Abstract:

Background: Turning is an integral component of independent mobility in which stroke survivors frequently fall. *Objective:* This study sought to measure the effects of competing cognitive demands on the stepping patterns of stroke survivors, compared to healthy age-match adults, during turning as a putative mechanism for falls. *Methods:* Walking and turning (90º) was assessed under single (walking and turning alone) and dual task (subtracting serial 3s while walking and turning) conditions using an electronic, pressure-sensitive walkway. Dependent measures were time to turn, variability in time to turn, step length, step width and single support time during three steps of the turn. Turning ability in single and dual task conditions was compared between stroke survivors (n= 17, mean ± SD: 59 ± 113 months post-stroke, 64 ± 10 years of age) and age-matched healthy counterparts (n = 15). *Results:* Both groups took longer, were more variable, tended to widen the second step and, crucially, *increased* single support time on the inside leg of the turn while turning and distracted. *Conclusions.* Increased single support time during turning may represent biomechanical mechanism, within stepping patterns of turning under distraction, for increased risk of falls for *both* stroke survivors and older adults.

Introduction

The ability to turn while walking, whether to avoid an obstacle or navigate corners, is an integral component of independent mobility. Turning accounts for as many as 45% of steps taken daily [1] and is a risky manoeuvre in which stroke survivors frequently fall [2]. Although falls while turning are more likely to be injurious than during other events [3] and stroke survivors' are at high risk of injury from falling [4], few studies have examined the mechanisms underlying falls during turning following stroke. Those that have, [5-7] showed that apart from delayed initiation of turns, longer time to turn and more steps, overall movement patterns were relatively unaffected, even in participants with a history of falls [5]. One clue to a possible mechanism of falling during turning lay in the observation that delayed initiation of turns was alleviated with external visual cues [6]. It was hypothesized that external cues may have served to focus attention on the required turn.

It has been proposed that control of turning may be more cognitively demanding than walking in a straight line [8-10] and that older adults and stroke survivors have limited cognitive capacity [11]. It has therefore been hypothesized [5] that falls during turning after stroke may not be due to an inability to produce movement patterns necessary to achieve a turn but due to cognitive-motor interference [12] (an inappropriate utilization of limited cognitive resources) which causes an exacerbation of motor impairments when additional cognitive demands are made.

Aims and research questions:

The proposed study aims to compare spatio-temporal stepping parameters of healthy older adults and stroke survivors while turning under single and dual task conditions. Stride adjustments have been shown to be an important contributor to the forces driving turning in healthy young adults [13]. As a result we sought to explore the effects of distraction specifically on stepping patterns as indicators of turning performance.

Methods:

Participants:

A convenience sample of stroke survivors was identified from community stroke support groups in Greater Manchester and participants of the University's previous studies who agreed to be contacted. We included stroke survivors, irrespective of time since stroke, who had completed their rehabilitation and were able to walk 10m and turn without assistance from walking aids or another person. Participants were excluded if they had language problems which prevented reliable participation in the spoken subtraction task.

Age-matched healthy volunteers aged over 50 years (the older adult group) were recruited from University staff and participants of previous studies. Exclusion criteria for both stroke and older-adult groups were any condition (apart from stroke) that limited mobility. The study was approved by the University Ethics Committee and all participants provided written informed consent.

Sample size Calculation:

A sample size calculation based on data from the first four stroke survivors indicated that a sample of 15 would detect differences in single support duration while turning under single and dual task conditions ($p<0.05$, power = 0.950). Single support time was chosen as the basis for the power calculation as it is related to turning capacity following stroke [7].

