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1 Minimal detectable change of kinematic and spatiotemporal parameters in patients with chronic stroke
2 across three sessions of gait analysis.

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19

20 **Abstract**

21 Three-dimensional gait analysis is the gold standard for gait-assessment in patients with stroke. This
22 technique is commonly used to assess the effect of treatment on gait parameters. In clinical practice,
23 three gait analyses are usually carried out (baseline, after treatment and follow-up), the objectives were
24 to define the reproducibility and the Minimum Detectable Change (MDC) for gait parameters in stance
25 and swing measured using 3D-gait analysis, and to assess changes in MDC across three repeated 3D-
26 gait analyses. Three gait analyses (V1, V2 and V3) were performed at 7-day intervals in twenty-six
27 patients with chronic stroke. Kinematic data (in the sagittal plane, during swing and stance) and
28 spatiotemporal data were evaluated for the paretic limb. Reliability was tested using repeated measures
29 ANOVA with a Tukey post hoc test, and the MDC values were calculated for each parameter. Only
30 the range of hip motion during swing changed significantly between V1 and V2, but no other
31 kinematic parameters changed. No significant differences were observed for the spatiotemporal
32 parameters. MDC values were always higher during the V1vsV2 comparison for both kinematic and
33 spatiotemporal parameters. This is the first study to evaluate the MDC for kinematic and
34 spatiotemporal parameters during stance and swing. Reliability of kinematic and spatiotemporal data
35 across sessions was very good over the three sessions. MDC values were the lowest between V2 and
36 V3 for most parameters. Use of the MDC will allow clinicians to more accurately determine the effect
37 of treatments.

38 *Key Words:* stroke, gait analysis, reproducibility, minimum detectable change.

39

40 1 Introduction

41 Stroke-related hemiparesis alters the gait pattern (Pélissier, Pérennou, & Laassel, 1997; Pinzur,
42 Sherman, DiMonte-Levine, & Trimble, 1987), and medical and surgical treatments and rehabilitation
43 often focus on improving gait (Bleyenheuft et al., 2009; Boudarham et al., 2014; Flansbjer, Downham,
44 & Lexell, 2006; Roche, Zory, et al., 2015). The effects of treatment can be measured using three-
45 dimensional gait analysis (3D-gait analysis) (Bleyenheuft et al., 2009; Pittock et al., 2003; Roche,
46 Zory, et al., 2015), the gold standard for gait assessment. 3D-gait analysis systems provide precise
47 measurements of spatiotemporal, kinematic and kinetic gait parameters (McGinley, Baker, Wolfe, &
48 Morris, 2009). The reliability of these system has been shown to be good in patients with stroke.
49 Reliability is high for kinematic parameters in the sagittal plane (Kadaba et al., 1989; McGinley et al.,
50 2009; Schwartz, Trost, & Wervey, 2004) and for spatiotemporal parameters (Oken, Yavuzer, Ergöçen,
51 Yorgancioglu, & Stam, 2008; Yavuzer, Oken, Elhan, & Stam, 2008), the reliability has been mainly
52 assessed using the intraclass coefficient correlation (ICC) and the standard error measurement (SEM).
53 However, another very important psychometric parameter to consider is the minimal detectable change
54 (MDC). MDC relates to measurement bias. If the change following treatment is greater than the MDC,
55 it is therefore likely due to the treatment. (Weir, 2005).

56 MDC values have been calculated for certain parameters evaluated during 3D-gait analysis in patients
57 with stroke, including gait profile score and gait deviation index (Correa et al., 2017; Devetak et al.,
58 2016), ground reaction forces (Campanini & Merlo, 2009) and kinematic (such as peak ankle angle
59 during swing or peak knee flexion during swing) and spatiotemporal (such as step length) parameters
60 and ground reaction forces during treadmill gait (Kesar, Binder-Macleod, Hicks, & Reisman, 2011).
61 However, treatment often aims to improve kinematic parameters during a specific phase of the gait
62 cycle to improve locomotion of patients with stroke (i.e botulinum toxin injection (BTI) in the rectus
63 femoris muscle to increase peak knee flexion in swing phase, or surgery to the triceps surae to improve
64 ankle dorsiflexion in swing phase). It is thus important to determine the MDC for specific kinematic
65 parameters during stance and swing in patients with chronic stroke-related hemiparesis to better
66 analyses results from studied using gait analysis to assess effect of a given treatment in a specific gait

67 phase.. Furthermore, hemiparetic gait is characterized by an asymmetry between duration of swing and
68 stance phase, knowing the MDC of these parameters could also be relevant to better analyses results of
69 studied aiming to restore the symmetry of phases (Bohannon, 1987; Pinzur et al., 1987; Sheffler &
70 Chae, 2015).

71 The effect of treatment is often evaluated over three 3D-gait analyses: baseline, mid-treatment and end
72 of treatment, or baseline, end of treatment and after a wash out period to determine if the effect is
73 maintained. It is therefore important to assess the MDC over three sessions.

74 The aim of this study was thus to define the MDC for hip, knee and ankle angles in the sagittal plane
75 during both stance and swing and the MDC of spatiotemporal parameters and to assess changes in
76 MDC across three repeated 3D-gait analyses. To that end, the kinematic and spatiotemporal
77 parameters of patients with chronic stroke-related hemiparesis were compared over three 3D-gait
78 analyses performed at 7-day intervals. We hypothesized that performance would be most variable
79 during the first 3D-gait analysis, inducing a larger MDC than during the second and third analyses. If
80 this was confirmed, it would imply that an initial 3D-gait analysis should be carried out simply for
81 familiarization purposes prior to the data collection.

