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Atypical anticipatory postural adjustments during gait initiation among individuals with subacute stroke

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Abstract

Anticipatory postural adjustments, executed prior to gait initiation, help preserve lateral stability when stepping. Atypical patterns of anticipatory activity prior to gait initiation may occur in individuals with unilateral impairment (e.g., stroke). This study aimed to determine the prevalence, correlates, and consequences of atypical anticipatory postural adjustment patterns prior to gait initiation in a sub-acute stroke population. Forty independently-ambulatory individuals with sub-acute stroke stood on two force plates and initiated gait at a self-selected speed. Medio-lateral centre of pressure displacement was calculated and used to define anticipatory postural adjustments (shift in medio-lateral centre of pressure >10 mm from baseline). Stroke severity, motor recovery, and functional balance and mobility status were also obtained. Three patterns were identified: single (typical), absent (atypical), and multiple (atypical) anticipatory postural adjustments. Thirty-five percent of trials had atypical anticipatory postural adjustments (absent and multiple). Frequency of absent anticipatory postural adjustments was negatively correlated with walking speed. Multiple anticipatory postural adjustments were more prevalent when leading with the non-paretic than the paretic limb. Trials with multiple anticipatory postural adjustments had longer duration of anticipatory postural adjustment and time to foot-off, and shorter unloading time than trials with single anticipatory postural adjustments. A high prevalence of atypical anticipatory control prior to gait initiation was found in individuals with stroke. Temporal differences were identified with multiple anticipatory postural adjustments, indicating altered gait initiation. These findings provide insight into postural control during gait initiation in individuals with sub-acute stroke, and may inform interventions to improve ambulation in this population.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest related to this research.

Keywords

Stroke; Gait; Gait initiation; Rehabilitation

INTRODUCTION

When walking, execution of the first step is crucial as it requires transitioning from a large base of support (two limbs) to a small base of support (one limb).[1] This transition challenges lateral stability,[1] requiring precise coordination between descending motor commands to maintain stability.[2] In the early phase of gait initiation, the swing limb pushes against the ground to accelerate the centre of mass (COM) forward and laterally over the stance foot.[2–4] The lateral component of the associated centre of pressure (COP) excursion shifts toward the swing limb to generate the necessary force to move the COM towards the stance limb. This shift in COP and associated movement of the COM prior to limb unloading is known as an anticipatory postural adjustment (APA), and functions to minimize lateral instability created when the swing foot is lifted from the ground.[5,6] This behaviour is well documented in both healthy young and older adults.[7,8]

Past work has identified differences in APA patterns post-stroke, depending on the limb (paretic or non-paretic) used to initiate stepping.[9] In clinical assessments, we have observed atypical APA patterns during gait initiation among individuals with sub-acute stroke, specifically absent APAs (i.e., no significant shift in ML COP towards the swing limb) and multiple APAs (i.e., perseverating COP pattern). Regarding the former, individuals with stroke generally stand asymmetrically, with more weight on the non-paretic than the paretic limb.[10] Given that the stance limb is pre-loaded, an APA may not be necessary to shift the patient's COM toward the stance limb when initiating gait with the paretic limb. Patchay and Gahéry[11] found that asymmetrical loading affected COP patterns prior to gait initiation in healthy adults, such that increased loading on the stance limb resulted in a reduced ML COP shift prior to gait initiation. Furthermore, participants with hemiparesis tend to shift their body weight towards their non-paretic limb before stepping, as it is stronger and more capable of handling the increased weight.[12] This tendency may contribute to the ML COP being located closer to the participant's non-paretic limb during the stance phase, thereby requiring a smaller amplitude ML COP shift during gait initiation in the paretic limb compared to the non-paretic limb.[12]

The occurrence of atypical APA patterns has been documented in other neurologically-impaired populations, such as individuals with Parkinson's disease.[4,6,13] Multiple APAs have been documented in people with Parkinson's disease during gait initiation and when stepping in response to an unexpected postural perturbation.[13,14] The authors speculated that multiple APAs represented deficits related to planning motor actions or difficulty in execution. Previous research has observed large oscillations of ML COP prior to gait initiation with the non-paretic limb among individuals with stroke.[12] These oscillations may be due to weakness in the paretic limb and its inability to properly support the body during its stance phase.[12] However, this study did not characterize the identified oscillations into different categories of APAs, and we are unaware of any study to describe atypical APAs post-stroke.

