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Gorst, Terry; Freeman, Jenny; Yarrow, Kielan; Marsden, Jonathan

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1 **Assessing plantar sensation in the foot using the FOOt Roughness**
2 **Discrimination Test (FoRDT™): a reliability and validity study in**
3 **stroke**

4 Article Category: Original Research Paper

5
6 Terry Gorst¹, Jenny Freeman¹, Kielan Yarrow², & Jonathan Marsden¹

7 ¹ School of Health Professions, University of Plymouth, Plymouth, UK

8 ² Dept of Psychology, City, University of London, London, UK

9
10 Corresponding Author:

11 Dr Terry Gorst, School of Health Professions, Peninsula Allied Health Centre, University of
12 Plymouth, Derriford Road, PL6 8BH, UK.

13 Email: terry.gorst@plymouth.ac.uk ; Tel: 01752 587599

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29 **Assessing plantar sensation in the foot using the F_ooT Roughness Discrimination Test**
30 **(FoRDT™): a reliability and validity study in stroke**

31

32 **Abstract**

33 **Background:** The foot sole represents a sensory dynamometric map and is essential for balance and gait
34 control. Sensory impairments are common, yet often difficult to quantify in neurological conditions, particularly
35 stroke. A functionally oriented and quantifiable assessment, the Foot Roughness Discrimination Test
36 (FoRDT™), was developed to address these shortcomings.

37 **Objective:** To evaluate inter- and intra-rater reliability, convergent and discriminant validity of the Foot
38 Roughness Discrimination Test (FoRDT™).

39 **Design:** Test-retest design.

40 **Setting:** Hospital Outpatient.

41 **Participants:** Thirty-two people with stroke (mean age 70) at least 3 months after stroke, and 32 healthy, age-
42 matched controls (mean age 70).

43 **Main Outcome measures:** Roughness discrimination thresholds were quantified utilising acrylic foot plates,
44 laser-cut to produce graded spatial gratings. Stroke participants were tested on three occasions, and by two
45 different raters. Inter- and intra-rater reliability and agreement were evaluated with Intraclass Correlation
46 Coefficients and Bland-Altman plots. Convergent validity was evaluated through Spearman rank correlation
47 coefficients (ρ) between the FoRDT™ and the Erasmus modified Nottingham Sensory Assessment (EmNSA).

48 **Results:** Intra- and inter rater reliability and agreement were excellent (ICC =.86 (95% CI .72-.92) and .90 (95%
49 CI .76 -.96)). Discriminant validity was demonstrated through significant differences in FoRDT™ between
50 stroke and control participants ($p < .001$). Stroke fallers had statistically significant higher FoRDT™ scores
51 compared to non-fallers ($p = .01$). Convergent validity was demonstrated through significant and strong
52 correlations (ρ) with the Erasmus MC Nottingham Sensory Assessment ($r = .69$, $p < .01$). Receiver Operator
53 Curve analysis indicated the novel test to have excellent sensitivity and specificity in predicting the presence of
54 self- reported sensory impairments. Functional Reach test significantly correlated with FoRDT™ ($r = .62$, $p <$
55 $.01$) whilst measures of postural sway and gait speed did not ($r = .16$ -.26, $p > .05$).

56 **Conclusions:** This simple and functionally oriented test of plantar sensation is reliable, valid and clinically
57 feasible for use in an ambulatory, chronic stroke and elderly population. It offers clinicians and researchers a
58 sensitive and robust sensory measure and may further support the evaluation of rehabilitation targeting foot
59 sensation.

60 **Level of Evidence: III**

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89 **Introduction**

90 The foot represents the only interface between the ground and the person. It is a highly specialised and dynamic
91 unit, vital for sensing and responding to relative ground/body motion and changes in support surface properties.
92 The plantar aspect of the foot is thus suggested to be a sensory ‘dynamometric map’ for human balance control
93 [1,2] where enhanced or reduced tactile sensory inputs to the sole of the foot impact standing postural control
94 [3], gait kinematics [4] and foot placement [5].

95 Sensory impairment to this functionally important unit is characteristic of several neurological
96 populations and is associated with reduced standing balance, increased falls, slower gait speed, and altered
97 postural control [6-8]. Following stroke, impairment of tactile sensation in the lower limb affects 30-56% of
98 people [9,10], with lower limb tactile sensation showing less recovery compared to proprioception and upper
99 limb somatosensation [9]. Reduced sensation in the foot is reported by people with stroke to impact walking,
100 balance and is implicated in falls [7,11] whilst somatosensory deficits and motor weakness result in worse
101 functional outcomes than motor weakness alone [12].

102 Evidence from cross-sectional studies of stroke populations, however, does not demonstrate strong
103 associations between lower limb tactile sensation and functional outcomes [10,13]. Moreover, retraining of
104 sensory impairments tend to be largely overlooked in favour of motor rehabilitation [14,15]. One interpretation
105 contributing to this position may lie with the methods of tactile sensory assessment utilised in research and
106 clinical settings.