82 2 Methods

83 2.1 Sample

84 Twenty-six -patients with chronic stroke were included in the study (n=19 men; mean age 58.2 ± 13.1
85 years; mean time since stroke 9.7 ± 7.1 years; n=14 right hemiparesis). They were recruited during
86 routine follow-up visits in the physical medicine and rehabilitation department of a university teaching
87 hospital. Subjects were eligible for inclusion if they: i) were over eighteen years old, ii) had
88 hemiparesis due to a single stroke more than six month previously, and iii) were able to walk 10
89 minutes independently with or without walking aids. Subjects were excluded if they had: i) bilateral
90 cortical lesions, ii) cerebellar syndrome, iii) severe comprehensive deficit or severe aphasia, iv)
91 apraxia or v) musculoskeletal surgery less than six months ago. All subjects gave written informed
92 consent before participation. The study was performed in accordance with the ethical codes of the

93 World Medical Association (Declaration of Helsinki) and was approved by the local Ethics
94 Committee.

95 2.2 Study design

96 Each subject participated in 3 visits at 7-day intervals (V1, V2 and V3). One 3D-gait analysis was
97 carried out at each visit.

98 2.2.1 Gait analysis

99 At least three trials were performed before the beginning of the recording in order to familiarise the
100 patient with the experimental conditions, since it has been shown that the first three trials of a gait
101 analysis session differ from subsequent trials (Boudarham, Roche, et al., 2013). A minimum of 4 trials
102 were then recorded at a spontaneous walking speed in a 10-meter-long corridor. To balance the
103 influence of each visit, the same number of gait cycles was analysed for each subject (based on the
104 visit with the least number of gait cycles). We manually deleted the gait cycles in excess. Therefore,
105 the number of gait cycles analyzed varied across subjects (from 5 to 18). Seven optoelectronic cameras
106 (Motion Analysis Corporation, Santa Rosa, CA, USA, 100 Hz sampling frequency) recorded the
107 trajectories of 30 reflective markers, positioned on the skin of the subjects according to the Helene
108 Hayes model. The trajectories were manually processed using Cortex 1.3 and OrthoTrack 6.5 software
109 (Motion Analysis Corporation, Santa Rosa, CA, USA) to extrapolate joint kinematics and
110 spatiotemporal parameters.

111 The same operator positioned all the markers for each patient at each visit and carried out the whole
112 3D-gait analysis in order to limit extrinsic variability (McGinley et al., 2009).

113 2.3 Data Analysis

114 2.3.1 3D gait analysis

115 Kinematic data in the sagittal plane (peak hip and knee flexion and extension, ankle dorsiflexion and
116 plantarflexion and total range of motion (RoM) during the stance and swing phases) were calculated
117 for the paretic lower limb. Spatiotemporal gait parameters (gait speed, cadence, stride length, step

118 length, step width and duration of stance phase) were also calculated. Values for each parameter were
119 averaged across all the gait cycles for each patient and the mean was used for the analysis.

120 2.3.2 Analysis of raw differences, reliability and minimal detectable change

121 Mean values of the kinematic and spatiotemporal parameters were compared to determine if there
122 were significant differences between each visit. Reproducibility of measures is often evaluated by
123 comparing two datasets with different indices. The most common and relevant indices are the ICC and
124 the SEM, the MDC is then derived from the SEM. ICC is useful to observe the correspondence
125 between two measures, however it is dependent on the standard deviation in the sample (Weir, 2005).
126 To give more weight to the reliability of the data assessed by the ICC, it is necessary to concomitantly
127 evaluate the SEM and the MDC. Low SEM and MDC values signify that changes observed are likely
128 due to the treatment and not the measurement (Correa et al., 2017; Devetak et al., 2016; Flansbjerg,
129 Holmbäck, Downham, Patten, & Lexell, 2005; Kadaba et al., 1989; McGinley et al., 2009; Weir,
130 2005).

131 Reliability was thus evaluated using two methods, the ICC and the SEM. ICC was calculated using
132 custom software written by Arash Salarian (Copyright 2016) in MATLAB (Mathworks). The $ICC_{3,k}$,
133 was used because the data were acquired over three sessions by the same operator and the trials within
134 each session were averaged (Shrout & Fleiss, 1979; Weir, 2005). The formulae used to calculate the
135 ICC was:

$$\frac{MS_S - MS_E}{MS_S}$$

136 Where MS_S is the subjects mean square and MS_E is the error mean square of the 2-way ANOVA used
137 to compare the data (Weir, 2005). The ICC varies between 0 and 1; the higher the $ICC_{3,k}$ the higher the
138 reproducibility. There is no real consensus regarding "cut-off" values, however, it has been suggested
139 that values <0.59 reflect "poor reproducibility", $0.60-0.79$ "moderate reproducibility" and > 0.80 "high
140 reproducibility" (Bushnell, Johnston, & Goldstein, 2001). The SEM can be calculated using two
141 formulae : $SEM = SD\sqrt{1 - ICC}$, or $SEM = \sqrt{MS_E}$, MS_E being the square root of the within-subjects

142 error of the repeated measures ANOVA (Weir, 2005). $\sqrt{MS_E}$ was chosen because the ICC depends on
143 the standard deviation of the data, thus for two sets of data with the same means and two different
144 standard deviations, data with a low standard deviation will have a lower ICC than data with a large
145 standard deviation. $\sqrt{MS_E}$ takes this into account (Weir, 2005).

