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Characterisation of foot clearance during gait in people with early Parkinson's disease: Deficits associated with a dual task

Lisa Alcock [a,b], Brook Galna [a,b], Sue Lord [a,b], Lynn Rochester [a,b,*]

[a] Institute of Neuroscience, Newcastle University, Newcastle upon Tyne NE4 5PL, UK
[b] Newcastle University Institute for Ageing, Newcastle University, Newcastle upon Tyne NE4 5PL, UK

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ABSTRACT

Tripping is a common cause of falls in older adults and people with Parkinson's disease (PD). Foot clearance during gait may be impaired when distracted by a dual task and thus inform trip risk. This study aimed to evaluate whether foot clearance is impaired in PD and is adversely affected by a dual task.

81 older adults and 76 PD walked at a comfortable pace for two minutes under single and dual task conditions (digit recall). Temporal spatial gait was measured using an instrumented walkway. Heel and toe trajectories were obtained bilaterally using 3-dimensional motion capture.

Foot clearance was reduced in PD ($p < .001$) and under dual task ($p < .027$). The take-off (toe) gradient was reduced under dual task irrespective of group and the landing (heel) gradient was reduced in PD irrespective of task ($p < .001$). An increased proportion of unimodal toe distributions were observed for PD, particularly under dual task. Group differences were retained when controlling for step length (landing gradient and peak toe clearance in late swing) and gait velocity (landing gradient).

Distinct differences in foot clearance were observed even in the early clinical stages of PD. Dual tasking may increase trip risk due to insufficient toe clearance (early swing) for both older adults and PD. Inadequate heel clearance (late swing) may increase falls risk in PD. Clearance deficits in PD are partially related to a reduced gait velocity and step length which may be targeted in tailored therapies. Further work is necessary to understand the mechanisms underlying this pathology-associated deficit.

1. Introduction

Falls are a large public health issue placing considerable strain on the healthcare system with escalating costs of £4.6 billion/year in the UK alone (Age UK, 2010). It is estimated that one third of older adults (Department of Health, 2009) and two thirds of people with Parkinson's disease (PD) (Ashburn et al., 2001; Wood et al., 2002) fall every year, with the majority of falls resulting from a trip (Blake et al., 1988; Gazibara et al., 2014). Tripping occurs when there is an unanticipated foot contact with the ground and a fall ensues when balance recovery is insufficient. Inadequate limb elevation (specifically foot clearance) during gait is an under-reported and poorly understood factor likely contributing to the high prevalence of trips in older adults and PD. This is surprising when considering that a high proportion of indoor (14.3%) and outdoor (66%) falls by PD are the result of a trip or slip (Gazibara et al., 2014). Consequently, understanding the mechanisms underpinning trip risk is of importance and profiling foot clearance may inform the development of interventions to reduce trip risk (Lai et al., 2012; Hamacher et al., 2014).

Foot clearance during swing follows a typical pattern whereby heel displacement progresses both anteriorly and vertically until a peak (~25 cm in the young (Winter, 1992)) is reached mid-swing. Toe clearance is often biphasic with a peak in early and late swing. One of the gait events posing the greatest risk for tripping is considered to occur mid-swing, when the anterior velocity of the toe reaches a peak and a minimum clearance of ~1.5 cm is achieved in young adults (Winter, 1992). Further work is required to establish whether other foot clearance events may be used to distinguish between clinical groups to evaluate falls risk. Unanticipated contact of the toe with either the ground/environmental object may also occur during early swing, when the foot is plantarflexed and accelerating to facilitate limb elevation. Conversely, unanticipated contact of the heel with the ground/environmental object may occur during late swing when the foot is dorsiflexed and decelerating in preparation for foot contact. Limited evidence suggests that foot clearance is reduced in established PD when compared to controls and worsens with disease severity although

* Corresponding author at: Clinical Ageing Research Unit, Campus for Ageing and Vitality, Institute of Neuroscience and Newcastle University Institute for Ageing, Newcastle University, Newcastle upon Tyne NE4 5PL, UK. Tel: +44 (0) 191 208 1291; fax: +44 191 208 1251.
E-mail address: lynn.rochester@newcastle.ac.uk (L. Rochester).

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these studies included small samples ($n=10$–21)(Knutsson, 1972; Cho et al., 2010) and require affirming with larger cohorts.