107 Clinicians widely acknowledge the clinical importance of sensory assessment and its prognostic value
108 following stroke [14]. The clinical evaluation of sensation following stroke, however, is typically undertaken in
109 a subjective, non-standardized and unreliable manner with low proportions of clinicians using standardised
110 methods [14]. Whilst standardised measures of sensation have been developed and evaluated in stroke and
111 neurological populations [16], they are for the most part largely based on the clinical neurological examination.
112 They are entrenched in providing clinical utility so are primarily screening tools which use ordinal scales to
113 categorise individual tactile sensory modalities as absent, impaired or normal, making the clinical interpretation
114 of the results difficult. They are administered passively to the patient in sitting or supine targeting the detection
115 of stimuli; the lowest level of sensory processing [17]. This has led to several concerns: they may be insufficient
116 to identify and uncover the presence, severity or complexity of sensory performance following CNS injury, they

117 do not provide functionally meaningful somatosensory data, and they lack responsiveness to detect change [16-
118 18].

119 Discriminating the textural qualities of a surface through touch is proposed to test the limits and
120 capabilities of the tactile system [17,18]. Psychometrically robust and functionally oriented texture
121 discrimination tests targeting the hand [19-21] and foot [22] have been developed and evaluated. Most adopt an
122 active or haptic sensation paradigm, that is, they involve the manual exploration of a surface for the express
123 purpose of obtaining somatosensory information. The movements selected optimize the relevant somatosensory
124 receptors to gather the pertinent sensory qualities of the surface being explored. The manual exploration of a
125 stimulus for the purpose of sensory information thus combines tactile and proprioception inputs to form a
126 sensory perception [23], and is more strongly associated with measures of motor function in the upper limb and
127 hand [24,25]. Such tests have been shown to possess greater sensitivity, uncovering greater proportions of
128 sensory impairments and may better reflect sensorimotor system functioning [18,24].

129 To the best of our knowledge, however, no study to date has established the reliability or validity of
130 using a roughness discrimination test, using active sensation, to quantify plantar sensory ability in people with
131 stroke.

132 The aim of this study was to develop a functionally oriented, standardised test of foot sensation and
133 evaluate its psychometric properties. Specific objectives were to evaluate intra- and inter-rater reliability,
134 discriminant validity and convergent validity.

135

136 **Methods**

137 This is a reliability and validity study. Ethical approval was obtained from the NHS Health Research Authority
138 NRES - Committee South Central – Berkshire B (15/SC/0191).

139 **Participants**

140 Participants were recruited from a convenience sample identified through UK NHS community services and
141 stroke support groups. Eligibility criteria were: aged ≥ 18 , stroke diagnosis confirmed via CT scan and clinical
142 presentation, >3months post-stroke, able to independently stand (with or without walking aid), and able to
143 independently walk at least 10m indoors. Potential participants were excluded if they had other neurological
144 disease or co-morbidities/injuries that would affect mobility and/or foot sensory function.

145 Sample size calculations were based on the work of Shoukri et al [26]. For a 95% CI of 0.25 and a
146 planned ICC of 0.8 ($\alpha=0.05$), 32 participants were required. For inter-rater reliability, a study sample of 20 with
147 two raters and a planned ICC of 0.8 ($\alpha=0.05$) provides sufficient power for establishing a 95% CI of ~0.4 [27].
148 A sample size of 32 was sufficient for the test of convergent validity to detect a correlation coefficient of 0.3
149 (power=0.85, $\alpha=0.05$) and for discriminant validity to detect an effect size of 0.86 (power=0.85, $\alpha=0.05$).

150 **The Foot Roughness Discrimination Test (FoRDT™)**

151 This novel test was developed to assess sensory ability of the plantar aspect of the foot. It comprised 10 graded
152 acrylic foot plates, machine laser cut to provide a range of standardised, quantifiable and graded stimuli of
153 roughness using standardised ratio measurements (Fig 1a). The gratings run 90° to the long axis of the foot (Fig
154 1b). Spatial interval (SI) and dimensions are measured in micrometres (μm) ($1\mu\text{m} = 1/1000$ millimetre (mm)).
155 The larger the spatial interval, the rougher the surface texture is perceived to be up to a point of between 3000 -
156 3500 μm [28]. The spatial interval of the base stimulus is 1.5mm (1500 μm) meaning it is the smoothest,
157 increasing to 3.5mm for the roughest plate (3500 μm). Comparator plates increase (in roughness) from the base
158 stimulus by spatial intervals ranging from 50 μm up to a maximum of 2000 μm . This represents a spatial interval
159 change or just noticeable difference (JND) from the base stimulus of between 3.3% and 133% respectively. A
160 JND between 5-19% is considered the discrimination threshold in the fingertips of unimpaired older adults
161 [18,28] but can be as high as 100% in stroke patients [18]. No normative data exists for the foot.

