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# Investigating the relationships between three important functional tasks early after stroke: Movement characteristics of sit-to-stand, sit-to-walk and walking

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14 **Keywords: Stroke<sup>1</sup>, walking<sup>2</sup>, sit-to-stand<sup>3</sup>, sit-to-walk<sup>4</sup>, Neuromuscular recovery<sup>5</sup>,**  
15 **measurement<sup>6</sup>, movement fluidity<sup>7</sup>, biomechanics<sup>8</sup>.**

## 16 **Abstract**

17 **Background:** Walking, sit-to-stand (STS) and sit-to-walk (STW) are all considered important  
18 functional tasks in achieving independence after stroke. Despite knowledge that sensitive  
19 measurement of movement patterns is crucial to understanding neuromuscular restitution, there is  
20 surprisingly little information available about the detailed biomechanical characteristics of, and  
21 relationships between, walking, sit-to-stand and sit-to-walk, particularly in the important time  
22 window early after stroke. Hence, here, the study aimed to:

23 1. To identify the biomechanical characteristics of and determine any differences in both  
24 movement fluidity (hesitation, coordination and smoothness) and duration of movement  
25 phases, between sit-to-stand (STS) and sit-to-walk (STW) in people early after stroke

26 2. To determine whether measures of movement fluidity (hesitation, coordination, and  
27 smoothness) and movement phases during sit-to-stand (STS) and/or sit-to-walk (STW) are

28 correlated strongly to commonly used measures of walking speed and/or step length ratio in  
29 people early after stroke

30 **Methods:** This study consisted of secondary data analysis from the SWIFT Cast Trial. Specifically,  
31 we investigated movement fluidity using established assessments of smoothness, hesitation and  
32 coordination and the time duration for specific movement phases in a group of 48 people after stroke.  
33 Comparisons were made between STS and STW and relationships to walking measures were  
34 explored.

35 **Results:** Participants spent significantly more time in the initial movement phase, flexion  
36 momentum, during STS (mean time (SD) 1.74s  $\pm$ 1.45s) than they did during STW (mean time  
37 (SD)1.13s  $\pm$ 1.03s). STS was also completed more smoothly but with more hesitation and greater  
38 coordination than the task of STW. No strong relationships were found between movement fluidity  
39 or duration with walking speed or step length symmetry.

#### 40 **Conclusions:**

41 Assessment of movement after stroke requires a range of functional tasks and no one task should  
42 predominate over another. Seemingly similar or overlapping tasks such as STS and STW create  
43 distinct biomechanical characteristics which can be identified using sensitive, objective measures of  
44 fluidity and movement phases but there are no strong relationships between the functional tasks of  
45 STS and STW with walking speed or with step-length symmetry.

46

#### 47 **Introduction**

48 Regaining the ability to walk again after stroke is a priority for stroke survivors (1). Current evidence  
49 indicates that task-specific activity i.e. practice of functional walking activity, is the best approach to  
50 promoting recovery, where recovery is defined as “the extent to which body structure and functions,  
51 as well as activities, have returned to their pre-stroke state” (2). But provision of evidenced-based  
52 task-specific walking practice is challenging, especially for people with substantial motor  
53 impairments. This challenge is particularly pertinent early after stroke when it is important to provide  
54 intensive input, focused on restitution of neuromuscular function, whilst people are still in the period  
55 of injury-induced neuroplasticity (3)(4). Other rehabilitation tasks are often used when walking  
56 rehabilitation is not possible in everyday therapy.

57 For example, clinical therapy early after stroke often centers on perhaps less challenging, but  
58 nonetheless important, functional activities such as sit-to-stand (STS) and sit-to-walk (STW). STS is  
59 a relatively simple, symmetrical movement, easy to train as a single task, and is important for  
60 independence in activities of daily living such as washing and dressing (5)(6). Conversely, the  
61 associated functional task of sit-to-walk (STW) is a more complex, asymmetric activity that  
62 combines rising from sitting and gait initiation, via fluent movement transitions, to enable speed and  
63 efficiency of movement. Indeed, fluidity of STW could be seen as an expression of intact motor  
64 control and, like walking, this complex movement is challenging for people with motor deficit after  
65 stroke (7). As such, it is possible that STW may be associated with other important dynamic  
66 functions that require fluid movement between transitions, such as walking, and, in particular,  
67 walking that requires adaptation of parameters to meet environmental demands (8). Certainly, work  
68 on a previously developed Fluidity Index (9) suggested an association with fluidity measures during  
69 rising to walk and gait speed, though this was not tested statistically, and this same work found a

70 significant correlation between overall movement duration and gait speed. It should be noted that the  
71 Index used in this work (9) was based on Centre of Mass (CoM) velocity in one direction only. STS  
72 duration has also been shown to relate to spatiotemporal parameters of walking including walking  
73 speed but not to symmetry (10) or more complex measures of fluidity (6). In order to more fully  
74 understand the potential relationships between these important, commonly adopted functional tasks  
75 more fully, a detailed assessment using measures that reflect the complexity of the tasks, is required.

76 However, despite the established importance of these key functional tasks- STS, STW and walking-  
77 and some indication of relationships between them, detailed assessment of their biomechanical  
78 characteristics in the same group of people in the important time window early after stroke remains  
79 sparse, both in research and clinical practice. An understanding of such characteristics is crucial to  
80 understanding neuromuscular restitution (11). Sensitive, objective measurement of movement  
81 patterns is key to this understanding and can be achieved using kinetics and kinematics during  
82 functional activity (11)(12), yet, other measures predominate; walking speed is a current foremost  
83 measure of functional ability (13). This may not be the appropriate measure to investigate  
84 neuromuscular restitution, as observation indicates that people using compensatory movement  
85 patterns- 'neuromuscular substitution'- can walk at the same speed as people who do not (13). Other  
86 temporal-spatial characteristics of gait are also measured in some trials. But they too may not be  
87 measuring neuromuscular restitution alone, although derived measures of symmetry such as step  
88 length ratio could be indicative of change in movement patterns.