Online cognitive processing and execution of motor actions often occur concurrently during real world locomotion and therefore constructing assessments using a dual task paradigm offers a more ecologically valid evaluation of gait. Under dual task conditions (visual reaction time), no significant difference in minimum toe clearance was observed for young and old men (Sparrow et al., 2008). However these changes were observed whilst walking on a treadmill which does not allow for the natural acceleration and deceleration inherent in bipedal gait. Conversely, alterations in foot clearance appear to be exacerbated most with the addition of a secondary cognitive task (as opposed to a secondary motor task) with the mean minimum toe clearance for some individuals as low as 2 mm when required to answer standardised questions whilst walking compared to single task walking or completing an additional motor task when the mean minimum toe clearance was >4 mm (Schulz et al., 2010). Considering the motor (Morris et al., 1994; Jankovic, 2008) and non-motor (cognitive) (Chaudhuri et al., 2006; Hou and Lai, 2007; Poewe, 2008; Park and Stacy, 2009) symptoms of PD, gaps in our knowledge surrounding the influence of a dual task on foot clearance exist. Trip risk may be further exacerbated under dual task, particularly tasks that challenge cognitive reserve, although this remains unknown.

Characteristics of foot clearance have been associated with temporal-spatial components of gait in young (Osaki et al., 2007; Cho et al., 2010) and older adults (Sparrow et al., 2008). Slower gait velocity, a shorter step length and increased asymmetry and variability of temporal-spatial gait parameters are recognised gait deficits in early (Galna et al., 2014) and established (Morris et al., 1996; Hausdorff et al., 1998; Yogev et al., 2007; Roiz et al., 2010; Hass et al., 2012) PD. Slower velocities in PD are thought to be a product of reduced step length rather than altered cadence which may be modulated to meet increasing velocity demands (Morris et al., 1994). Holistically, anterior progression during gait (velocity) is a product of temporal (timing) and spatial (distance) control. A slowness (bradykinesia) and reduced magnitude of movement (hypokinesia) are hallmark impairments associated with PD gait. The association between temporal (step time), spatial (step length) and these factors combined (gait velocity) and foot clearance in PD is unknown and understanding this association may help to tailor therapeutic interventions targeting fall prevention in PD.

The aims of this exploratory study were to evaluate if foot clearance is: 1) altered in early PD compared to controls; 2) negatively influenced by a concurrent cognitive (dual) task; and 3) associated with altered temporal-spatial components of gait in PD. To this end, characterisation of foot clearance during single and dual task gait in early PD will serve as a baseline from which disease progression and falls risk may be estimated longitudinally. Based on the limited empirical evidence available, it was hypothesised that: i) foot clearance would be reduced in the PD cohort compared to controls; ii) the addition of a dual (cognitive) task would have a negative influence on temporal-spatial characteristics of gait and foot clearance in both groups, with larger changes in PD; and iii) foot clearance would be largely dependent on both temporal and spatial components of gait.

2. Materials and methods

2.1. Participants

Participants were recruited into the ICICLE-GAIT study within 4 months of diagnosis. This is a collaborative study with ICICLE-PD, an incident cohort study (Incidence of Cognitive Impairment in Cohorts with Longitudinal Evaluation – Parkinson's disease) conducted between June 2009 and December 2011 (Khoo et al., 2013; Yarnall et al., 2014). ICICLE-GAIT recruited a subset of the cohort at the same time point. A diagnosis of idiopathic PD was given by a Movement Disorders Specialist according to the UK Parkinson's Disease Brain Bank Criteria (Hughes et al., 1992). Older adults of similar age and sex were recruited from community resources. A subgroup of 81 older adults and 76 PD underwent clinical gait analysis and represent the sample in this study (Galna et al., 2014; Rochester et al., 2014) which was approved by the local National Health Service Research Ethics Committee (Ref:09/H0906/82). Written informed consent was obtained according to the Declaration of Helsinki (World Medical Association, 2001).

For all PD participants, disease severity (Hoehn and Yahr stage (Hoehn and Yahr, 1967)) and motor phenotype were quantified (Stebbins et al., 2013). PD participants were tested whilst optimally medicated approximately 1-hour post dopaminergic medications. Global cognitive function was quantified using the Mini Mental State Examination (MMSE) (Folstein et al., 1975).

