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ORIGINAL COMMUNICATION

Ambulatory activity in incident Parkinson's: more than meets the eye?

Sue Lord · Alan Godfrey · Brook Galna · Dadirayi Mhiripiri · David Burn · Lynn Rochester

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Abstract Physical activity is important for people with Parkinson's disease (PD) to improve disease-specific impairment and ameliorate secondary consequences related to deconditioning. Activity may also have a neuroprotective role if instigated early. Ambulatory activity has not been examined in incident PD. Eighty-nine newly diagnosed PD cases [mean (SD) age 67.3 (9.9) years] and 97 controls [mean (SD) 69.2 (7.7) years] wore an activity monitor (activPAL^{TM}) for 7 days. Volume, pattern and variability outcomes were compared. Accumulation of activity (α) was classified as short (< 30 s), medium (30 s–2 min) and long (> 2 min) bouts of walking. Associations between sustained walking (> 2 min) and motor, cognitive and affective characteristics were identified. Activity outcomes were considered with respect to global health recommendations. Total steps (volume), accumulation of bout length (α), and variability ($S2_w$) outcomes were significantly different (all $P < 0.001$). PD participants (including Hoehn & Yahr (H&Y) stage I) accumulated significantly less time in long bouts (> 2 min) of walking compared with controls, due to performing fewer long bouts, rather than a reduction in time spent in walking per bout. For PD and controls there were weak but significant correlations for a range of characteristics and sustained walking. Fewer people with PD achieved the recommended 30 min of walking per day comprised of bouts > 10 min ($P = 0.02$) and bouts > 2 min ($P < 0.001$). People with PD were significantly less active than controls, with an inability to sustain levels of walking, and with differences apparent very early on in the disease process. A focus on increasing general ambulatory activity and exercise from the outset is recommended.

Keywords Parkinson's disease · Accelerometer · Physical activity · Ambulatory activity

Introduction

Maintaining optimal levels of activity is challenging for healthy older adults, but even more so for people with chronic disease, such as Parkinson's disease (PD). Not surprisingly, people with PD are less physically active compared with age-matched healthy controls. Earlier reports show a reduction of around 20 to 30 % in the volume of activity [1–3], along with subtle differences in the accumulation of activity throughout the day that become more marked when disease severity increases [4]. The benefits of physical activity may be more important in PD than in healthy ageing, given its potentially neuroprotective role against disease-specific deterioration and its ability to delay the evolution of secondary problems, such as musculoskeletal and aerobic deconditioning [5].

Guidelines advocate that people living with chronic diseases remain active to mitigate multisystem deconditioning brought on by increased sedentary behavior [6, 7], which is an independent risk factor for poor health outcomes [8]. We have, however, very limited understanding of the effects of PD on levels of physical activity and also the drivers of activity. While it can be assumed that motor

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S. Lord · A. Godfrey · B. Galna · D. Mhiripiri · D. Burn · L. Rochester (✉)
Clinical Ageing Research Unit, Institute for Ageing and Health, Newcastle University, Campus for Ageing and Vitality, Newcastle upon Tyne NE4 5PL, UK
e-mail: lynn.rochester@ncl.ac.uk

dysfunction plays an important role, it is also possible that non-motor features make an important contribution. We therefore need to understand the impact of PD on real-world activity and its correlates to be able to provide effective advice and ultimately develop sensible guidelines/recommendations.

Measurement of activity has progressed beyond use of self-report questionnaires, which over-estimate activity levels and exclude ambulatory activity derived from activities of daily living [9]. Quantitative evaluation is possible using light-weight, motion-sensing accelerometer-based devices that continuously record positional change and motion over days [10]. Novel metrics calculated from accelerometry data enables a detailed analysis of volume, patterns of accumulation and variability of activity to provide a wider perspective and a more detailed picture to emerge [11, 12].

The aim of this study was to objectively quantify ambulatory activity, which we defined as any period (bout) of walking from accelerometry data collected over 7 days of free living activity in a large incident cohort of PD cases and age matched controls. We were interested to understand the impact of PD on the ability to retain an active lifestyle, as determined by the amount and pattern of ambulatory activity that individuals engaged in, and how this relates to public health guidelines. We also wished to explore the effect of disease severity on levels of activity and gain a greater understanding of the motor and non-motor correlates of ambulatory activity. We hypothesized that (1) the volume of activity would be reduced in PD compared to controls and that this would: (2) manifest as changes to the pattern of activity; (3) be influenced by disease severity; (4) be multi-factorial with a broad range of correlates; and (5) impact on attainment of recommended levels of activity.