162 (insert fig 1 around here)

163

164 A two-alternative forced choice design (2AFC) in combination with a “one-up, three-down” staircase
165 procedure [29] was employed. The 2AFC staircase task is a psychophysical method where the aim is to
166 determine at what point two (different) stimuli, cannot be accurately and consistently discriminated. The 2AFC
167 aspect attempts to eliminate inconsistencies that can otherwise arise from different observers being more or less
168 conservative when making subjective reports about ambiguous, near threshold stimuli. It is a fundamental
169 methodology used in sensory science [30].

170 Applying the 2AFC design to this test involved presenting two textured plates at a time in a series of
171 increasingly difficult trials. Each trial included a base stimulus (A), and a changeable comparator stimulus (B).
172 A and B were presented randomly (i.e. AB or BA) over the course of up to 11 trials. Stimuli were presented in a
173 way that participants were unable to rely on any visual or auditory clues. The plates were presented in quick

174 succession (within 5 seconds of each other) with participants required to discriminate between base and
175 comparator stimuli, indicating which felt the roughest. The staircase approach to the 2AFC design involved the
176 systematic updating of the comparator plate depending on whether the participant was able to discriminate
177 between the plates. The task became more difficult after three correct responses (i.e. participants could tell the
178 difference) or became easier after one incorrect response. This procedure is designed to converge over time on
179 the threshold value that yields 79% correct performance. The discrimination threshold was calculated from the
180 average of four reversals (i.e. changes from a series of correct to a series of incorrect responses, or vice versa),
181 triggered by the first incorrect response. A greater discrimination threshold indicates worse somatosensory
182 ability.

183 **Procedures**

184 Data collection was conducted in an outpatient hospital setting. Stroke participants (n=32) were tested with the
185 FoRDT™ on two occasions, between one week and up to two weeks apart. The primary researcher (TG) was
186 the rater on test session 1 and test session 2. A third testing session, involving 20 stroke participants, was
187 completed by a physiotherapy assistant practitioner (PAP) trained in the test administration three days to one
188 week after test session 2. Control participants (n=32) were tested on just one occasion.

189 The FoRDT™ was undertaken in standing with full weight bearing important to reflect real life foot-
190 ground sensorimotor interactions and enhance ecological validity. Concentration, working memory and attention
191 were key requirements of the test so the testing environment was an enclosed, quiet room on each occasion. A
192 small pilot study confirmed the FoRDT™ took a maximum of 10 minutes to complete and was well understood
193 by people with stroke.

194 For the purposes of validity testing, in addition to the FoRDT™, further data was collected. This
195 included: participant demographics and stroke characteristics, self-reported falls in the previous 3 months,
196 subjective reporting of lower limb sensory changes, Erasmus MC version of the Nottingham Sensory
197 Assessment (EmNSA) [31], 10 metre timed walk test at fastest speed [32], standing Forward Reach Test (FRT)
198 [33], and postural sway (COP velocity) recorded using a Tekscan pressure mat (Matscan, Biosense medical,
199 Essex, UK).

200 **Statistical analysis**

201 Statistical analyses were performed using SPSS version 22.0. Data were summarised using frequencies and
202 percentages, mean and standard deviation (SD) or median and inter-quartile range (IQR) as appropriate. Data

203 presented for the FoRDT™ represents the roughness discrimination threshold, expressed in the original
204 measurement unit (μm) and the Just Noticeable Difference (JND) between base and comparator stimuli,
205 expressed as a percentage (%).

206 Necessary assumptions in reliability testing were accounted for [34]. Both inter- and intra-rater
207 reliability and agreement were analysed using intra class correlation coefficient ($\text{ICC}_{2,1}$) and Bland –Altman
208 plots in line with recommendations [35]. Standard error of measurement (SEM) provided an indication of the
209 score likely due to measurement error. Coefficient of repeatability (CoR), provided a score change (in the
210 original measurement scale) which included random and measurement error and was likely reflective of a
211 true/real change [36].

212 FoRDT™ performance of the paretic stroke foot and matched healthy control foot allowed for an
213 evaluation of discriminant validity. Stroke fallers/non-fallers were also compared. A Mann Whitney U test was
214 used to determine statistical significance ($p < 0.05$) as data was not normally distributed as indicated by Shapiro-
215 Wilks test ($p < 0.05$). Receiver Operator Characteristic (ROC) analysis was used to generate the area under the
216 curve (AUC) or concordance (c-statistic) to give a direct quantitative measure of the ability of FoRDT™ scores
217 to discriminate between the respective groups (i.e. control/stroke and stroke fallers/stroke non-fallers). Stroke
218 participants were categorised as fallers if they reported at least one fall within the previous three-month period
219 [37].

220 There is no “gold-standard” measure of tactile sensation, although the EmNSA is considered a robust
221 and clinically usable measure of sensation in neurological populations [16]. The magnitude of the relationship
222 between the EmNSA and the FoRDT™ was determined using a Spearman’s rank order correlation (ρ). To
223 provide evidence of convergent validity it was anticipated that roughness discrimination thresholds would have
224 a moderate, negative correlation with the tactile sub-score of the EmNSA. The magnitude of the relationship
225 between stroke participants’ FoRDT™ performance and measures of gait speed, FRT, falls and COP velocity
226 were evaluated using Spearman and Pearson correlational analysis where appropriate. Strength of correlations
227 were interpreted using the classification where ≤ 0.29 = weak, $0.30 - 0.49$ = moderate and, ≥ 0.50 = strong [38].