2.2. Gait protocol

Participants walked around a 25-m circuit at their preferred pace for two minutes under single task conditions. A subsample of this cohort completed the same circuit under dual task conditions (Galna et al., 2013). For dual task conditions, the forward digit span (Wechsler, 1997) normalised to maximum recall capacity was used (determined as the maximum length of a randomly generated string of numbers recalled successfully on two out of three attempts). Strings of digits were presented through a speaker system (Creative, Inspire S2, Singapore) at a frequency of 1 digit/s. Repeated digit recall was assessed whilst seated continuously for 2-min to quantify cognitive task performance (Rochester et al., 2014). Digit span errors (%) during both sitting and walking were calculated.

Temporal-spatial components of gait were collected using a 7-metre instrumented walkway (Platinum model GAITRite®, software v.4.5, CIR systems Inc., United States of America, 240 Hz). Participants were instructed to wear their own comfortable flat-soled shoes. No participants wore high heeled shoes for the gait assessments. Reflective, spherical markers (14 mm diameter) were affixed over the shoe surface on the heel and the toe bilaterally. Three dimensional motion of foot trajectories were recorded using a 10-camera Vicon© system (M × 3þ VICON, California, USA; Nexus software, v.1.83) sampling at 100 Hz and targeting a capture volume of 13.5 m^3 (6 m × 1.5 m × 1.5 m). Task order (single and dual) was counterbalanced between groups.

2.3. Data analysis

Footfall data were processed and temporal-spatial components of gait were extracted from the GAITRite® database using Microsoft® Access 2007. Marker trajectories were labelled within Vicon© Nexus (v.1.8.5, Oxford, UK) for periods when participants walked across the instrumented walkway. Trajectories were smoothed using a Woltering filter (Mean square error: 20 mm). The remaining computational steps were completed in MATLAB® (R2012a, Mathworks, Natick, MA). Trajectories were organised into a matrix of time-normalised (101 points) gait cycles which were detected using a vertical velocity-threshold of the heel trajectory of 250 mm/s. Using velocity thresholds alone to identify foot contacts is problematic (Schulz et al., 2010) and to overcome this we developed an algorithm for detecting erroneous gait cycles that relied on known elements of foot trajectories during gait, i.e. appropriate minima/maxima etc. Success of this error detection algorithm was affirmed through visual inspection of all extracted gait cycles. Corrections to the vertical offset resultant from variation in marker placement were applied to ensure that when the foot was flat on the floor (i.e. during mid-stance) clearance was 0 mm. A vertical offset corrected the heel marker and an angular offset aligned the toe marker with the heel. Foot trajectory characteristics were extracted bilaterally per trial and included: the maximum vertical toe displacement during the first (T1) and second half (T3) of swing; the minimum vertical toe displacement mid-swing (T2); the peak vertical heel displacement (H1) and trajectory gradients of the toe during the first half of swing (take-off) and of the heel during the second half of swing (landing) (Fig. 1). To reduce the chance of false peak detection, the algorithm defined that a peak had occurred when a data point was larger than the three samples before and after. The take-off and landing gradients were defined as the change in vertical (toe/heel) displacement, divided by the change in time (5% of the start or end of the swing phase, respectively). Ensemble averages per participant were compiled combining both limbs and all gait cycles obtained per condition. Toe trajectories were examined for unimodal (single peak) and bimodal (two peaks) distributions (Cho et al., 2010). The algorithm defined that participants displaying a unimodal toe trajectory will not exhibit a T1 or T2 event for that gait cycle. For each of the foot clearance characteristics, the variability (within-person differences in steps) and asymmetry (within-person difference between right and left limbs) were calculated. Variability was calculated as the square root of the variance associated with the right and left sides and asymmetry was calculated as the absolute difference between the average of the left side minus the average of the right side (Galna et al., 2013).

2.4. Statistical analysis

Data distributions were visually inspected using histograms and measures of dispersion were used to confirm visual interpretation. Mean variables were normal thus parametric statistics were used. A lambda (λ) correction informed by Box Cox

