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

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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.

53 1 INTRODUCTION

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

66

67 Foot clearance during swing follows a typical pattern whereby heel displacement progresses both anteriorly
68 and vertically until a peak (~25cm in the young(Winter,1992)) is reached mid-swing. Toe clearance is often
69 biphasic with a peak in early and late swing. One of the gait events posing the greatest risk for tripping is
70 considered to occur mid-swing, when the anterior velocity of the toe reaches a peak and a minimum
71 clearance of ~1.5cm is achieved in young adults(Winter,1992). Further work is required to establish whether
72 other foot clearance events may be used to distinguish between clinical groups to evaluate falls risk.
73 Unanticipated contact of the toe with either the ground/environmental object may also occur during early
74 swing, when the foot is plantarflexed and accelerating to facilitate limb elevation. Conversely, unanticipated
75 contact of the heel with the ground/environmental object may occur during late swing when the foot is
76 dorsiflexed and decelerating in preparation for foot contact. Limited evidence suggests that foot clearance is
77 reduced in established PD when compared to controls and worsens with disease severity although these
78 studies included small samples (n=10-21)(Knutsson,1972;Cho et al.,2010) and require affirming with larger
79 cohorts.

80

81 Online cognitive processing and execution of motor actions often occur concurrently during real world
82 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 2mm 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 >4mm (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

114 clearance would be reduced in the PD cohort compared to controls; ii) the addition of a dual (cognitive) task
115 would have a negative influence on temporal-spatial characteristics of gait and foot clearance in both groups,
116 with larger changes in PD; and iii) foot clearance would be largely dependent on both temporal and spatial
117 components of gait.

118

119 **2 MATERIALS AND METHODS**

120 **2.1 Participants**

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

131

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

136

137 **2.2 Gait protocol**

138 Participants walked around a 25-metre circuit at their preferred pace for two minutes under single task
139 conditions. A subsample of this cohort completed the same circuit under dual task conditions(Galna et
140 al.,2013). For dual task conditions, the forward digit span(Wechsler,1997) normalised to maximum recall
141 capacity was used (determined as the maximum length of a randomly generated string of numbers recalled
142 successfully on two out of three attempts). Strings of digits were presented through a speaker system

143 (Creative, Inspire S2, Singapore) at a frequency of 1 digit/second. Repeated digit recall was assessed whilst
144 seated continuously for 2-minutes to quantify cognitive task performance(Rochester et al.,2014). Digit span
145 errors (%) during both sitting and walking were calculated.

146

147 Temporal-spatial components of gait were collected using a 7-metre instrumented walkway (Platinum model
148 GAITRite®, software v.4.5, CIR systems Inc., United States of America, 240Hz). Participants were instructed
149 to wear their own comfortable flat-soled shoes. No participants wore high heeled shoes for the gait
150 assessments. Reflective, spherical markers (14mm diameter) were affixed over the shoe surface on the heel
151 and the toe bilaterally. Three dimensional motion of foot trajectories were recorded using a 10-camera
152 Vicon© system (Mx3p VICON, California, USA; Nexus software, v.1.83) sampling at 100Hz and targeting a
153 capture volume of 13.5m³ (6m x 1.5m x 1.5m). Task order (single and dual) was counterbalanced between
154 groups.

155

156 2.3 Data Analysis

157 Footfall data were processed and temporal-spatial components of gait were extracted from the GAITRite®
158 database using Microsoft® Access 2007. Marker trajectories were labelled within Vicon© Nexus (v.1.8.5,
159 Oxford, UK) for periods when participants walked across the instrumented walkway. Trajectories were
160 smoothed using a Woltering filter (Mean square error: 20mm). The remaining computational steps were
161 completed in MATLAB® (R2012a, Mathworks, Natick, MA). Trajectories were organised into a matrix of time-
162 normalised (101 points) gait cycles which were detected using a vertical velocity-threshold of the heel
163 trajectory of 250mm/s. Using velocity thresholds alone to identify foot contacts are problematic(Schulz et
164 al.,2010) and to overcome this we developed an algorithm for detecting erroneous gait cycles that relied on
165 known elements of foot trajectories during gait, i.e. appropriate minima/maxima etc. Success of this error
166 detection algorithm was affirmed through visual inspection of all extracted gait cycles. Corrections to the
167 vertical offset resultant from variation in marker placement were applied to ensure that when the foot was flat
168 on the floor (i.e. during mid-stance) clearance was 0mm. A vertical offset corrected the heel marker and an
169 angular offset aligned the toe marker with the heel. Foot trajectory characteristics were extracted bilaterally
170 per trial and included: the maximum vertical toe displacement during the first (T1) and second half (T3) of
171 swing; the minimum vertical toe displacement mid-swing (T2); the peak vertical heel displacement (H1) and
172 trajectory gradients of the toe during the first half of swing (take-off) and of the heel during the second half of