228 Sensitivity and specificity was used to quantify diagnostic ability, with sensitivity indicating the
229 proportion of true positives that are correctly identified, and specificity, the proportion of true negatives
230 correctly identified [34]. The sensitivity and specificity of the novel test was evaluated using Receiver Operator

231 Characteristic (ROC) curve analysis against the dichotomous variable of stroke participant self-report sensory
232 impaired/not impaired.

233

234

235 **Results**

236 Thirty-two people with chronic stroke and 32 healthy age matched controls participated in the study (table 1).

237 Mean age (SD) for stroke participants was 70 ± 9 years and for control participants 70 ± 7 years.

238 (Insert table 1 here)

239 Scores for stroke participants on the FoRDT™ were not normally distributed, as indicated by the Shapiro-Wilks
240 test ($p < 0.05$). The distributional properties of the FoRDT™ is illustrated in Fig 2.

241 (insert Fig.2 around here)

242 Reliability

243 Intra- and inter-rater reliability data are presented in table 2. Figures are expressed in micrometers (μm) which
244 represents the groove width difference between the base stimulus and comparator stimulus (i.e the point at
245 which stimuli could not be discriminated). Both intra-and inter rater reliability was good-excellent (ICC = 0.86,
246 95% CI .72-0.92; ICC=0.90, 95%CI 0.76-0.96) respectively.

247 (insert table 2 here)

248 Bland-Altman plots demonstrated no significant anomalies across both inter and inter rater agreement
249 (Figures 3 and 4). The line of equality/zero was within the 95% CI of the mean of the differences (d) for both
250 inter- and intra –rater testing indicating no systematic bias. Intra rater testing indicated that eight of the 32
251 participants scored the same in testing session 1 and testing session 2.

252 (insert fig 3 and 4 around here)

253 Discriminant validity

254 Roughness discrimination threshold scores of the stroke foot (median = $750\mu\text{m}$, JND= 50%) were significantly
255 higher than the matched control foot (median= $300\mu\text{m}$, JND=20%, $U = 267$, $z = -3.313$, $p = .001$, $r = 0.58$, c-statistic
256 0.74, 95% CI 0.61-0.86, $p < 0.01$). Stroke fallers also had significantly higher roughness discrimination
257 thresholds (median $1200\mu\text{m}$, JND=80%) than stroke non- fallers (median $400\mu\text{m}$, JND=26.6%, $U = 268$, $z = -2.41$,

258 $r=.43$; c-statistic 0.78, 95% CI 0.61-0.94, $p=0.01$). In contrast, EmNSA tactile scores were not significantly
259 different between stroke fallers and non-fallers (table 3). Roughness discrimination thresholds strongly
260 correlated with the measure of balance, the FRT ($r=.62$, $p<.01$) but not gait speed ($r=.26$, $p>.05$) or COPvelocity
261 ($r=.17$; $p>.05$)

262 (insert table 3 around here)

263

264

265 The FoRDT™ had strong and statistically significant correlation with the total tactile score of the EmNSA
266 ($r=0.69$; $p<0.01$) and its constituent tactile parts ($r=0.43-0.67$) (table 4)

267 (insert table 4 here)

268

269 Sensitivity and specificity

270 The sensitivity and specificity of the FoRDT™ and the EmNSA against the dichotomous variable of stroke
271 participant self-report sensory impaired/not impaired was analysed using ROC analysis. The area under the
272 curve (AUC) c statistic for the FoRDT™ was 0.92 (SE 0.057, 95% CI 0.83-1.00, $p = .001$). AUC statistic for the
273 tactile component of the EmNSA was 0.78 (SE=0.085, 95%CI 0.61-0.92, $p=.05$). The optimal cut off point to
274 predict subjectively reported sensory impairment using the FoRDT™ was a roughness discrimination threshold
275 of 500 μ m or JND of 33% (Youden index 0.67). At this level, our novel test demonstrated a sensitivity of 83%
276 and a specificity of 87%.

277

278

279 **Discussion:**

280 Since it is the Central Nervous System rather than the peripheral sensory transducer that is affected after stroke,
281 there is a clear rationale that any measure designed to evaluate somatosensory ability in stroke populations
282 should attempt to assess 'higher level' processing of somatosensory perception [17]. This study evaluated the
283 psychometric properties of the FoRDT™: our novel test of active tactile sensation targeting roughness
284 discrimination in the sole of the foot. Our study provided data to support the feasibility, reliability and validity
285 of the FoRDT™. Our novel test demonstrated superior sensitivity and specificity over the EmNSA in predicting

286 self-reported sensory changes in chronic stroke and stronger associations with dynamic balance and reported
287 falls in stroke participants.