146 The MDC was calculated using the following equation: $MDC = SEM * 2.056 * \sqrt{2}$. The value 2.056
147 corresponds to the student-t distribution with a 95% confidence interval for the study sample size
148 (n=26) (Beckerman et al., 2001). SEM and MDC are expressed in raw units and not in percentages to
149 facilitate future comparisons with other studies. However, the mean MDC and SEM values for the
150 spatiotemporal parameters are presented as percentages in order to compare parameters with different
151 units (McGinley et al., 2009). The MDC% was calculated using the following formula: $MDC\% =$
152 $\left(\frac{MDC}{\bar{X}}\right) * 100$, \bar{X} being the mean value of the parameter compared between 2 sessions (either V1/V2 or
153 V1/V3 or V2/V3) (Flansbjer et al., 2005). The SEM% was calculated using the same technique.

154 2.4 Statistical analysis

155 The statistical analysis was based on the recommendations of Weir et al. (2005) (Weir, 2005). If the
156 data followed a normal distribution (according to the Shapiro-Wilk test), a one-factor (time), repeated
157 measures ANOVA was performed (sessions V1, V2 and V3). If the results of the repeated measures
158 ANOVA were significant, a post hoc Tukey HSD test was performed to determine which visits
159 differed: (V1 vs V2 or V1 vs V3 or V2 vs V3). If the data did not follow a normal distribution, a Friedman
160 test was performed. Significant differences were analysed using a Wilcoxon test to identify which
161 visits differed significantly from each other. Simultaneously, the $ICC_{3,k}$, SEM and MDC were
162 calculated for each parameter between V1 and V2, V1 and V3; V2 and V3.

163 3 Results

164 3.1 Kinematics

165 Table 1 shows the kinematic values (mean and SD) for each parameter studied during each visit. The
166 details of the repeated measures ANOVAs are available in S1 appendix Table A.

167 Table 1: Kinematic parameters during the swing (SwP) and stance phases (StP) of gait cycle. Positive
168 values denote flexion and negative values denote extension.

169 --Table 1--

170 The only parameter that changed significantly was hip RoM in swing, which increased significantly
171 ($p=0.045$) from V1 to V2 (Tables 1 and table A).

172 3.1.1 ICC and SEM

173 The mean ICC values were high for all parameters between all visits (from 0.96 to 0.97). The
174 reliability was higher between V2 and V3 than between the other visits as showed by higher ICC
175 (0.97) and lower SEM (2.01°) in V2vsV3 than in V1vsV2 and V1vsV3 (see Table 2).

176 3.1.2 MDC Values

177 The mean MDC was lowest between V2vsV3 (5.86°) than in V1vsV2 (7.20°) and V1vsV3 (6.48°)
178 (Table 2).

179 Table 2: ICC, SEM and MDC of kinematic parameters of the paretic lower limb during the swing
180 (SwP) and stance phases (StP) of gait cycle. The lowest MDC values are in bold

181 --Table2--

182 3.2 Spatiotemporal parameters

183 Table 3 presents the values (means and SD) of spatiotemporal parameters during the three visits. All
184 the results of the ANOVAs are available in appendix S1 Table A.

185 Table 3: Spatiotemporal parameters with mean and SD at each visit.

186 --Table3--

187 There were no significant differences between the values of the spatiotemporal parameters for the
188 three visits.

189 3.2.1 ICC and SEM

190 Mean ICC values were high for all parameters between all visits (0.96 to 0.97). The reliability was
191 higher between V2 and V3 than between the other visits as showed by higher ICC (0.97) and lower
192 %SEM (3.90%) in V2vsV3 than in V1vsV2 and V1vsV3 (see Table 4).

193 3.2.2 MDC values

194 The mean %MDC was lowest between V2vsV3 (11.45%) than in V1vsV2 (13.75%) and V1vsV3
195 (13.10%) (Table 4).

196 Table 4: ICC, SEM and MDC of spatiotemporal parameters in paretic lower limb. The lowest MDC
197 values are in bold. The mean values of SEM and MDC are presented as percentages in order to
198 rationalize and compare the different units.

199 --Table 4--

200 4 Discussion

201 The purpose of this study was to determine the MDC for paretic-limb kinematic and spatiotemporal
202 parameters in both swing and stance phase, evaluated during 3D gait analysis, in order to improve
203 interpretation of the results of treatments in patients with hemiparesis following stroke. Reliability was
204 higher between the second and third visits than between the first and second and first and third visits:
205 ICC values were higher and mean SEM and MDC values were lower. However, the differences in
206 reliability across sessions were small, likely because of the lack of differences in kinematic values
207 across sessions that resulted in high ICC values. This result is in accordance with previous studies that
208 have also found a high reliability of raw kinematic data in a similar population of patients (Correa et
209 al., 2017; Devetak et al., 2016).