Methods

Participants

This study was nested within a larger study—Incidence of Cognitive Impairment in Cohorts with Longitudinal Evaluation—Parkinson's disease (ICICLE-PD) [13], which aimed to recruit all new cases of parkinsonism from secondary care services in Newcastle upon Tyne and Gateshead from June 2009 to December 2011. In brief, diagnosis of PD was confirmed by a specialist according to UK Parkinson's Disease Brain bank criteria [14], and by expert consensus if the diagnosis was uncertain. Exclusion criteria comprised: (1) people suspected of parkinsonism prior to the onset of the study on the basis that they were prevalent rather than incident; (2) significant memory impairment at presentation [defined as Mini Mental State Examination (MMSE) score < 24] [15], or meeting Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) criteria for dementia or the Movement Disorders Society (MDS) criteria for dementia at presentation; (3) presenting with other parkinsonism syndromes such as dementia with Lewy bodies [16], drug-induced parkinsonism, 'vascular parkinsonism', progressive supranuclear palsy, multiple system atrophy, or corticobasal degeneration, according to accepted diagnostic criteria [17]; (4) insufficient working knowledge of English; and (5) unable to consent.

Control participants were recruited from research active general practices via a regional primary care research network, from local hospital trusts via advertising, and via the Public Engagement Team based at Newcastle University. Inclusion criteria were: (1) greater than 60 years of age; (2) able to walk independently without a walking aid; and (3) no significant cognitive impairment, mood or movement disorder. The study was approved by the Newcastle and North Tyneside Research Ethics Committee and all participants gave informed consent. Clinical testing took place 1 h after medication intake to ensure optimal function. Full details of the recruitment process and testing protocol are described elsewhere [13].

Measurement of ambulatory activity

Activity data were captured using the validated activPAL^{TM}[1] activity monitor [18]. It is a small ($53 \times 35 \times 7$ mm), lightweight (20 g), uniaxial accelerometer-based sensor worn on the upper thigh, with a sampling frequency of 10 Hz, which identifies postures such as sitting/lying, standing and walking and the number of steps. Activity is recorded in 15 s windows, and at least one step is required to register each window as a stepping bout. Participants were fitted with the activPAL, which was worn for 7 days. Raw data were exported to an Excel[2] spreadsheet for further analysis in MATLAB. The MATLAB program extracted individual ambulatory bouts, where a 'bout' was any period of time spent walking. Volume, pattern and variability outcomes for physical activity and sedentary behaviour are detailed elsewhere [19, 20], and are sensitive to subtle differences in sedentary behaviour in more advanced PD [11] and to changes in physical activity after deep brain stimulation surgery in PD [21]. In preliminary analysis for this study, we compared sedentary behaviour for this early PD cohort with controls. There were no significant differences and further analysis was not

[1] PAL Technologies, Glasgow, UK.

[2] Microsoft Corp., Redmond, WA, USA.

conducted (see Table 1, supplementary data). The following outcomes are described for ambulatory activity:

Volume

(1) total amount of walking time per day (summation of all ambulatory bouts, normalised as a percentage of 7 days); (2) Total step count reported as per day counts.

Pattern

(1) Alpha (α): defined the distribution of ambulatory bouts, with a lower α indicating that the distribution is derived from a greater proportion of long bouts. α is described in detail elsewhere, and has been described previously in PD research [11] and in healthy older adults [12]; (2) Time spent walking per week for each participant categorised as: short bouts (30 s), medium bouts (30 s–2 min) and long bouts (2–10 min); (3) Frequency of walking bouts; (4) Average time spent walking per bout.

Variability ($S2_w$)

The 'within subject' variability of bout length. This was calculated from a maximum likelihood technique as the distribution of bout length is log normally distributed [21]. A high $S2_w$ indicates a more varied pattern of walking.

Clinical outcomes

Gait was measured during a 2 min continuous walk around a 25 m circuit using a 7 m long instrumented walkway (GAITRite[3]) that captured individual footfall data using embedded pressure sensors [22]. Participants were asked to walk at their preferred speed. Data were collected at 240 Hz and analysed using proprietary software. For the timed chair stand (a proxy for bradykinesia and muscle strength), participants were asked to stand up from a seated position with arms folded across their chest and sit down five times, as quickly as possible [23]. Balance self-efficacy was measured using the Activities Balance Self Confidence Scale [24], depression with the Geriatric Depression Scale [25], and physical fatigue was measured with the Multidimensional Fatigue Inventory [26]. Levodopa equivalent dose (LEDD) scores were calculated according to established methods [27].