173 swing (landing) (Figure 1). To reduce the chance of false peak detection, the algorithm defined that a peak
174 had occurred when a data point was larger than the three samples before and after. The take-off and landing
175 gradients were defined as the change in vertical (toe/heel) displacement, divided by the change in time (5%
176 of the start or end of the swing phase, respectively). Ensemble averages per participant were compiled
177 combining both limbs and all gait cycles obtained per condition. Toe trajectories were examined for unimodal
178 (single peak) and bimodal (two peaks) distributions(Cho et al.,2010). The algorithm defined that participants
179 displaying a unimodal toe trajectory will not exhibit a T1 or T2 event for that gait cycle. For each of the foot
180 clearance characteristics, the variability (within-person differences in steps) and asymmetry (within-person
181 difference between right and left limbs) were calculated. Variability was calculated as the square root of the
182 variance associated with the right and left sides and asymmetry was calculated as the absolute difference
183 between the average of the left side minus the average of the right side(Galna et al.,2013).

184

185 2.4 Statistical Analysis

186 Data distributions were visually inspected using histograms and measures of dispersion were used to
187 confirm visual interpretation. Mean variables were normal thus parametric statistics were used. A lambda (λ)
188 correction informed by Box Cox regression was used to transform variability ($\lambda=-0.50$) and asymmetry
189 ($\lambda=0.30$) data. A series of ANOVA were used to identified group differences in the temporal-spatial
190 components of gait (i.e. gait velocity, step length, step time) and foot clearance characteristics (i.e. minima,
191 maxima, trajectory gradients) under single task conditions (Control n=81, PD n=76). Then, a series of
192 ANCOVA were used to quantify the main and interaction effects of task (single, dual) and group (Control,
193 PD) on foot clearance characteristics using pairwise comparisons from a subset of the same cohort (Control
194 n=48, PD n=40). No group differences were found for age ($p=.917$) or sex ($\chi^2 .546$, $p=.460$) therefore they
195 were not entered as covariates. Task order (single or dual task first) was accounted for within the model.
196 Additional ANCOVAs were used to further examine whether significant group and task differences from the
197 second set of ANOVA (Aim 2) were retained when controlling for temporal-spatial differences in gait (Aim 3).
198 Increased stringency was used to detect statistical significance ($p<.01$) to account for multiple comparisons.
199 This relates to a minimum Bayes factor of .036 and moderate-to-strong strength of
200 evidence(Goodman,1999a, b). The percentage of unimodal toe trajectories was not normally distributed and
201 was analysed using non-parametric statistics throughout. Statistical procedures were undertaken with SPSS
202 (v.21.0, IBM).

203

Toe profile distributions

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).

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	-	I n = 9
		II n = 45		II n = 23
		III n = 13		III n = 8
Motor Phenotype (n)	-	PIGD n = 33	-	PIGD n = 20
		ID n = 5		ID n = 2
		TD n = 38		TD n = 18

215

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 * denotes significant between-group differences (p<.05)

218

219

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).