210 The aim of treatment is often to improve peak hip extension in stance, and peak knee and ankle flexion
211 in the swing phase of the gait cycle (Pomeroy, King, Pollock, Baily-Hallam, & Langhorne, 2006). The
212 MDC values for these three parameters were lowest between V2 and V3. There was a difference of 1°
213 to 3° in the MDCs depending on the visits compared. This is highly relevant considering the small, but

214 statistically significant changes reported in the literature following various treatments (Bonnyaud et
215 al., 2014; Boudarham, Hameau, et al., 2013; Novak, Olney, Bagg, & Brouwer, 2009; Pradon et al.,
216 2011; Robertson et al., 2009; Roche, Boudarham, Hardy, Bonnyaud, & Bensmail, 2015). Some
217 changes reported in studies of patients with stroke are close to, or sometimes lower than, the smallest
218 MDC defined in the present study. Roche et al, (2015) found a significant improvement in peak hip
219 flexion during swing of 4.2° (MDC= 9.1°) after BTI in the rectus femoris (Roche, Boudarham, et al.,
220 2015); Roche et al, (2015), Robertson et al, (2009) and Boudarham et al, (2013) found significant
221 improvements in peak knee flexion in swing of respectively 6.5° , 8° and 3.4° (MDC= 6.5°) after BTI in
222 the rectus femoris (Boudarham, Hameau, et al., 2013; Robertson et al., 2009; Roche, Boudarham, et
223 al., 2015). Pradon et al, (2011) found a significant increase in peak ankle dorsiflexion in stance of 4°
224 (MDC= 5.4°) and a significant increase in peak knee flexion in swing of 6° to 10° (MDC= 6.5°) after
225 BTI in the triceps surae (Pradon et al., 2011). Novak et al, (2009) found a significant decrease in
226 plantarflexion at the end of the swing phase of 2.5° (MDC= 5.8°) after BTI in the triceps surae (Novak
227 et al., 2009). Bonnyaud et al, (2014) found a significant increase in peak knee flexion during swing of
228 2.5° (MDC= 6.5°) after a single Lokomat session (Bonnyaud et al., 2014). Thus, it is not possible to
229 know how much the change relates to the treatment and how much to the repetition of the
230 measurements. Treatment also aims to improve gait speed, stride length and step length. The MDCs
231 for the former two parameters were lowest between the second and third visits, while the MDC for
232 step length was lowest between the first and third visits. The changes in spatiotemporal parameters
233 reported in patients with stroke following treatments are often close to or below the MDC values
234 found in this study. Wallard et al (2015) found an increase in gait speed of 35 cm/s (MDC=14.6 cm/s)
235 and a 2 cm increase step length (MDC=6.3 cm) after 20 intensive sessions of lokomat training
236 (Wallard, Dietrich, Kerlirzin, & Bredin, 2015). After a single session of Lokomat training, Bonnyaud
237 et al, (2014) found a significant increase in gait speed of 5.4 cm/s (MDC=14.6 cm/s), of 3.1 step/min
238 in cadence (MDC=8.6 step/min) and 3.6cm in step length (MDC=6.3 cm). Pradon et al, (2011) found a
239 significant increase in gait velocity of 17 cm/s (MDC=14.6 cm/s), and a 7 cm increase in step length
240 (MDC=6.3 cm) and 15 cm in stride length (MDC=11.9 cm) after BTI in the triceps surae (Pradon et
241 al., 2011).

242 Thus, statistically significant improvements in kinematic and spatiotemporal parameters are often
243 close to, or even below, the lowest MDC values found in the present study. The purpose of these
244 comparisons is not to diminish the scientific impact of these studies, far from it. We believe that our
245 study supports the need to decrease CMD values in studies using the 3D gait-analysis to evaluate the
246 effects of a treatment. This familiarization visit seems important to reduce as possible the MDC
247 values, but comparisons are only possible between populations with similar characteristics such as
248 walking speed, thus this does not apply to all studies, so these comparisons should be used sparingly.
249 Indeed, in our study the average gait speed of patients was 0.77 m/s; in Roche et al., (2015) it was 0.58
250 m/s, in Robertson et al., (2009) it was 0.52 m/s, in Boudarham et al., (2013) it was 0.61 m/s, in Pradon
251 et al., (2011) it was 0.55 m/s, in Novak et al., (2009) it was 0.50 m/s, in Bonnyaud et al., (2014) it was
252 0.76 m/s, in Wallard et al., (2015) it was 0.84m/s.

253 In contrast with our hypothesis, kinematic data were very reliable across visits as shown by the
254 ANOVAs results (only one parameter shown a significant modification between V1 and V2) and ICC
255 values (0.95 to 0.97). This is in accordance with the literature (Awad, Kesar, Reisman, & Binder-
256 Macleod, 2013; Correa et al., 2017; Devetak et al., 2016; Kadaba et al., 1989; McGinley et al., 2009).
257 Only hip RoM during swing differed between visits one and two. Spatiotemporal data were also highly
258 reliable across visits as shown by the ANOVAs results (none significant ANOVAs) and ICC values
259 (0.96 to 0.97). This is also in agreement with the literature (Cho, Lee, & Lee, 2015; Kesar et al., 2011).

260 A study of five 3D-analyses of treadmill gait found no changes in mean peak knee and ankle angles or
261 standard deviations across sessions. The authors therefore did not recommended the use of a
262 familiarization session (Awad et al., 2013). However, gait on a treadmill is different from gait over-
263 ground (Bayat, Barbeau, & Lamontagne, 2005; Brouwer, Parvataneni, & Olney, 2009; Kautz,
264 Bowden, Clark, & Neptune, 2011). The results of the present study indicate that for over-ground gait
265 analysis, a familiarization session would increase the reliability of the data, particularly for hip
266 extension in swing and stance, as well as ankle RoM in swing which showed the greater decreased of
267 MDC value because of the familiarization visit.

268 5 Conclusion

269 In conclusion, kinematic and spatiotemporal data recorded during three 3D-gait analyses at intervals of
270 7 days were reliable. However, the MDC was lowest between the second and third visits, suggesting
271 that patients should attend a familiarization session prior to carrying out the actual evaluations. This
272 would ensure changes measured are related to the treatment and are not an effect of the repeated
273 evaluations.