Data analysis

Univariate analysis was used to describe demographic, clinical and accelerometry data for ambulatory activity after inspection for normality distribution. Data was transformed where necessary to meet assumptions for parametric tests. Students *t* test and Chi χ^2 test (Fisher's exact test) were used to compare clinical characteristics for PD and controls. ANCOVA was used to compare volume, pattern and variability outcomes for control and PD participants who were first classified according to Hoehn & Yahr (H&Y) stages (between subjects measure), controlling for age, and sex. Bout length (<30 s, 30 s–2 min, >2 min,) was included as a repeated measures factor in when comparing accumulation of activity between groups. Spearman's correlation coefficient was used to examine associations between clinical characteristics and time accumulated in bouts $>$ 2 min, which was selected because all participants achieved this criterion. Finally, we examined the data with respect to broader health recommendation and public guidelines for activity [28, 29], and compared the proportion of controls and PD participants who accumulated 30 min of daily ambulatory activity from bouts of >10 min and from bouts $>$ 2 min (Chi χ^2 test for between-group comparisons). For all analyses, the significance level was set at $P < 0.05$ and data were analysed using SPSS (version 17).

Results

ICICLE-PD identified 121 newly diagnosed PD, of which 103 cases were consented for this study along with 98 controls. Accelerometry data for 14 consented PD participants were not available due to withdrawal from the study prior to testing because testing times were problematic ($n = 7$), incomplete data sets ($n = 5$) and lost devices ($n = 2$). The mean (SD) age of the 32 ICICLE-PD participants (17 men and 15 women) who did not take part was 64.8 (11.5) years. Study participants presented with mild to moderate PD, with most classified as H&Y I and II ($n = 71$; 79.78 %). Twelve (9.9 %) reported freezing of gait and 17 (17.5 %) reported falling. Controls were healthy older adults, with 12 (9.9 %) who presented with a hip or knee joint replacement and two (2.0 %) who reported falling. Compared with controls, people with PD walked significantly slower, were slower in their timed chair stand test and had lower scores for balance self-efficacy. PD participants also presented with poorer cognition and higher depression scores. Twelve (13.4 %) of the PD cohort and five (5.1 %) controls reached the threshold for prominent depressive symptomatology (≥ 5) [30], although the mean values were lower than this criterion for both groups (Table 1).

Ambulatory activity outcomes

There were significant between-group differences for all ambulatory activity outcomes. For volume metrics, PD participants spent significantly less time per day walking and

[3] CIR Systems Inc., NJ, USA.

Table 1 Clinical and gait characteristics for Parkinson's disease (PD) and control participants

Characteristic	PD ($n = 89$) Mean (SD)	Controls ($n = 97$) Mean (SD)	P
Male/female	62/27	50/47	<0.001*
Age (years)	67.3 (9.9)	69.2 (7.7)	0.167
Height (m)	1.6 (0.07)	1.6 (0.09)	0.594
Levodopa equivalents	174.6 (124.1)	–	–
H&Y stages 1–3 (n) (%)	I) 20 (22.5 %), II) 51 (57.3 %), III) 18 (20.2 %)		
UPDRS III	25.0 (10.7)	–	–
GDS (0–15)	2.6 (2.1)	1.0 (1.8)	<0.001
MMSE (0–30)	28.5 (1.3)	29.3 (0.90)	<0.001
Timed chair stand (s)	13.7 (4.3)	12.4 (3.6)	0.042
ABCs (0–100 %)	82.9 (18.0)	92.1 (11.3)	<0.001
MFI (physical fatigue domain) (0–20)	10.6 (4.0)	7.9 (3.3)	<0.001
Gait speed (m/s)	1.12 (.20)	1.27 (0.19)	<0.001

H&Y Hoehn & Yahr; *UPDRS* United Parkinson's Disease Rating Scale; *GDS* Geriatric Depression Scale; *MMSE* Mini Mental State Examination; *ABCs* Activities Balance Confidence Scale; *MFI* Multidimensional Fatigue Inventory

* Chi square test comparisons; all other comparisons Students t test

took significantly fewer steps per day than controls. For patterns of activity, PD participants had a significantly higher alpha (α), indicating that ambulatory activity was comprised of proportionally more short bouts compared to controls (Table 2). PD participants also demonstrated less variable ($S2_w$) bout length compared to controls, further indicating a more constrained pattern of ambulatory activity.