226

227 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 (msec)	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]

228

229

230 Data are presented mean [SD]. * denotes statistical significance $p < .05$ and ** indicates statistical significance $p < .01$. During single task,
 231 two control participants and one PD participant demonstrated unimodal toe clearance distributions for all steps analysed, therefore $n = 79$
 232 and $n = 75$, respectively for T1 and T2 variables only.
 233

234 3.2 Influence of pathology and task

235 General linear models were constructed using a sub sample of the larger cohort (Control=48, PD=40) to
 236 identify the main and interaction effects due to PD and task. There was a main effect of task such that gait
 237 velocity and step length were reduced and step time was increased under dual task conditions (Table
 238 3; $p < .001$). Similarly, a main effect of task was found for peak heel clearance (H1), peak toe clearance (T1
 239 and T3) and the take-off (toe) gradient which were all reduced with the addition of a secondary task ($p < .027$).
 240 A main effect of task was noted for peak heel clearance (H1) variability only, indicating that H1 was more
 241 variable during dual task walking in both groups ($p = .009$, Supplementary Material 2). A significantly reduced
 242 gait velocity and step length was observed in PD irrespective of task ($p < .007$). Main effects for group
 243 indicated that the peak toe clearance in late swing (T3) and the landing gradient were significantly reduced in
 244 PD. No significant interactions were observed.

245
246

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)		
	Older adults (n = 48)	PDs (n = 40)	Older adults (n = 48)	PDs (n = 40)	Main effect		Interaction
					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] ¹	23 [11, 35] ^{1,2}	-	-	-

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. Shaded grey cells denotes statistical significance p<.05 and * indicates statistical significance p<.01. 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. ¹ denotes significant differences between groups (Mann-Whitney test, p=.002) and ² denotes significant differences between task (single vs. dual) for the PD group only (Wilcoxon signed rank, p=.003). 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.

247

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

255

256 3.3 Influence of temporal-spatial gait differences

257 A reduced gait velocity and shorter step length were observed in the PD group consistently during both
258 single and dual task conditions. Group differences in foot clearance may have been attributed to temporal-
259 spatial gait deficits in PD. Correlations between temporal-spatial components of gait and foot clearance
260 revealed that the strongest associations were found for gait velocity ($r=.51-.82$) and step length ($r=.41-.89$)
261 (Supplementary Material 3). To further evaluate this relationship, we re-ran the ANCOVAs for the variables
262 which resulted in significant group differences (landing gradient and peak toe clearance (T3)) using gait
263 velocity and step length as covariates. One model controlled for task order and step length (average of
264 single and dual task step length) and a separate model controlled for task order and gait velocity (average of
265 single and dual task gait velocity). When controlling for step length, group differences in the landing gradient
266 ($p=.006$) and peak toe clearance (T3, $p=.046$) (Table 3, $p<.001$) were retained. When controlling for gait
267 velocity, group differences in the landing gradient were retained ($p=.005$) but became non-significant for the
268 peak toe clearance late swing ($p=.069$).

269

270

271

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

274 4 DISCUSSION

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

279

280 4.1 Influence of pathology

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

299

300 A significantly greater proportion of unimodal toe trajectories (absence of T1) were observed in PD
301 compared with controls under single task but PD also demonstrated a greater relative proportion during dual
302 task. The absence of a peak toe clearance in late swing (T3) has been observed in PD when walking at
303 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 (0.8m/s) in young adults(Osaki et al.,2007). In the present study; the majority of PD walked quicker than 0.8m/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.

320

321 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 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).

332

333 4.3 Association between temporal-spatial gait and foot clearance

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

348

349 4.4 Study considerations

350 This study represents the largest database of foot trajectories for older adults and early PD for which velocity
351 was not constrained or manipulated(Lai et al.,2012) or kept constant(Sparrow et al.,2008) as is the case
352 during treadmill walking which can alter foot trajectories significantly, especially in older adults(Nagano et
353 al.,2011). One limitation of the current study is the simplistic marker set used. Whilst alternative methods are
354 available for comprehensive foot modelling (e.g. geometric modelling(Sparrow et al.,2008;Alcock et al.,2013)
355 or segment digitisation(Startzell and Cavanagh,1999;Loverro et al.,2013;Telonio et al.,2013)) or correcting
356 for the minute irregularities in floor surfaces(Schulz,2011), appropriate steps were taken to correct the signal
357 for the measurement-induced offset. Furthermore, the protocol used was adequate to detect alterations in
358 foot clearance due to pathology and dual task. This study characterised foot clearance whilst PD were
359 optimally medicated and ambulating in their comfortable shoes to preserve external validity. However, factors
360 not controlled for which may have been influential include visual function and correction(Johnson et
361 al.,2007), shoe sole geometry(Thies et al.,2015) and medication(Cho et al.,2010). Subsequent analysis will
362 include the longitudinal evaluation of subtle changes in gait and foot clearance to disentangle the complex
363 influence of ageing and pathology. Further work is required to determine the relationship between reduced