274 6 Limitations

275 The results of this study may not be generalizable to the whole population of patients with stroke since
276 the patients included all had moderate to good functional recovery (based on mean gait speed)
277 (Beyaert, Vasa, & Frykberg, 2015). In clinical practice, gait analyses may be carried out at intervals
278 greater than 7 days. It is possible that the reliability and MDC may differ for intervals of 1 month for
279 example. Further studies are required to test this.

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283 8 Disclosure

284 None.

285 9 References

- 286 Awad, L. N., Kesar, T. M., Reisman, D., & Binder-Macleod, S. A. (2013). Effects of repeated
287 treadmill testing and electrical stimulation on post-stroke gait kinematics. *Gait & Posture*, *37*(1),
288 67–71. <https://doi.org/10.1016/j.gaitpost.2012.06.001>
- 289 Bayat, R., Barbeau, H., & Lamontagne, A. (2005). Speed and temporal-distance adaptations during
290 treadmill and overground walking following stroke. *Neurorehabilitation and Neural Repair*,
291 *19*(2), 115–24. <https://doi.org/10.1177/1545968305275286>
- 292 Beckerman, H., Roebroek, M. E., Lankhorst, G. J., Becher, J. G., Bezemer, P. D., & Verbeek, A. L.
293 (2001). Smallest real difference, a link between reproducibility and responsiveness. *Quality of*
294 *Life Research: An International Journal of Quality of Life Aspects of Treatment, Care and*

- 295 *Rehabilitation*, 10(7), 571–8. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11822790>
- 296 Beyaert, C., Vasa, R., & Frykberg, G. E. (2015). Gait post-stroke: Pathophysiology and rehabilitation
297 strategies. *Neurophysiologie Clinique = Clinical Neurophysiology*, 45(4–5), 335–55.
298 <https://doi.org/10.1016/j.neucli.2015.09.005>
- 299 Bleyenheuft, C., Cockx, S., Caty, G., Stoquart, G., Lejeune, T., & Detrembleur, C. (2009). The effect
300 of botulinum toxin injections on gait control in spastic stroke patients presenting with a stiff-knee
301 gait. *Gait & Posture*, 30(2), 168–72. <https://doi.org/10.1016/j.gaitpost.2009.04.003>
- 302 Bohannon, R. W. (1987). Gait performance of hemiparetic stroke patients: selected variables. *Archives*
303 *of Physical Medicine and Rehabilitation*, 68(11), 777–81. Retrieved from
304 <http://www.ncbi.nlm.nih.gov/pubmed/3675175>
- 305 Bonnyaud, C., Pradon, D., Boudarham, J., Robertson, J., Vuillerme, N., & Roche, N. (2014). Effects
306 of gait training using a robotic constraint (Lokomat®) on gait kinematics and kinetics in chronic
307 stroke patients. *Journal of Rehabilitation Medicine*, 46(2), 132–8.
308 <https://doi.org/10.2340/16501977-1248>
- 309 Boudarham, J., Hameau, S., Pradon, D., Bensmail, D., Roche, N., & Zory, R. (2013). Changes in
310 electromyographic activity after botulinum toxin injection of the rectus femoris in patients with
311 hemiparesis walking with a stiff-knee gait. *Journal of Electromyography and Kinesiology :
312 Official Journal of the International Society of Electrophysiological Kinesiology*, 23(5), 1036–
313 43. <https://doi.org/10.1016/j.jelekin.2013.07.002>
- 314 Boudarham, J., Roche, N., Pradon, D., Bonnyaud, C., Bensmail, D., & Zory, R. (2013). Variations in
315 kinematics during clinical gait analysis in stroke patients. *PloS One*, 8(6), e66421.
316 <https://doi.org/10.1371/journal.pone.0066421>
- 317 Boudarham, J., Roche, N., Pradon, D., Delouf, E., Bensmail, D., & Zory, R. (2014). Effects of
318 quadriceps muscle fatigue on stiff-knee gait in patients with hemiparesis. *PloS One*, 9(4),
319 e94138. <https://doi.org/10.1371/journal.pone.0094138>
- 320 Brouwer, B., Parvataneni, K., & Olney, S. J. (2009). A comparison of gait biomechanics and
321 metabolic requirements of overground and treadmill walking in people with stroke. *Clinical
322 Biomechanics (Bristol, Avon)*, 24(9), 729–34. <https://doi.org/10.1016/j.clinbiomech.2009.07.004>
- 323 Bushnell, C. D., Johnston, D. C., & Goldstein, L. B. (2001). Retrospective assessment of initial stroke
324 severity: comparison of the NIH Stroke Scale and the Canadian Neurological Scale. *Stroke*,
325 32(3), 656–60. <https://doi.org/10.1161/01.STR.32.3.656>
- 326 Campanini, I., & Merlo, A. (2009). Reliability, smallest real difference and concurrent validity of
327 indices computed from GRF components in gait of stroke patients. *Gait & Posture*, 30(2), 127–
328 31. <https://doi.org/10.1016/j.gaitpost.2009.03.011>
- 329 Cho, K. H., Lee, H. J., & Lee, W. H. (2015). Test-retest reliability of the GAITRite walkway system
330 for the spatio-temporal gait parameters while dual-tasking in post-stroke patients. *Disability and
331 Rehabilitation*, 37(6), 512–6. <https://doi.org/10.3109/09638288.2014.932445>
- 332 Correa, K. P., Devetak, G. F., Martello, S. K., de Almeida, J. C., Pauleto, A. C., & Manffra, E. F.
333 (2017). Reliability and Minimum Detectable Change of the Gait Deviation Index (GDI) in post-
334 stroke patients. *Gait & Posture*, 53, 29–34. <https://doi.org/10.1016/j.gaitpost.2016.12.012>
- 335 Devetak, G. F., Martello, S. K., de Almeida, J. C., Correa, K. P., Iucksch, D. D., & Manffra, E. F.
336 (2016). Reliability and minimum detectable change of the gait profile score for post-stroke
337 patients. *Gait & Posture*, 49, 382–387. <https://doi.org/10.1016/j.gaitpost.2016.07.149>
- 338 Flansbjerg, U.-B., Downham, D., & Lexell, J. (2006). Knee muscle strength, gait performance, and

