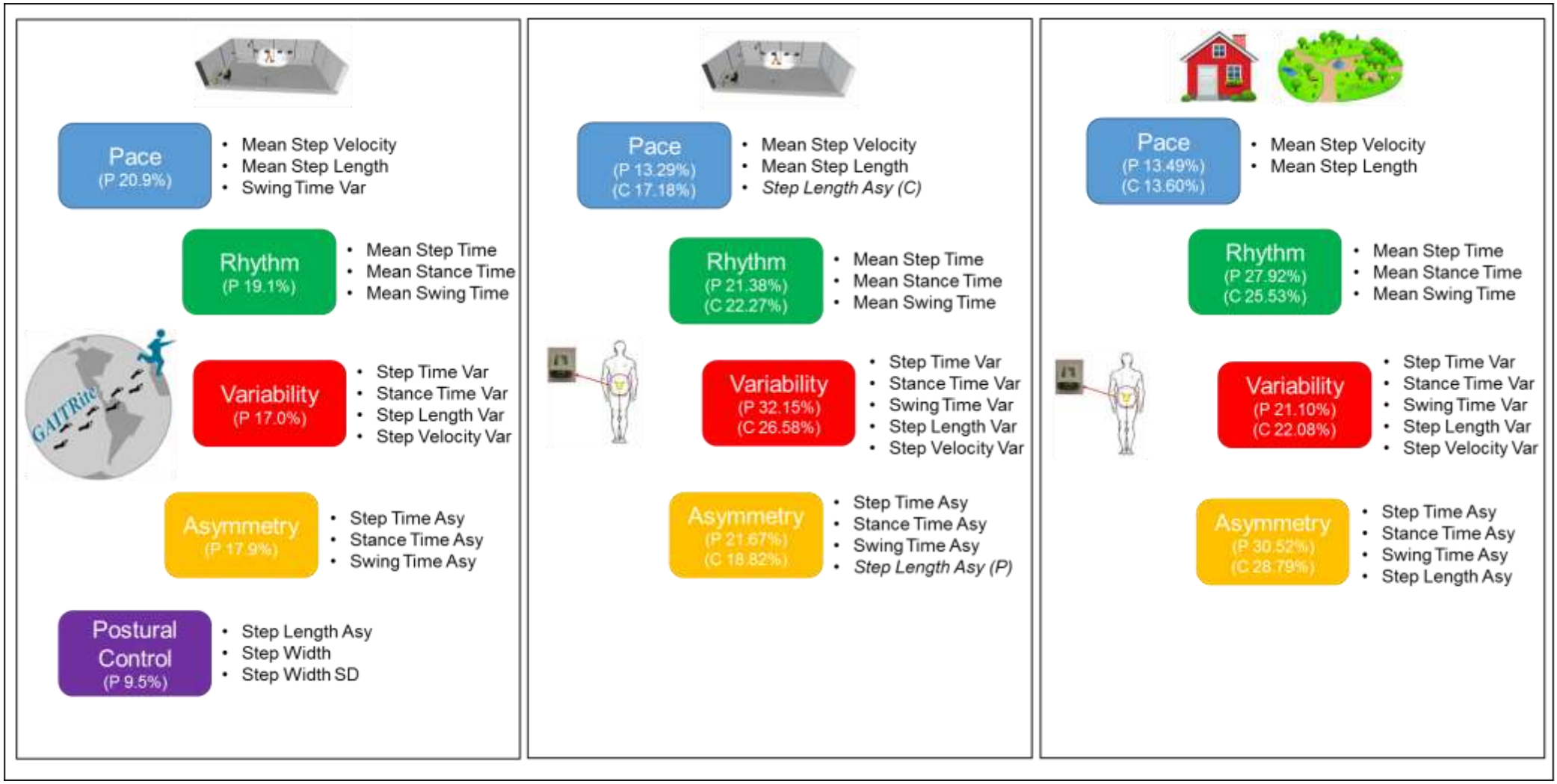

Table 1. Item loadings of the principle component analysis for controlled (laboratory) BWM gait (Varimax rotation)

