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Movement smoothness in chronic post-stroke individuals walking in an outdoor environment—A cross-sectional study using IMU sensors

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Abstract

Background

Walking speed is often used in the clinic to assess the level of gait impairment following stroke. Nonetheless, post-stroke individuals may employ the same walking speed but at a distinct movement quality. The main objective of this study was to explore a novel movement quality metric, the estimation of gait smoothness by the spectral arc length (SPARC), in individuals with a chronic stroke displaying mild/moderate or severe motor impairment while walking in an outdoor environment. Also, to quantify the correlation between SPARC, gait speed, motor impairment, and lower limb spasticity focused on understanding the relationship between the movement smoothness metric and common clinical assessments.

Methods

Thirty-two individuals with a chronic stroke and 32 control subjects participated in this study. The 10 meters walking test (10 MWT) was performed at the self-selected speed in an outdoor environment. The 10 MWT was instrumented with an inertial measurement unit system (IMU), which afforded the extraction of trunk angular velocities (yaw, roll, and pitch) and subsequent SPARC calculation.

Results

Movement smoothness was not influenced by gait speed in the control group, indicating that SPARC may constitute an additional and independent metric in the gait assessment. Individuals with a chronic stroke displayed reduced smoothness in the yaw and roll angular velocities (lower SPARC) compared with the control group. Also, severely impaired participants presented greater variability in smoothness along the 10 MWT. In the stroke group, a

smoother gait in the pitch angular velocity was correlated with lower limb spasticity, likely indicating adaptive use of spasticity to maintain the pendular walking mechanics. Conversely, reduced smoothness in the roll angular velocity was related to pronounced spasticity.

Conclusions

Individuals with a chronic stroke displayed reduced smoothness in the yaw and roll angular velocities while walking in an outdoor environment. The quantification of gait smoothness using the SPARC metric may represent an additional outcome in clinical assessments of gait in individuals with a chronic stroke.

Introduction

Individuals with chronic stroke often display reduced motor control, muscle weakness, and spasticity in the lower limbs [1,2]. This may lead to asymmetries while standing or walking [3], slower gait with poor coordination [4], greater metabolic consumption while walking [5], and postural instability, ultimately leading to reduced community ambulation [6]. In the clinic, gait assessments often include the quantification of gait speed, which is easily and reliably measured using a chronometer and a fixed distance. This assessment is considered a good indicator of the overall walking performance in individuals with stroke and may be accomplished, for example, using the 10 meters walking test (10 MWT) [7–9]. Although gait speed and functional scales provide a broad picture of the post-stroke gait impairment, the detailed assessments of postural behavior and instability are usually accomplished using kinematics or kinetics. Similar to gait speed and functional scales, the gait spatiotemporal symmetry represents a good metric to estimate the above-mentioned walking asymmetries and is associated with gait speed in the stroke gait [3]. However, gait speed and spatiotemporal symmetry offer limited information about the deficits in dynamic posture and smoothness during walking, including the compensatory postural adjustments to maintain/change symmetry and speed [10,11]. Thus, movement smoothness estimated from a waist-mounted inertial measurement unit (IMU) may constitute an important additional metric to quantifying the quality of movement [10,11], including postural adjustments—since one may walk with a perfectly symmetric but unsmooth gait pattern [12].

An adequate movement smoothness has been associated with satisfactory scores of balance [13,14], motor control [15], and gait speed [10]. Recently, the spectral arc length (SPARC) was proposed to quantify point-to-point reach in stroke, with excellent ability to deal with duration artifacts. Longer movements may overshadow other movement smoothness metrics such as trajectory, velocity, and acceleration (jerk) adjustments. SPARC measurement assumes less smooth movements are more complex (more frequency composition) when approaching the original signal with a Fourier series. Therefore, it measures the movement smoothness by defining the signal's complexity by the power spectrum profile [16]. In point-to-point reach tasks, the use of SPARC was shown to outstand traditional and adjusted smoothness measures [12]. Importantly, SPARC was recently adapted and recommended for estimating movement smoothness using data extracted from IMUs [17]. Thus, SPARC constitutes an optimal measure of smoothness given the reduced impact of duration—since the analysis is conducted in the frequency-domain. Evaluation of movement smoothness is useful in neurorehabilitation because it may enable the quantification of motor recovery [18,19] and predict post-stroke

motor control [14,15] in great detail. Also, as mentioned earlier, the ability to account for the postural adjustment and compensations may provide important information, especially in the cases of post-stroke individuals with fast and symmetric gait patterns.