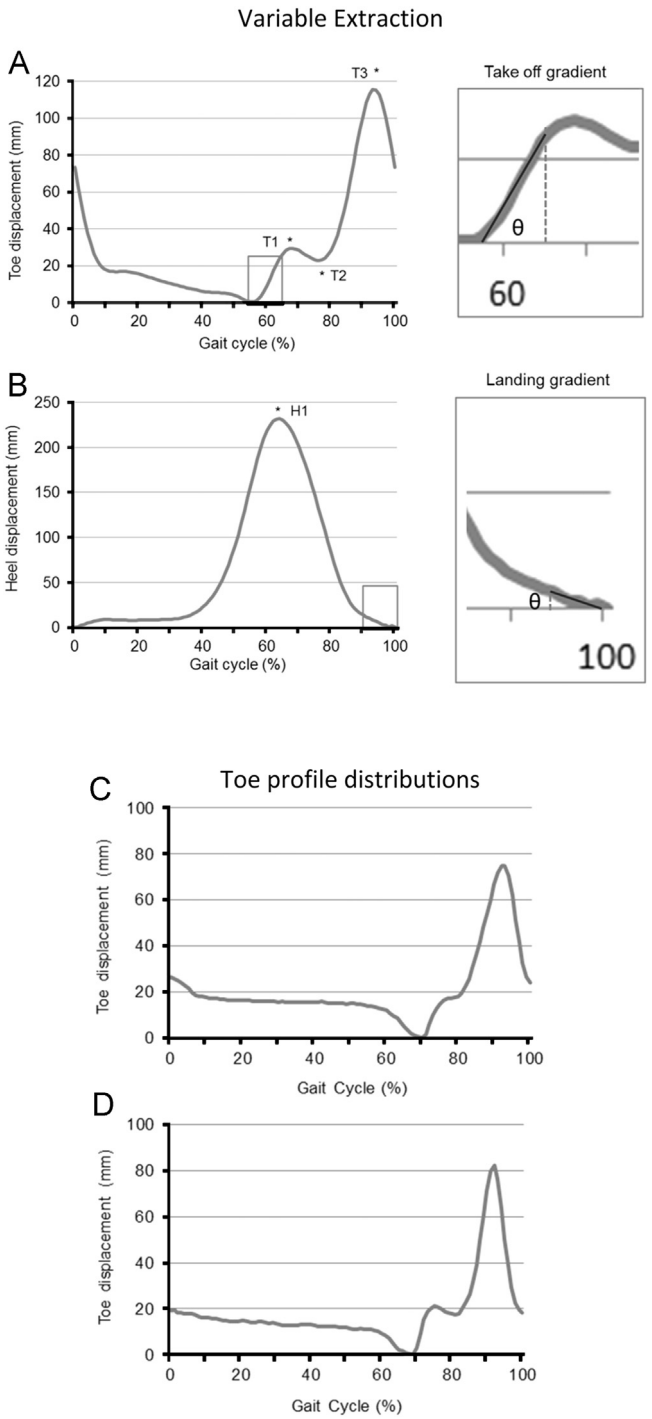

Fig. 1. Extracted variables for the toe (A) and heel (B) trajectories are provided with illustration of gradient extraction (inset) and examples of unimodal (C) and bimodal (D) toe distributions.

regression was used to transform variability ($\lambda = -0.50$) and asymmetry ($\lambda = 0.30$) data. A series of ANOVA were used to identified group differences in the temporal-spatial components of gait (i.e. gait velocity, step length, step time) and foot clearance characteristics (i.e. minima, maxima, trajectory gradients) under single task conditions (Control $n=81$, PD $n=76$). Then, a series of ANCOVA were used to quantify the main and interaction effects of task (single, dual) and group (Control, PD) on foot clearance characteristics using pairwise comparisons from a subset of the same cohort (Control $n=48$, PD $n=40$). No group differences were found for age ($p=.917$) or sex ($\chi^2.546$, $p=.460$) therefore they were not entered as covariates. Task order (single or dual task first) was accounted for within the model. Additional ANCOVAs were used to further examine whether significant group and task differences from the second set of ANOVA (Aim 2) were retained when controlling for temporal-spatial differences in gait (Aim 3). Increased stringency was used to detect statistical significance ($p<.01$) to account for multiple comparisons. This relates to a minimum Bayes factor of .036 and moderate-to-strong strength of evidence (Goodman, 1999a, 1999b). The percentage of unimodal toe trajectories was not normally distributed and was analysed using non-parametric statistics throughout. Statistical procedures were undertaken with SPSS (v.21.0, IBM).

3. Results

No significant differences existed between the groups for age, height or mass for either the single or dual task cohorts (Table 1). Under single task conditions, a total of 4256 steps were analysed (Control $n=2320$, PD $n=1936$) and 2082 steps for dual task (Control $n=1194$, PD $n=888$).

3.1. Influence of pathology

As expected, the PD group walked with a significantly reduced gait velocity and step length and increased step time compared to controls during single task (Table 2; $p<.005$). Under single task conditions, peak toe clearance in late swing (T3) and the landing (heel) gradient were both significantly reduced in PD ($p<.01$). There were no significant group differences in the percentage of unimodal toe distributions or for foot clearance asymmetry or variability (Supplementary material 1).

