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Lower limb somatosensory discrimination is impaired in people with Parkinson's disease: novel assessment and associations with balance, gait and falls

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1 **Title: Lower limb somatosensory discrimination is impaired in people with Parkinson's disease:**
2 **novel assessment and associations with balance, gait and falls.**

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27 **Abstract**

28 Background: People with Parkinson's disease (PD) often have compromised walking and balance.
29 This may be due to impaired lower limb tactile and proprioceptive sensation. Existing clinical
30 measures may not be sufficiently sensitive to uncover these sensory impairments.

31 Objective: Determine whether novel measures of lower limb somatosensory discrimination are
32 psychometrically robust and associated with mobility outcomes in people with PD.

33 Methods. Lower limb somatosensation was assessed on two occasions, 3-7 days apart, using three
34 novel tests: gradient discrimination, roughness discrimination, and step height discrimination. Static
35 and dynamic balance (Brief Balance Evaluations Systems Test), falls incidence, falls confidence
36 (Falls Efficacy Scale), gait (speed and step length) were also obtained. Participants were twenty-
37 seven people with PD and twenty-seven healthy controls (HC).

38 Results: Novel tests showed good-excellent intra-rater reliability (ICC=0.72-0.92). Significantly
39 higher gradient and step height discrimination thresholds ($p < 0.01$) were demonstrated in PD
40 compared to HC, indicating worse position sense at the ankle, knee and hip. Significant correlations
41 were identified between gradient discrimination and falls incidence ($r = 0.55$), falls confidence
42 ($r = 0.44$), balance ($r = 0.63$), but not gait ($r = 0.21$). Step height discrimination was significantly
43 correlated with balance ($r = 0.54$). Foot roughness discrimination was not significantly different
44 between people with PD and HC and was not significantly correlated with mobility measures
45 ($p > 0.05$).

46 Conclusion: These novel tests are psychometrically robust and identify impaired lower limb position
47 sense which were associated with balance and falls in this sample of PD. Interventions targeting
48 somatosensory processing in PD may improve aspects of balance and reduce falls risk. Further
49 research is warranted.

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52 **Introduction**

53 Parkinson's disease (PD) is the second-most common neurodegenerative disease after
54 dementia.¹ It is a progressive neurological condition characterised by both motor and non-motor
55 symptoms with many clinical symptoms related to difficulties with movement. Such difficulties often
56 lead to postural instability, reductions in walking ability and impaired balance which negatively
57 impact participation in activities of daily living, quality of life and falls.^{2,3}

58 The view that movement difficulties in people with Parkinson's disease (PD) are attributable
59 purely to motor deficits has been challenged in recent years by evidence of impaired processing and
60 integration of somatosensory information⁴. Tactile and proprioceptive sense, referred to as
61 somatosensation, arise from sensory receptors in skin, joints, tendons, and muscles providing
62 feedback of an individual's body position, body and limb motion, and interaction with the
63 environment.⁵ Studies have shown people with PD to have deficits in somatosensory processing such
64 as elevated thresholds to spatial and temporal stimuli,⁴ diminished proprioceptive and position sense
65 awareness,^{6,7} and impaired haptic sensation.⁸ Moreover, when visual feedback cannot be used,
66 people with PD lack precision in their stepping,⁹ show greater errors in obstacle clearance,¹⁰ and have
67 greater difficulty controlling postural orientation on the basis of available somatosensory and
68 vestibular information compared to healthy controls¹¹. Unsurprisingly, deficits in lower limb
69 proprioception are significantly associated with falls incidence in people with PD.⁷ It is feasible to
70 posit that sensory deficits may contribute to many of the movement and balance difficulties which are
71 the hallmark of PD. Accurately identifying and quantifying the severity of lower limb somatosensory
72 abnormalities and, crucially, how they are associated with activity and participation limitations
73 represents an important goal to inform rehabilitation interventions.