Procedures:

Participants walked along a (3.7m) pressure sensitive mat (GAITRite) and turned 90° to exit the mat to either the left or right. Start and end points were marked on the floor with tape 1m from either end of the mat (to exclude acceleration and deceleration phases on the mat) and to mark the turning point to exit walkway (see figure 1 A). As participants walked along the GAITrite, pressure sensors are activated during stance and deactivated during swing phase of each limb, providing spatial and temporal parameters of walking with demonstrated validity and reliability [14]. Participants walked and turned (under single task conditions) and while subtracting serial 3's from a random number in the 100s, aloud (dual task condition). This dual task was chosen because we sought a task that was sufficiently challenging to show differences in turning under distractions to attention [11], should they exist and verbal subtraction has been shown [15] to interrupt gait more than other cognitive tasks.

Six trials under each condition (single or dual task) and turning to each direction (to the paretic or non-paretic side) were performed; 24 walking trials in total. The order of trials was randomized to balance and minimize effects of learning and fatigue. Participants walked at their self-selected pace with rest breaks as needed and after every 6 trials.

Measures:

Gait speed, step length, stride time and stride time variability were taken during the straight portion of the walking trial [16]. These measures were selected because of their known sensitivity to dual-task interference after stroke [17]. Specifically, low stride-to-stride variability reflects automatic processes that require minimal attention and is associated with efficient gait control and gait safety [18]. As participants may use a different number of steps to achieve a turn, mean and standard deviations of spatial and temporal parameters were compared on a step by step basis over the last 2-3 steps before the participant left the mat. These turning steps were identified as Step 1 (penultimate) and Step 3 (ultimate) steps of the foot ipsilateral to the turn (figure 1 A). Step 2 was the last step of the foot contralateral to the turn.

Gait parameters were calculated by GaitRite software including; step width; step length (relative to line of progression in accordance with recommendations on measuring spatial stepping parameters in non-linear walking [19] (figure 1 A) and single support time. Time taken to turn was calculated as the difference (in time) between initial contact of Step 1 and the last contact of Step 3 (if registered) or Step 2 (if step 3 was already clear of the walkway). Variability of time to turn was calculated as the standard deviation, across trials, of the time to turn.

Mean values of step parameters were only taken when data for a given step was present for a minimum of three trials in each condition. Therefore, if participants had already exited the walkway by Step 3 on more than three trials (i.e. they carried out the turn in two steps) then data for Step 3 would not be available for analysis.

Performance on the cognitive task was measured as the number of correct responses (normalized to the time taken) while completing the walk and turn. The scores on the serial subtraction task were normalized as those taking longer to walk and turn would have more time to provide answers during serial subtraction.

Measures to describe the stroke participants' impairment and activity limitations were also taken: The Dual Task Telephone Search (sustained attention) and Elevator counting with distraction (attentional switching) subtests from the Test of Everyday Attention (TEA) [20] assessed attentional abilities; the Timed Up and Go (TUG) [21] assessed mobility and the Berg Balance Scale (BBS) [22] assessed balance.

Statistical Analyses:

Mixed analysis of variance for repeated measures was used to determine differences in spatial and temporal gait measures *separately* for the straight walking portion of the trial and during each of the 3 turning steps. The 'between subject factor' was group (stroke vs older-adults) and the 'within subject factors' were; task condition (single vs. dual task) and direction of turn (to the paretic vs non-paretic side). The within subject factor of direction was not used for straight walking analyses. For purposes of comparison, the left side was assigned as paretic for older-adults. A p value of < 0.05 was used for statistical significance. If the overall F test was significant, inspection of means were used to identify where significant difference(s) lay. The software package SPSS (version 20) was used.

Results:

Participants

Seventeen stroke survivors participated; the group had a mean (± SD) age of 64 (±10) years and a mean time since stroke of 59 months (±113), three were female and 6 right hemiplegic. Further details are found in Table 1.