288 The FoRDT™ evaluates tactile sensation in the whole of the foot sole in full weight-bearing. Our test
289 utilises an established and robust psychophysical testing approach to evaluate somatosensory discrimination.
290 The FoRDT™ utilises an interval measurement scale rather than a coarse ordinal scale and in this study sample,
291 has no floor or ceiling effects. Our test provides an indication of impairment severity which may show greater
292 responsiveness to change following intervention with further investigation. The FoRDT™ is feasible to
293 administer, shows excellent reliability, and is strongly correlated with clinical measures of dynamic balance and
294 reported falls. To our knowledge, this is the first study to evaluate active sensation in foot sole during full
295 weight bearing.

296 This study further demonstrates that textured gratings provide a feasible, standardised and graded
297 stimulus to evaluate roughness perception in the sole of the foot. The use of commonly found textures such as
298 sand, gravel and turf have been recently used to assess discriminative ability in the foot of elderly and stroke
299 subjects [38]. Whilst test-retest reliability and validity was demonstrated, such textures, whilst ecologically
300 valid, were not quantifiably graded stimuli. A tactile test in which the stimulus is quantifiably graded is
301 important and a feature of the FoRDT™. The grading and quantification of sensory ability along a continuous
302 or interval scale provides a potential indicator of impairment severity so is of potential use in monitoring
303 change. Textured gratings also produce the best match to psychophysical data of roughness perception [39] and
304 multiple cortical and sub cortical neural correlates have been identified during texture discrimination tasks using
305 gratings [40, 41].

306 Reliability and agreement of the FoRDT™ was excellent and evaluated in accordance with
307 recommendations [35]. Inter-rater reliability of an outcome measure is crucial, particularly in long-term
308 neurological populations who may have multiple interactions with different health-care professionals during the
309 course of their rehabilitation. Poor or lower inter-rater reliability is commonly reported in standardised measures
310 of sensation [16] so these data are encouraging. Coefficient of repeatability (CoR) data from this study also
311 provide an indication of true real change. For example, a discrimination threshold change above 438µm (JND of
312 29%) is likely to indicate real change in sensation between testing occasions. Such a change could be due to
313 recovery and/or therapeutic intervention, so this information is critical for the monitoring of recovery and the
314 development of more effective interventions that target sensory impairment following stroke.

315 Convergent validity is supported by the strong and significant correlations with tactile scores of the
316 EmNSA although this study contributes to the ongoing discussion as to whether individual sensory modalities
317 (i.e. light touch, pressure, pinprick, sharp-blunt discrimination) which comprise the tactile component of several
318 measures need to be assessed individually. Previous research in this area has demonstrated variable correlations
319 between tactile sensory modalities [9,31,42] and hence the data from this study supports the need for further
320 research in this area. Roughness discrimination thresholds may provide an alternative, appropriate and feasible
321 method of determining the limits and capabilities of the tactile system in those with CNS lesions.

322 The FoRDT™ was also able to discriminate between stroke and control participant sensory ability. The
323 median roughness discrimination threshold of stroke participants in this study was significantly higher than
324 controls. Higher threshold scores, and therefore a greater JND indicate poorer discriminatory ability. There are
325 no other studies in the foot to compare these data, although Carey et al,[18] found a mean JND of 17%-19% in
326 the fingertips of control participants, and a modal JND of 100% in the fingertips of stroke participants; data that
327 is comparable to our findings. One might expect healthy control discrimination thresholds in the hand to be
328 much lower than in the foot given the increased sensory acuity of the hand and greater cortical representation
329 compared with the foot [43], which was not the case. One explanation may be the surface areas of cutaneous
330 skin being stimulated. The greater number of peripheral mechanoreceptors activated, equates to greater central
331 processing of that activity [39]. Discrimination thresholds may be influenced by cutaneous-surface contact area.
332 It also suggests that sensory ability of the hand and feet may not be as different as generally considered, at least
333 with regard to this aspect of sensory discrimination, and supports that the foot is a complex sensory organ [1,2].
334 Further studies in the foot would be required to validate this.

335 Validity was further supported by the ability of the FoRDT™ to discriminate between stroke
336 participants who reported falling compared to those who did not, and the strong correlations demonstrated
337 between roughness discrimination thresholds and dynamic balance. With respect to this, our novel measure
338 performed favourably compared to a range of other sensory measures, including the EmNSA, Q-tip cotton bud
339 [44] and pin-prick detection as part of the National Institutes of Health Stroke Scale (NIHSS) [37], all of which
340 showed weak and non-significant correlations with falls incidence or balance disability. This suggests that
341 existing measures of sensory detection, widely used in clinical practice, may be inadequate for uncovering the
342 complexities of sensory performance following CNS injury; and that novel measures such as the FoRDT™ are
343 required to further elucidate our understanding in this area.