Effect of disease severity on activity

Post-hoc analysis showed that those with H&Y II and H&Y III accumulated a similar duration of activity as controls in short bouts (<30 s), but significantly less in medium bouts (30 s–2 min) and longer bouts (>2 min). Those with mild PD (H&Y I) accumulated a similar duration of activity as controls in short and medium bouts, but not as much in longer bouts (Fig. 1a). We then examined frequency of walking bouts and average time spent walking per bout to identify which contributed most to the between-group differences. We found that people with PD accumulated less activity primarily because they did not perform as many longer bouts (Fig. 1b), rather than as a feature of time spent walking per bout, which was comparable for PD and controls (Fig. 1c). There were few significant differences between H&Y groups. Alpha (α) was significantly different between H&Y groups I and II for short bouts (higher for H&Y 1) and medium bouts (higher for H&Y II), and frequency of activity bouts was higher for H&Y 1 (medium bout length) (see also Table 2).

Correlates of activity

For PD participants, higher levels of sustained activity (time accumulated in bouts >2 min) were significantly associated with younger age; higher scores for cognition, balance self-efficacy, time chair stand, and gait speed; and a lower burden of disease. There were fewer significant correlations for control participants, with higher levels of sustained activity significantly associated with higher scores for balance self-efficacy and lower fatigue scores (Table 3).

Attainment of recommended criterion for daily activity

With respect to the public health guidelines for activity, there was a significant between-group difference for 30 min of walking per day comprised of bouts > 10 min ($P = 0.02$). Attainment was low in both groups, with only 12 (12.3 %) controls and three (3.4 %) PD participants achieving this criterion (see Fig. 2a). A significant between-group difference was found for 30 min of walking per day comprised of bouts > 2 min ($P < 0.001$), with attainment higher for both groups [59 (60.8 %) controls and 19 (21.3 %) PD] and discrimination across H&Y groups (see Fig. 2b).

Discussion

Key results show significant differences to the volume and pattern of daily ambulatory activity in incident PD compared with controls. These differences are evident even for people with mild disease severity. PD participants took on average 30 % fewer steps per day compared with controls. This corresponds with earlier work in more severe PD [1, 21] and in a longitudinal study, which showed a significant reduction in activity over 12 months that amounted to approximately 45 min less activity per week [2]. Importantly, our study showed a similar reduction in the volume