Using the walking speed thresholds described in the Walking Handicap Scale [23]; four participants were not functional walkers (in everyday life) (speed <0.4ms); six were mobile indoors (walking speed 0.4-0.6 m/s) and five were limited outdoor walkers (speed = 0.6-0.8 m/s). None had unlimited outdoor mobility (>0.8 m/s). Using 14s as the threshold to indicate a high risk of falls on the TUG test[24]; four participants had a high risk of falls; two of whom reported falling in the last year. None of the stroke survivors scored less than 45 on the BBS, which is a proposed threshold [25] of increased falls risk post-stroke. Five stroke survivors had 'abnormal' scores (<5th percentile of normative scores) on subtests of the Test of Everyday Attention (TEA). Six participants were unable to perform one or both of the TEA tests as they were without reading glasses or had hearing impairments.

The fifteen healthy older-adults participants had a mean age of 68.5 (range 55-82) years, mean self-selected walking speed of 0.65 m/s (range 0.48-0.77) and TUG time of 10.05 seconds (range = 7.14-14.66 sec). All lived independently in the community and none reported falling in the past year.

INSERT TABLE 1

Engagement with the Dual Task

There were no statistical differences in the number of correct responses during serial subtraction between older-adults and stroke survivors (mean (SD) = 0.76 (0.23) and 0.63 (0.30) correct responses per second, respectively). Similarly, there were no statistical differences in performance on the cognitive task according to the direction of the turn (to the paretic or non-paretic side).

Effects of Dual Task on Straight Walking (Figure 1 B).

A main effect of task was found indicating speed was slower under dual task conditions than single task ($p<0.001$, $f(1,27) = 43.52$). A significant interaction between task and group ($p<0.001$, $f(1,27) = 13.04$) indicated stroke survivors walked slower than older-adults under single task conditions but showed no difference between groups under dual task conditions (see figure 1 B). A main effect of task on stride time indicated stride time increased ($p<0.001$, $f(1,27)=36.00$) under dual task conditions. A significant interaction effect between task and group ($p<0.001$, $f(1,27)=14.29$) indicated that older-adults have shorter stride time in single task conditions than stroke survivors and in comparison to dual task conditions (see figure 1 B). A main effect of task on variability of stride time indicates variability greater ($p=0.013$, $f(1,27)=6.99$) under dual than single task conditions for both stroke survivors and older-adults (mean (SD) = 0.105s (0.068) and 0.067s (0.063) respectively).

INSERT FIGURE 1

Stepping Patterns While Turning Under Single Task Conditions

Details of values for each parameter and the comparisons between stroke survivors and older-adults, single and dual tasks while turning are shown in Table 2. There was no difference in the time to turn between older-adults and stroke survivors but a main effect of turn direction indicated turns to the non-paretic side took longer (mean = (2.08s (SD 0.43)) than the paretic (2.02s, (0.42); p =0.029, f(1,27) = 5.32) in both groups. Variability of time to turn showed no differences between groups or directions of turn. Stroke survivors used shorter, narrower steps at steps 1 and 2 during the turn and had shorter single support time than older-adults (see table 2).

INSERT TABLE 2

Stepping patterns while turning under dual task compared to single task conditions (Table 2, Figure 1 C)

The data for comparisons of turning under single and dual tasks conditions are detailed in Table 2. Main effects of task indicate both stroke survivors and older-adults turned more slowly under dual than single task conditions (p =0.013, f(1,27) = 7.42). Variability of time to turn was higher during dual than single task conditions for both groups (p =0.043, f(1,27) = 4.53).

There were no significant differences in step length or width at steps 1 and 3 of the turn between single and dual task conditions, but there was a trend for step 2 to be wider under dual task conditions (see Table 2). Single support phase was longer during dual than single task conditions for both stroke survivors and older-adults ($p = 0.001$, $f(1,29)=13.08$), and older-adults had a longer single stance phase than stroke survivors under dual task conditions (Figure 1 C).