89 At present, there is little, if any information available on the best measures to assess neuromuscular  
90 restitution required for performance of important functional tasks (14). Nor has sufficient  
91 consideration been given to how neuromuscular improvement in one functional task may, or may not,  
92 generalize beyond that task e.g. from STS to STW, and STW and/or STS to walking. This is  
93 potentially important for future clinical recommendations - if walking speed and/or step length ratio  
94 are strongly correlated to one or more components of movement fluidity in other commonly trained  
95 functional activity such as STS and STW, then measurement of the latter could be superfluous,  
96 Furthermore, training of STS and STW in the early stages after stroke when walking practice is  
97 challenging, could improve walking parameters. And then, if there is a strong correlation between  
98 movement fluidity components during STS and STW after stroke then it is not essential to use both  
99 mobility tasks.

100 Therefore, to identify relevant biomechanical characteristics of neuromuscular restitution, according  
101 to rehabilitation science consensus (11) we should firstly establish and compare movement fluidity  
102 measures (hesitation, coordination and smoothness) and/or measures of timing within movement  
103 phases from a set of functional tasks after stroke, such as STS and STW, not just walking. Then, the  
104 relationship between those measures and more commonly used clinical measures of walking should  
105 be explored. Such detailed investigation of these issues are warranted before further steps towards  
106 future clinical recommendations on the type of training to be used can be made (11).

107 Hence, the overarching hypothesis driving the study reported here is that measurement of fluidity  
108 derived from kinematic and kinetic variables during the functional tasks of STS, STW and walking  
109 show strong association. In order to investigate this hypothesis, the specific aims of the study  
110 reported here were:

- 111 1. To firstly identify the detailed biomechanical characteristics of, and determine any differences  
112 in, both movement fluidity (hesitation, coordination and smoothness) and duration of

113 movement phases between sit-to-stand (STS) and sit-to-walk (STW) in people early after  
114 stroke

115 2. To then determine whether measures of movement fluidity (hesitation, coordination, and  
116 smoothness) and movement phases during sit-to-stand (STS) and/or sit-to-walk (STW) are  
117 correlated strongly to commonly used measures of walking speed and/or step length ratio in  
118 people early after stroke

119

## 120 **Materials and Methods**

### 121 **Design**

122 This was an observational study comparing the same group of participants early after stroke during  
123 sit-to-stand (STS) sit-to-walk (STW) and walking. The study aims here were addressed by secondary  
124 data analysis of movement data collected during the SWIFT Cast Trial (15).

### 125 **Participants**

126 People were included as participants in the primary SWIFT Cast Trial [15] if they were:

127 (1) over 18 years old;

128 (2) between 3 and 42 days after stroke, either infarct or hemorrhage;

129 (3) considered to be fit for rehabilitation, having peripheral oxygen saturations 90%+ on air, resting  
130 pulse <101 beats/minute;

131 (4) able to take at least three steps with abnormal initial foot contact and/or decreased ability to take  
132 full body weight through the paretic lower limb during stance; with the assistance of up to two people  
133 if required;

134 (6) able to follow a 1-stage command; and

135 (7) free from contractures or loss of skin integrity in lower limb.

136 For inclusion in the secondary analysis presented here, participants were those who met the above  
137 criteria, 1-7, and who were:

138 (8) able to complete a STS and STW task at the outcome measurement time point (approximately six  
139 weeks after start of the intervention phase) without physical assistance from another person, object or  
140 aid (e.g. walking stick).

### 141 **Data collection**

142 Kinematic and kinetic data were collected in the movement laboratories of the University of  
143 Strathclyde and the University of East Anglia. Vicon motion capture cameras (Oxford Metrics,  
144 Oxford, UK) were used to capture 3D trajectories of 48, 14mm reflective markers attached to the  
145 body at anatomical locations in accordance with a bespoke biomechanical model that used a  
146 combination of cluster and anatomical markers (16). This biomechanical model has also been

147 validated for use among stroke patients (17). Marker trajectory data were sampled at 100Hz.  
 148 Embedded force plates were used to record ground reaction forces sampled at 1000Hz at the  
 149 University of Strathclyde (Kistler Instrumente AG, Switzerland) and 2000Hz at the University of  
 150 East Anglia (Bertec, Columbus, OH).

151 Participants wore tight-fitting Lycra shorts and vest along with comfortable flat shoes. The STS and  
 152 STW movements were completed from a height adjustable plinth, setup to allow the participant to sit  
 153 with their feet flat on the floor, hips and knees as close to 90 degrees as possible. Each foot was  
 154 positioned on an embedded force plate, approximately shoulder width apart and facing the direction  
 155 of progression. Participants were asked *not* to use their upper limbs to assist them in the task.  
 156 However, they were not *prevented* from using their upper limbs to steady themselves when they felt  
 157 unsafe as they rose. For the analysis presented here, these trials were included as they represent the  
 158 pragmatic movement strategy adopted by these participants who were representative of the  
 159 clinical population. In effect, a quarter of the participants steadied themselves during rising in one or  
 160 more trials. For each task, a minimum of three and a maximum of six repetitions of each task (trials)  
 161 were undertaken.

162 STS task: participants were instructed to stand up as soon as they heard a buzzer, and remain  
 163 standing until they saw a red light accompanied by a second buzzer, at which point they sat down.

164 Sufficient time was given between buzzers to enable a stable upright standing position to be  
 165 achieved, determined by researcher observation.

166 STW task: participants were instructed to go and pick up a cup from a table as soon as they heard the  
 167 buzzer. This instruction was designed to elicit a voluntary STW movement. The distance between the  
 168 and the participants' seated position was standardized at 3m.

169 Data collection and analysis for walking speed and walking step length symmetry is described in  
 170 earlier publications (18) (19). In brief, participants walked at a self-selected speed along a 6m mat  
 171 which was marked with lines 1cm, 5cm and 10cm apart. Circular black and white markers were  
 172 placed over each participant's skin to mark the joint centers of the hip, knee and ankle. High speed  
 173 video cameras (EXFH20, Casio, Tokyo, Japan) were used to record the participant walking and  
 174 additionally to detect the timing of when the participant crossed into and out of the 6m space. The  
 175 start and end times were identified by a flash emitted from a light source when infra-red beams at the  
 176 start and end of the mat were broken by the participant passing through. Video data was processed  
 177 using Pro-trainer 10.1 (Sports Motion Inc. Ca, USA) to determine step times and to extract step  
 178 lengths using the markings on the mat. Step length symmetry values were calculated using the  
 179 equation

$$180 \quad \text{Step Length Symmetry} = \frac{2P}{P + LP} - 1$$

181 where P = Paretic leg and LP = Less paretic leg values. A positive value implies longer step length  
 182 on the paretic leg, and a negative value longer length in the non-paretic

### 183 **Data Processing**

184 Kinematic and kinetic data were synchronized using Vicon Nexus software (Oxford Metrics, Oxford,  
 185 UK). Marker trajectories were filtered using a Woltring filter with a predicted mean square error of

186 20mm. Model outputs were filtered using a low pass (cut off frequency 6Hz) sixth order Butterworth  
187 filter.