Table 2 Ambulatory outcomes for all participants and Hoehn & Yahr groups

Ambulatory outcomes[a]	Controls ($n = 97$)	PD ($n = 89$)	P*	HY I ($n = 20$)	HY II ($n = 59$)	HY III ($n = 18$)
Volume						
Total time spent walking (%)	6.9 (2.3, 6.4–7.4)	5.1 (2, 4.7–5.5)	<0.001	5.8 (1.8, 5–6.6)	5.1 (2.2, 4.5–5.7)	4.4 (1.6, 4.1–6.1)
Total number of steps	7,816 (5,452, 6,731–8,901)	5,452 (2,501, 4,932–5,972)	<0.001	6,302 (2,311, 5,289–7,315)[c]	5,335 (2,716, 4,590–6,080)[c]	4,840 (1,851, 4,080–6,590)[c]
Pattern						
Alpha (α) (accumulation of bout length)	1.35 (0.02, 1.35–1.35)	1.38 (0.03, 1.37–1.39)	<0.001	1.37 (0.02, 1.36–1.38)[c]	1.38 (0.03, 1.37–1.39)[c]	1.38 (0.03, 1.37–1.39)[c]
Time spent walking (secs)						
<30 s	1,540 (440, 1,452–1,628)	1,461 (432, 1,371–1,551)	0.445	1,636 (409, 1,457–1,815)	1,383 (453, 1,259–1,507)[b]	1,488 (348, 1,174–1,592)
30 s–2 min	2,002 (841, 1,835–2,169)	1,588 (836, 1,414–1,762)	<0.01	1,463 (826, 1,101–1,825)	1,483 (748, 1,278–1,688)[b,c]	1,822 (877, 1,137–1,829)[c]
>2 min	2,386 (1,515, 2,085–2,687)	1,257 (1,104, 1,028–1,486)	<0.001	1,337 (821, 977–1,697)	1,340 (1,284, 988–1,692)[c]	936 (755, 747–1,933)[c]
Frequency of walking bouts						
<30 s	142 (42, 134–150)	142 (42, 133–151)	0.619	156 (44, 137–175)	135 (43, 123–147)	146 (34, 115–155)
30 s–2 min	38 (15, 35–41)	30 (15, 27–33)	<0.01	37 (14, 31–43)	28 (15, 24–32)[b,c]	29 (14, 21–35)[c]
>2 min	8 (4, 7–9)	4 (4, 3–5)	<0.001	5 (3, 4–6)[c]	5 (4, 4–6)[c]	3 (2, 3–7)[c]
Average time spent walking per bout						
<30 s	10.9 (0.8, 10.7–11.1)	10.2 (1.1, 10–10.4)	<0.001	10.6 (0.9, 10.2–11)	10.2 (1, 9.9–10.5)[c]	9.8 (0.2, 9.7–9.9)[c]
30 s–2 min	53.6 (4, 53–54)	51.4 (4, 51–52)	<0.001	52.7 (3, 52–54)	51.5 (4, 50–53)[c]	49.7 (1, 49–50)[c]
>2 min	304.8 (107, 284–326)	288.7 (103, 267–310)	0.138	269.2 (98, 226–312)	296.1 (150, 255–337)	289.5 (120, 227–365)
Variability						
$S2_w$ (variability of bout length)	1.23 (0.09, 1.21–1.25)	1.17 (0.08, 1.15–1.19)	<0.001	1.17 (0.06, 1.14–1.2)[c]	1.18 (0.09, 1.16–1.2)[c]	1.14 (0.08, 1.14–1.22)[c]

Mean (SD, 95 % confidence interval)

[a] All outcomes reported are daily, other than time spent in activity, which is reported for 7 days

[b] Significantly different from H&Y I

[c] Significantly different from controls

* P values derived from ANCOVA (controlling for age and sex)

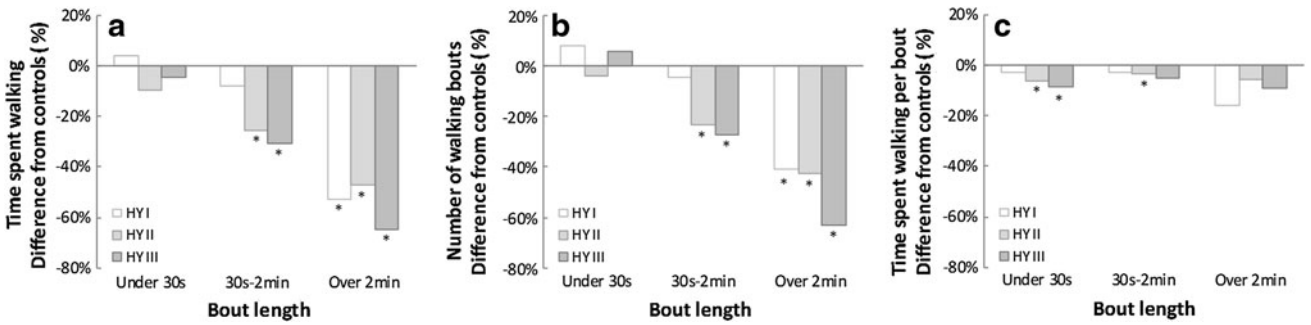

Fig. 1 Patterns of activity for controls and Hoehn & Yahr groups for different bout lengths: **a** Time spent walking; **b** Number of walking bouts; **c** Average time spent walking per bout

Table 3 Spearmans's correlation for clinical characteristics correlated with time accumulated in bouts > 2 min

Characteristic	Control ($n = 97$)	P	PD ($n = 89$)	P
Age	−0.191	0.061	**−0.216**	**0.042**
Gender	−0.175	0.087	−0.032	0.763
United Parkinson's disease rating scale III	–	–	**−0.227**	**0.033**
MMSE	0.057	0.579	0.184	0.084
Timed chair stand (s)	−0.197	0.056	**−0.298**	**0.006**
Geriatric depression scale	−0.154	0.131	−0.109	0.308
Physical fatigue domain from MFI	**−0.217**	**0.032**	−0.177	0.098
Activities balance self efficacy scale	**0.249**	**0.014**	**0.254**	**0.016**
Gait speed (m/s)	**0.310**	**0.001**	**0.309**	**0.003**