364 foot clearance characteristics and the incidence, frequency and type of falls in older adults and people with
365 PD. Moreover, given that this is the first study to present novel foot clearance metrics; we suggest future
366 work is necessary to evaluate what constitutes a clinically meaningful change in trajectory gradients. The
367 exploratory nature of this study allowed us to provide a thorough description of foot clearance during gait in
368 PD and older adults. These findings will inform a more targeted hypothesis driven approach when
369 establishing the clinical utility of specific foot clearance metrics, such as identifying falls risk in people with
370 PD, understanding the mechanisms of these trips and falls, and further developing personalised falls
371 reduction interventions.

372

373 **5 CONCLUSIONS**

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

380

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387

388 **CONFLICT OF INTEREST STATEMENT**

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

REFERENCES

- Age UK, 2010. Falls in the over 65s cost NHS £4.6 million a day. Press Release [www.ageuk.org.uk/latest-news/archive/cost-of-falls/].
- Alcock, L., Vanicek, N., O'Brien, T.D., 2013. Alterations in gait speed and age do not fully explain the changes in gait mechanics associated with healthy older women. *Gait Posture* 37, 586-592.
- Ashburn, A., Stack, E., Pickering, R.M., Ward, C.D., 2001. A community-dwelling sample of people with Parkinson's disease: characteristics of fallers and non-fallers. *Age and Ageing* 30, 47-52.
- Begg, R., Best, R., Dell'Oro, L., Taylor, S., 2007. Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. *Gait & posture* 25, 191-198.
- Best, R., Begg, R., 2008. A method for calculating the probability of tripping while walking. *Journal of Biomechanics* 41, 1147-1151.
- Blake, A.J., Morgan, K., Bendall, M.J., Dallosso, H., Ebrahim, S.B.J., Arie, T.H.D., Fentem, P.H., Bassey, E.J., 1988. Falls by Elderly People at Home - Prevalence and Associated Factors. *Age and Ageing* 17, 365-372.
- Chaudhuri, K., Healy, D.G., Schapira, A.H.V., 2006. Non-motor symptoms of Parkinson's disease: diagnosis and management. *The Lancet Neurology* 5, 235-245.
- Cho, C., Kunin, M., Kudo, K., Osaki, Y., Olanow, C.W., Cohen, B., Raphan, T., 2010. Frequency-velocity mismatch: a fundamental abnormality in parkinsonian gait. *Journal of neurophysiology* 103, 1478-1489.
- Department of Health, 2009. Falls and fractures - Effective interventions in health and social care. http://webarchive.nationalarchives.gov.uk/20130107105354/http://www.dh.gov.uk/prod_consum_dh/groups/d_h.digitalassets/@dh/@en/@pg/documents/digitalasset/dh_109122.pdf
- Folstein, M.F., Folstein, S.E., McHugh, P.R., 1975. Mini-Mental State: a practical method for grading the cognitive state of patients for the clinician. Pergamon Press.
- Galna, B., Lord, S., Burn, D.J., Rochester, L., 2014. Progression of gait dysfunction in incident Parkinson's disease: Impact of medication and phenotype. *Movement Disorders*.
- Galna, B., Lord, S., Rochester, L., 2013. Is gait variability reliable in older adults and Parkinson's disease? Towards an optimal testing protocol. *Gait & posture* 37, 580-585.
- Gazibara, T., Pekmezovic, T., Tepavcevic, D.K., Tomic, A., Stankovic, I., Kostic, V.S., Svetel, M., 2014. Circumstances of falls and fall-related injuries among patients with Parkinson's disease in an outpatient setting. *Geriatric Nursing* 35, 364-369.
- Goodman, S.N., 1999a. Toward evidence-based medical statistics. 1: The P value fallacy. *Annals of internal medicine* 130, 995-1004.
- Goodman, S.N., 1999b. Toward evidence-based medical statistics. 2: The Bayes factor. *Annals of internal medicine* 130, 1005-1013.