188 STW gait events of ‘foot strike’ and ‘foot off’ were independently marked and verified by two  
189 researchers. Where available, force-plate data were used to further verify the time-position of events.  
190 Marker trajectories and model outputs were exported and custom scripts in Python (Python Software  
191 Foundation, www.python.org) were used for all further analyses.

## 192 **Movement phases**

193 Movement phases were assessed by the total time taken for STS and STW tasks, along with timing of  
194 specific within-task movement phases as described by Kerr (20). These movement phases were  
195 adapted here, as data collection did not include kinematic data to mark seat off, and due to difficulties  
196 identifying gait initiation in this group of people early after stroke (see phase descriptions below).  
197 Direct comparison between STS and STW can only be made for Phases 1 and 2 which are shared by  
198 both STS and STW. Phase 3 begins with the same biomechanical event for STS and STW, but due to  
199 the different nature of the tasks, the end event differs. The authors considered that to exclude Phase 3  
200 would be an omission so comparison is included; however, it is most useful for consideration in  
201 addressing aim two.

202 Phase 1, *flexion momentum*, began with initiation of movement of the clavicle marker and continued  
203 until peak vertical force was reached. Phase 2, *seat-off*, was defined as the time between peak vertical  
204 force and peak vertical velocity of the clavicle marker. Phase 3, *extension momentum*, began at peak  
205 vertical velocity of the clavicle marker and ended at (i) maximum height of the clavicle marker for  
206 STS or (ii) foot off during the first swing phase of gait for STW (unloading). Finally, Phase 4, *stance*,  
207 occurs in STW only. It denotes the time between foot off of initial swing phase, until the foot off of  
208 the opposite leg (the initial stance leg). As reported previously in this study population (21)(22), it  
209 was not possible to reliably identify the mediolateral ground reaction force denoting the start of gait  
210 initiation; foot off was therefore used to mark transition between Phases 3 and 4 during STW.

## 211 **Fluidity measures**

212 All fluidity measures for STS and STW- smoothness, hesitation and coordination, were calculated  
213 from time normalized data. For the purpose of this analysis, both tasks began with the initiation of  
214 movement. Initiation was defined here as the instance when the vertical velocity of the clavicle  
215 marker changed by more than  $0.5 \text{ mms}^{-1}$  from baseline and was sustained for at least 50 ms prior to  
216 the clavicle marker’s minima position in the vertical plane. The movement cycles ended at the  
217 maximal peak of vertical displacement of the clavicle marker for STS and foot contact at the end of  
218 the second step i.e., foot contact of the original stance leg, for STW.

219 Previous studies have used model derived Centre-of-Mass (COM) to calculate smoothness and  
220 hesitation; however, this requires full visibility of all tracking markers. Tasks which incorporate a  
221 sitting or flexed position present challenges for marker visibility; this, combined with the need for  
222 close supervision to maintain safety, resulted in some trials with missing marker position data. Gap  
223 filling interpolation methods are not applicable if the gap is at the beginning or end of the movement,  
224 or if gaps in the trajectory data are large. Hence, here we used the clavicle marker to track the fluidity  
225 of the trunk as it was reliably in view throughout trials. This simplified metric, when compared to  
226 COM, cannot fully account for the contribution of the upper limbs and head; nevertheless, it provides  
227 a useful and clinically applicable comparative measure as the trunk cannot act in isolation of the head  
228 and limbs. The sternum has previously been used to represent the COM during biofeedback to stroke

229 survivors (23). Further, to check our decision, sternum and clavicle positional data were compared to  
230 COM positions in 11 of the included participants for whom COM data was available. The magnitude  
231 of both COM, Sternum and Clavicle positional data was normalised and compared using the  
232 coefficient of determination which revealed an average correlation of the two signals of 95%.

233 **Smoothness** of the STS and STW tasks were defined according to the principles of Kerr et al (2013)  
234 (24); where smoothness is derived from the rate of change of acceleration (jerk), calculated as the  
235 third time derivative of the horizontal position of the clavicle marker. The jerk signal was tested  
236 against a logic statement to count all instances when the signal was either (i) greater than the previous  
237 two samples and greater than the successive two samples, or (ii) less than the previous two samples  
238 and less than the subsequent two samples (24). Instances where the logic statement was met were  
239 defined as inflections in the jerk signal. Smoothness of the task was determined by the total inflection  
240 count, with a lower value indicating a smoother overall movement.

241 **Hesitation** of both STS and STW was measured as the percentage of normalized time between the  
242 maximum forward velocity and the maximum upward acceleration of the clavicle marker, where a  
243 low value indicates a fluid movement without hesitation. In contrast to previous publications  
244 (24)(25), here hesitation does not measure the depression in horizontal momentum. It was considered  
245 important to change the calculation for hesitation to provide an equitable measure between the tasks  
246 of STS and STW: STW is fundamentally about forward momentum, whereas STS is not.

247 **Coordination** was also defined according to Kerr et al (2013) (24). Two separate coordination values  
248 were calculated. Coordination One (C1) was derived from the temporal overlap between the knee and  
249 hip, in the sagittal plane, at the end of initial hip flexion and the start of knee extension; and  
250 Coordination Two (C2) derived from the temporal overlap between the knee and hip, in the sagittal  
251 plane at the end of hip extension and start of knee flexion on the initial step of STW (24). The events  
252 marking the start and end of hip and knee flexion were identified by first fitting a polynomial curve  
253 to the model derived data before calculating the differential values. The peaks in the resulting data  
254 describe the start and end events of hip and knee flexion. Previous studies have considered C1 of the  
255 paretic leg during STS (6) and C1 and C2 of the stepping leg during STW (24). For this analysis, C1  
256 was calculated for both paretic and non-paretic legs during STS and STW tasks where marker  
257 visibility allowed. A lower value here indicates a more coordinated movement.