74 Several measures of somatosensory function have been evaluated and reviewed¹² in
75 neurological populations, with the Erasmus MC modified Nottingham Sensory Assessment
76 (EmNSA)¹³, and the sensory scale of the Fugl-Meyer Assessment¹⁴ suggested to provide the best
77 balance of clinical utility and psychometric robustness¹². Those measures, however, have been widely
78 criticised for largely assessing the detection of stimuli - the lowest level of sensory processing¹⁵, not

79 providing functionally meaningful somatosensory data, and being insufficient for uncovering the
80 complexities of somatosensory perception^{4,16,17}. Furthermore, they have not been evaluated in people
81 with PD. A recent review of proprioception assessment methods¹⁸ highlights a concerning paradox:
82 measures which possess clinical utility lack accuracy, whilst those which possess accuracy lack
83 clinical utility. More complex tests of tactile sensation and proprioceptive function such as matching
84 one or more standardised sensations to another, integrating sensation with motor output or
85 distinguishing the temporal or spatial qualities of two stimuli have been shown to uncover
86 somatosensory dysfunction in Parkinson's, yet are largely limited to the laboratory setting.^{4,6} In
87 response to the perceived shortcomings of existing clinical measures, we developed three novel and
88 functionally oriented tests of somatosensory discrimination: the Foot Roughness Discrimination Test
89 (FoRDT™), the Step height Discrimination Test (StepDT™) and the Gradient Discrimination Test
90 (GradDT™). These functionally oriented tests have been described and evaluated previously in a
91 stroke population^{19,20} showing superior psychometric properties to the clinically feasible and
92 psychometrically robust sensory measure the Erasmus MC modified version of the Nottingham
93 Sensory Assessment (EmNSA).¹³ To date, however, our novel tests have not been evaluated in people
94 with PD.

95 The aim of this study was to evaluate the psychometric properties of these novel somatosensory
96 measures in people with PD, and report on their associations with clinical measures of gait, balance
97 and falls. Specific objectives were to evaluate intra-rater reliability of the novel measures and
98 convergent and known-group validity. Further, we wished to explore the association between our
99 novel measures with functional measures of gait, balance and falls in people with PD.

100 **Method**

101 **Participants**

102 We recruited a convenience sample of 27 people with PD and 27 age matched healthy
103 controls. People with PD were identified through local branches of Parkinson's UK (a UK charity)
104 and healthy age matched controls were recruited through the University of the 3rd Age (a UK

105 volunteer-led organisation providing educational and leisure opportunities to retired/semi-retired
106 individuals). Inclusion criteria were: ability to provide informed consent, walk 10 meters
107 unsupervised (with or without a walking aid), have no have significant cognitive impairment ($\geq 24/30$
108 Mini Mental State Examination, MMSE)²¹ or comorbidities known to affect somatosensation (e.g.
109 diabetic neuropathy). Age matched control participants were included providing they had no
110 pathological conditions known to affect balance, mobility or sensation. Sample size calculations²²
111 indicated a sample size ≥ 27 per group was sufficient for: a 95% CI of 0.25 and a planned ICC of 0.8
112 ($\alpha=0.05$); detecting a correlation coefficient of 0.29 (power=0.85, $\alpha=0.05$); and effect size of 0.79
113 (power=0.85, $\alpha=0.05$).

114 **Procedures**

115 Ethical approval was obtained from the University of Plymouth, Faculty of Health and
116 Human Sciences Research Ethics Committee (ref: 17/18-86). People with PD (n=27) were tested with
117 the novel sensory measures on two occasions, between 3-7 days apart at the same time of day and in
118 their self-reported ON state; that is the state in which they felt they were optimally responsive to their
119 medication. The first author was the rater on test session 1 and test session 2. Control participants
120 (n=27) were tested with the novel measures on just one occasion.

121 Participant demographic characteristics (age, gender) and in the case of people with PD, time
122 since diagnosis, upper and lower limb motor function (Movement Disorder Society - Unified
123 Parkinson's Disease Rating Scale motor score Part III (MDS -UPDRS III)²³ was collected. Alongside
124 the somatosensory tests a range of different health constructs were measured, described below.

125 **Outcome measures:**

126 The *EmNSA*¹³ was used to determine convergent validity of our novel tests. It is considered to
127 be a psychometrically robust and clinically feasible assessment tool¹² involving the assessment of
128 exteroceptive sensation (light touch, pressure touch, and pin-prick), higher cortical discriminatory
129 sensation (sharp-blunt) and proprioception (movement detection and discrimination).