Quantifying acceleration, deceleration, and angular velocity using a lumbar IMU affords the estimation of the intermittency of rhythmic movements. The presence of such intermittencies in movement is quantified by the SPARC metric, which reflects the presence of movement arrest periods [17,18,20]. IMUs are noninvasive inertial sensors used to assess gait in the laboratory and outdoor environments [12,20,21]. The portability of IMU systems allows the investigation of gait biomechanics outside the laboratory environment. Walking in outdoor environments may be challenging for individuals with motor impairment, especially those with severe compromise [22,23]. For this reason, it is interesting to evaluate individuals with stroke and with different levels of motor impairment while walking in "real contexts" outside the laboratory setting. Natural constraints of the environment may provide a better picture of the 'real-life' gait impairments that stroke survivors face in daily walking activities. Thereby, we think it may provide a valid approach to assess the presence of movement arrest periods in stroke individuals whose motor impairment was previously classified in the laboratory environment. IMUs are a good alternative to evaluate such movement arrest periods in real contexts and mitigate typical limitations of laboratory settings–such as the highly controlled environment and reduced experimental area [24].

Several metrics are described in the literature to quantify smoothness [20], such as the jerk [11] and the harmonic ratio [12]. However, SPARC has been pointed out as a superior approach compared to others [11,25]. SPARC captures the movement intermittency, e.g., movement arrest periods [17], with reduced influence of movement amplitude or duration, and has been used to quantify gait smoothness in the oldest-old [26] and individuals with Parkinson's disease [11,21]. Nonetheless, no study to date explored the ability of SPARC obtained from IMU sensors in quantifying the hemiplegic gait. Considering the use of gait smoothness as a complement to the traditional gait speed assessment, this study aimed: a) to quantify gait smoothness (SPARC) in individuals with a chronic stroke while walking in an outdoor environment; b) to compare SPARC features of post-stroke individuals with mild/moderate and severe motor impairment; and c) to explore the correlation of SPARC with gait speed, gait symmetry, motor impairment, and lower limb spasticity. We hypothesized that SPARC would quantify the gait deficits in individuals with a stroke, represent an additional metric to complement the traditional gait speed assessment, and correlate with clinical assessments of motor impairment and spasticity.

Materials and methods

Study design

This cross-sectional study was approved by the Ethics and Research Committee of the Santa Casa de Misericórdia Hospital of Porto Alegre (CAAE 64819617.0.0000.5335) and was conducted according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist [27].

Participants

Volunteers were recruited through a Santa Casa de Misericórdia Neurology service database in Porto Alegre, Brazil, institutional sites, and social media. Those individuals who met the following criteria were included as convenience sample: aged between 18 and 80 years; with a diagnosis of cortical or subcortical unilateral cerebrovascular accident confirmed by imaging (tomography or magnetic resonance imaging); time since the stroke from 6 months to 10

Table 1. Demographic characteristics.