- Hamacher, D., Hamacher, D., Schega, L., 2014. Towards the Importance of Minimum Toe Clearance in Level Ground Walking in a Healthy Elderly Population. *Gait & Posture*.
- Hass, C.J., Malczak, P., Nocera, J., Stegemöller, E.L., Shukala, A., Malaty, I., Jacobson Iv, C.E., Okun, M.S., McFarland, N., 2012. Quantitative normative gait data in a large cohort of ambulatory persons with Parkinson's disease. *PloS one* 7, e42337.
- Hausdorff, J.M., Cudkowicz, M.E., Firtion, R., Wei, J.Y., Goldberger, A.L., 1998. Gait variability and basal ganglia disorders: Stride-to-stride variations of gait cycle timing in parkinson's disease and Huntington's disease. *Movement disorders* 13, 428-437.
- Hoehn, M., Yahr, M., 1967. Parkinsonism: onset, progression and mortality. *Neurology* 17, 427-442.
- Hou, J.-G.G., Lai, E.C., 2007. Non-motor symptoms of Parkinson's disease. *International Journal of Gerontology* 1, 53-64.
- Hughes, A.J., Daniel, S.E., Kilford, L., Lees, A.J., 1992. Accuracy of clinical diagnosis of idiopathic Parkinson's disease: a clinico-pathological study of 100 cases. *Journal of Neurology, Neurosurgery & Psychiatry* 55, 181-184.
- Jankovic, J., 2008. Parkinson's disease: clinical features and diagnosis. *Journal of Neurology, Neurosurgery & Psychiatry* 79, 368-376.
- Johnson, L., Buckley, J.G., Scally, A.J., Elliott, D.B., 2007. Multifocal spectacles increase variability in toe clearance and risk of tripping in the elderly. *Investigative ophthalmology & visual science* 48, 1466-1471.
- Khandoker, A.H., Lynch, K., Karmakar, C.K., Begg, R.K., Palaniswami, M., 2010. Toe clearance and velocity profiles of young and elderly during walking on sloped surfaces.
- Khoo, T.K., Yarnall, A.J., Duncan, G.W., Coleman, S., O'Brien, J.T., Brooks, D.J., Barker, R.A., Burn, D.J., 2013. The spectrum of nonmotor symptoms in early Parkinson disease. *Neurology* 80, 276-281.
- Knutsson, E., 1972. An analysis of parkinsonian gait. *Brain* 95, 475-486.
- Lai, D.T.H., Taylor, S.B., Begg, R.K., 2012. Prediction of foot clearance parameters as a precursor to forecasting the risk of tripping and falling. *Human movement science* 31, 271-283.
- Loverro, K.L., Mueske, N.M., Hamel, K.A., 2013. Location of minimum foot clearance on the shoe and with respect to the obstacle changes with locomotor task. *Journal of biomechanics* 46, 1842-1850.
- Mills, P.M., Barrett, R.S., Morrison, S., 2008. Toe clearance variability during walking in young and elderly men. *Gait & Posture* 28, 101-107.
- Morris, M.E., Iansek, R., Matyas, T.A., Summers, J.J., 1994. The pathogenesis of gait hypokinesia in Parkinson's disease. *Brain* 117, 1169-1181.
- Morris, M.E., Iansek, R., Matyas, T.A., Summers, J.J., 1996. Stride length regulation in Parkinson's disease normalization strategies and underlying mechanisms. *Brain* 119, 551-568.
- Nagano, H., Begg, R.K., Sparrow, W.A., Taylor, S., 2011. Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking. *Clinical Biomechanics* 26, 962-968.