130 The *Gradient Discrimination Test (GradDT™)* evaluates sensory-perceptual ability to
131 discriminate underfoot surface gradient or slope during standing. It has been described previously and
132 shown to be reliable and valid in a stroke population.²⁰ It utilises a two alternative forced choice
133 paradigm (2AFC),²⁴ in which two differing sloping platforms, a base and a comparator, are mentally
134 compared (discriminated). The test procedure involves participants standing on a series of adjustable
135 sloping platforms until a discrimination threshold is reached (i.e. the point at which the participant
136 cannot discriminate between two different slopes). This provides a discrimination threshold in degrees
137 (°). The test takes 7-10 minutes to complete.

138 The Step height Discrimination Test (StepDT™) utilises the 2AFC approach as detailed
139 above and has been described and psychometrically evaluated previously in stroke.²⁰ This test
140 assesses an individual's ability to discriminate the height of a step, through lower limb position sense,
141 without visual feedback. The test involves the passive placement of the test limb onto a series of
142 adjustable steps. The 2AFC test procedure involves increasingly difficult trials until the point at which
143 the individual cannot consistently discriminate which of the two presented steps is highest. This
144 provides a discrimination threshold in centimetres (cm).

145 The Foot Roughness Discrimination Test (FoRDT™), described and evaluated previously,¹⁹
146 assesses haptic tactile sensory ability of the plantar aspect of the foot. It comprises a series of textured
147 foot plates, each with standardised and quantifiable gratings. The test involves the haptic exploration
148 of underfoot textured plates in a series of increasingly difficult trials until a roughness discrimination
149 threshold is reached (i.e. the point at which the participant cannot discriminate between two textures).
150 The gratings are expressed as spatial intervals (i.e. the distance between measured in micrometres
151 (μm) ($1\mu\text{m} = 1/1000$ millimetre (mm)). The larger the spatial interval, the rougher the surface is
152 perceived to be up to a point of between 3000 -3500 μm .²⁵ This provides a roughness discrimination
153 threshold in micrometres (μm).

154 These discrimination tests are undertaken with the participant in standing to reflect, as near as
155 possible, "real life" foot-ground sensorimotor interactions. Upper limb support was provided for
156 safety and to aid participants with balance/weight transfer. Participants were requested to look straight

157 ahead and avoid looking down at their feet during the testing procedure. In each test, a greater
158 discrimination threshold indicates worse somatosensory ability.

159 **Measures of balance, gait and falls**

160 The *Brief Balance Evaluation Systems Test (Brief BESTest)*²⁶ is an eight item test, developed
161 from the original BESTest,²⁷ and assesses six subsystems of static and dynamic balance control:
162 biomechanical constraints, stability limits/verticality, anticipatory postural responses, postural
163 responses, sensory orientation, and stability in gait. Administration time is less than 10 minutes,
164 making it feasible to use in clinical practice, whilst concurrent and convergent validity has been
165 demonstrated in individuals with Parkinson's disease.²⁸

166 The *10 metre Walk Test (10mWT)*²⁹ was used to assess gait speed (comfortable walking speed
167 using a rolling start) and stride length calculated in metres per second and steps per metre
168 respectively. The 10mWT is recommended for use in assessing gait speed in PD.³⁰

169 *Falls Incidence.* Falls data was collected through participant retrospective recall over the
170 previous three month period. This is recommended as a simple, and effective starting point for
171 establishing falls history.³¹ We used a well-accepted definition of falls: 'an unexpected event in which
172 the participant comes to rest on the ground, floor, or lower level'³²

173 Fear of falling. Fear of falling was measured using the *Falls Efficacy Scale - International*
174 (*FES-I*)³³ a 16-item self-report tool, which measures an individual's level of concern about falling
175 during social and physical activities inside and outside the home. Higher scores indicate greater fear
176 of falling, which is associated with future falls, activity limitations and reduced quality of life in PD.³⁴

177 **Statistical analysis**

178 Statistical analyses were performed using SPSS version 22.0. Data were summarised using
179 frequencies and percentages, mean and standard deviation (SD) or median and inter-quartile range
180 (IQR) as appropriate. Data distribution was assessed for normality using Shapiro-Wilks tests and
181 assumed normally distributed when $p > 0.05$. Data presented for the GradDT™, StepDT™ and

182 FoRDT™ represent discrimination thresholds expressed in the original measurement units. Larger
183 discrimination thresholds indicate worse sensory function.