MMSE Mini Mental State Examination, *MFI* Multidimensional Fatigue Inventory, *PD* Parkinson's disease

Significant correlations highlighted in bold

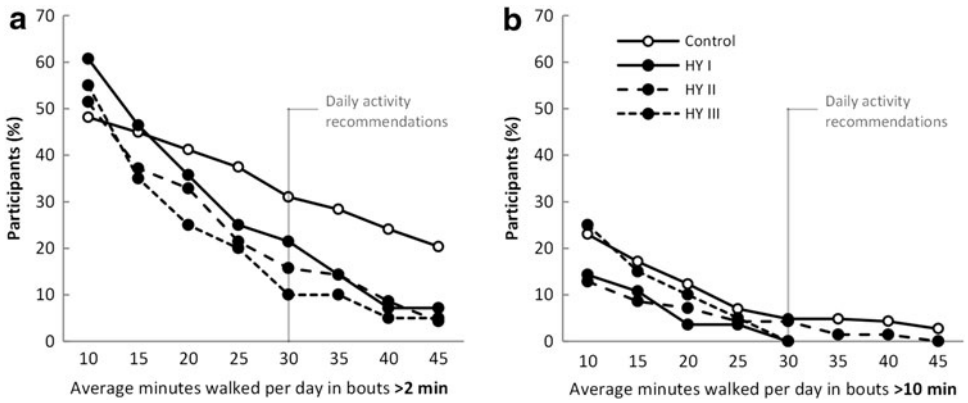

Fig. 2 Attainment of 30 min of daily activity comprised of: **a** 2 min bouts for PD and controls; and **b** 10 min bouts for controls and H&Y groups

and a similar pattern of inactivity in participants with early disease staging (H&Y I) compared to those with more severe disease presentation. This suggests that reduced ambulatory activity is established as a very early feature in PD, and it is possible that incipient change may even precede diagnosis.

The patterns that underpin accumulation of ambulatory activity in PD were different from controls. Between-group differences for Alpha show that the distribution of ambulatory activity in people with PD is derived from a greater proportion of short bouts and subsequent analysis of bout lengths support this finding. PD participants did not sustain levels of activity (medium and long bouts of walking), as previously reported in more advanced PD [2, 21]. This finding was evident even for H&Y I and did not improve with increasing disease severity, showing that once the capacity is lost, it is unlikely to be reversed. People with PD do not compensate for this loss by accumulating more short bouts of walking to boost their total volume—overall, they achieve fewer bouts and fewer sustained bouts. Activity is comprised of numerous short bouts of walking. Further analysis of the pattern of activity shows that,

perhaps not surprisingly, people with PD show less variability (a lower $S2_w$) in the range of walking bouts accumulated, suggesting poverty of choice and an inflexible repertoire of walking activity. This finding supports earlier work that reported significantly lower values for a metric comparable to $S2_w$ (approximate entropy: randomness of activity fluctuations) in a group of inactive older adults, compared with those who were more active [31]. There were few significant differences across H&Y groups, suggesting that disease severity does not impact greatly on activity levels. This may because once a threshold of (reduced) activity is reached, it does not change a lot, especially at this early stage in the disease process.

Reduced activity cannot simply be explained by disease severity, and while this makes a contribution, it is less than we anticipated. Overall, associations were weak. Gait speed was not a convincing correlate, which tests the assumption that robust gait is sufficient to ensure activity. Significant correlations between gait speed and balance self-efficacy and activity bouts were common to both groups; however, a wider range of independent variables was significantly associated for PD participants. This reflects not only the multidimensional nature of ambulatory activity, but also the non-motor symptom burden already present in this newly diagnosed cohort. However, consistent with our previous work in PD and older adults, we did not convincingly identify correlates of ambulatory activity in either group [3, 12]. Self-efficacy may be particularly important and deserves closer investigation. The significant associations found here support our earlier work showing the Falls Efficacy Scale International [comparable to the activities balance confidence scale (ABCs)] as a significant predictor of physical activity in older adults [12]. Results from this study also show that a broader set of explanatory characteristics needs to be considered to explain ambulatory activity.