Discussion

The aim of this study was to determine the effects of increased cognitive demands on stepping patterns while turning in stroke survivors and age-matched healthy older-adults. We sought to explore the effects of cognitive-motor interference on the stepping patterns of turning in order to identify possible biomechanical mechanisms for falls while turning. We hypothesized that stroke-related movement impairments during turning may be induced or exacerbated by ineffective utilisation of cognitive resources (distraction). Overall, our findings support this hypothesis. Results indicate both groups took longer, were more variable, tended to widen the second step and, crucially, *increased* single support time on the leg ipsilateral to the turn when distracted. These findings confirm the idea that control of turning requires cognitive resources [8,9] and importantly identifies changes to stepping patterns which may underlie increased falls risk during turning in older-adults and stroke survivors.

In contrast to improved stability when gait speed is reduced in response to distraction during straight walking [11], the result of slower turning is that longer is spent in single support phase. As one turns, the swing leg on the outside of the turn (step 2) must travel further around the arc of the turn than the stance leg (step 1) on the inside of the curve [13]. The slower the turn, the longer it will take the swinging leg to complete the arc of the turn (unless a greater number of steps are taken within the turn). Consequently single support time on the contra-lateral/ inside limb (step 1) is increased. Single support is an inherently unstable phase of gait as the base of support is at its smallest and longer time in this phase is correlated with increased trunk leaning to the inside of the turn [13]. Thus our finding that both stroke survivors and older-adults tend to spend longer in single stance while turning under cognitively demanding conditions is a likely contributor to the high incidence of falls observed during this activity. Further, these findings corroborate previous suggestions that turning ability is linked to single support duration in stroke survivors [7].

Turning may be particularly challenging for stroke patients due to the fact that the maneouvre imposes step asymmetries on an already asymmetric walking pattern and hence turns to a particular direction may be more difficult depending on the side of underlying asymmetry. However, our results show few differences in stepping patterns according to turn direction; a finding that has also been reported in previous studies [5-7]. Given that the direction and extent of step asymmetry has been shown to vary according to age, motor recovery level and walking speed [26-28], systematic differences in stepping patterns according to the direction of the turn may be obscured by the complexity of relationships between these variables.

This is the first report of turning under dual task conditions and so opportunities for like-for-like comparisons with other studies are limited. However, there are similarities with reports of other aspects of the effects of cognitive demands on walking and turning after stroke, that support the validity of our findings. Although our participants tended to walk more slowly [5-7] the movement patterns described while turning under single task conditions are similar; stroke survivors used wider, shorter steps than age-matched counterparts but demonstrated similar speed and variability [5-7].

Further, our results of the effect of dual-task conditions on straight walking (increased stride time and variability in *both* groups) are also in-line with previous reports [16]. Given that dual-task conditions are known to degrade walking performance even in healthy elderly [11,15] and that turning is a major contributor to falls in the elderly [29], it is not surprising that older-adults also show difficulties in dual-task turning. It has been suggested that cognitive and motor conflicts are greater with more complex locomotor tasks and/or if the gait pattern is already impaired [10,15] so it may be that the dual-task turning was challenging for both groups. Indeed, fewer stroke survivors showed evidence of impaired attention than previously reported [30] and it may be that older adults had undetected cognitive/mobility deficits equalizing dual-task decrements across groups in this study.

Limitations:

Like most dual-task studies [16], this study is limited in ecological validity as testing was conducted in a controlled environment and we do not know how the movement patterns measured under such conditions relate to 'real life'. It is possible that the impact of dual tasks on turning might be even greater in a community environment. Further, participants of this study were relatively high functioning; as they needed to be sufficiently mobile to take part in the protocol, and so findings may not be generalizeable to those with even more severe limitations. But, again, one would predict that the impact of dual tasks on turning in more severely limited participants could be even greater.

We have taken a cross-sectional approach to the investigation; more research is needed to investigate how movement patterns during turning may be associated with falls incidence/risk, and how turning ability changes over the course of recovery following stroke and with increasing frailty in ageing. It may be that stroke survivors and older-adults who recover/maintain unlimited community ambulation would not exhibit the same dual task decrements to turning as we have seen here. It remains to be seen if less risky compensatory strategies for turning could be identified and taught, or if dual task training can be effective either by way of increasing automaticity of the motor task, or improving the capacity of cognitive resources (or both).