## 258 **Data and Statistical Analysis**

259 The SWIFT Cast Trial did not find statistically significant differences between the experimental and  
260 control groups therefore, for addressing study aims here, participants were analyzed as a single  
261 group. Descriptive statistics were used to describe clinical characteristics of participants. Statistical  
262 analyses were performed using Stata 16.0/SE. A sample size calculation was not performed due to  
263 this being a secondary analysis of an existing data set; a formal sample size calculation was carried  
264 out for the primary study (15)

265 Fluidity measures of smoothness, hesitation and coordination were calculated per participant for all  
266 available trials along with total time to complete each task and duration of time spent in each defined  
267 movement phase. Repetitions of the STS and STW, respectively, were combined and the mean value  
268 calculated for each participant and task.

269 Paired *t*-tests were used to determine the differences between STS and STW (aim one) for:

270 a) fluidity measures; and



271 b) movement phase durations.

272 To determine whether measures of movement fluidity (hesitation, coordination and smoothness) and  
 273 the time spent in movement phases during i) STS and ii) STW are correlated strongly to walking  
 274 speed and/or step length ratio in people after stroke (aim two), Pearson's bivariate correlations were  
 275 calculated for:

276 a) walk speed with movement phase duration and fluidity measures of STS;

277 b) walk speed with movement phase duration and fluidity measures of STW;

278 c) step length ratio with movement phase duration and fluidity measures of STS;

279 d) step length ratio with movement phase duration and fluidity measures of STW.

280 All tests were evaluated using a significance level of 0.05. Correlations were considered to be strong  
 281 if 0.6 or above, moderate at a value of 0.4 to 0.6 and weak if 0.4 or below, suitably reversed for  
 282 negative values (26)

283

## 284 Results

### 285 Participant flow

286 **Figure 1** illustrates participant flow through the analyses, with reasons for exclusion. A total of 105  
 287 participants were recruited into the original randomized controlled trial; of these, 91 attended the six-  
 288 week assessment from which data for this study were collected. At this assessment, 51 participants  
 289 were able to attempt both STS and STW assessments. Three datasets were excluded because  
 290 participants used walking aids or had physical assistance from another person. Consequently, 48  
 291 datasets were available for assessment of movement phase duration, smoothness and hesitation  
 292 during STS and STW. A further six sets of data were excluded from coordination analysis because of  
 293 large gaps in marker trajectories or excessive movement of cluster markers during the assessments. It  
 294 was not possible to determine movement phases using our custom scripts for one participant during  
 295 the STS task meaning 47 sets of data were available for analysis. Three participants completed STS  
 296 and STW assessments but were unable to walk 3m unaided, these participants were assigned a  
 297 walking speed of  $0\text{ms}^{-1}$  and their step length ratio was treated as missing data.

298 The clinical characteristics of included participants are provided in **Table 1**. In summary, at outcome  
 299 assessment participants' mean age was 65 years, their mean number of days post-stroke was 64 and  
 300 they had a mean Functional Ambulatory Categories (FAC) score of 4.10/5. The average walking  
 301 speed for all participants was  $0.53\text{ms}^{-1} \pm$  Standard deviation (SD)  $0.30\text{ms}^{-1}$  with a step length ratio  
 302 average of  $-0.03 \pm$  SD 0.19.

### 303 Comparison of fluidity and movement phases between STS and STW

304 **Table 2** shows comparisons between STS and STW for both fluidity and movement phases. There  
 305 was no significant difference in the mean overall time taken to complete the tasks of STS ( $M = 3.27\text{s}$   
 306  $\pm$  SD 0.85s) and STW ( $M = 3.23\text{s} \pm$  SD 2.00s) (95%CI -0.05(-0.43, 0.53),  $p=0.84$ ). Analysis  
 307 according to the pre-defined movement phases of STS and STW demonstrated that Phase 1 (*flexion*

308 *momentum*, from initiation of movement until peak vertical velocity) lasts significantly longer during  
 309 STS ( $M = 1.74s \pm SD 1.45s$ ) than in STW ( $M = 1.13s \pm SD 1.03s$ ) (95% CI -0.61 (-0.36, -0.86)  $p =$   
 310  $<0.0001$ ).

311 Fluidity measures show that STS had a statistically significant lower smoothness value (STS  $M =$   
 312  $55.28$  inflections  $\pm SD 6.63$  inflections, STW  $M = 68.43$  inflections  $\pm SD 11.48$  inflections, 95% CI  
 313  $13.13$  (9.08, 17.21)  $p = <0.0001$ ) indicating less inflections in the jerk signal and a smoother  
 314 movement overall. Hesitation values show that STS is a more hesitant movement than STW with  
 315 participants spending a significantly greater percentage of time in the transition between maximum  
 316 forward velocity and the maximum upward acceleration (STS  $M = 23.54\% \pm SD 14.13\%$ , STW  $M =$   
 317  $14.27\% \pm SD 8.65\%$ , 95% CI -9.27 (-14.29, -4.26)  $p = <0.01$ ). During STS, C1 in both paretic ( $M =$   
 318  $7.38\% \pm SD 5.49\%$ ,  $p = <0.01$ ) and non-paretic ( $M = 7.53\% \pm SD 4.33\%$ ,  $p = <0.01$ ) sides is  
 319 shortened when compared to C1 in STW (paretic  $M = 15.39\% \pm SD 12.99\%$ , non-paretic  $M =$   
 320  $15.36\% \pm SD 11.17\%$ ). This shows that the percentage of normalized time spent in between the  
 321 events of the end of initial hip flexion, prior to seat off, and the start of knee extension is reduced for  
 322 STS compared to STW indicating a more coordinated movement. Both C1 and Hesitation occur in  
 323 movement Phase 1 of STS and STW.

### 324 **Relationship between STS and STW with walk speed**

325 The relationships between walking speed, fluidity measures and movement phase durations of STS  
 326 and STW are provided in **Table 3**. Although statistical significance was reached for some variables  
 327 none showed a strong correlation with walking speed ( $r = -0.51$  to  $r = 0.42$ ).