184 Necessary assumptions in reliability testing were accounted for which included stability
185 between testing sessions of participant sensory function and consistency in the testing situation
186 (environment, test procedure, medication and time of day). Intra-rater reliability were analysed using
187 Intra class Correlation Coefficient (ICC_{2,1}) in line with the Guidelines for Reporting Reliability and
188 Agreement Studies (GRRAS).³⁵ Standard error of measurement (SEM) provided an indication of the
189 score likely due to measurement error. Coefficient of repeatability (CoR), a measure of absolute
190 reliability provided a score change (in the original measurement scale), which included random and
191 measurement error and so any score above CoR reflects true/real change or smallest real difference.³⁶
192 It was calculated by multiplying the SEM by 2.77 ($\sqrt{2} \times 1.96$).³⁶

193 Sensory performance of the lower limbs of people with PD and matched healthy controls
194 allowed for an evaluation of known group validity. A Mann Whitney U test was used to determine
195 statistical significance between the groups ($p < 0.05$) as data for each sensory measures was not
196 normally distributed. Effect size (Cohen's *d*) was calculated to show the size of any difference, using
197 a standardised formula³⁷ and interpreted using Cohen's³⁸ criteria of 0.1 = small effect, 0.3 =medium
198 effect and 0.5 =large effect. Convergent validity was evaluated by comparing our novel tests with the
199 EmNSA with the magnitude of the relationship determined using a Spearman's rank order correlation.
200 The magnitude of the relationship between our novel measures of somatosensation and measures of
201 gait, falls and dynamic balance were evaluated using Spearman and Pearson correlational analysis
202 where appropriate. Strength of correlations were interpreted using the classification where ≤ 0.29 =
203 weak, 0.30- 0.49 = moderate and, ≥ 0.50 = strong.³⁸

204 **Results**

205 *Demographic and clinical characteristics:* Fifty-four people, 27 people with PD (mean age 71
206 +/- 5.8 years, male/female = 19/8, and 27 age matched healthy adults (mean age 70 +/- 7 years,
207 male/female = 17/10) were recruited. Parkinson's participants had a mean Movement Disorder

208 Society - Unified Parkinson's Disease Rating Scale motor score (MDS-UPDRS III) of 30.11 +/- 14.7
209 (Table 1)

210 *Intra-rater reliability:* Test-retest reliability of the novel measures is shown in table 2. Good
211 to excellent mean ICC values were demonstrated in each novel test (ICC =0.72-0.92). Wide 95%
212 confidence intervals in the foot roughness and step height discrimination tests were demonstrated.
213 Coefficient of repeatability scores (i.e. random and measurement error) in the GradDT™ represented
214 37% of baseline score, 68% in the FoRDT™ and 55% in the StepDT™. Higher scores represent
215 larger random and measurement error. *Known Groups Validity:* People with PD performed worse on
216 sensory measures compared to healthy controls, indicating worse somatosensory function in the lower
217 limbs (Table 3). A Mann Whitney U test revealed significant differences in gradient discrimination
218 thresholds of PD (median=2.5°) and healthy controls (median =1.4°, U=179, z=-3.86, p<0.001,
219 r=.52). Foot roughness discrimination thresholds in PD (median 400µm) whilst higher than healthy
220 controls (median =300µm) were not significantly different (U=353, z=-1.207, p=0.22, r=0.16). Step
221 height discrimination thresholds were significantly different between PD (median =1.8cm) and
222 healthy controls (median=1.2cm, U=209, z=-3.478, p=0.001, r=0.47). EmNSA tactile sensation scores
223 in PD (median =64) were not significantly different from healthy controls (median =62, U=399, Z=-
224 0.533, p=0.59, r= 0.07). EmNSA proprioception scores were also not significantly different between
225 people with PD (median =16) and healthy controls (median =16, U=392, z=-1.013, p=0.31, r=0.13).