This study aimed to determine the prevalence, clinical correlates, and consequences of atypical APAs (absent and multiple APAs) post-stroke when initiating gait with the paretic and non-paretic limbs. Regarding absent APAs, we hypothesize that: there will be a higher frequency of absent APAs among individuals with greater motor impairment when initiating with the paretic limb than the non-paretic limb; frequency of absent APAs will be negatively correlated with self-selected walking speed; absent APA trials will be characterized by high weight-bearing asymmetry prior to the trial, with more weight on the stance than the swing limb; and trials with absent APAs will have shorter swing durations of the first step, and greater displacement of the COM from the stance limb at foot-off, compared to single APA trials. With respect to multiple APA trials, we hypothesize that there will be a higher frequency of multiple APAs among individuals with greater motor impairment when initiating with the non-paretic limb than the paretic limb; and trials with multiple APAs will have a delayed time to foot-off compared to trials with single APAs.

METHODS

Participants

This study involved retrospective review of data from 40 individuals with sub-acute stroke attending in-patient rehabilitation (Table 1). All patients were able to stand independently for 30 seconds, initiate gait without using a gait aid, follow verbal instructions, and provide consent for participation in the balance assessment as part of routine clinical care. Patients were excluded if they presented with bilaterally affected limbs, previous lower limb surgery or injuries, or had any other neurological, musculoskeletal, or psychiatric conditions that would affect balance control. This analysis was approved by the institution’s Research Ethics Board on the basis of a retrospective chart review.

The following information was obtained from patients’ medical charts: age, sex, height, weight, stroke date, location and type, Chedoke-McMaster Stroke Assessment leg and foot scores (CMSA; a measure of motor recovery[15]), the Clinical Outcome Variables Scale (a measure of functional mobility status[16]), the Berg Balance Scale (a measure of functional balance[17]), and self-selected walking speed.

Protocol

Participants completed six trials of gait initiation during the balance and mobility assessment conducted as part of routine clinical care. Participants stood in a comfortable posture with their arms resting at their sides and feet in a standardized foot position (heel centres 17 cm apart with 14° between the long axes of the feet[18]) and each foot on a separate force plate (25 × 50 cm; Advanced Mechanical Technology, Inc., Watertown, USA). A third force plate (46 × 51 cm; Advanced Mechanical Technology, Inc., Watertown, USA) was located in front of participants to capture contact of the first step. Participants were instructed to step with a specific limb prior to the trial, and to initiate forward gait at a self-selected speed when ready after a verbal “go” signal. Participants were told to stop once they reached the end of

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the platform, which was mounted even with the force plates and extended 80 cm beyond the end of the final force plate, and allowed for approximately 3–5 steps forward. A physiotherapist stood close by for safety in the event the participant should need physical assistance during the trial. Rest breaks were provided as needed. Each participant completed six trials: three consecutive trials leading with each limb. If participants stepped with the wrong limb, hesitated due to a misunderstanding of the instructions, or required physical assistance from the physiotherapist, the trial was repeated.

The force plates recorded three-dimensional ground reaction forces and moments during the trials. Force plate data were collected for 15 s at 256 Hz and low-pass filtered using a zero phase-lag Butterworth filter at 10 Hz prior to analysis. Net ML centre of pressure (COP) under both limbs combined was calculated prior to foot-off. Temporal and spatial characteristics of the APAs were determined from a custom threshold-based algorithm implemented with MATLAB (Mathworks, Inc., Massachusetts, USA), determined from the ML displacement of the net COP recorded beneath both feet (Figure 1). The COM position in the transverse plane was estimated by double integrating the ML shear force divided by participants' body weight.[19] Average ML COP and COM were calculated for 250 ms prior to foot-off time in order to establish a baseline value for both signals. Visual inspection of time series data indicated that ML COP and COM were relatively stable for this time period for all trials. Table 2 provides specific outcome measures and their definitions.

Three types of APA patterns were identified: single APA, absent APA, or multiple APA (Figure 1). If there was no shift greater than 10 mm from baseline ML COP prior to foot-off, the trial was classified as an absent APA trial.[4] A multiple APA occurred if the subject did not lift a foot off the ground after the initial APA and exhibited additional shifts in ML COP that exceeded the baseline by ±10 mm.[13] Single APAs were considered typical APAs, while atypical APAs were considered to trials without an APA (absent) or with multiple APAs.