- Osaki, Y., Kunin, M., Cohen, B., Raphan, T., 2007. Three-dimensional kinematics and dynamics of the foot during walking: a model of central control mechanisms. *Experimental brain research* 176, 476-496.
- Park, A., Stacy, M., 2009. Non-motor symptoms in Parkinson's disease. *Journal of neurology* 256, 293-298.
- Poewe, W., 2008. Non-motor symptoms in Parkinson's disease. *European Journal of Neurology* 15, 14-20.
- Rochester, L., Galna, B., Lord, S., Burn, D., 2014. The nature of dual-task interference during gait in incident Parkinson's disease. *Neuroscience* 265, 83-94.
- Roiz, R.M., Cacho, E.W.A., Pazinato, M.M., Reis, J.G., Cliquet Jr, A., Barasnevicius-Quagliato, E., 2010. Gait analysis comparing Parkinson's disease with healthy elderly subjects. *Arquivos de neuro-psiquiatria* 68, 81-86.
- Santhiranyagam, B.K., Lai, D.T.H., Sparrow, W.A., Begg, R.K., 2015. Minimum toe clearance events in divided attention treadmill walking in older and young adults: a cross-sectional study. *Journal of neuroengineering and rehabilitation* 12, 1.
- Schulz, B.W., 2011. Minimum toe clearance adaptations to floor surface irregularity and gait speed. *Journal of Biomechanics* 44, 1277-1284.
- Schulz, B.W., Lloyd, J.D., Lee Iii, W.E., 2010. The effects of everyday concurrent tasks on overground minimum toe clearance and gait parameters. *Gait & posture* 32, 18-22.
- Snijders, A.H., Van De Warrenburg, B.P., Giladi, N., Bloem, B.R., 2007. Neurological gait disorders in elderly people: clinical approach and classification. *The Lancet Neurology* 6, 63-74.
- Sparrow, W.A., Begg, R.K., Parker, S., 2008. Variability in the foot-ground clearance and step timing of young and older men during single-task and dual-task treadmill walking. *Gait & posture* 28, 563-567.
- Startzell, J.K., Cavanagh, P.R., 1999. A three-dimensional approach to the calculation of foot clearance during locomotion. *Human movement science* 18, 603-611.
- Stebbins, G.T., Goetz, C.G., Burn, D.J., Jankovic, J., Khoo, T.K., Tilley, B.C., 2013. How to identify tremor dominant and postural instability/gait difficulty groups with the movement disorder society unified Parkinson's disease rating scale: comparison with the unified Parkinson's disease rating scale. *Movement Disorders* 28, 668-670.
- Telonio, A., Blanchet, S., Maganaris, C.N., Baltzopoulos, V., McFadyen, B.J., 2013. The detailed measurement of foot clearance by young adults during stair descent. *Journal of Biomechanics* 46, 1400-1402.
- Thies, S.B., Price, C., Kenney, L.P.J., Baker, R., 2015. Effects of shoe sole geometry on toe clearance and walking stability in older adults. *Gait & Posture*.
- Wechsler, D., 1997. WAIS-III: Administration and scoring manual: Wechsler adult intelligence scale. Psychological Corporation.
- Winter, D.A., 1992. Foot trajectory in human gait: a precise and multifactorial motor control task. *Physical Therapy* 72, 45-53.
- Wood, B.H., Bilclough, J.A., Bowron, A., Walker, R.W., 2002. Incidence and prediction of falls in Parkinson's disease: a prospective multidisciplinary study. *Journal of Neurology, Neurosurgery & Psychiatry* 72, 721-725.

World Medical Association, 2001. World Medical Association Declaration of Helsinki. Ethical principles for medical research involving human subjects. Bulletin of the World Health Organization 79, 373.

Yarnall, A.J., Breen, D.P., Duncan, G.W., Khoo, T.K., Coleman, S.Y., Firbank, M.J., Nombela, C., Winder-Rhodes, S., Evans, J.R., Rowe, J.B., 2014. Characterizing mild cognitive impairment in incident Parkinson disease The ICICLE-PD Study. *Neurology* 82, 308-316.

Yogev, G., Plotnik, M., Peretz, C., Giladi, N., Hausdorff, J.M., 2007. Gait asymmetry in patients with Parkinson's disease and elderly fallers: when does the bilateral coordination of gait require attention? *Experimental Brain Research* 177, 336-346.