226 Using the EmNSA sensory measure, 55% of people with PD (n=15/27) scored the maximum
227 score (64/64) on tactile sensation component (range 49-64). In the proprioception component of the
228 EmNSA, 81% (n=22/27) of people with PD scored maximally (i.e. 16/16); comparable to healthy
229 control performance (88%, n=24/27). In the novel measures, no single person with PD nor control
230 participant scored the maximum or minimum.

231 *Convergent validity:* To evaluate convergent validity, strength of associations between the
232 novel measures and an existing measure of tactile and proprioceptive sensation, the EmNSA were
233 evaluated (table 4). The Foot Roughness discrimination test (FoRDT) showed moderate and
234 significant inverse correlation (r=-0.45, p<0.05) with the tactile component of the EmNSA. As tactile

235 discrimination thresholds increased, scores on the EmNSA fell, indicating worse tactile sensation. No
236 other significant correlations were demonstrated between our novel measures and the tactile or
237 proprioception components of the EmNSA ($r=0.11-0.28$, $p>0.05$).

238 *Associations between novel measures and balance, gait and falls:* Gradient discrimination as
239 measured with the GradDT™ showed the strongest correlations with functional measures of falls and
240 balance (table 5). A significant and strong inverse relationship between the GradDT™ and
241 BriefBESTest ($r=-0.63$, $p<0.01$) indicates that those with higher gradient discrimination thresholds
242 (i.e worse position sense) had lower scores on the BriefBESTest (i.e worse balance performance). The
243 GradDT™ also showed a strong positive correlation with falls incidence and moderate correlation
244 with the Falls Efficacy Scale – International (FES-I), indicating that those with worse gradient
245 discriminative ability reported more falls ($r=0.55$, $p<0.01$) and had greater concerns about falling
246 ($r=0.44$, $p<0.05$). No significant associations between any sensory measure and spatial or temporal
247 aspects of gait were demonstrated.

248 **Discussion**

249 In this study, we evaluated three novel tests of lower limb somatosensory function in a cohort
250 of people with PD and healthy age matched control participants. The sensory-perceptual ability to
251 discriminate surface gradient or slope was assessed during full weight-bearing using the GradDT™.
252 Discrimination of step height using lower limb position sense was assessed with the StepDT™, and
253 the ability to discriminate underfoot surface roughness was evaluated using the FoRDT™. Our study
254 results provide preliminary evidence to support the reliability and validity of these tests in people with
255 PD, and demonstrate people with PD to have impaired lower limb somatosensory discrimination.
256 Moreover, these deficits are associated with worse static and dynamic balance, greater falls incidence
257 and fear of falling.

258 Our novel measures target key sensorimotor functions related to stance and stepping and use a
259 robust psychophysical testing approach to establish somatosensory discrimination thresholds, i.e. the
260 ability to discriminate the spatial qualities (roughness/gradient/step height) of a stimulus. In contrast

261 to the more traditional, manual method of assessing lower limb movement detection and direction (i.e.
262 the proprioceptive component of the EmNSA), our weight-bearing tests of gradient discrimination
263 (GradDT™) and step height discrimination (StepDT™) highlighted increased somatosensory
264 discrimination thresholds in people with PD and found these deficits had moderate to strong
265 significant correlations with balance, reported falls and concern about falling. In line with our
266 findings, elevated somatosensory discrimination thresholds to temporal stimuli (STDT), that is, the
267 shortest time interval required for two tactile stimuli to be perceived as separate, have also been found
268 in people with PD compared to healthy controls. Elevated discrimination thresholds at the finger and
269 face³⁹ and toe⁴⁰ have been identified in PD, and have mostly been observed to be correlated with
270 movement performance⁴¹; our findings lend further support to the presence of somatosensory
271 dysfunction in people with PD, and its impact on movement performance, movement function and
272 sensorimotor integration.