328 The correlations that were statistically significant indicate moderate to weak relationships between  
 329 walking faster and shorter duration of both the STS and STW tasks,  $r = -0.41$ ,  $p = <0.01$  and  $r = -$   
 330  $0.31$ ,  $p = 0.03$  respectively. Faster walking also showed a moderate to weak correlation with: STS  
 331 Phase 1 ( $r = -0.42$ ,  $p = <0.01$ ), STS Phase 3 ( $r = -0.37$ ,  $p = 0.01$ ), STW Phase 3 ( $r = -0.51$ ,  $p = 0.00$ )  
 332 and STW Phase 4 ( $r = -0.28$ ,  $p = 0.05$ ).

333 A statistically significant, weak relationship was identified between greater smoothness and higher  
 334 walking speed for STS ( $r = -0.34$ ,  $p = 0.02$ ). The opposite relationship was found for STW with a  
 335 significant but moderate correlation ( $r = 0.42$ ,  $p = <0.01$ ) between less smooth movement and higher  
 336 walking speed.

337 No other fluidity measures for STS were correlated significantly to walking speed. For STW a weak  
 338 relationship was found between C1 of the less-paretic lower limb and greater walking speed ( $0.36$ ,  $p$   
 339  $= 0.02$ ).

### 340 **Relationship between STS and STW with step length ratio**

341 **Table 4** demonstrates the relationship between step length ratio; duration of movement phases and  
 342 fluidity measures from STS and STW. All correlation coefficients were weak ( $r = -0.27$  to  $r = -0.21$ )  
 343 and none were statistically significant.

344

## 345 **Discussion**

### 346 **Summary of findings**

347 Our results do not support the hypothesis that measures of movement fluidity and movement timing  
348 during STS and STW are correlated strongly with walking speed and step length symmetry in people  
349 early after stroke.

350 The study found that whilst people who were a mean of 64 days after stroke took the same amount of  
351 time to complete both STS and STW, participants took significantly longer to complete the flexion  
352 momentum phase of STS than of STW (aim 1). Differences between performance of the two tasks  
353 were also found for movement fluidity. Specifically, compared to STW, the STS task was performed  
354 significantly smoother but with greater hesitancy and greater hip/knee coordination (aim 1). No  
355 strong relationship was found for stroke survivors between: walking speed and STS or STW; walking  
356 speed and duration of STS or STW or their constituent phases; step length ratio during walking and  
357 STS or STW; or, step length ratio during walking and STS or STW (aim 2). However, significant  
358 weak to moderate relationships indicated that stroke survivors who walked faster may also: perform  
359 the STS task more smoothly, but perform STW less smoothly and have reduced hip/knee  
360 coordination on their non-paretic leg during STW. Unsurprisingly, faster walkers also take less time  
361 to complete STS and STW; they spend less time in the flexion momentum phase of STS and have  
362 shorter durations of Phase 3 (*extension momentum*) of STS and STW and Phase 4 (*stance*) of STW.

363 In summary, our findings indicate that the lack of a strong relationship between walking speed/step  
364 length symmetry to movement fluidity and duration of STS and STW means that all three tasks  
365 require distinct training after stroke. No one task is superfluous for stroke rehabilitation.

### 366 **The differences between movement fluidity and duration of phases between STS & STW**

367 Significantly greater hesitation was observed during STS than during STW in this group of people  
368 early after stroke. This finding is similar to previous findings that hesitation is greater during STS  
369 than STW in healthy younger adults (25) despite the variation in the description and calculation of  
370 hesitation between studies. As the events of hesitation (maximum forward velocity and maximum  
371 upward acceleration) both occur around the end of Phase 1 of movement, the *flexion momentum*,  
372 these data indicate that hesitation is likely contributing factor to the longer Phase 1 of movement seen  
373 in STS compared to STW. A prolonged Phase 1 has previously been described in studies examining  
374 STW in stroke survivors when compared to healthy adults; here stroke survivors spent a greater  
375 amount in Phase 1 because of increased time spent in hip flexion (7). A lengthened Phase 1 of  
376 movement is also seen in older adults, when compared to younger adults attributed to an increased  
377 angle of trunk flexion (27). Hesitation may be a critical time window in which balance is tightly  
378 regulated to create the breaking impulse previously identified as an important differentiation between  
379 these tasks in healthy adults (25)(28).

380 STS was found to be both a smoother and a more coordinated movement than STW. This likely  
381 reflects the less challenging nature of the STS task without asymmetric unloading of the swing leg,  
382 gait initiation and initial steps and the balance perpetuations associated with these actions. The  
383 biomechanical events measured to determine C1 appear to occur around the transition between  
384 movement Phases 1 and 2 indicating that in stroke survivors, preparation for seat-off in STW takes  
385 longer than in STS. This may reflect the time required for the medio-lateral ground reaction force and  
386 unloading of the swing leg seen in STW but not in STS in healthy adults (25)(28). It is interesting  
387 that when compared to previous data from healthy adults, who begin knee extension before hip  
388 flexion ends (24), stroke survivors here show an inverse pattern of movement during C1,  
389 demonstrating an inability to begin knee extension until after the end of hip flexion.

390 This assessment of STS and STW in the same group of stroke survivors shows that the functional  
391 tasks of STS and STW create distinct biomechanical characteristics which can be identified using  
392 sensitive, objective measures of fluidity and timing within movement phases. The identification of  
393 these characteristics may be indicative of the different movement intentions and therefore the motor  
394 planning strategies required for the seemingly similar tasks of STS and STW. This clearly  
395 demonstrates that it is not possible to assess recovery post-stroke with just one task even if that task  
396 shows clear similarities to another. Similarly, interpretations of STS data cannot be made in relation  
397 to a STW task and vice-versa.