Zhou, X., Draganich, L.F., Amirouche, F., 2002. A dynamic model for simulating a trip and fall during gait. *Medical engineering & physics* 24, 121-127.

Supplementary Material 1 – Asymmetry and variability of foot clearance characteristics during single task walking

	Single task	
	Older adults (n = 81)	PDs (n = 76)
Asymmetry		
Peak heel clearance (H1, mm)	4.4 [2.5, 8.5]	4.9 [2.9, 11.4]
Peak toe clearance (T1, mm)	4.3 [1.9, 8.5]	3.9 [1.7, 9.6]
Minimum toe clearance (T2, mm)	4.2 [2.1, 8.5]	4.8 [1.9, 10.4]
Peak toe clearance (T3, mm)	7.1 [3.5, 11.3]	9.3 [4.4, 18.7]
Take-off gradient (hallux)	0.6 [0.3, 1.1]	0.6 [0.3, 1.3]
Landing gradient (calcaneus)	0.4 [0.2, 0.6]	0.4 [0.2, 0.7]
Variability		
Peak heel clearance (H1, mm)	6.3 [4.9, 8.0]	6.3 [5.3, 8.0]
Peak toe clearance (T1, mm)	4.2 [3.2, 11.3]	4.8 [3.4, 11.5]
Minimum toe clearance (T2, mm)	5.4 [4.0, 11.4]	6.1 [4.6, 10.8]
Peak toe clearance (T3, mm)	8.2 [6.8, 9.8]	9.1 [7.3, 10.5]
Take-off gradient (hallux)	0.9 [0.5, 1.6]	0.8 [0.6, 1.4]
Landing gradient (calcaneus)	0.8 [0.6, 1.0]	0.8 [0.6, 1.0]

Data are presented median [IQR25, IQR75]. * denotes statistical significance $p < .05$ and ** indicates 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.

Supplementary Material 2 – Asymmetry and variability of foot clearance characteristics during dual task walking in a subset of older adults and people with Parkinson's disease

	Single task		Dual task		General Linear Model (p)		
	Older adults (n = 48)	PDs (n = 40)	Older adults (n = 48)	PDs (n = 40)	Main effect Task	Group	Interaction Task * Group
Asymmetry							
Peak heel clearance (H1, mm)	6.0 [2.6, 8.2]	4.7 [2.9, 11.5]	5.3 [2.4, 11.0]	5.1 [2.2, 12.0]	.139	.542	.338
Peak toe clearance (T1, mm)	5.3 [2.4, 9.9]	4.9 [1.6, 10.3]	5.0 [2.3, 9.3]	4.5 [1.8, 10.3]	.461	.920	.941
Minimum toe clearance (T2, mm)	5.8 [2.2, 12.2]	5.2 [2.6, 11.6]	4.1 [1.7, 8.4]	4.9 [2.1, 9.6]	.101	.555	.852
Peak toe clearance (T3, mm)	7.5 [4.3, 11.3]	9.2 [4.4, 18.4]	6.3 [3.8, 11.8]	10.1 [2.9, 15.2]	.273	.121	.520
Take-off gradient (hallux)	0.7 [0.3, 1.4]	0.7 [0.3, 1.7]	0.9 [0.3, 1.3]	1.0 [0.4, 2.0]	.229	.433	.844
Landing gradient (calcaneus)	0.4 [0.2, 0.7]	0.5 [0.2, 0.9]	0.3 [0.2, 0.6]	0.5 [0.2, 0.8]	.430	.116	.464
Variability							
Peak heel clearance (H1, mm)	6.8 [4.8, 7.8]	6.1 [5.0, 7.8]	7.1 [5.1, 8.6]	6.9 [5.7, 8.5]	.009 **	.491	.920
Peak toe clearance (T1, mm)	5.4 [3.3, 12.1]	8.5 [3.6, 11.6]	4.6 [3.2, 16.8]	4.8 [3.3, 10.0]	.167	.783	.527
Minimum toe clearance (T2, mm)	7.4 [4.1, 12.0]	8.6 [5.0, 11.4]	6.8 [4.1, 13.3]	5.8 [3.6, 10.2]	.100	.876	.169
Peak toe clearance (T3, mm)	8.3 [6.6, 9.6]	8.9 [7.8, 9.8]	8.8 [6.8, 10.3]	8.7 [7.4, 9.9]	.402	.739	.405
Take-off gradient (hallux)	1.1 [0.6, 2.0]	1.1 [0.7, 1.7]	1.2 [0.6, 1.9]	1.2 [0.7, 1.7]	.832	.848	.603
Landing gradient (calcaneus)	0.8 [0.6, 1.1]	0.8 [0.5, 1.1]	0.8 [0.6, 1.1]	0.7 [0.5, 1.1]	.185	.280	.348