273 Movement and balance are reliant on a complex interaction between sensory and motor
274 systems⁴² whilst the central processing of sensory information ensures the production of a motor plan
275 for task execution that is appropriate to the sensory environment.⁴³ In PD it is postulated that deficits
276 of central processing of somatosensory information, rather than pathology of the peripheral nervous
277 system result in altered integration of sensory and motor information^{4,44} and in particular
278 proprioceptive information⁴⁵. An important function of the dorsal striatum within the basal ganglia
279 (one of the main channels of information processing) is suggested to be the treatment of sensory and
280 motor information coming from the sensorimotor cortex and integrating visual and proprioceptive
281 information onto the motor command.⁴⁶ Using methods which target the integrity of these central
282 processes and the perceptual constructs they sustain may be better achieved by sensory measures
283 which assess discriminative perception rather than simple touch or movement detection. Our data
284 suggest our lower limb novel measures may be better suited to capturing the complexity of
285 somatosensory dysfunction in PD compared to an existing, widely used clinical measure.

286 That our novel measures of gradient discrimination and step height discrimination were only
287 weakly correlated with the proprioceptive component of the EmNSA suggests they may be measuring

288 different constructs. This may, at least in part, be accounted for by the fact that the EmNSA assessed
289 proprioception with the participant in supine/sitting, in contrast to our novel measures which assessed
290 position sense with the participant standing in full weight-bearing. Sense of position and sense of
291 movement have also been shown by others to only weakly correlate⁴⁷ which may further help to
292 explain this finding.

293 The presence of plantar tactile sensory dysfunction in people with PD was not evident in this
294 study as neither tactile scores of the EmNSA nor discrimination thresholds to roughness perception
295 (FoRDT™) were significantly different from healthy controls. Furthermore, tactile plantar sensation
296 as measured by the FoRDT™ did not significantly correlate with our mobility outcomes. Current
297 evidence pertaining to the presence of plantar tactile sensory deficits in people with PD is
298 equivocal^{4,48} with contrasting results explained by variations in study sample characteristics such as
299 disease stage, symptom severity and sensory assessment methods. That most participants in our study
300 were in the early-moderate stages of PD (mean Hoehn & Yahr stage =2.3; time since diagnosis =5.7
301 years) suggests that reported plantar tactile sensory changes may not occur in early PD. We also
302 recognise the complex and multifactorial nature of balance impairment in PD and the involvement of
303 several ‘systems’ in addition to the somatosensory system²⁷ and so factors other than plantar tactile
304 deficits may also contribute to balance deficits. Nonetheless, that significant deficits of plantar
305 sensation were not evident in our sample, yet proprioceptive deficits were, supports the potential for
306 interventions targeting the plantar aspect of the foot to enhance lower limb position
307 sense/proprioception.

308 Our study supports that diminished position sense awareness of the lower limbs may also
309 contribute to an increased risk of falls. The strong and significant correlations between lower limb
310 position sense as measured with the GradDT™ and StepDT™ falls incidence and falls confidence
311 indicates worse position sense awareness of the lower limb is significantly associated with more falls
312 and greater fear of falling. This is in line with the findings of others who have found greater error
313 performance and variability in judging obstacle heights when relying on lower limb proprioception¹⁰
314 which may contribute to an increased risk of trips; and that people with PD who fall have significantly

315 worse lower limb proprioception, compared to those who don't fall.⁷ The link between falls and lower
316 limb proprioceptive impairment has also been identified in other clinical populations.^{16,49}

317 Neither temporal nor spatial aspects of gait, as measured by straight line gait speed and
318 number of steps, respectively, were significantly associated with lower limb somatosensory function.
319 Similar findings have been identified in previous studies of healthy and neurological populations^{16,50}
320 and explained by the increased use or sensory weighting of visual information during walking tasks,
321 which may reduce the need for accurate somatosensory information from the lower limbs. In essence,
322 'simple' straight line gait tasks may be completed using minimal somatosensory information and
323 processing as visual feedback compensates. EEG studies,^{51,52} demonstrate that more complex gait
324 tasks, such as uphill walking and narrow beam walking result in increased activation within
325 somatosensory cortical regions compared with simple straight line gait tasks on the flat, suggesting a
326 greater role for somatosensory information during more complex walking tasks.