Conclusions:

Importantly, this is the first study to identify a vulnerability to falling in the biomechanics of turning in healthy older-adults and following stroke. Surprisingly, we found that stroke survivors and older-adults demonstrated similar dual task decrements to turning. These findings highlight the importance of considering the interaction between cognitive processes and walking in the research and treatment of *all* populations at risk of falling. Further, research and treatment should extend to advanced gait skills, such as turning, which are necessary for safe independent community ambulation.

Conflict of interest statement: The authors declare no conflicts of interest.

Figure Legends

Table 1: Participant information. Mean self-selected walking speed = SSWS. BBS = Berg Balance Scale; TUG = Timed Up & Go test; M = male; f = female. Scores for the TEA are the mean score and corresponding percentiles for the participants' age group. TEA scores with an * are those classified as abnormal i.e. below the 5^{th} percentile.

Table 2: Summary of turning performance between groups and task conditions. Means, standard deviations and statistics are reported for main effect comparisons between groups and task conditions. Significant interaction effects between task and group were only found for single support duration and this is discussed within the text with means presented in Figure 1 C.

Figure 1 A: Schematic of methods. Paretic /Left footprints are depicted with dashed outlines and non-paretic with solid outlines. Exit walkways and starting lines are delineated by tape on the floor. Line AC is the line of progression from heel centre of two consecutive footfalls of the same foot. Line segment DB is perpendicular to the line of progression. Line segment AB is step length of step 2, line segment BC is step length of step 3. Step width is from midpoint of current footprint to midpoint of previous footprint on the opposite foot. To avoid computational mistakes, step length and width were calculated as the distances between successive footfalls relative to the change in direction at each stride in accordance with recommendations by Huxham et al, (2006).

Figure 1 B: **Effects of Dual Task on Straight Walking**. Bottom left panel shows stride time (s) and walking speed (m/s) *during straight walking* in older adults and stroke survivors. Single task conditions are shown in dark filled bars and dual task in lightly filled bars. Error bars represent standard error. Significant differences are denoted by parentheses.

Figure 1 C: **Effects of Dual Task on Turning**. Upper most panel illustrates time taken to turn (s). Bars represent mean turn time (s). The middle panel illustrates mean variability of time to turn (s). Lower right panel illustrates mean single support phase (s) during step 1 of the turn. Bars are for Older Adults and Stroke, during single task (dark grey) and dual task conditions (light grey). Error bars represent standard error. Significant differences are denoted by parentheses.