### 398 **The relationship of fluidity measures to walk speed**

399 Previous publications have described associations between total STW duration and walking speed ( $r$   
400  $-0.42$ ,  $p < 0.01$ ) in older adults (29) and a fluidity index with a 10m timed walk ( $r = -0.73$ ,  $p < 0.0001$ )  
401 in chronic stage stroke survivors (30). The data in our study show much weaker correlations between  
402 walking speed and STS smoothness ( $r = -0.34$ ,  $p = 0.02$ ), STW smoothness ( $r = 0.42$ ,  $p < 0.01$ ), STW  
403 C1 of the non-paretic leg ( $r = 0.36$ ,  $p = 0.02$ ), overall time to complete STS ( $r = -0.41$ ,  $p = < 0.01$ ),  
404 overall time to complete STW ( $r = -0.31$ ,  $p = 0.03$ ), time to complete Phases 1 ( $r = -0.42$ ,  $p < 0.01$ )  
405 and 3 ( $r = -0.37$ ,  $p = 0.01$ ) of STS and time to complete Phases 3 ( $r = -0.51$ ,  $p < 0.01$ ) and 4 ( $r = -0.28$ ,  
406  $p = 0.05$ ) of STW. However, whilst it is important to acknowledge findings from similar work in the  
407 field, direct comparisons with these existing studies are challenged by use of an older adult study  
408 population without specific neurological impairment (29) and use of the previously discussed  
409 Fluidity Index that perhaps does not reflect the complexity required to measure motor control  
410 strategies in people early after stroke, as we have done here (30).

411 In this analysis, the overall speed at which the functional movements of STS and STW are completed  
412 shows moderate correlation to the speed at which a stroke survivor can walk. These measures are a  
413 simple measure of functional ability but cannot be interpreted in relation to neuromuscular  
414 restitution. The duration of movement Phases 1 and 3 in STS and 3 and 4 in STW also show a  
415 moderate relationship to walking speed. The duration of Phases 3 and 4 during STW have been  
416 previously identified as prolonged in stroke survivors when compared to healthy control participants  
417 (30). The correlation of STW Phases 3 and 4 may suggest that both gait initiation and initial step of  
418 STW may reflect aspects of walking. However, the nature of gait initiation from a seated position in  
419 STW is likely a more challenging and dynamic movement than walking at a self-selected speed, in a  
420 straight line, across a level surface. Although significance was not reached it is interesting to note  
421 that for both STS and STW the duration of Phase 2, i.e. *seat-off*, shows the opposite pattern to the  
422 rest of the movement phases. Here a slower movement is seen, which may be indicative of the  
423 importance of motor control around the crucial event of seat-off where optimum balance is essential.

424 Measures of movement fluidity during STS and STW showed a moderate relationship between the  
425 ability to STS in a smooth movement and walking speed whereas the opposite was found for STW.  
426 This may be due to the decision made here to collect STS data until the peak vertical displacement of  
427 the clavicle marker whereas the STW data is collected until foot contact of the second step. As a  
428 result, the STW data encompasses gait initiation and the initial two steps which require rapid  
429 acceleration and deceleration of the COM not required for a STS movement. A smoother STW may  
430 be seen in those participants who essentially STS, pause and then tentatively start to walk whilst  
431 maintaining tight control due to lack of confidence or balance. Significant breaking impulses prior to  
432 seat-off have been previously identified in stroke survivors performing a STW task (31) which may  
433 contribute to less smooth movement of STW compared to STS, further investigation is required to  
434 confirm this.

435 The only other fluidity measure to show a relationship to walking speed is that of C1 (the temporal  
436 overlap between the knee and hip during rising). Here a larger value, indicating less coordination,  
437 shows a moderate relationship to walking speed. C1 has previously been investigated during STS (6)  
438 and the stepping leg of STW (24). Here we made the decision that, where marker visibility allowed,  
439 we would investigate C1 of both the stepping and stance legs. In this analysis, almost all participants  
440 used their paretic leg to take the initial step and therefore, with few exceptions, all of the C1 data  
441 from STW relates to the stance leg which has not previously been investigated. The greater value  
442 seen in C1 during STW may indicate a different motor strategy to that used in STS, perhaps the  
443 preparation for/beginning of forward propulsion through the stance leg.

444 The absence of any identified strong relationships between the measures of walking speed, fluidity  
445 measures and timing within movement phases during either STS or STW demonstrates the  
446 complexity of assessing recovery after stroke. Although relationships between the functional tasks of  
447 STS, STW and walking had previously been suggested, the data in this study indicates that any  
448 relationship is, at best, tenuous. Walking speed is simple and easy to measure; however, its  
449 usefulness in the assessment of motor recovery in stroke survivors is limited. Speed can be achieved  
450 through a variety of compensatory techniques and it is probably a better indicator of balance and  
451 confidence than recovery. Speed of STS, STW or their movement phases showed the strongest  
452 relationship to walking speed of all the measures used in this study. This may indicate that these  
453 commonly used measures of STS and STW are, like walking speed, just a measure of functional  
454 ability without the sophistication to measure the underlying reasons for a faster movement.

455 Fluidity measures of smoothness, hesitation and coordination were developed with the aim of  
456 measuring the ability to move in a controlled and fluid way without rapid changes. Both hesitation  
457 and coordination measure normalized time between biomechanical events; however, unlike  
458 movement phases, the events used were chosen with the specific aim of providing an objective  
459 measure of a therapists subjective observation- that improving fluidity could improve function (32).  
460 This is a clear demonstration of the need to carefully consider the mechanisms behind assessment  
461 tasks to fully appreciate what is being measured.

#### 462 **The relationship of fluidity measures to step-length ratio**

463 No relationship was found for any of the measures described when compared to step length  
464 symmetry. A fluid STS or STW is thought to be indicative of motor control (9); however, there is a  
465 lack of evidence for measures that can identify motor control during gait. Step length symmetry was  
466 chosen as a comparator in this study because of the potential to provide information regarding  
467 movement quality which cannot be discerned from walking speed. The lack of relationship between  
468 gait symmetry and walking speed (33)(34) further strengthens the idea that spatiotemporal symmetry  
469 measures different aspects of walking from those measured by velocity.

#### 470 **Implications of findings to the measurement of neuromuscular recovery after stroke**

471 Walking, STS and STW clearly have points of commonality. Both STS and STW involve forward  
472 lean of the trunk and bilateral lower limb extension to rise from a seated position to bipedal standing.  
473 Likewise, STW and walking involve transition of bodyweight between the supporting feet whilst  
474 moving body position in space. Consequently, there is an expectation of relationships between some  
475 elements of the three movement tasks and therefore some transferability of rehabilitation training  
476 benefit between the tasks. However, the results of this study indicate that, in a group of early stroke  
477 survivors there are: significant differences between STS and STW for movement fluidity

478 (smoothness, hesitation and coordination); only moderate relationships at best between walking  
479 speed and: movement fluidity during either STS or STW; duration of STS or STW and its phases and  
480 no relationship between symmetry (step length ratio) and the tasks of STS and STW. The different  
481 movement characteristics of the three tasks likely mean that measures of any one of these three tasks  
482 cannot be used to infer ability to perform either of the others. Likewise, it follows that rehabilitation  
483 needs to consider separate training of the three tasks after stroke.