344 ROC curve analysis demonstrated that the FoRDT™ was better able to predict self-reported sensory
345 impairments compared to the EmNSA. The data indicate that a discrimination threshold in stroke participants
346 $\geq 500\mu\text{m}$ (JND 33%) is indicative of the presence of reported sensory impairments. Of note, the lower
347 discrimination threshold of healthy controls ($300\mu\text{m}$ - JND 20%) indicate that stroke participants not reporting
348 impairment still performed worse than healthy, age matched controls. Several interpretations, which require
349 further evaluation through future work, may account for these. Motor weakness in some stroke participants for
350 example may have limited full active exploration of the gratings, resulting in increased threshold scores.
351 However, textures with spatial intervals greater than $100\mu\text{m}$ are encoded spatially through the firing of slow
352 adapting mechanoreceptors, so roughness perception is largely independent of movement, speed of movement
353 or direction of movement [39].

354 Neither gait speed nor postural sway were significantly or strongly associated with roughness
355 discrimination thresholds suggesting foot tactile discrimination may not be important during certain gait or
356 balance tasks. Sensory reweighting in which altered or unreliable somatosensory information can be
357 compensated for through increased use of visual and/or vestibular information [45, 46], may, however, explain
358 these findings. Moreover, challenging locomotor tasks involve greater somatosensory cortical activity compared
359 to more simple walking tasks [47, 48] suggesting clinical measures, such as the 10 metre walk, often used for its
360 clinical utility, may not capture the sensorimotor interactions necessary for “real life” walking.

361 To develop targeted rehabilitation interventions, greater understanding of how somatosensory function
362 maps onto participation function, is critical [49]. A key component to this is the availability and use of
363 appropriate, sensitive and valid assessment tools. The development and use of sensory measures which are more
364 closely aligned with the sensori-motor function of the foot may enhance understanding in this relatively
365 understudied area. Our intention in developing the FoRDT™ was to address the issue that most standardised
366 sensory measures are geared toward identifying the presence of impairment. In rehabilitation, however, the
367 presence of an impairment is not necessarily important. Clinicians, and in particular patients, are most
368 concerned with addressing the factors which impede function. Qualitative and laboratory based studies suggest
369 foot sensation to be functionally important, and preliminary exploration of the psychometric qualities of the
370 FoRDT™ suggests this test holds promise in corroborating this position. Sufficiently sensitive and robust
371 measures such as the FoRDT™ which demonstrate associations between balance and mobility function and foot
372 sensation may further support the evaluation of rehabilitation efforts which target foot sensation. It is hoped that
373 this study provides further insight and opens up dialogue into quantifying the complex tactile sensory inputs that

374 enable individuals to recognise and respond to variable foot-ground interactions during functional, weight
375 bearing activities such as walking and balance.

376 **Study limitations**

377 This study recognises the testing of somatosensory discriminative ability, through its very nature, places greater
378 demands than tests of detection on cognitive functions such as attention and working memory; functions which
379 may also be impaired post stroke [50]. Discriminative ability may be further confounded by factors such as
380 fatigue and motivation – known sequelae of stroke [51]. Formal assessment of cognitive functions were not
381 undertaken in this study sample, so the extent to which they influenced test outcome cannot be quantified. That
382 these tests were evaluated in a cohort of chronic stroke also limits their generalisability to the wider stroke
383 population. Symptoms of stroke, their recovery and potential compensations that occur over time, suggest
384 further evaluation of these tests is required in other phases of stroke and across settings.

385 **Conclusion**

386 The FoRDT™ provides clinicians and researchers with a novel test of active tactile sensation for the foot, which
387 has demonstrated good intra and inter-rater reliability and validity in a chronic stroke sample. It has several
388 advantages over existing measures in terms of the sensitivity to detect somatosensory impairment, the ability to
389 quantify impairment severity, and associations with functional measures of balance and reported falls in chronic,
390 ambulatory stroke survivors. Such a measure has the potential to inform the development of targeted tactile
391 rehabilitation of lower limb somatosensory impairments following stroke.

392

393 **References**

- 394 1. Kavounoudias A, Roll R, & Roll J-P. The plantar sole is a 'dynamometric map' for human balance
395 control. *Neuroreport*. 1998; 9(14):3247-52
- 396 2. Wright W, Ivanenko & Gurfinkel V. Foot anatomy specialization for postural sensation and control *J*
397 *Neurophysiol* 2012; 107: 1513–1521
- 398 3. Qui F, Cole M, Davids K, Hennig E, Silburn P, Netscher H, et al. Enhanced somatosensory information
399 decreases postural sway in older people. *Gait Posture* 2012;35:630–5.
- 400 4. Collings R, Paton J, Chockalingam N, Gorst T, Marsden J. Effects of the site and extent of plantar
401 cutaneous stimulation on dynamic balance and muscle activity while walking. *The Foot* 2015;
402 25(3):159-163
- 403 5. Zehr E, Nakajima T, Barss T et al. Cutaneous stimulation of discrete regions of the sole during
404 locomotion produces “sensory steering” of the foot. *BMC Sports Science, Medicine, and Rehabilitation*
405 2014, 6:33