Analysis

Frequency of multiple and absent APAs was compared between trials leading with the paretic and non-paretic limbs using chi-square tests. Spearman's correlation was used to correlate CMSA leg and foot scores and frequency of multiple and absent APAs for trials leading with the non-paretic and paretic limbs. Outcome measures specific to APA characteristics were rank-transformed and compared. We compared dependent variables within participants who showed both APA types (single APAs versus absent APAs and single APAs versus multiple APAs) using one-way repeated measures analyses of variance (ANOVA). One-way ANOVA was also used to compare dependent variables between groups of participants (i.e., comparing all trials for participants who showed only typical APAs with absent/multiple APA trials for those participants who showed some absent/multiple APAs). The dependent variables were: weight-bearing asymmetry, initial COM position, COM position at foot-off, change in COM position, unloading time, and swing duration (single versus absent APA analyses); and weight-bearing asymmetry, APA duration, unloading time, and total time to foot-off (single versus multiple APA analyses). Alpha was set at $p<0.05$ and adjusted using the Holm-Bonferroni method.[20]

RESULTS

Overall, 35% of trials (84/240) had atypical APA patterns. Atypical APAs were observed in at least one trial for 31 participants (78%); 13 participants had multiple and single APAs, 9 participants had absent and single APAs, 1 participant had multiple and absent APAs, and 8 participants had all three APA patterns. No participant had only absent APAs or only multiple APAs.

Absent APAs

The frequencies of absent APAs when initiating gait with the paretic limb (21/120 trials; 17.5%) and non-paretic limb (17/120 trials; 14.2%) did not differ significantly (p=0.48). When stepping with the non-paretic limb, the frequency of absent APAs was significantly negatively correlated with CMSA foot scores (r=−0.48; p=0.0018; Table 3). Frequency of absent APAs was significantly negatively correlated with self-selected walking speed (r= −0.53, p=0.0010; Figure 2). For the between-participants comparisons, unloading time for absent APA trials was almost twice that of single APA trials, and swing time for absent APA trials was approximately 100 ms shorter than that of single APA trials; however, these differences were not statistically significant after adjusting for multiple comparisons (p-values>0.017). There were no other statistically-significant differences either within or between participants (p-values>0.43; Table 4).

Multiple APAs

Multiple APAs were significantly more prevalent when leading with the non-paretic limb (33/120; 27.5%) compared to leading with the paretic limb (13/120 trials; 10.8%; p=0.001). There were no significant correlations between CMSA scores and frequency of multiple APAs (p-values>0.077; Table 3). Multiple APA trials had a significantly longer average APA duration (p<0.0001) and longer total time to foot-off (p<0.0001) than single APA trials, both between- and within-participants (Table 4). Unloading time was also significantly lower for multiple APA trials compared to single APA trials when compared within participants (p=0.0090).

DISCUSSION

This study reports on the prevalence, clinical correlates, and consequences of atypical APAs (i.e., absent or multiple APAs) prior to gait initiation among individuals with sub-acute stroke. Overall, 35% of all trials had atypical APAs and most participants had at least one trial with an atypical APA.

Absent APAs

For the purpose of this study, absent APA trials were classified as atypical APAs. However, walking speed influences the size of ML COP shifts prior to foot-off.[21] We found that absent APAs were more prevalent among individuals who walked slowly. Therefore, it is possible that some of the absent APA trials may have resulted from the slow walking speed if the ML COP shift did not reach the threshold to be considered an APA, as opposed to a trial in which there was truly no APA. Slow walking speeds may also, at least partially, explain the significant correlation between frequency of absent APAs and motor impairment.

There were no statistically-significant differences in characteristics of the first step either within- or between-participants. However, there was a trend for longer unloading times (260 ms greater) and shorter swing times (100 ms) during the absent APA trials. Potentially, the longer unloading times may be due to insufficient strength or selective motor control (or a combination thereof) to shift the COM towards the non-paretic limb when trials were initiated with the paretic limb. During trials in which the non-paretic limb was used to initiate gait, the longer unloading times may result from participants shifting the COM towards the paretic limb in a slower and well-controlled manner. The shorter swing times potentially indicated that participants were unstable during swing as a result of the absent APA and shortened swing time in order to quickly establish double support.