- 339 perceived participation after stroke. *Archives of Physical Medicine and Rehabilitation*, 87(7),
340 974–80. <https://doi.org/10.1016/j.apmr.2006.03.008>
- 341 Flansbjerg, U.-B., Holmbäck, A. M., Downham, D., Patten, C., & Lexell, J. (2005). Reliability of gait
342 performance tests in men and women with hemiparesis after stroke. *Journal of Rehabilitation*
343 *Medicine*, 37(2), 75–82. <https://doi.org/10.1080/16501970410017215>
- 344 Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gaine, J., Gorton, G., & Cochran, G. V.
345 (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait.
346 *Journal of Orthopaedic Research: Official Publication of the Orthopaedic Research Society*,
347 7(6), 849–60. <https://doi.org/10.1002/jor.1100070611>
- 348 Kautz, S. A., Bowden, M. G., Clark, D. J., & Neptune, R. R. (2011). Comparison of motor control
349 deficits during treadmill and overground walking poststroke. *Neurorehabilitation and Neural*
350 *Repair*, 25(8), 756–65. <https://doi.org/10.1177/1545968311407515>
- 351 Kesar, T. M., Binder-Macleod, S. A., Hicks, G. E., & Reisman, D. S. (2011). Minimal detectable
352 change for gait variables collected during treadmill walking in individuals post-stroke. *Gait &*
353 *Posture*, 33(2), 314–7. <https://doi.org/10.1016/j.gaitpost.2010.11.024>
- 354 McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional
355 kinematic gait measurements: a systematic review. *Gait & Posture*, 29(3), 360–9.
356 <https://doi.org/10.1016/j.gaitpost.2008.09.003>
- 357 Novak, A. C., Olney, S. J., Bagg, S., & Brouwer, B. (2009). Gait changes following botulinum toxin A
358 treatment in stroke. *Topics in Stroke Rehabilitation*, 16(5), 367–76.
359 <https://doi.org/10.1310/tsr1605-367>
- 360 Oken, O., Yavuzer, G., Ergöçen, S., Yorgancıoğlu, Z. R., & Stam, H. J. (2008). Repeatability and
361 variation of quantitative gait data in subgroups of patients with stroke. *Gait & Posture*, 27(3),
362 506–11. <https://doi.org/10.1016/j.gaitpost.2007.06.007>
- 363 Péliissier, J., Pérennou, D., & Laassel, E. (1997). Analyse instrumentale de la marche de
364 l'hémiplégique adulte: revue de la littérature. *Annales de Réadaptation et de Médecine Physique*,
365 40(5), 297–313. [https://doi.org/10.1016/S0168-6054\(97\)89510-4](https://doi.org/10.1016/S0168-6054(97)89510-4)
- 366 Pinzur, M. S., Sherman, R., DiMonte-Levine, P., & Trimble, J. (1987). Gait changes in adult onset
367 hemiplegia. *American Journal of Physical Medicine*, 66(5), 228–37. Retrieved from
368 <http://www.ncbi.nlm.nih.gov/pubmed/3324770>
- 369 Pittock, S. J. J., Moore, a. P. P., Hardiman, O., Ehler, E., Kovac, M., Bojakowski, J., ... Coxon, E.
370 (2003). A double-blind randomised placebo-controlled evaluation of three doses of botulinum
371 toxin type A (Dysport) in the treatment of spastic equinovarus deformity after stroke.
372 *Cerebrovascular Diseases (Basel, Switzerland)*, 15(4), 289–300.
373 <https://doi.org/10.1159/000069495>
- 374 Pomeroy, V. M., King, L., Pollock, A., Baily-Hallam, A., & Langhorne, P. (2006). Electrostimulation
375 for promoting recovery of movement or functional ability after stroke. *The Cochrane Database*
376 *of Systematic Reviews*, (2), CD003241. <https://doi.org/10.1002/14651858.CD003241.pub2>
- 377 Pradon, D., Hutin, E., Khadir, S., Taiar, R., Genet, F., & Roche, N. (2011). A pilot study to investigate
378 the combined use of Botulinum toxin type-a and ankle foot orthosis for the treatment of spastic
379 foot in chronic hemiplegic patients. *Clinical Biomechanics (Bristol, Avon)*, 26(8), 867–72.
380 <https://doi.org/10.1016/j.clinbiomech.2011.04.003>
- 381 Robertson, J. V. G., Pradon, D., Bensmail, D., Fermanian, C., Bussel, B., & Roche, N. (2009).
382 Relevance of botulinum toxin injection and nerve block of rectus femoris to kinematic and
383 functional parameters of stiff knee gait in hemiplegic adults. *Gait & Posture*, 29(1), 108–12.