	Control (n = 32)	Stroke (n = 32)	p = value	Mild/Moderate impairment (n = 16)	Severe impairment (n = 16)	p = value
Gender, n (%)						
Male	22 (68.8)	22 (68.8)	1.000	10 (62.5)	12 (75)	0.444
Age, years, mean ±SD	56.81 ± 8.88	56.84 ± 9.10	0.989	55.88 ± 11.42	57.81 ± 6.22	0.557
Height (m)	1.72 ± 8.23	1.68 ± 9.73	0.221	168.63 ± 9.74	170.56 ± 7.86	0.540
Body mass (kg)	78.26 ± 12.97	75.13 ±11.90	0.318	76.13 ± 12.27	74.13 ± 11.83	0.642
MMSE Score, median (min-max)	30 (27–30)	29 (25–30)	**<0.001***			
Time since stroke, mth, median (min-max)		39.41 (6–96)		43 (6–96)	23 (6–84)	0.220
Stroke type, n (%)						
Ischemic		24 (75)		11(68.75)	13 (81.25)	0.412
Hemorrhagic		8 (25)		5 (31.25)	3 (18.75)	
Affected hemisphere, n (%)						
Right		19 (59.4)		9 (56.2)	10 (62.5)	0.719
Left		13 (40.6)		7 (43.8)	6 (37.5)	
FMA-LL (0–34), median (min-max)		19.63 (11–32)		23 (20–32)	15 (11–18)	**<0.001***
MAS, frequency (0/1/1⁺/2/3/4)						
Plantiflexors		0/3/2/4/11/12		0/2/2/4/4/4	0/1/0/0/7/8	**0.029***
Knee extensors		5/7/6/4/8/2		4/5/2/2/3/0	1/2/4/2/5/2	**0.033***
Adductors		5/4/4/12/7/0		4/3/3/4/2/0	1/1/1/8/5/0	**0.021***

FMA-LL, Fugl Meyer Assessment—Lower Limb; MAS, Modified Ashworth Scale; max, maximum; min, minimum; n, number of participants; SD, standard deviation.
Mild-Moderate: FMA-LL scores of 20–34; Severe: FMA-LL scores below than 19. t-Student and U-Mann-Whitney tests were used for parametric or nonparametric data, respectively. Likelihood Ratio Chi-Square Tests were used for data of gender, type of stroke, affected hemisphere and MAS.

years; ability to walk at least 10 meters with or without assistive devices; minimum score of 20/30 points (illiterate) or > 24/30 points (literate) in the Mini-Mental State Examination (MMSE) [28]. Individuals with a clinical diagnosis of musculoskeletal diseases, significant visual deficit, and history of falls in the last 3 months were excluded.

The study also included a reference group of healthy individuals, paired by age and sex. Exclusion criteria for the reference group were: previous history of neurological or musculo-skeletal disorders that induced visible gait abnormalities. All participants signed the informed consent after an explanation about the objectives and possible complications of the study. According to the MMSE score, all participants were presumed competent for decision-making and, for this reason, signed the informed consent (Table 1).

Procedures

This study was conducted at the Federal University of Health Sciences of Porto Alegre (UFC-SPA) between January 2018 and May 2019. Each participant performed a clinical and docu-mented evaluation session. The same researcher applied all clinical assessments.

Clinical measurement

Lower limb motor impairment. The motor function domain of Fugl-Meyer Assessment (FMA) was used to assess lower limb (LL) motor impairment [29]. We included only the motor domain scale, without other domains (nonmotor domains: sensation, balance, joint range of motion, and joint pain). The motor subscale measures the voluntary movement,

velocity, coordination, and reflex activity about the hip, knee, and ankle. Each item has three possible scores, 0 (cannot be performed), 1 (partially performed), and 2 (performed entirely). The maximum score for the LL is 34 points. According to the FMA-LL score, the participants were classified following their motor impairment as severe (0 to 19), moderate (20–28), or mild ($\geq$29 points) [30].

Modified Ashworth Scale (MAS). MAS was used to evaluate resistance to passive movements. This measure corresponds to an indirect assessment of spasticity [31]. This scale consists of 6 ordinal values ranging from 0 (no tonus increase) to 4 (stiffness) [32]. Participants were evaluated lying in the supine position and instructed to remain relaxed during the test. Spasticity of plantar flexors, knee extensors, and hip adductors was tested.