- 406 6. Deshpande N, Metter EJ, Ferrucci L. et al. Validity of clinically derived Cumulative Somatosensory
407 Impairment Index. *Arch Phys Med Rehabil* 2010;91:226-32.
- 408 7. Bowen C, Ashburn A, Cole et al. A survey exploring self-reported indoor and outdoor footwear habits,
409 foot problems and fall status in people with stroke and Parkinson's. *Journal of Foot and Ankle*
410 *Research* 2016; 9:39
- 411 8. Citaker S, Gunduz AG, Guclu M et al. Relationship between foot sensation and standing balance in
412 patients with multiple sclerosis *Gait Posture* 2011;34:275-278
- 413 9. Connell, L. Lincoln, N., and Radford, K. Somatosensory impairment after stroke: frequency of
414 different deficits and their recovery. *Clin Rehabil* 2008; 22(8): 758–67
- 415 10. Gorst T, Rogers A, Morrison SC, Cramp M, Paton J, Freeman J & Marsden J. The prevalence,
416 distribution, and functional importance of lower limb somatosensory impairments in chronic stroke
417 survivors: a cross sectional observational study. *Disab Rehabil* 2018, DOI:
418 10.1080/09638288.2018.1468932
- 419 11. Gorst T, Lyddon A, Marsden J et al Foot and ankle impairments affect mobility and balance in stroke
420 (FAiMiS): the views of people with stroke. *Disabil Rehabil*. 2016;38(6):589-96.
- 421 12. Patel A, Duncan P, Lai S, Studenski S. The relation between impairments and functional outcomes
422 poststroke. *Arch Phys Med Rehabil*. 2000; 81(10):1357-63
- 423 13. Tyson S, Crow L, Connell L, Winward C, & Hilier S. Sensory Impairments of the lower limb after
424 stroke; A pooled analysis of individual patient data. *Topics in Stroke Rehabilitation* 2013; 20(5): 441-
425 449
- 426 14. Pumpa L., Cahill L., & Carey L. Somatosensory assessment and treatment after stroke: An evidence-
427 practice gap. *Aust Occ Ther J*. 2015; 62(2):93-104
- 428 15. Bolognin N, Russo C, & Edwards D. The sensory side of post-stroke motor rehabilitation. *Restor*
429 *Neurol Neurosci* 2016; 34(4): 571-586
- 430 16. Connell, L & Tyson, S. Measures of sensation in neurological conditions; a systematic review. *Clin*
431 *Rehabil* 2012; 26: 68
- 432 17. Borstad A & Nichols-Larsen D. Assessing and Treating Higher Level Somatosensory Impairments Post
433 Stroke. *Topics in Stroke Rehabilitation* 2014; 21(4): 290-295
- 434 18. Carey L & Matyas T. Frequency of Discriminative Sensory Loss in the Hand after Stroke in a
435 Rehabilitation Setting. *J Rehabil Med* 2011; 43: 257–263
- 436 19. Carey LM, Oke LE and Matyas T. Impaired touch discrimination after stroke: a quantitative test. *J*
437 *Neuro Rehab* 1997; 11: 219–32
- 438 20. Eckstrand E, Lexell J, & Brogardh C. Test-retest reliability of the Shape/Texture Identification test in
439 people with chronic stroke. *Clinical Rehabil* 2016; 30(11):1102-1127
- 440 21. Miller K, Phillips B, Martin C, Wheat H, Goodwin and Galea M. The AsTex : clinimetric properties of
441 a new tool for evaluating hand sensation following stroke. *Clin Rehabil* 2009; 23: 1104–15
- 442 22. Ofek H, Alperin M, Knoll T et al. Assessment of texture discrimination ability at the sole of the foot in
443 subjects with chronic stroke compared with young and elderly subjects with no neurological deficits: a
444 reliability and validity study. *Disab Rehabil* 2018; 40(16):1960-1966
- 445 23. Blanchard C, Roll R, Roll JP, Kavounoudias A. Combined contribution of tactile and proprioceptive
446 feedback to hand movement perception. *Brain Res*. 2011 25; 1382 :219-29.
- 447 24. Blennerhassett JM, Matyas TA and Carey LM. Impaired discrimination of surface friction contributes
448 to pinch grip deficit after stroke. *Neurorehabil Neural Repair*. 2007;21:263–272
- 449 25. Meyer S., De Bruyn N., Lafosse C. et al. Somatosensory Impairments in the Upper Limb Poststroke:
450 Distribution and Association With Motor Function and Visuospatial Neglect. *Neurorehabil Neural*
451 *Repair* 2016; 30(8): 731–742
- 452 26. Shoukri M, Asayli M, Donner A. Sample size requirements for the design of reliability studies: review
453 and new results. *Statistical Methods in Medical Research* 2004; 13: 1:21
- 454 27. Doros G and Lew R. Design Based on Intra-Class Correlation Coefficients. *American Journal of*
455 *Biostatistics* 2010;1 (1): 1-8,
- 456 28. Morley J, Goodwin A, Darians Smith I. Tactile Discrimination of gratings. *Experimental Brain*
457 *Research* 1983; 49(2): 291-299