	PD (n=67)					Control (n=103)			
	Pace	**Rhythm**	**Asymmetry**	**Variability**		**Pace**	**Rhythm**	**Asymmetry**	**Variability**
Pace					**Pace**				
Step Velocity	**0.974**	0.108	-0.132	0.131	Step Velocity	**0.936**	0.201	-0.100	-0.024
Step Length	**0.888**	-0.415	-0.143	0.010	Step Length	**0.845**	-0.422	-0.143	-0.082
					Step Length Asy	*0.578*	*-0.203*	*0.231*	*0.171*
Rhythm					**Rhythm**				
Step Time	-0.065	**0.951**	0.052	0.285	Step Time	-0.100	**0.970**	0.115	0.152
Stance Time	-0.067	**0.880**	0.152	0.192	Stance Time	-0.039	**0.938**	0.133	0.052
Swing Time	-0.050	**0.855**	-0.055	0.332	Swing Time	-0.161	**0.856**	0.074	0.245
Asymmetry					**Asymmetry**				
Step Time Asy	-0.035	-0.048	**0.927**	0.104	Step Time Asy	0.126	0.118	**0.808**	-0.039
Stance Time Asy	-0.112	0.074	**0.968**	0.089	Stance Time Asy	-0.076	0.089	**0.956**	0.071
Swing Time Asy	-0.093	0.098	**0.961**	0.099	Swing Time Asy	-0.056	0.085	**0.965**	0.070
Step length Asy	*-0.184*	*0.352*	*0.405*	*0.251*					
Variability (SD)					**Variability (SD)**				
Step Time Var	-0.027	0.222	0.196	**0.922**	Step Time Var	-0.038	0.228	-0.024	**0.922**
Stance Time Var	-0.048	0.269	0.129	**0.922**	Stance Time Var	-0.074	0.244	0.025	**0.919**
Swing Time Var	-0.065	0.275	0.126	**0.920**	Swing Time Var	-0.163	0.281	0.039	**0.905**
Step Length Var	0.133	0.227	0.058	**0.889**	Step Length Var	0.400	-0.079	0.079	**0.782**
Step Velocity Var	0.177	0.098	0.042	**0.909**	Step Velocity Var	0.473	-0.280	0.080	**0.679**
% Variance (88.43%)	*13.29%*	*21.38%*	*21.67%*	*32.15%*	**% Variance (84.84%)**	*17.18%*	*22.27%*	*18.82%*	*26.58%*

Table 2. Item loadings of the principle component analysis for free-living BWM gait (Varimax rotation).

	PD (n=58)					Control (n=89)			
	Pace	**Rhythm**	**Asymmetry**	**Variability**		**Pace**	**Rhythm**	**Asymmetry**	**Variability**
Pace					**Pace**				
Step Velocity	**0.991**	-0.024	-0.016	0.014	Step Velocity	**0.797**	-0.054	-0.109	-0.156
Step Length	**0.789**	-0.562	0.122	0.140	Step Length	**0.970**	-0.558	0.119	-0.027
Rhythm					**Rhythm**				
Step Time	-0.088	**0.974**	0.160	0.114	Step Time	-0.110	**0.982**	0.072	0.120
Stance Time	-0.067	**0.927**	0.248	0.166	Stance Time	-0.065	**0.950**	0.166	0.132
Swing Time	-0.131	**0.945**	0.014	0.079	Swing Time	-0.191	**0.936**	-0.033	0.136
Asymmetry					**Asymmetry**				
Step Time Asy	-0.002	0.130	**0.959**	0.209	Step Time Asy	-0.104	0.085	**0.968**	0.099
Stance Time Asy	-0.029	0.130	**0.967**	0.140	Stance Time Asy	-0.082	0.043	**0.968**	0.115
Swing Time Asy	-0.060	0.101	**0.950**	0.119	Swing Time Asy	-0.082	0.096	**0.915**	0.117
Step Length Asy	0.274	0.058	**0.780**	0.240	Step Length Asy	0.227	-0.053	**0.728**	0.047
Variability (SD)					**Variability (SD)**				
Step Time	-0.165	0.463	0.522	**0.664**	Step Time	-0.251	0.358	0.493	**0.704**
Stance Time	-0.182	0.465	0.533	**0.624**	Stance Time	-0.241	0.280	0.525	**0.711**
Swing Time	-0.215	0.542	0.435	**0.660**	Swing Time	-0.229	0.448	0.451	**0.682**
Step Length	0.088	0.226	0.073	**0.856**	Step Length	-0.100	0.228	-0.070	**0.784**
Step Velocity	0.242	-0.261	0.231	**0.869**	Step Velocity	0.123	-0.193	0.033	**0.946**
% Variance (93.03%)	*13.49%*	*27.92%*	*30.52%*	*21.10%*	**% Variance (90.00%)**	*13.60%*	*25.53%*	*28.79%*	*22.08%*