Gait assessment. Participants were requested to walk at a self-selected speed on a 10-meters flat pathway of the university outdoors. This pathway was sheltered from the rain, but participants regularly crossed with other people and received several sensory stimuli during the task. Data were acquired at least twice for each participant. During the evaluation, participants wore an inertial sensor (BTS G-Walk BTS Bioengineering Corporation, Italy, with a sampling rate of 100 Hz) that measured the acceleration along three accelerations axes: vertical acceleration (V), mediolateral acceleration (ML), anterior posterior acceleration (AP); and three angular velocity axes: yaw, pitch, and roll. In the smoothness analysis, we only consider the angular velocity axes. The inertial sensor was attached to the subjects' waists with a semielastic belt, covering the L5 S1 segments [33]. Acceleration data were transmitted via Bluetooth to a PC and processed using dedicated software (BTS G-STUDIO, version: 2.6.12.0) (Fig 1). Finally, offline processing of the acquired acceleration signals was performed as described below.

Data processing

Data was calculated over an average of 2–3 trials for controls, 2–5 trials for mild stroke, and 2–3 trials for severe stroke ($\approx$ 32–40 steps to 48–60 strides or 96–120 steps). To determine the onset and offset of movement, the researcher was visually guided by the pitch angle, which depicts the anteroposterior body oscillations. The onset was defined when the pitch angle reached its first peak, corresponding to the first step, and the offset when the pitch angle presented the last peak, corresponding to the last step. Portions of the signal outside these limits were excluded and deemed to contain acceleration and deceleration phases of the gait, respectively.

Spectral arc length (SPARC). Raw data from the G-Studio software was extracted, exported as ASCII files, and analyzed offline using LabVIEW® (National Instruments, USA, v.18.0) custom software routines to obtain speed and smoothness variables.