The lack of statistical significance between outcome measures from the single APA and absent APA trials in the present study may have been due, at least in part, to the high variability in some of the APA outcome measures. Generally, there is high inter-individual variability in kinematic, kinetic, and muscle activation profiles among individuals with stroke,[22,23] and therefore the large standard deviations identified for some of the outcome measures are to be expected for this population. Given that the individuals in the present study were in the sub-acute stages of stroke recovery, variability may have been further increased due to the large changes in motor recovery occurring in the weeks after stroke.[24,25] Furthermore, participants did not use their usual gait aid during the testing, which may have resulted in an increased number of atypical APAs. Only trials without a gait aid were included in the present analysis due to complications with the calculation of COP when a gait aid is present. For some participants, the gait initiation tests may have been their first attempt to ambulate without a gait aid since their strokes, which also may have introduced additional variability into the results.

Multiple APAs

The data supported our hypothesis that a higher frequency of multiple APAs would be observed when initiating with the non-paretic limb relative to the paretic limb. Similar to our findings, previous research has observed large oscillations of ML COP prior to gait initiation (similar to our definition of multiple APAs) with the non-paretic limb among individuals with stroke, but did not specifically identify if these oscillations fit the criteria to be APAs (e.g., if the COP oscillations passed the ±10 mm threshold).[12] The authors concluded that these oscillations were due to weakness in the paretic limb and its inability to provide sufficient support to the body during its stance phase.[12] Gait initiation represents an internally-induced perturbation to an individual's upright standing balance. Therefore, the large ML COP oscillations observed during multiple APA trials may result from participants responding to this perturbation through excessive postural sway in the ML direction, which may be further influenced by functional differences between the limbs post-stroke. While frequency of multiple APAs was higher when initiating with the non-paretic than the paretic limb, our data suggest that high frequency of multiple APAs were not influenced by motor impairment. Physical factors such as strength and power in the lower extremity muscles,

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spasticity, or poor balance and trunk control, cognitive factors such as presence of perceptual disorders (e.g., hemispatial neglect) or speed of processing, and psychological factors such as fear of falling[26] may influence gait initiation strategies, and may be warranted to investigate in future work.

Trials with multiple APAs resulted in longer APA durations and total times to foot-off. Similar results were found for individuals with Parkinson's disease executing reactive steps following backwards platform translations, with trials with multiple APAs often observed.[27] The authors concluded that multiple APAs may be related to a need for additional time to select a motor program for stepping.[27] Similar to the present study, trials with multiple APAs included delayed APA onsets and delayed foot-off times.[27] Potentially, this suggests delays in achieving forward progression when multiple APAs are present during gait initiation. These delays may explain slower gait initiation speeds identified in individuals with stroke initiating gait with the non-paretic limb.[28] This delay may also translate to slowed steady-state walking. Hesitation when loading the paretic leg may partially explain slow walking speeds[29] and temporal asymmetry[30,31] among those with post-stroke motor impairment. However, it is important to acknowledge that only the ML COP was used in the identification of APAs and associated characteristics in the present study. COP in the ML direction is crucial in maintaining stability,[5,6] while COP in the AP direction is more important in forward progression. Quantification of AP COP was beyond the scope of the present analysis. Therefore, we were unable to determine whether the timing delays during the multiple APA trials were solely due to an ML COP mechanism, or a combination of differences in the ML and AP directions; or to confirm that the delayed timing of multiple APAs contributed to delays in forward progression.

Lastly, a significant difference in unloading time was identified between single and multiple APA trials when compared within participants. This difference appears to have been primarily driven by trials in which participants stepped with the paretic limb and exhibited only a single APA; these trials tended to have a much longer unloading time than those with multiple APAs. Taken together with the correlations between the presence of atypical APAs and motor impairment, this finding may suggest that, when initiating gait with the paretic limb, multiple APAs may be required to propel the COM over the stance limb. Therefore, multiple APAs may represent an adaptive strategy to facilitate gait initiation with the paretic limb.