- 384 <https://doi.org/10.1016/j.gaitpost.2008.07.005>
- 385 Roche, N., Boudarham, J., Hardy, A., Bonnyaud, C., & Bensmail, B. (2015). Use of gait parameters to
386 predict the effectiveness of botulinum toxin injection in the spastic rectus femoris muscle of
387 stroke patients with stiff knee gait. *European Journal of Physical and Rehabilitation Medicine*,
388 *51*(4), 361–70. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/25213306>
- 389 Roche, N., Zory, R., Sauthier, A., Bonnyaud, C., Pradon, D., & Bensmail, D. (2015). Effect of
390 rehabilitation and botulinum toxin injection on gait in chronic stroke patients: a randomized
391 controlled study. *Journal of Rehabilitation Medicine*, *47*(1), 31–7.
392 <https://doi.org/10.2340/16501977-1887>
- 393 Schwartz, M. H., Trost, J. P., & Werve, R. A. (2004). Measurement and management of errors in
394 quantitative gait data. *Gait & Posture*, *20*(2), 196–203.
395 <https://doi.org/10.1016/j.gaitpost.2003.09.011>
- 396 Sheffler, L. R., & Chae, J. (2015). Hemiparetic Gait. *Physical Medicine and Rehabilitation Clinics of*
397 *North America*, *26*(4), 611–23. <https://doi.org/10.1016/j.pmr.2015.06.006>
- 398 Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability.
399 *Psychological Bulletin*, *86*(2), 420–8. <https://doi.org/10.1037/0033-2909.86.2.420>
- 400 Wallard, L., Dietrich, G., Kerlirzin, Y., & Bredin, J. (2015). Effects of robotic gait rehabilitation on
401 biomechanical parameters in the chronic hemiplegic patients. *Neurophysiologie Clinique =*
402 *Clinical Neurophysiology*, *45*(3), 215–9. <https://doi.org/10.1016/j.neucli.2015.03.002>
- 403 Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the
404 SEM. *Journal of Strength and Conditioning Research*, *19*(1), 231–40.
405 <https://doi.org/10.1519/15184.1>
- 406 Yavuzer, G., Oken, O., Elhan, A., & Stam, H. J. (2008). Repeatability of lower limb three-dimensional
407 kinematics in patients with stroke. *Gait & Posture*, *27*(1), 31–5.
408 <https://doi.org/10.1016/j.gaitpost.2006.12.016>

10 Appendix

Supporting Information

S1 Table A: Results of statistical analyses for kinematic and spatiotemporal parameters.

--Table A--

11 Tables

Table 1: Kinematic parameters during the swing (SwP) and stance phases (StP) of gait cycle.

Maximum values denote flexion/dorsiflexion and minimum values denote extension/plantarflexion.

Kinematic Parameters	Gait Cycle Phases	Description (degrees)					
		V1		V2		V3	
		mean	SD	mean	SD	mean	SD
Hip Maximum Angle	SwP	33.42	9.03	33.29	8.72	32.19	9.62
	StP	29.35	9.13	28.81	9.09	27.91	9.1
Hip Minimum Angle	SwP	7.95	9.52	6.36	10.35	6.23	10.75
	StP	-2.05	9.92	-3.14	10.22	-3.54	10.63
Hip RoM	SwP*	25.47	9.99	26.93	11.36	25.96	10.4
	StP	31.4	11.97	31.95	12.64	31.45	12.43
Knee Maximum Angle	SwP	43.97	15.07	43.2	14.28	44.25	15.2
	StP	31.91	9.95	30.67	9.1	31.83	9.47
Knee Minimum Angle	SwP	12.21	9.65	11.36	8.91	11.19	9.32
	StP	1.74	10.01	0.77	9.39	0.98	9.53
Knee RoM	SwP	31.76	16.13	31.85	15.41	33.05	16.52
	StP	30.17	9.14	29.9	7.97	30.85	8.82
Ankle Maximum Angle	SwP	-0.2	6.22	-0.13	5.84	-0.07	6.12
	StP	10.73	4.75	10.75	4.71	11.59	4.63
Ankle Minimum Angle	SwP	-10.33	6.68	-10.28	5.94	-9.59	6.72
	StP	-9.29	6.01	-8.95	5.69	-8.75	6.45
Ankle RoM	SwP	10.13	5.53	10.14	5.05	9.52	4.78
	StP	20.02	4.26	19.7	4.18	20.34	4.42

SwP: swing phase, StP: stance phase, RoM: range of motion. *indicate a significant modification

revealed by the ANOVA.

Table 2: ICC, SEM and MDC of kinematic parameters of the paretic lower limb during the swing (SwP) and stance phases (StP) of gait cycle. The lowest MDC values are in bold.