484 Specific training of the separate tasks of STS, STW and walking is also indicated by knowledge of  
485 the muscle synergies (activation patterns of muscles used) that produce the movement required to  
486 undertake complex movement tasks (35–37). Muscle synergies have been described as the building  
487 blocks of complex movements and vary depending on the movement task in people who do not have  
488 a stroke lesion (35–37). Pertinent to the current study is that STS and walking involve the use of  
489 different muscle synergies (38,39) and presumably STW contains elements of both. Consequently,  
490 rehabilitation to restore pre-stroke body function, that identified in people without a stroke lesion, (2)  
491 should focus on the specific movement tasks required for independent living. Furthermore, measures  
492 to assess whether the pre-stroke body function is being restored should also be specific to the task  
493 being trained. The work presented here has expanded knowledge on the content and use of such  
494 measures- our measures of fluidity were directly informed by and expanded on previous valuable  
495 work on a Fluidity Index by Dion and colleagues (31). Where this previous Fluidity Index was based  
496 on CoM velocity in one direction, we have represented the complexity of the task in an attempt to  
497 identify areas that might be targeted by therapists (25) and applied our measures in this current work  
498 to evaluate important functional tasks in a large group of people in the early weeks after stroke.

499 Two messages are clear from this analysis: firstly, that assessment of movement after stroke is about  
500 more than just walking speed or even walking task performance. A range of functional tasks are  
501 required to gain a full understanding of recovery and no one task should predominate over another.  
502 Measuring seemingly similar tasks such as STS and STW is not superfluous as the differing nature  
503 and ultimate intention of the tasks makes each challenging in different ways. Secondly, mechanisms  
504 behind the assessment measures must be thoroughly considered and it is this that should determine  
505 the appropriate task and assessment

506

## 507 **Methodological Considerations**

508 Our study had several limitations which should be considered in the interpretation of the methods and  
509 results. The main limitation is that, whilst the intention was to make comparisons of the different  
510 functional tasks of STS, STW and walking there are not truly comparable measures available for the  
511 tasks. Every effort was made to ensure measures between STS and STW were as similar as possible,  
512 but the different natures of the tasks made complete transferability impossible. This particularly  
513 affected the comparison of smoothness between the tasks due to the different end point of each task.  
514 We also recognize that allowing participants to use one or both hands as they rose, if this was  
515 required for safety reasons led to some potentially slightly altered movement strategies, though this  
516 did enable pragmatic representation of the strategies adopted here in this clinically representative  
517 population. The other limitation to this study is the amount of lost data from the original SWIFT Cast  
518 Trial. These measures proved difficult to capture in a clinical population early after stroke, some  
519 participants were unable to carry out the tasks, some carried out the task but used walking aids or  
520 received assistance, which made their inclusion in this analysis impossible due to a lack of  
521 standardization. Marker visibility was restricted by stroke related postures and movement along with

522 the need to maintain a researcher close to the participant for safety. As a result, we were unable to  
 523 consistently collect COM data and had to instead use a single clavicle marker to reflect the  
 524 movement of the trunk. Finally, some data was lost due to unusual movement patterns which could  
 525 not be identified by the custom-made script. Many versions were written to try to account for every  
 526 eventuality but the variation in movement exhibited by stroke survivors could not be completely  
 527 expected and therefore it was not always possible to identify events using a script.

528 The methodological strengths of the study are that it used kinetic and kinematic data to explore  
 529 established measures during the functional tasks of STS, STW and walking. Importantly, these data  
 530 were collected from the same group of stroke survivors, at the same assessment, which enabled  
 531 investigation of how the ability to perform one functional task may or may not influence another. To  
 532 the best of our knowledge this is the first study to examine this. Although it was not possible to  
 533 include all the data collected in this study a sample size of forty-eight is relatively high in comparison  
 534 to many other biomechanical studies. This, coupled with the fact that participants were on average  
 535 just sixty-four days post-stroke and recruited from a clinical population, means that these data can  
 536 make a substantial contribution to knowledge about measures of assessment and rehabilitation  
 537 techniques early after stroke.

538

## 539 **Conclusion**

540 The main findings of this study are that: i) different movement intentions between STS and STW  
 541 create distinct biomechanical characteristics which can be identified using sensitive objective  
 542 measures of fluidity and movement phases but ii) despite findings of statistical significance there are  
 543 no strong relationships between the functional tasks of STS and STW with walking speed iii)  
 544 symmetry during walking, measured by step-length symmetry, shows no relationship to any  
 545 measures of fluidity or movement phases during STS and STW.

546

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674 **Tables**675 **Table 1.** Clinical characteristics of participants included in this analysis

<b>Total sample (n=48)</b>	
<b>PARTICIPANT DEMOGRAPHICS</b>	
<b>Gender = Male, n (%)</b>	28 (57.1)
<b>Age (years)*, Mean <math>\pm</math> SD</b>	64.67 $\pm$ 15.58
<b>CLINICAL CHARACTERISTICS</b>	
<b>Time since stroke (days)*, Mean <math>\pm</math> SD</b>	63.56 $\pm$ 27.55
<b>Type of stroke = Infarct, n (%)</b>	39 (81.25)
<b>Paretic side = Right, n (%)</b>	30 (62.5)
<b>BASELINE CLINICAL SCORES</b>	
<b>FAC (score/5) Mean <math>\pm</math> SD</b>	4.10 $\pm$ 0.63
<b>MRFMI (score/40) Mean <math>\pm</math> SD</b>	36.58 $\pm$ 3.94

676 \* Time at Outcome Assessment

677

678 **Table 2.** Comparison of fluidity and duration of movement phase variables between STS and STW  
679 (Mean (SD))

Fluidity Measure	STS			STW			t-test	
	n	Mean	(SD)	n	Mean	(SD)	Difference (SD)	p-value
<b>Smoothness (inflection count)</b>	48	55.28	6.63	48	68.43	11.48	13.13 (9.08, 17.21)	<b>&lt;0.001</b>