Clinical implications

We report the prevalence of atypical APAs in individuals with stroke and consequences of these movement patterns. This study also revealed a potential mechanism for atypical APAs in individual with stroke, in that atypical APAs were significantly related to motor impairment. Improved understanding of mechanisms underlying atypical APAs may aid in the creation of rehabilitation interventions to improve stability during gait initiation (i.e., addressing motor impairment may contribute to an improved ability or willingness to employ APAs during gait initiation). While both absent and multiple APAs were considered to be atypical movement patterns for the purpose of the present study, multiple APAs may actually represent an adaptive strategy to aid with initiating gait on the paretic limb.

Conversely, a lack of APA during gait initiation may indicate insufficient strength or selective motor control, which may represent areas of focus in designing rehabilitation programs for these individuals.

CONCLUSION

This study suggests that foot motor impairment and slow walking speed are possible factors in atypical APA patterns prior to gait initiation. Further research is needed to determine how atypical APA patterns affect gait stability after initiation, and how the central nervous system compensates for this instability while walking. Future work should also isolate the possible cause(s) of atypical APAs to create specific therapeutic interventions to improve gait initiation and stability.

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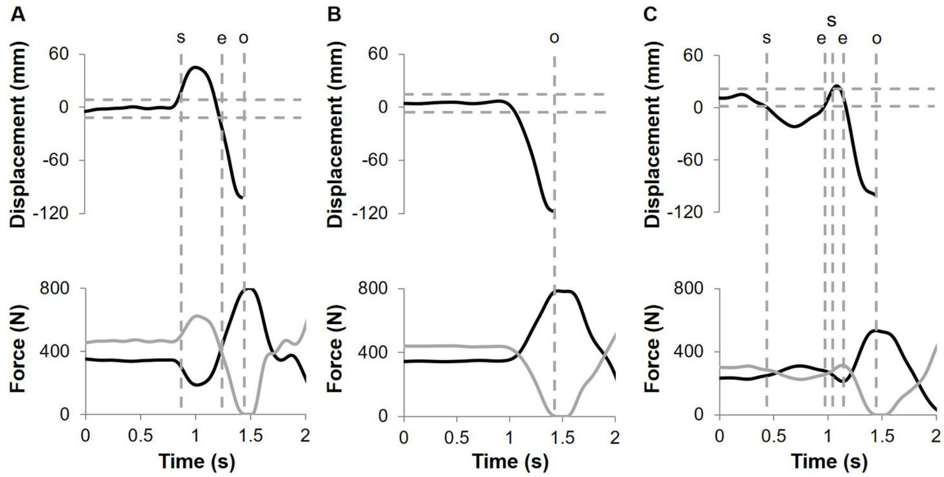

Figure 1. Medio-lateral (ML) centre of pressure (COP) and vertical forces during gait initiation

Panel A shows a single APA trial, panel B shows an absent APA trial, and panel C shows a multiple APA trial. Time series' in the top row of graphs represent ML displacement of the COP, while black and grey time series' in the bottom row of graphs represent ground reaction forces under the right and left limbs, respectively. Vertical dashed lines represent APA events. APA start time (*s*) was the time when the ML COP passed the 10 mm threshold (indicated by the horizontal dashed lines). APA end time (*e*) was the time when the ML COP returned to the 10 mm threshold. Foot-off time (*o*) was the time when the vertical force under the swing limb was <1% body weight. APA duration was the length of time from APA start to APA end, unloading time was the difference between foot-off time and APA end, and total time to foot-off was the difference between foot-off and APA start.