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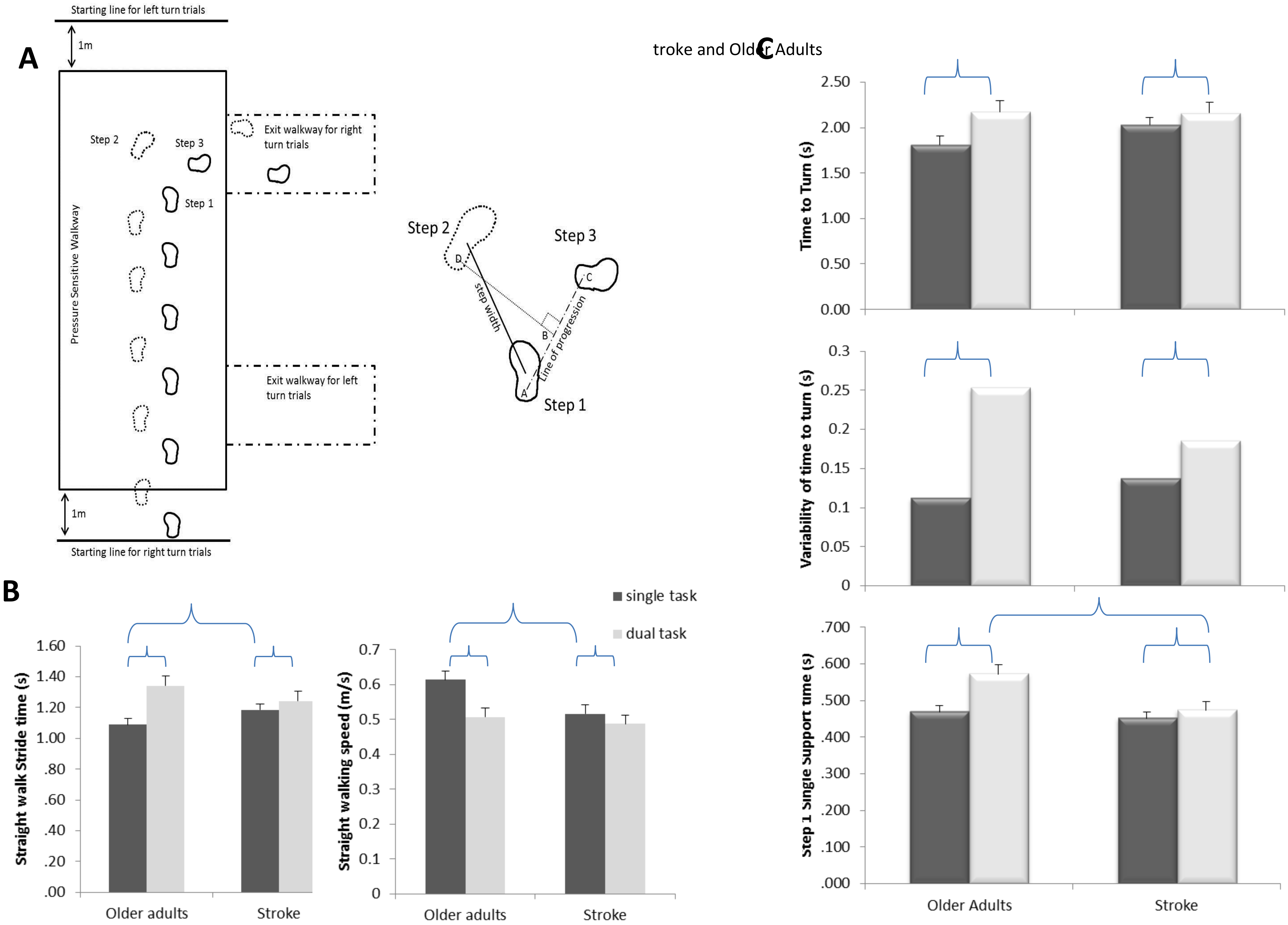
participant	gender	Age (years)	time since stroke (mos)	paretic side	SSWS (m/s)	TUG (s)	BBS	TEA-sustained attention elevator with distraction	TEA- divide attention ability telephone with distraction	Falls
01	m	71	24	left	0.31	16.3	49	Unable to complete; hearing impairment		0
02	m	50	32	left	0.61	7.7	56	7 (12.2-20.2%)	6 (6.7-12.2%)	0
03	m	65	13	left	0.66	10.1	53	5 (3.3-6.7%)*	9 (30.9-43.3%)	0
04	m	79	22	left	0.38	15.4	53	7 (12.2-20.2%)	12 (69.2-79.8%)	2
05	m	53	17	right	0.58	9.6	56	8 (20.2-30.9%)	7 (12.2-20.2%)	0
06	m	69	3	left	0.49	11.4	56	6 (6.7-12.2%)	7 (12.2-20.2%)	0
07	f	65	12	left	0.4	8.5	56	5 (3.3-6.7%)*	Unable to complete; no reading glasses	0
08	m	59	96	right	0.53	12.6	49	Unable to complete; hearing impairment		0
09	m	59	16	left	0.67	8.2	53	8 (20.2-30.9%)	14 (87.8-93.3%)	0
10	m	60	21	left	0.38	9.94	55	Unable to complete; hearing impairment		0
11	f	79	24	left	0.64	10.6	52	11 (56.6-69.2%)	5 (3.3-6.7%)*	0
12	m	78	12	right	0.44	10.3	55	11 (56.6-69.2%)	Unable to complete; no reading glasses	0
13	f	51	127	left	0.48	12	52	7 (12.2-20.2%)	8 (20.2-30.9%)	0
14	m	71	11	left	0.66	8.7	56	6 (6.7-12.2%)	10 (43.4-56.6%)	0
15	m	61	34	right	0.44	16	48	6 (6.7-12.2%)	3 (0.6-1.5%)*	0
16	m	52	65	left	0.23	19.5	52	Unable to complete; hearing impairment		1
17	m	66	480	right	0.52	11.9	52	3 (6.7-12.2%)*	5 (3.3-6.7%)*	1
Means (SD)	**3 female**	**64 (9.6)**	**59.4 (113.3)**	**6 right**	**0.49 (0.13)**	**11.7 (3.3)**	**53.1 (2.6)**	**7 (2.1) [12-20%ile]**	**8 (3.2) [20.2-30.9%]**	**3 fallers**