We interpreted ambulatory activity with respect to public health guidelines that endorse physical activity over the life span in recognition of its protective effects on global health, independence and survival [32]. Few people in either group met the recommended guidelines for daily activity. Although controls accumulated more activity than PD, with total step count attainment comparable to earlier work [33], most did not meet the criterion, which states that the daily (total) step count should be comprised of 30 min of ambulatory activity made up of bouts greater than 10 min [28, 29, 34]. The guidelines suggest these 10 min activity bouts should be of moderate to vigorous intensity. Activities such as gardening or brisk walking may be considered moderate, but 'leisure' activities such as casual walking or grocery shopping, and domestic tasks such as meal preparation are considered light-intensity. We estimate a long bout of walking (> 2 min) equivalent to walking at least 140 m, which is unlikely to be performed in the home.

It may be even more critical for people with PD to engage in an active lifestyle. Emerging evidence argues for a protective role of exercise in PD, although this needs to be substantiated and thresholds for activity identified [35]. Animal model research suggests that exercise has a neuroprotective effect and an adaptive effect through neuronal preservation and reduced terminal loss in striatal and nigrostriatal dopaminergic neurons [5, 36], and a compensatory effect on surviving cell templates through optimised dopamine signalling mechanisms [37]. Other neurochemical effects include reversal of increased glutamatergic drive characteristic of PD [38]. Epidemiological evidence indicates that daily activities such as brisk walking can be health-protective in older adults [39, 40] and in PD [41], and maybe easier to implement than formal exercise routines [28, 39]. Authors of a recent randomised controlled trial in 586 people with PD highlight the challenges inherent in promoting physical activity. A behavioural change programme did not improve levels of activity [measured by the LASA Physical Activity Questionnaire (LAPAQ)] compared with physiotherapy. However, secondary outcomes (activity diaries and accelerometers) both showed significant between-group differences, suggesting the primary outcome was not responsive. Correlation for the LAPAQ and step counts derived from a pedometer is only moderate (Spearman's $\rho = 0.43$) [42], indicating that the instruments measure somewhat different constructs.

Results from our study are highly relevant to clinical practice. People with early PD stand to gain from adopting an active lifestyle, and strategies for managing the disease at this stage need to reflect this. Barriers to exercise need to be identified early on by clinicians [43], and a direct and emphatic approach used to encourage people with newly diagnosed PD to increase their volume of daily ambulatory activity and to recommend that they adopt a flexible approach to accumulation of that activity. It is critical to embed this attitude whilst disease severity is still mild, because once inactivity is established, it is unlikely that it will be reversed.

To the best of our knowledge, this is the largest quantitative study of ambulatory activity in PD and the first to quantify changes with respect to the volume, pattern and variability of ambulatory activity. A strength of this study is the inclusion of an incident cohort identified using robust methodology providing a representative sample of newly diagnosed PD with relatively mild disease severity. Importantly, our results show that even in very mild PD, activity is drastically reduced and this has important implications for disease progression and management. The deleterious effects of inactivity contribute to the burden of pathology through attenuation of cardiovascular health and

neuro-musculoskeletal integrity, impacting on independence and activities of daily living. An important feature of the study was that all forms of ambulatory activity were captured and the data presented are therefore independent of intensity or task in keeping with an 'active living' approach that embraces the broader concept of health [40, 44]. As such, reduced ambulatory activity, particularly with reference to subtle changes in patterns of activity, may be a useful biomarker of disease onset and disease progression. It is important to note that although activPAL records activity in 0.1 s, it classifies any (brief) period of standing separately from continuous walking, and so would segment periods of continuous walking. This potentially overestimates bouts of ambulatory activity. However, this feature is common to all accelerometer-based data classification and is unlikely to bias one group over another. Further investigation is required for optimal classification of bouts of ambulatory activity where periods of short pauses disrupt what may have been continuous walking bouts. A limitation of the study is the small sample size for H&Y groups, which may have underpowered some analysis. Although not examined in this manuscript, the non-significant findings for sedentary behaviour support earlier reports that identify it as a separate feature of habitual behaviour [12] and independent risk factor for ill-health [8].

In conclusion, people with early PD, even those with less severe disease, do not sustain optimal levels of ambulatory activity. Both the volume of activity and the pattern of accumulation of that activity are affected. These findings suggest that the secondary consequences of PD aligned with inactivity will be established early on in the disease process. Maintenance of activity in PD is important, and management strategies are required to mitigate the consequences of inactivity if at all possible.

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Conflicts of interest The authors declare that they have no conflict of interest.

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