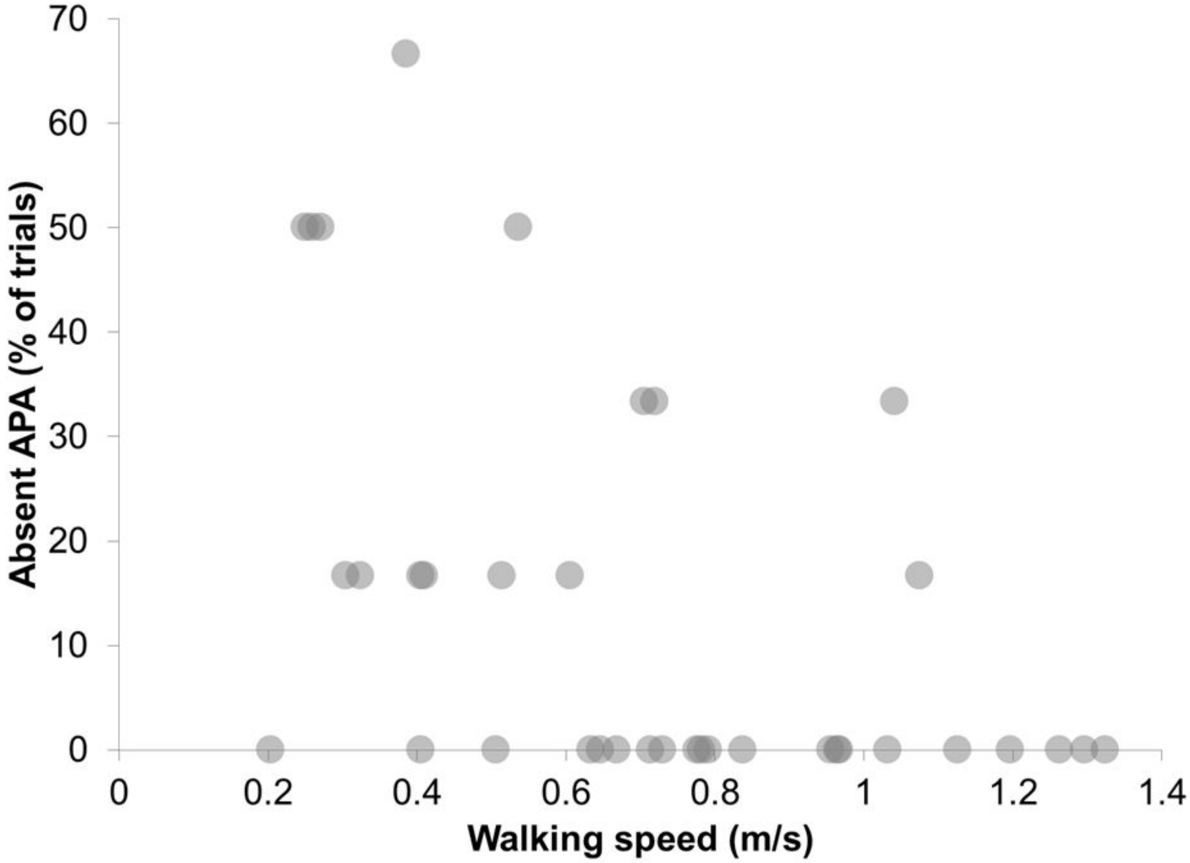

Figure 2. Relationship between self-selected walking speed and frequency of absent APA trials

Each data point represents a different individual. Note that self-selected walking speed was not available for two individuals. There was a significant moderate correlation between self-selected walking speed and frequency of absent APA trials (Spearman's correlation coefficient (r)r=−0.53; p=0.0010).

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Table 1

Characteristics for the 40 participants in the study at the time of admission to the stroke unit

Values presented are means (for continuous measures) or counts (for categorical measures).

	Mean or number	Standard deviation	Minimum	Maximum
Age (years)	67.8	14.3	37	94
Sex (number)				
Men	19			
Women	21			
Height (cm)	165	11	145	188
Weight (kg)	73.7	19.9	31.0	124.7
Time post-stroke (days)	43	40	5	174
Affected hemisphere (number)				
Right	16			
Left	24			
Affected side (number)				
Right	23			
Left	17			
Stroke type (number)				
Ischemic	28			
Hemorrhagic	10			
Transforming to hemorrhagic	2			
Berg balance scale (score)	39.5	14.7	4	56
CMSA leg (score)	4.9	1.3	2	7
CMSA foot (score)	4.6	1.3	1	7
Clinical outcome variables scale (score)	72.6	14.6	31	91
Self-selected walking speed (m/s) *	0.71	0.32	0.20	1.32

*Data missing for 4 participants.

CMSA = Chedoke-McMaster Stroke Assessment

Table 2

Measures extracted from the COP, COM, and ground reaction force time series'.