Data 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. * denotes statistical significance $p < .05$ and ** indicates statistical significance $p < .01$. 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.

Supplementary Material 3 - Correlation matrix for temporal spatial gait parameters and foot clearance characteristics under single and dual task

	Single task						Dual task					
	Controls (n = 81)			PD (n = 76)			Controls (n = 48)			PD (n = 40)		
	Velocity (m/s)	Length (cm)	Time (msec)	Velocity (m/s)	Length (cm)	Time (msec)	Velocity (m/s)	Length (cm)	Time (msec)	Velocity (m/s)	Length (cm)	Time (msec)
Peak heel clearance (H1 MSW, mm)	.552***	.769***	.001	.708***	.801***	-.174	.525***	.735***	-.102	.792***	.844***	-.353*
H1 variability	.562***	.362**	-.543***	.340**	.379**	-.133	.415**	.310*	-.374**	.459**	.530***	-.197
H1 asymmetry	-.111	-.089	.100	-.016	.035	.111	-.116	-.160	.081	-.117	-.091	.181
Peak toe clearance (T1 ESW, mm)	.265*	.355**	-.009	.461***	.491***	-.162	.298*	.333*	-.111	.563***	.590***	-.306
T1 variability	.101	.083	-.078	.168	.140	-.130	.032	-.030	-.112	.246	.162	-.338*
T1 asymmetry	-.080	-.083	.054	.022	.130	.179	-.120	-.082	.120	.231	.282	-.038
Minimum toe clearance (T2 MSW, mm)	.230*	.334**	.023	.476***	.529***	-.129	.269	.305*	-.094	.586***	.609***	-.310
T2 variability	.138	.128	-.090	.087	.094	-.017	-.001	-.025	-.050	.181	.098	-.303
T2 asymmetry	-.111	-.065	.128	-.143	-.030	.260*	.039	.150	.133	.190	.214	-.078
Peak toe clearance (T3 LSW, mm)	.511***	.707***	.020	.699***	.797***	-.154	.560***	.794***	-.048	.822***	.892***	-.296
T3 variability	-.172	-.212	.002	.036	-.101	-.274*	-.302*	-.406**	.027	-.169	-.247	-.093
T3 asymmetry	.038	.050	-.027	-.268*	-.208	.281*	-.011	-.066	-.086	-.139	-.012	.367*
Take-off gradient (ESW, hallux)	.299**	.435***	.058	.381**	.498***	.009	.251	.313*	-.072	.647***	.684***	-.289
Take-off gradient variability	.135	.049	-.186	.045	.027	-.086	.035	.016	-.038	.195	.052	-.386*
Take-off gradient asymmetry	.083	.021	-.150	-.095	-.026	.193	.111	.166	-.029	.019	.054	.040
Landing gradient (LSW, calcaneus)	.342**	.460***	.013	.509***	.542***	-.143	.278	.426**	.041	.272	.295	-.002
Landing gradient variability	.136	.067	-.175	-.053	-.032	-.015	.115	.077	-.115	.132	.145	-.110
Landing gradient asymmetry	.060	.148	.136	-.160	-.094	.183	.026	.088	.068	-.143	-.164	.027

* denotes $p \leq .05$, ** denotes $p \leq .01$, *** denotes $p \leq .001$. For visual interpretation and clarity grey shading indicates correlations $p \leq .01$.