327 Intra-rater reliability was excellent in the GradDT™ although wide reliability confidence
328 intervals and substantial coefficient of repeatability scores for the FoRDT™ and StepDT™ highlight
329 the occurrence of random and/or measurement error. Reliability is an issue in sensory assessments
330 particularly in neurological populations¹² and whilst we attempted to control for random and
331 measurement error, we postulate that the effect of fluctuations in participant energy levels, fatigue and
332 possibly attention, may account for this. The clinical implication is that somatosensory function in
333 people with PD, as with other symptoms, may not be established through one-off assessments, but
334 should be assessed on several occasions in order to gain a true picture. Nonetheless, our novel
335 measures have demonstrated to have distinct advantages over existing measures of lower limb
336 sensation in that they employ an interval level of measurement and show, in this sample, no floor or
337 ceiling effects. The SEM and CoR data provide an indication of random and measurement error which
338 enables interpretation of the true change in scores. Because the CoR is quantified in the same units as
339 the assessment tool, it lends itself for easy clinical interpretation, and can be used to guide decision
340 making. A change in discriminative ability in the gradient test of +/- 0.85° for example, would

341 indicate change beyond random and measurement error; critical for the monitoring of disease
342 progression and the evaluation of interventions.

343 This study has several limitations. The testing of discriminative ability places demands on
344 cognitive functions such as attention and working memory; functions which are known to be affected
345 in PD⁵³ and may be further confounded by fatigue and/or motivation.⁵⁴ Formal assessment of fatigue
346 or motivation was not undertaken in this study, so the extent to which it influenced test outcome
347 cannot be determined. We also did not run separate analysis on the effect of lower limb tremor or
348 dyskinesia on somatosensory performance so cannot rule out the impact of these symptoms as our
349 novel tests were designed to reflect ‘real life’ foot-ground sensorimotor interactions during weight-
350 bearing. A further limitation relates to the generalisability of our findings. Our sample was comprised
351 of people in the mild to moderate stages of PD who were tested during the ‘ON’ phase, and so the
352 results may not generalise to those in the more advanced stages of the disease, nor reflect
353 somatosensory function during the ‘OFF’ phase.

354 **Conclusion**

355 To develop targeted and appropriate rehabilitation interventions for people with PD, the
356 recognition that lower limb sensation informs movement and balance function is critical. Key to this
357 is the availability and use of appropriate, clinically feasible and psychometrically robust assessment
358 tools. The development and use of sensory measures which are more closely aligned with the complex
359 sensory-motor function of the lower limb, such as the novel measures evaluated in this article, may
360 enhance understanding in this relatively understudied area of PD. It is hoped that this study provides
361 further insight, and generates discussion into recognising the importance of evaluating somatosensory
362 ability, its relevance to movement, and its rehabilitation in this clinical population.

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367 **Author Roles**

- 368 1. Research project: A. Conception, B. Organization, C. Execution;
369 2. Statistical Analysis: A. Design, B. Execution, C. Review and Critique;
370 3. Manuscript Preparation: A. Writing of the first draft, B. Review and Critique

371 **T.G.:** 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B

372 **J.F.:** 1A, 2C, 3B

373 **J.M.:** 2A, 3B

374 **Disclosures**

375 *Funding Sources and Conflict of Interest:* No specific funding was received for this work. The authors
376 declare that there are no conflicts of interest relevant to this work.

377 *Financial Disclosures for the previous 12 months:* The authors declare that there are no additional
378 disclosures to report.

379 Ethical Publication Guidelines Statement: This study was conducted in accordance with the
380 University of Plymouth, Faculty of Health and Human Sciences Research Ethics Committee (ref:
381 17/18-86). Written informed consent was gained from each participant prior to taking part in this
382 study and documented. We confirm that we have read the Journal's position on issues involved in
383 ethical publication and affirm that this work is consistent with those guidelines.

384

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Table 1. PD and control participant demographic and clinical characteristics

Characteristics	PD (n=27)	Control (n=27)
Age, years, mean (SD)	71 (5.8)	70 (7.0)
Gender n (%)		
Male	19 (70.4)	17 (62.9)
Female	8 (29.6)	10 (37.1)
Time since diagnosis, years mean (SD)	5.7 (4.9)	-
Hoehn & Yahr stage, n (%)		
1	3 (11.1)	-
2	14 (51.9)	-
3	9 (33.3)	-
4	1 (3.7)	-
MDS-UPDRS Score, mean (SD)	30.1 (14.7)	
Number of falls reported n (%)		
0	12 (44.4)	20 (74)
1	3 (11.1)	4 (15)
2	2 (7.4)	3 (11)
3	4 (14.8)	0
>4	6 (22.3)	0