Measure	Definition
Measures based on ML COP	
APA start	The time when ML COP displacement was 10 mm greater than (for steps with the right limb) or less than (for steps with the left limb) the baseline value[13]
Unloading onset time	The time prior to foot-off when the ML COP was 10 mm greater than (for steps with the left limb) or less than (for steps with the right limb) the baseline value
APA end	The time when the last APA returned back to its original baseline value
APA duration◢	The difference between APA start and APA end
Measures based on COM position	
Initial COM position*	The position of the COM during the baseline 250 ms prior to gait initiation
COM position at foot-off*	The position of the COM at the time of foot-off
Change in COM position*	The difference between initial COM position and COM position at foot-off
Measures based on ground reaction forces	
Weight-bearing asymmetry*	The load borne on the stance limb during the baseline 250 ms prior to gait initiation, expressed as a percentage of total body weight (%BW)
Foot-off time	The time when the vertical force under one force plate was <1 % of body weight
Foot-on time	The time when >1 % of the patients' body weight was recorded by the front force plate
Swing time*	The difference between foot-off and foot-on times
Measures based on ML COP and ground reaction forces	
Unloading time*◢	The difference between APA end and foot-off time
Total time to foot-off◢	The period from the time when ML COP first reached the baseline ±10 mm threshold to foot-off

*Measures included in the analysis of absent APAs compared to single APAs.

◢Measures included in the analysis of multiple APAs compared to single APAs.

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Table 3

Correlations between Chedoke-McMaster Stroke Assessment leg and foot scores and frequency of atypical APAs

Values presented are Spearman's correlation coefficients (r) and associated p-values. Statistically significant correlations are indicated with an asterisk (revised α=0.007).

	CMSA foot score		CMSA leg score	
	R	**p-value**	**r**	**p-value**
Leading with the paretic limb				
Absent APA	−0.25	0.12	−0.21	0.20
Multiple APA	−0.28	0.078	−0.17	0.30
Leading with the non-paretic limb				
Absent APA	−0.48	0.0018*	−0.28	0.084
Multiple APA	−0.16	0.32	−0.18	0.26

Table 4

Mean (standard deviation) values for outcome measures compared between single and absent APA trials, and between single and multiple APA trials

Distance measures are presented relative to the midline between the feet with the sign indicating whether the COM was closer to the stance or swing limb. Positive values indicate that the COM was located toward the stance limb, whereas negative values indicate the COM was located toward the swing limb. None of the comparisons between single and absent APA trials were statistically significant after adjusting for multiple comparisons (revised α=0.0042). Statistically significant differences between single and multiple APA trials, when adjusted for multiple comparisons, are indicated with an asterisk (revised α=0.017).

Comparison between single and absent APA trials	**Between-participants comparison**			**Within-participants comparison**		
	Single APA (n=9)	**Absent APA (n=18)**	***p*-value**	**Single APA (n=17)**	**Absent APA (n=17)**	***p*-value**
Weight-bearing asymmetry (% body weight on stance limb)	50.0 (1.5)	52.1 (8.6)	0.92	50.5 (4.0)	52.2 (8.8)	0.99
Initial COM position (cm)	0.0 (0.4)	0.6 (1.8)	0.69	0.0 (0.8)	0.6 (1.9)	0.81
COM position at foot-off (cm)	1.1 (0.9)	1.4 (2.2)	0.76	1.2 (1.4)	1.4 (2.3)	0.99
Change in COM position (cm)	1.1 (0.8)	0.8 (2.3)	0.76	1.2 (1.0)	0.8 (2.4)	0.43
Unloading time (ms)	297 (111)	560 (351)	0.020	508 (221)	498 (239)	0.87
Swing time (ms)	359 (66)	261 (101)	0.017	256 (105)	259 (104)	0.57
Comparison between single and multiple APA trials	**Between-participants comparison**			**Within-participants comparison**		
	Single APA (n=9)	**Multiple APA (n=22)**	***p*-value**	**Single APA (n=21)**	**Multiple APA (n=21)**	***p*-value**
Weight-bearing asymmetry (% body weight on stance limb)	50.0 (1.5)	51.4 (10.5)	0.67	50.7 (7.2)	51.8 (10.6)	0.71
APA duration (ms)	330 (82.3)	890 (348)	<0.0001*	338 (86)	844 (281)	<0.0001*
Unloading time (ms)	297 (111)	289 (209)	0.50	409 (195)	301 (207)	0.0090*
Total time to foot-off (ms)	626 (104)	1180 (369)	<0.0001*	737 (178)	1145 (340)	<0.0001*