<b>Hesitation (temporal overlap, %)</b>	48	23.54	14.13	48	14.27	8.65	-9.27 (-14.29, -4.26)	<b>&lt;0.01</b>
<b>Coordination<sup>1</sup> (C1) Paretic (temporal overlap, %)</b>	20	7.38	5.49	34	15.39	12.99	-13.48 (-21.35, -5.60)	<b>&lt;0.01</b>
<b>Coordination<sup>1</sup> (C1) Non-Paretic (temporal overlap, %)</b>	21	7.53	4.33	38	15.36	11.17	-8.76 (-13.11, -4.42)	<b>&lt;0.01</b>
<b>Coordination<sup>2</sup> (C2) Paretic (temporal overlap, %)</b>	NA	NA	NA	30	-14.11	15.93	NA	NA
<b>Coordination<sup>2</sup> (C2) Non-Paretic (temporal overlap, %)</b>	NA	NA	NA	10	-14.44	17.02	NA	NA
<b>Movement phases</b>								
<b>Overall Time (s)</b>	47	3.27	0.85	48	3.23	2.00	-0.05 (-0.43, 0.53)	0.84
<b>Phase 1 Time (s)</b>	47	1.74	1.45	48	1.13	1.03	-0.61 (-0.36, -0.86)	<b>&lt;0.0001</b>
<b>Phase 2 Time (s)</b>	47	-0.14	0.80	48	-0.14	0.86	0.03 (-0.39, 0.33)	0.87
<b>Phase 3 Time (s)</b>	47	1.68	0.85	48	1.36	1.30	-0.36 (-0.03, 0.75)	0.07
<b>Phase 4 Time (s)</b>	NA	NA	NA	48	0.74	0.18	NA	NA

680

681 **Table 3.** Correlations between walking speed and measures of fluidity and duration of movement  
682 phases during STS and STW

Fluidity Measure	STS		STW	
	Correlation	p-value	Correlation	p-value

<b>Smoothness (inflection count)</b>	-0.34	<b>0.02</b>	0.42	<b>&lt;0.01</b>
<b>Hesitation (temporal overlap, %)</b>	0.19	0.19	-0.08	0.58
<b>Coordination<sup>1</sup> (C1) Paretic (temporal overlap, %)</b>	0.05	0.85	0.24	0.16
<b>Coordination<sup>1</sup> (C1) Non-Paretic (temporal overlap, %)</b>	0.23	0.32	0.36	<b>0.02</b>
<b>Coordination<sup>2</sup> (C2) Paretic (temporal overlap, %)</b>	NA	NA	-0.35	0.06
<b>Coordination<sup>2</sup> (C2) Non-Paretic (temporal overlap, %)</b>	NA	NA	-0.51	0.13
<b>Movement phases</b>				
<b>Overall Time (s)</b>	-0.41	<b>&lt;0.001</b>	-0.31	<b>0.03</b>
<b>Phase 1 Time (s)</b>	-0.42	<b>&lt;0.001</b>	-0.15	0.31
<b>Phase 2 Time (s)</b>	0.28	0.06	0.25	0.08
<b>Phase 3 Time (s)</b>	-0.37	<b>0.01</b>	-0.51	<b>&lt;0.001</b>
<b>Phase 4 Time (s)</b>	NA	NA	-0.28	<b>0.05</b>

683

684 **Table 4.** Correlations between step length ratio during walking and measures of fluidity and duration  
685 of movement phases during STS and STW

<b>Fluidity Measure</b>	<b>STS</b>		<b>STW</b>	
	<b>Correlation</b>	<b>p-value</b>	<b>Correlation</b>	<b>p-value</b>
<b>Smoothness (inflection count)</b>	-0.01	0.97	-0.04	0.79

<b>Hesitation (temporal overlap, %)</b>	-0.11	0.49	-0.25	0.10
<b>Coordination<sup>1</sup> (C1) Paretic (temporal overlap, %)</b>	0.03	0.89	-0.09	0.62
<b>Coordination<sup>1</sup> (C1) Non-Paretic (temporal overlap, %)</b>	0.05	0.82	-0.01	0.95
<b>Coordination<sup>2</sup> (C2) Paretic (temporal overlap, %)</b>	NA	NA	0.06	0.77
<b>Coordination<sup>2</sup> (C2) Non-Paretic (temporal overlap, %)</b>	NA	NA	-0.25	0.49
<b>Movement phases</b>				
<b>Overall Time (s)</b>	-0.06	0.72	-0.14	0.35
<b>Phase 1 Time (s)</b>	0.02	0.88	-0.18	0.25
<b>Phase 2 Time (s)</b>	-0.17	0.26	0.21	0.17
<b>Phase 3 Time (s)</b>	0.02	0.88	-0.27	0.07
<b>Phase 4 Time (s)</b>	NA	NA	-0.24	0.11

686

687 **Figure 1.** Flow chart of participant inclusion in this analysis

688

689 **Conflict of Interest**

690 The authors declare that the research was conducted in the absence of any commercial or financial  
691 relationships that could be construed as a potential conflict of interest.

692 **Author Contributions**

693 EC: conceptualization of this study, methodology, data collection, data processing, writing-original  
694 draft preparation, writing-reviewing and editing, approval of submitted version.

695 TS: methodology, script writing for data analysis, writing-reviewing, editing and approval of  
696 submitted version.

697 VP: conceptualization of this study, data collection, writing-original draft preparation, writing-  
698 reviewing, editing and supervision, approval of submitted version.

699 AC: data analysis, writing-reviewing and editing, approval of submitted version.

700 AK: data collection, data processing, writing-reviewing and editing, approval of submitted version.

701 PR: writing-reviewing and editing, approval of submitted version.

702 UU: data collection, data processing, writing-reviewing and editing, approval of submitted version.

703 JS: data collection, data processing, writing-reviewing, approval of submitted version.

704 NH: conceptualization of this study, methodology, data processing, writing-original draft preparation,  
705 writing-reviewing, editing and supervision, approval of submitted version.

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## 716 **Data Availability Statement**

## 717 **Ethics statement**

718 The SWIFT Cast trial received a favorable ethical approval from the National Research and Ethics  
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