3.2. Influence of pathology and task

General linear models were constructed using a sub sample of the larger cohort (Control=48, PD=40) to identify the main and interaction effects due to PD and task. There was a main effect of task such that gait velocity and step length were reduced and step time was increased under dual task conditions (Table 3; $p<.001$). Similarly, a main effect of task was found for peak heel clearance (H1), peak toe clearance (T1 and T3) and the take-off (toe) gradient which were all reduced with the addition of a secondary task ($p<.027$). A main effect of task was noted for peak heel clearance (H1) variability only, indicating that H1 was more variable during dual task walking in both groups ($p=.009$, Supplementary material 2). A significantly reduced gait velocity and step length was observed in PD irrespective of task ($p<.007$). Main effects for group indicated that the peak toe clearance in late swing (T3) and the landing gradient were significantly reduced in PD. No significant interactions were observed.

A higher proportion of unimodal toe trajectories were observed in PD compared to controls during dual task conditions ($p=.002$, Fig. 2). Moreover, PD demonstrated a higher proportion of unimodal trajectories during dual task compared with single task ($p=.003$). The majority of PD ($n=28$, 70%) demonstrated less unimodal trajectories during single task compared to dual task compared to controls for which some demonstrated less ($n=17$, 35%) and others more ($n=19$, 40%) unimodal distributions during single task. The percentage of unimodal distributions for single task was positively correlated with those observed during dual task (Fig. 2) for both controls (rho=.722, $p<.001$) and PD (rho=.784, $p<.001$).

3.3. Influence of temporal-spatial gait differences

A reduced gait velocity and shorter step length were observed in the PD group consistently during both single and dual task conditions. Group differences in foot clearance may have been attributed to temporal-spatial gait deficits in PD. Correlations between temporal-spatial components of gait and foot clearance revealed that the strongest associations were found for gait velocity ($r=.38$–$.82$) and step length ($r=.41$–$.89$) (Supplementary Material 3). To further evaluate this relationship, we re-ran the

Table 1
Participant demographics and clinical measures.

	Single task		Dual task	
	Controls $n=81$	**PDs $n=76$**	**Controls($n=48$)**	**PDs($n=40$)**
Age (years)	69.7 [7.5]	67.5 [10.0]	68.3 [7.6]	68.5 [9.1]
Height (m)	1.69 [0.1]	1.70 [0.1]	1.72 [0.1]	1.70 [0.1]
Mass (kg)	76.0 [14.2]	78.2 [15.1]	80.3 [13.6]	77.4 [15.9]
Sex (m/f; n)	39m, 42f *	50m, 26f*	30m, 18f	28m, 12f
Global cognition: MMSE (/30)	29.2 [1.1]*	28.6 [1.3] *	29.1 [1.2] *	28.5 [1.2] *
Maximum digit span	–	–	6 [5, 7]	6 [5, 6]
Digit span errors (sitting, %)	–	–	17 [8, 41]	15 [9, 33]
Digit span errors (walking, %)	–	–	12 [2, 25]	15 [7, 25]
PD specific clinical outcomes				
Self-reported PD duration (months)	–	6.7 [5.0]	–	6.9 [4.6]
Hoehn and Yahr disease stage	–	I $n=18$ II $n=45$ III $n=13$	–	I $n=9$ II $n=23$ III $n=8$
Motor phenotype (n)	–	PIGD $n=33$ ID $n=5$ TD $n=38$	–	PIGD $n=20$ ID $n=2$ TD $n=18$

Data are presented mean [SD] except for digit span data which are presented median [25th. 75th percentile]. PIGD: postural instability gait index. ID: indeterminate. TD: tremor dominant

* Significant between-group differences ($p<.05$)

ANCOVAs for the variables which resulted in significant group differences (landing gradient and peak toe clearance (T3)) using gait velocity and step length as covariates. One model controlled for task order and step length (average of single and dual task step length) and a separate model controlled for task order and gait velocity (average of single and dual task gait velocity). When controlling for step length, group differences in the landing gradient ($p=.006$) and peak toe clearance (T3, $p=.046$) (Table 3, $p<.001$) were retained. When controlling for gait velocity, group differences in the landing gradient were retained ($p=.005$) but became non-significant for the peak toe clearance late swing ($p=.069$).

Table 2
Temporal-spatial characteristics of gait and foot clearance during single task walking.