Kinematic Parameters	Gait Cycle Phase	ICC			SEM (degrees)			MDC (degrees)		
		V1vsV2	V1vsV3	V2vsV3	V1vsV2	V1vsV3	V2vsV3	V1vsV2	V1vsV3	V2vsV3
Hip Maximum Angle	SwP	0.93	0.94	0.94	3.21	3.09	3.12	9.36	9.01	9.12
	StP	0.95	0.95	0.96	2.92	2.58	2.50	8.54	7.52	7.28
Hip Minimum Angle	SwP	0.93	0.94	0.97	3.58	3.22	2.59	10.44	9.39	7.56
	StP	0.94	0.95	0.98	3.26	2.96	2.22	9.53	8.63	6.48
Hip RoM	SwP	0.98	0.99	0.99	1.87	1.61	1.66	5.47	4.69	4.85
	StP	0.99	0.99	0.99	1.55	1.41	1.37	4.53	4.13	4.01
Knee Maximum Angle	SwP	0.98	0.99	0.99	2.61	2.43	2.24	7.61	7.10	6.54
	StP	0.96	0.97	0.98	2.46	2.40	1.69	7.19	7.01	4.93
Knee Minimum Angle	SwP	0.96	0.97	0.98	2.61	2.24	2.02	7.62	6.53	5.90
	StP	0.97	0.98	0.98	2.17	2.12	1.87	6.34	6.18	5.47
Knee RoM	SwP	0.98	0.99	0.98	2.80	2.20	2.91	8.16	6.43	8.49
	StP	0.96	0.98	0.96	2.44	1.80	2.23	7.12	5.25	6.52
Ankle Maximum Angle	SwP	0.92	0.93	0.95	2.38	2.22	1.87	6.93	6.49	5.47
	StP	0.91	0.91	0.92	1.94	1.83	1.71	5.65	5.33	4.99
Ankle Minimum Angle	SwP	0.92	0.95	0.95	2.43	2.00	1.95	7.10	5.84	5.69
	StP	0.9	0.95	0.94	2.57	2.01	2.14	7.50	5.86	6.24
Ankle RoM	SwP	0.92	0.89	0.99	2.08	2.33	0.70	6.08	6.80	2.05
	StP	0.93	0.93	0.94	1.51	1.53	1.35	4.40	4.48	3.95
Mean		0.95	0.96	0.97	2.47	2.22	2.01	7.20	6.48	5.86

Table 3: Spatiotemporal parameters with mean and SD at each visit.

Spatiotemporal Parameters	Description					
	V1		V2		V3	
	mean	SD	mean	SD	mean	SD
Gait speed (cm/s)	77.44	23.03	80.17	26.56	80.03	23.25
Stride length (cm)	97.02	19.04	98.29	21.58	98.32	18.96
Cadence (step/min)	94.44	12.69	96.12	15.13	96.52	14.35
Step length (cm)	50.48	8.94	51.34	9.68	51.36	8.19
StP (%)	60.41	5.41	60.53	5.37	60.35	5.05
SwP (%)	39.59	5.41	39.47	5.37	39.65	5.05
Width (cm)	19.99	4.79	19.96	4.89	20.38	4.45

Table 4: ICC, SEM and MDC of spatiotemporal parameters in paretic lower limb. The lowest MDC values are in bold. The mean values of SEM and MDC are presented as percentages to rationalize and compare the different units.

Spatiotemporal Parameters	ICC			SEM			MDC		
	V1vsV2	V1vsV3	V2vsV3	V1vsV2	V1vsV3	V2vsV3	V1vsV2	V1vsV3	V2vsV3
Gait speed (cm/s)	0.96	0.96	0.98	6.38	6.08	5.03	18.54	17.67	14.61
Stride length (cm)	0.98	0.98	0.98	4.38	4.13	4.11	12.73	12.02	11.96
Cadence (step/min)	0.95	0.95	0.98	4.06	4.09	2.95	11.81	11.9	8.58
Step length (cm)	0.96	0.97	0.96	2.42	2.18	2.42	7.02	6.33	7.02
StP (%)	0.96	0.97	0.97	1.52	1.30	1.24	4.42	3.79	3.60
SwP (%)	0.96	0.97	0.97	1.52	1.30	1.24	4.42	3.79	3.60
Step width (cm)	0.97	0.96	0.98	1.03	1.12	0.85	3.00	3.25	2.47
Mean (% for SEM and MDC)	0.96	0.97	0.97	4.66	4.32	3.90	13.75	13.10	11.45

Table A: Results of statistical analyses of all the spatiotemporal and kinematics parameters during swing phase (SwP), stance phase (StP). RoM means Range of Motion (amplitude total between flexion and extension).

Normal Distribution						Non Normal Distribution					
Variable	Phase	P Anova	HSD Tukey			Variable	Phase	P Friedman	Wilcoxon		
			V1VS2	V1VS3	V2VS3				V1VS2	V1VS3	V2VS3
Hip RoM	SwP	0.01*	0.01*	0.58	0.12	Minimum Hip Angle	SwP	0.36	-	-	-
	StP	0.33	-	-	-	Minimum Knee Angle	SwP	0.75	-	-	-
Maximum Hip Angle	SwP	0.32	-	-	-	Maximum Knee Angle	StP	0.03*	0.68	0.81	0.53
	StP	0.16	-	-	-	Knee RoM	SwP	0.11	-	-	-
Minimum Hip Angle	StP	0.17	-	-	-		StP	0.22	-	-	-
Maximum Knee Angle	SwP	0.29	-	-	-	Minimum Ankle Angle	StP	0.84	-	-	-
Minimum Knee Angle	StP	0.22	-	-	-	Ankle RoM	SwP	0.11	-	-	-
Maximum Ankle Angle	SwP	0.97	-	-	-	Stride		0.12	-	-	-
	StP	0.17	-	-	-	Cadence		0.08	-	-	-
Minimum Ankle Angle	SwP	0.39	-	-	-	StP		0.33	-	-	-
Ankle RoM	StP	0.31	-	-	-	SwP		0.33	-	-	-
Gait speed		0.18	-	-	-	Width step		0.08	-	-	-
Step length		0.32	-	-	-						