- 458 29. Leek M. Adaptive procedures in psychophysical research. *Perception & Psychophysics* 2001, 63 (8),
459 1279-1292
- 460 30. Bi J. *Sensory Discrimination Tests and Measurements: Statistical Principles, Procedures and Tables*.
461 2006. Blackwell Publishing
- 462 31. Stolk-Hornsveld F, Crow JL, Hendriks EP, van der Baan R and Harmeling-van der Wel BC. The
463 Erasmus MC modifications to the (revised) Nottingham Sensory Assessment: a reliable somatosensory
464 assessment measure for patients with intracranial disorders. *Clin Rehabil* 2006; 20: 160–72
- 465 32. Bohannon RW, Andrews AW, Thomas MW. Walking speed: reference values and correlates for older
466 adults. *J Orthop Sports Phys Ther*. 1996;24(2):86-90
- 467 33. Weiner, D. K., Duncan, P. W., et al. "Functional reach: a marker of physical frailty." *J Am Geriatr Soc*
468 1992; 40(3): 203-207
- 469 34. Bland M. *An introduction to medical statistics*. 4th edition. 2015. Oxford; Oxford University Press.
- 470 35. Kottner J, Audige L, Brorson S, et al. Guidelines for Reporting Reliability and Agreement Studies
471 (GRRAS) were proposed. *Journal of Clinical Epidemiology* 2011; 64: 96-106
- 472 36. Vaz S, Falkmer T, Passmore AE, Parsons R, Andreou P (2013) The Case for Using the Repeatability
473 Coefficient When Calculating Test–Retest Reliability. *PLoS ONE* 8(9): e73990.
- 474 37. Schmid A, Yaggi K, Burrus N et al. Circumstances and consequences of falls among people with
475 chronic stroke. *JRRD* 2013; 50(9):1277-1286
- 476 38. Cohen J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. New York, NY: Routledge
477 Academic
- 478 39. Hollins, M & Bensmaïa, S.J., 2007. The coding of roughness. *Can. J. Exp. Psychol.* 61, 184–195
- 479 40. Carey L, Abbott D, Harvey M, Puce A, Seitz R, Donnan G. Relationship Between Touch Impairment
480 and Brain Activation After Lesions of Subcortical and Cortical Somatosensory Regions.
481 *Neurorehabilitation and Neural Repair* 2011; 25(5): 443–457
- 482 41. Borstad A, Schmalbrock P, Choi S, Nichols-Larsen D. Neural correlates supporting sensory
483 discrimination after left hemisphere stroke. *Brain Research* 2012;1460: 78–87
- 484 42. Winward CE, Halligan PW and Wade DT. The Rivermead Assessment of Somatosensory Performance
485 (RASP): standardisation and reliability data. *Clin Rehabil* 2002; 16: 523–33
- 486 43. Akselrod M, Martuzzi R, Serino A, et al. Anatomical and functional properties of the foot and leg
487 representation in areas 3b, 1 and 2 of primary somatosensory cortex in humans: A 7T fMRI study.
488 *NeuroImage* 2017; 159:473–487
- 489 44. Robinson C, Shumway-Cook A, Matsuda P, & Ciol M. Understanding physical factors associated with
490 participation in community ambulation following stroke. *Disab Rehabil* 2011;33(12):1033-1042
- 491 45. Chien JH, Eikema, D-J, Mukherjee M & Stergiou N. Locomotor sensory organisation test: a novel
492 paradigm for the assessment of sensory contributions in gait. *Ann Biomed Eng.* 2014; 42(12): 2512–
493 2523
- 494 46. Bonan, I., et al., Sensory reweighting in controls and stroke patients. *Clin Neurophysiol*, 2013. 124(4):
495 p. 713-22.
- 496 47. Sipp A, Gwin J, Makeig S, Ferris D. Loss of balance during balance beam walking elicits a multifocal
497 theta band electrocortical response. *J Neurophysiol* 2013; 110:2050-2060
- 498 48. Bradford J, Lukos J, & Ferris D. Electrocortical activity distinguishes between uphill and level walking
499 in humans. *J Neurophysiol* 2016; 115:958-966
- 500 49. Carey L, Lamp G, & Turville M. The State-of-the-Science on somatosensory function and its impact
501 on daily life in adults and older adults and following stroke: A scoping review. *OTJR: Occupation,*
502 *Participation and Health*. 2016; 36(2s):27s-41s
- 503 50. Crichton S, Bray B, McKeivitt C, Rudd A & Wolfe C. Patient outcomes up to 15 years after stroke:
504 survival, disability, quality of life, cognition and mental health. *Neurol Neurosurg Psychiatry* 2016;
505 87:1091–1098
- 506 51. Acciarresi A, Bogousslavsky J, & Paciaroni M. Post-Stroke Fatigue: Epidemiology, Clinical
507 Characteristics and Treatment. *Eur Neurol* 2014;72:255–261