References

[1] Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. JAMA. 2011;305:50-8.

[2] Beauchet O, Annweiler C, Callisaya ML, De Cock A-M, Helbostad JL, Kressig RW, et al. Poor Gait Performance and Prediction of Dementia: Results From a Meta-Analysis. Journal of the American Medical Directors Association. 2016;17:482-90.

[3] Morris R, Lord S, Bunce J, Burn D, Rochester L. Gait and cognition: Mapping the global and discrete relationships in ageing and neurodegenerative disease. Neuroscience & Biobehavioral Reviews. 2016;64:326-45.

[4] Lord S, Galna B, Rochester L. Moving forward on gait measurement: Toward a more refined approach. Movement Disorders. 2013;28:1534-43.

[5] Lord S, Galna B, Verghese J, Coleman S, Burn D, Rochester L. Independent Domains of Gait in Older Adults and Associated Motor and Nonmotor Attributes: Validation of a Factor Analysis Approach. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2012.

[6] Verghese J, Wang C, Lipton RB, Holtzer R, Xue X. Quantitative gait dysfunction and risk of cognitive decline and dementia. Journal of Neurology, Neurosurgery, and Psychiatry. 2007;78:929-35.

[7] Hollman JH, McDade EM, Petersen RC. Normative spatiotemporal gait parameters in older adults. Gait & Posture. 2011;34:111-8.

[8] Lord S, Galna B, Coleman S, Yarnall A, Burn D, Rochester L. Cognition and gait show a selective pattern of association dominated by phenotype in incident Parkinson’s disease. Frontiers in Aging Neuroscience. 2014;6.

[9] Robles-García V, Corral-Bergantiños Y, Espinosa N, Jácome MA, García-Sancho C, Cudeiro J, et al. Spatiotemporal Gait Patterns During Overt and Covert Evaluatio in Patients With Parkinson's Disease and Healthy Subjects: Is There a Hawthorne Effect? Journal of applied biomechanics. 2015;31.

[10] Del Din S, Godfrey A, Rochester L. Validation of an Accelerometer to Quantify a Comprehensive Battery of Gait Characteristics in Healthy Older Adults and Parkinson's Disease: Toward Clinical and at Home Use. IEEE Journal of Biomedical and Health Informatics. 2016;20:838-47.

[11] Khoo TK, Yarnall AJ, Duncan GW, Coleman S, O’Brien JT, Brooks DJ, et al. The spectrum of nonmotor symptoms in early Parkinson disease. Neurology. 2013;80:276-81.

[12] Godfrey A, Lord S, Galna B, Mathers JC, Burn DJ, Rochester L. The association between retirement and age on physical activity in older adults. Age and Ageing. 2014;43:386-93.

[13] Del Din S, Godfrey A, Galna B, Lord S, Rochester L. Free-living gait characteristics in ageing and Parkinson’s disease: impact of environment and ambulatory bout length. Journal of NeuroEngineering and Rehabilitation. 2016;13:46.

[14] Field A. Discovering statistics using IBM SPSS statistics: Sage; 2013.

[15] Lowry KA, Smiley-Oyen AL, Carrel AJ, Kerr JP. Walking stability using harmonic ratios in Parkinson's disease. Movement Disorders. 2009;24:261-7.

[16] Galna B, Lord S, Rochester L. Is gait variability reliable in older adults and Parkinson's disease? Towards an optimal testing protocol. Gait & Posture. 2013;37:580-5.