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541 Table 2. Intra-rater reliability of novel sensory measures

Measure	<i>Intra-rater Reliability (Parkinson's n=27)</i>					
	Test 1 (T1)	Test 2 (T2)	Mean (T1 & T2)	SEM	ICC _(2,1) (95% CI)	CoR
GradDT™ threshold degrees (°) mean (SD)	2.4 (1.2)	2.2 (1.0)	2.3 (1.1)	0.31	0.92 (0.82-0.96)*	0.85
FoRDT™ threshold μm, mean (SD)	480 (240)	520 (210)	500 (235)	124	0.72 (0.38-0.87)*	340
StepDT™ threshold cm mean (SD)	1.8 (0.9)	1.9 (0.7)	1.8 (0.7)	0.36	0.73 (0.40-0.88)*	1.0

Abbreviations: GradDT, Gradient Discrimination Test; StepDT, Step-height Discrimination Test; FoRDT, Foot Roughness Discrimination Test; cm, centimetres; SD, Standard Deviation; SEM, Standard error of measurement; ICC(2,1) Intraclass Correlation Coefficient model 2,1; CI, Confidence Interval; CoR, Coefficient of Repeatability
*P<0.001

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558 Table 3. Comparison of sensory performance between people with Parkinson's disease (PD) and
 559 healthy control group

Sensory Measure	PD (n=27)	Control (N=27)	p	Effect Size <i>d</i>
GradDT™ threshold degrees (°) Median (IQR, range)	2.5° (1.75°, 5.5°)	1.4° (1.1°, 2.5°)	<0.001	0.52
FoRDT™ threshold μm Median (IQR, range)	400 (400, 900)	300 (325, 850)	0.22	0.16
StepDT™ threshold cm Median (IQR, range)	1.8 (1.2, 3.0)	1.2 (0.6, 1.8)	0.001	0.47
EmNSA score, median (IQR, range)				
Tactile Sensation (0-64)	64 (7,15)	62 (4,13)	0.59	0.07
Proprioception score (0-16)	16 (0, 2)	16 (0,2)	0.31	0.13

Abbreviations: GradDT, Gradient Discrimination Test; StepDT, Step-height Discrimination Test; FoRDT, Foot Roughness Discrimination Test; EmNSA, Erasmus modified version of Nottingham Sensory Assessment; cm, centimetres; SD, Standard Deviation; μm, micrometres; *d* Cohen's *d*.

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574 Table 4. Spearman rank order correlation coefficients between novel measures and Erasmus MC
575 modified Nottingham Sensory Assessment

Sensory Measure	EmNSA Sensory Modality	
	Tactile Score	Proprioception Score
GradDT™	-0.25	-0.21
StepDT™	-0.29	-0.28
FoRDT™	-0.45*	-0.11

*p<0.05

Abbreviations: EmNSA, Erasmus MC modified Nottingham Sensory Assessment; GradDT™, Gradient Discrimination Test; StepDT™, Step Height Discrimination Test; FoRDT™, Foot Roughness Discrimination Test

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592 Table 5. Spearman rank order correlation coefficients between sensory measures and functional
 593 mobility measures

Sensory Measure	Falls Incidence	Falls Efficacy Scale -I	Brief BESTest	Gait Speed m/s	Step length
GradDT	0.55**	0.44*	- 0.63**	0.20	0.06
StepDT	0.24	0.1	- 0.54**	0.12	0.09
FoRDT	0.03	0.15	-0.11	-0.17	0.05
EmNSA (Tactile)	-0.21	-0.37	0.17	0.03	0.02
EmNSA (Proprioception)	0.15	-0.37	-0.31	0.15	0.17

*p<0.05; **P,0.01; Abbreviations: GradDT, Gradient Discrimination Test; StepDT, Step height discrimination test; FoRDT, foot roughness discrimination test; EmNSA, Erasmus MC modified Nottingham Sensory Assessment; FES-I, Falls Efficacy Scale – International; BriefBESTest, Brief version of Balance Evaluations Systems Test;

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