Table 1

		OA	Stroke	Comparison between stroke survivors and older adults	Dual task condition	Single task condition	Comparison between single and dual task conditions
Mean time to turn (SD) seconds		1.99s (0.39)	2.12 (0.45)	no significant difference	2.2 (0.46)	1.92 (0.34)	p < 0.001, f(1,27)= 33.72
Mean variability of time to turn (SD) seconds		0.18 (0.09)	0.16 (0.08)	no significant difference	0.22 (0.10)	0.12 (0.06)	p<0.001, f(1,27) = 18.84
Step 1 Means (SD)	**Step-Width (cm)**	69.65 (8.53)	56.44 (11.08)	p=0.001, f(1,29) =14.48	62.61 (9.41)	63.48 (10.36)	no significant difference
	Step-Length (cm)	64.75 (14.19)	54.85 (13.57)	p=0.001, f(1,29)=13.96	60.26 (12.63)	61.43 (12.03)	no significant difference
	Single Support (s)	0.52 (0.12)	0.46 (0.09)	p= 0.046, f(1,29)= 4.36	0.52 (0.10)	0.46 (0.07)	p<0.001, f(1,29) = 30.73
Step 2 Means (SD)	**Step-Width (cm)**	61.73 (13.69)	54.56 (10.75)	p=0.007, f(1,29)=8.43	58.87 (13.11)	56.66 (12.37)	p= 0.51, f(1,29) = 4.13
	Step-Length (cm)	59.48 (13.99)	52.42 (11.29)	p=0.005, f(1,29) = 9.39	57.24 (11.69)	56.04 (10.91)	no significant difference
Step 3 Means (SD)	**Step-Width (cm)**	51.81 (13.35)	46.01 (11.06)	no significant difference	50.07 (9.81)	49.4 (12.53)	no significant difference
	Step-Length (cm)	42.64 (20.79)	31.76 (17.67)	no significant difference	39.6 (14.1)	38.3 (19.58)	no significant difference

Table 2


A
Starting line for left turn trials
1m
Pressure Sensitive Walkway
Step 2
Step 3
Step 1
Exit walkway for right turn trials
Exit walkway for left turn trials
1m
Starting line for right turn trials
Step 2
Step 3
Step 1
D
C
B
A
step width
Line of progression
B
single task
dual task
Straight walk Stride time (s)
1.60
1.40
1.20
1.00
.80
.60
.40
.20
.00
Older adults
Stroke
Straight walking speed (m/s)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Older adults
Stroke
troke and Older Adults
C
Time to Turn (s)
2.50
2.00
1.50
1.00
0.50
0.00
Variability of time to turn (s)
0.3
0.25
0.2
0.15
0.1
0.05
0
Step 1 Single Support time (s)
.700
.600
.500
.400
.300
.200
.100
.000
Older Adults
Stroke