	Single task	
	Older adults ($n=81$)	**PDs ($n=76$)**
Gait velocity (m/s)	1.25 [0.2]**	1.13 [0.2]**
Step length (m)	0.67 [0.1]**	0.63 [0.1]**
Step time (ms)	541.3 [47.8]**	563.3 [49.3]**
Peak heel clearance (H1, mm)	246.9 [25.2]	247.4 [27.7]
Peak toe clearance (T1, mm)	29.4 [8.1]	29.3 [9.4]
Minimum toe clearance (T2, mm)	28.1 [8.2]	27.9 [9.2]
Peak toe clearance (T3, mm)	129.0 [27.9]**	118.2 [31.7]**
Take-off gradient (hallux)	4.6 [1.6]	4.6 [1.5]
Landing gradient (calcaneus)	2.3 [0.7]**	2.1 [0.5]**
Unimodal distribution (%)	8 [0, 24]	15 [4, 38]

Data are presented mean [SD].

** Statistical significance $p<.01$. During single task, two control participants and one PD participant demonstrated unimodal toe clearance distributions for all steps analysed, therefore $n=79$ and $n=75$, respectively for T1 and T2 variables only.

4. Discussion

To our knowledge, this exploratory study is the largest to characterise foot clearance during overground gait using a broad range of measures in a large cohort of early PD and explore the effects of a concurrent cognitive (dual) task. We have demonstrated that foot clearance is altered even in the early clinical stages of PD and is adversely affected by a dual (cognitive) task in both older adults and PD.

4.1. Influence of pathology

Avoiding a trip-related fall is reliant on the ability to modulate gait patterns accordingly in response to changing environments. Adequate foot clearance is required to avoid unanticipated contact

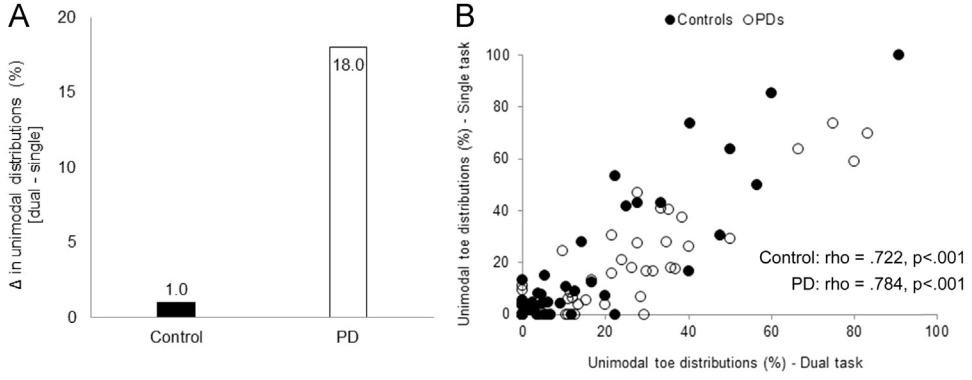

Fig. 2. (A) Group mean change in unimodal distributions (%) from single to dual task and (B) the relationship between unimodal toe distributions observed in single and dual task walking (%), in older adults and PD.

Table 3
Temporal-spatial characteristics of gait and foot clearance characteristics in a subset of older adults and Parkinson's disease during dual task walking.

	Single task		Dual task		General Linear Model (p)		
					Main effect		Interaction
	Older adults (n=48)	PDs (n=40)	Older adults (n=48)	PDs (n=40)	Task	Group	Task* group
Gait velocity (m/s)	1.25 [0.2]	1.11 [0.2]	1.17 [0.2]	1.05 [0.2]	<.001**	.004**	.695
Step length (m)	0.68 [0.1]	0.62 [0.1]	0.65 [0.1]	0.60 [0.1]	<.001**	.007**	.549
Step time (msec)	547.1 [50.0]	567.3 [50.6]	562.7 [56.8]	578.0 [53.1]	<.001**	.099	.490
Peak heel clearance (H1, mm)	247.1 [26.4]	244.0 [27.4]	242.9 [25.5]	239.3 [29.8]	<.001**	.489	.473
Peak toe clearance (T1, mm)	28.8 [7.9]	28.0 [8.4]	28.1 [8.3]	27.2 [8.1]	.027*	.543	.947
Minimum toe clearance (T2, mm)	27.0 [7.9]	26.3 [8.2]	26.5 [8.4]	25.6 [7.8]	.086	.545	.825
Peak toe clearance (T3, mm)	133.8 [27.2]	115.2 [33.1]	126.6 [23.1]	105.2 [31.0]	<.001**	.001**	.322
Take-off gradient (hallux)	4.7 [1.4]	4.4 [1.4]	4.5 [1.6]	4.2 [1.4]	<.001**	.271	.626
Landing gradient (calcaneus)	2.5 [0.7]	2.0 [0.4]	2.3 [0.6]	2.0 [0.5]	.061	<.001**	.178
Unimodal distribution (%)	4 [0, 16]	16 [4, 29]	5 [0, 22][a]	23 [11, 35][a,b]	–	–	–

Data are presented mean [SD] except for distribution, asymmetry and variability data which are presented median [IQR25, IQR75]. A Type I sequential model was used to determine the main effect for task (single vs. dual) and a Type III marginal model was used to determine the main effect for group. During dual task assessment, one control participant demonstrated unimodal toe clearance distributions for all steps analysed, therefore n=47 for T1 and T2 variables only. It is important to note that participants displaying 100% unimodal toe distribution will not exhibit T1 or T2. For participants demonstrating 100% unimodal toe distribution unilaterally, neither asymmetry nor variability for T1 or T2 was calculated.

* Statistical significance $p < .05$, ** statistical significance $p < .01$.

[a] Significant differences between groups (Mann-Whitney test, p=.002).

[b] Significant differences between task (single *vs.* dual) for the PD group only (Wilcoxen signed rank, p=.003).

with the ground/environmental obstacle to preserve locomotor stability. Should instability occur, appropriate responses must be actioned to prevent loss of balance. Unanticipated contact with the ground or environmental obstacle is one preceding event leading to potential postural disturbance and as such the minimum toe clearance occurring mid-swing is often regarded as an event when falls risk is high (Best and Begg, 2008; Lai et al., 2012) given its close proximity to the ground (increased risk of unanticipated contact) at peak anterior velocity (increasing the balance/stepping response required). From the literature, it is possible to surmise that the mean minimum toe clearance is not significantly affected by age (Begg et al., 2007; Mills et al., 2008; Sparrow et al., 2008; Nagano et al., 2011), however distribution of this parameter is often positively skewed (Begg et al., 2007; Khandoker et al., 2010; Nagano et al., 2011) and more variable in the old (Begg et al., 2007; Mills et al., 2008; Sparrow et al., 2008; Khandoker et al., 2010). For mean values, the observed skewness has been suggested to represent a motor control strategy aimed at reducing the variability of spread of low foot clearance thereby reducing overall trip risk (Begg et al., 2007; Mills et al., 2008; Sparrow et al., 2008). We observed no alteration in the minimum toe clearance at mid-swing due to group or task. However, variability of foot clearance was positively skewed prior to transformation suggesting that clearance variability was generally low in both groups and perhaps clearance during other gait phases may be more useful in informing falls risk.

A significantly greater proportion of unimodal toe trajectories (absence of T1) were observed in PD compared with controls under single task but PD also demonstrated a greater relative proportion during dual task. The absence of a peak toe clearance in late swing (T3) has been observed in PD when walking at slower velocities and biphasic toe displacement was always present when walking at quicker velocities (Cho et al., 2010). However, this study (Cho et al., 2010) measured foot clearance while participants walked on a motor driven treadmill which will alter the temporal-spatial components of gait. Previous work has demonstrated that the mean minimum toe clearance shifted vertically in position and earlier in the swing phase with slower treadmill-set velocities (0.8 m/s) in young adults (Osaki et al., 2007). In the present study; the majority of PD walked quicker than 0.8 m/s during both conditions suggesting that reduced velocities were not responsible for the increased proportion of unimodal distributions observed. Moreover, gait velocity was not manipulated or constrained and as such is likely to be more representative of habitual gait. It is noteworthy that individuals who walked with a higher proportion of unimodal toe trajectories did so for both single and dual task irrespective of group. This is in agreement with a recent study (Santhiranayagam et al., 2015) which showed that the proportion of unimodal trajectories observed was increased in young adults when challenged with an additional task or when asked to walk slowly and in older adults across a variety of conditions. The authors conclude that the absence of a minimum toe clearance mid-swing may be a conscious locomotor control strategy to minimise trip risk (Santhiranayagam et al., 2015), however the determinants and implications of unimodal toe trajectories are not well understood. Further work is required to understand how subtle changes in the segmental co-ordination of lower limb kinematics influence the presence of unimodal toe trajectories and the implications relating to falls risk.

4.2. *Influence of pathology and dual task*

During the swing phase of gait, the risk of tripping is heightened the closer the foot is to the floor and consequently it is important to consider foot clearance during early and late swing. The take-off (toe) gradient was adversely affected by dual task irrespective of group whereas the landing (heel) gradient was adversely affected by group irrespective of task. A reduced landing gradient in PD may be an early indication of the onset of a shuffling gait and scuffing (Snijders et al., 2007) which enhances our understanding of the factors underpinning falls risk in PD. Constructing gait assessments within a dual task paradigm offers a more ecologically valid and robust evaluation of gait when attentional resources are required for multiple tasks. The present study has shown that foot clearance is reduced in PD and is further compromised when attending to a dual (cognitive) task which likely contributes to the higher incidence of reported falls in the community in PD (Ashburn et al., 2001; Wood et al., 2002).

4.3. *Association between temporal-spatial gait and foot clearance*

Finally, this study aimed to establish the relationship between temporal-spatial components of gait and foot clearance due to known associations (velocity and stride frequency) already established in

young (Osaki et al., 2007; Cho et al., 2010) and older adults (Sparrow et al., 2008). The results suggest that altered foot clearance in PD is strongly associated with a reduced gait velocity and especially a shorter step length (Supplementary Material 3). This suggests that underlying hypokinesia is evident even in early stage pathology and influences foot clearance. Basal ganglia dysfunction results in poor utilisation of internal information and consequently external cues are often used to improve the rhythm and magnitude of movement. As such, it is suggested that external prompts (i.e. visual or auditory cues) targeting improved gait velocity and step length, rather than step time, may translate into improvements in foot clearance (particularly for mean values). Whilst altered foot clearance is heavily dependent on temporal-spatial components of gait, other contributing factors such as reduced hip and knee flexion (Knutsson, 1972) may explain the group differences that are retained even in the presence of a reduced step length. Complementary analysis may consider a kinematic analysis of lower limb mechanics in PD to further inform the nature of take-off and landing gradients.

4.4. Study considerations

This study represents the largest database of foot trajectories for older adults and early PD for which velocity was not constrained or manipulated (Lai et al., 2012) or kept constant (Sparrow et al., 2008) as is the case during treadmill walking which can alter foot trajectories significantly, especially in older adults (Nagano et al., 2011). One limitation of the current study is the simplistic marker set used. Whilst alternative methods are available for comprehensive foot modelling (e.g. geometric modelling (Sparrow et al., 2008; Alcock et al., 2013) or segment digitisation (Startzell and Cavanagh, 1999; Loverro et al., 2013; Telonio et al., 2013)) or correcting for the minute irregularities in floor surfaces (Schulz, 2011), appropriate steps were taken to correct the signal for the measurement-induced offset. Furthermore, the protocol used was adequate to detect alterations in foot clearance due to pathology and dual task. This study characterised foot clearance whilst PD were optimally medicated and ambulating in their comfortable shoes to preserve external validity. However, factors not controlled for which may have been influential include visual function and correction (Johnson et al., 2007), shoe sole geometry (Thies et al., 2015) and medication (Cho et al., 2010). Subsequent analysis will include the longitudinal evaluation of subtle changes in gait and foot clearance to disentangle the complex influence of ageing and pathology. Further work is required to determine the relationship between reduced foot clearance characteristics and the incidence, frequency and type of falls in older adults and people with PD. Moreover, given that this is the first study to present novel foot clearance metrics; we suggest future work is necessary to evaluate what constitutes a clinically meaningful change in trajectory gradients. The exploratory nature of this study allowed us to provide a thorough description of foot clearance during gait in PD and older adults. These findings will inform a more targeted hypothesis driven approach when establishing the clinical utility of specific foot clearance metrics, such as identifying falls risk in people with PD, understanding the mechanisms of these trips and falls, and further developing personalised falls reduction interventions.

5. Conclusions

Distinct differences in foot clearance during gait between older adults and PD were observed and these deviations were most notable under dual task. Further work is required to understand the kinematic co-ordination underpinning the presence of unimodal toe distributions. Interventions that improve gait velocity and step length will likely improve foot clearance in PD. Trajectory gradients may provide a unique insight into altered foot trajectories in PD and may help inform the design of falls prevention and exercise rehabilitation.

Conflict of interest statement

The authors have no financial or personal conflicts of interest to declare.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2016.06.007.

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