Gait smoothness was estimated using the SPARC metrics, as Beck et al., and Pinto et. al. [11,21] described previously. The algorithm was further optimized following the recent recommendations for estimating SPARC from IMUs [17]. We used the 3 calibrated angular velocities (yaw, roll, and pitch) (in °/s) from the IMU gyroscope data, mean subtractions were used to remove the direct current (DC) components from raw angular velocity data, and whenever signal manipulations caused the drifting of the signal. Since SPARC was initially developed for discrete point-to-point reaching, we also implemented a windowing procedure to reduce the effects of long, continuous data windows–often present during the 10MWT in stroke participants. Very long windows may increase the FFT resolution and the frequency complexity, respectively, which can induce a duration effect over SPARC. A conservative non-overlapping window size of 3 seconds (300 frames) was used to represent at least 1 full stride cycle in pathological gait. If the last window was less than 3 seconds, this window was automatically excluded
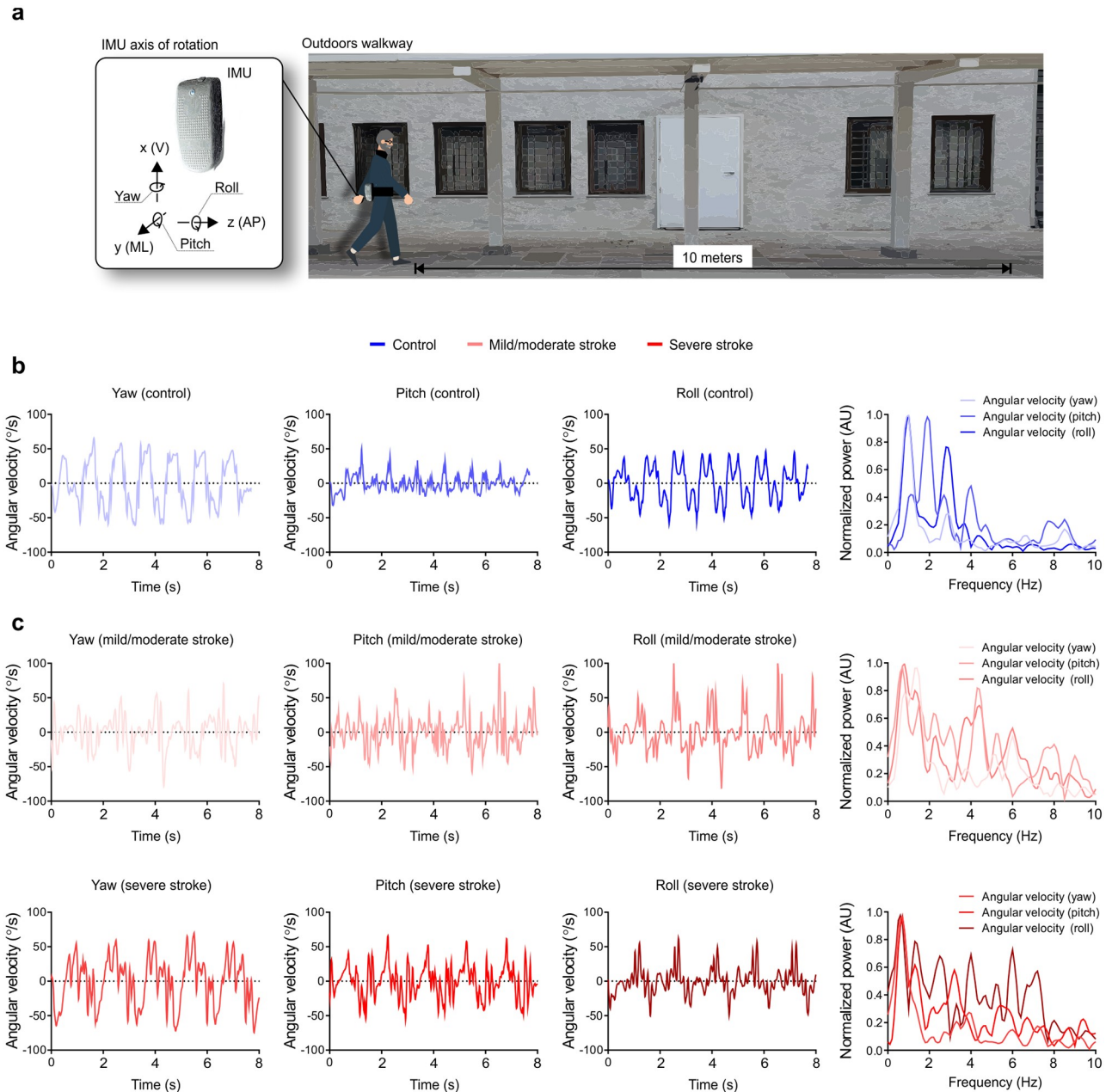
Fig 1. Experimental setup. (a) The instrumented 10 meters walking test (10 MWT) was performed outdoors using an inertial measurement unit (IMU) attached to the participant's waist and connected to a laptop (via Bluetooth). **(b)** Representative yaw, pitch, and roll angular velocities of the control group (blue lines). **(c, d)** Representative yaw, pitch, and roll angular velocities of stroke participants with mild/moderate (light red lines) and severe (dark red lines) impairment. Data were analyzed using time series of a non-overlapping moving window of 3 seconds. The normalized power (right panels) represents the last analyzed window for each of the angular velocities.

by the algorithm. Each cropped window was zero-padded to double the FFT frequency resolution, and SPARC was calculated. For SPARC calculation, the high frequencies not involved in pathological gait were removed when applying the limits of integration (lower bound = 0; upper bound = 10 Hz) [12]. The upper bound of 10 (ω_c: adaptive cut-off frequency) was chosen based on the presence of higher frequencies in pathological gaits, such as Parkinson's [21].

We calculated the SPARC $[\lambda_S^v(V)]$ for each 3 seconds window. The average of all SPARC windows contained in the walking trial was calculated.

$$\lambda_S^v(V) \triangleq - \int_0^{\omega_c} \sqrt{\left[\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2\right]} \, d\omega$$

$$\hat{V}(\omega) = \frac{V(\omega)}{V(0)}; \quad V(\omega) = F(\|V(t)\|_2) \tag{1}$$

where V (t) represents the velocity (angular) of a movement in the time domain, F(•) is the Fourier transform operator, ωc is an adaptive cut-off frequency (see Melendez-Calderon et al., 2021 [17] for details).

Movement arrest periods increase the complexity of the frequency composition, which is captured by the SPARC analysis. Because of the negative sign in (1), lower SPARC values indicate less movement smoothness (increased frequency domain complexity).

Also, we conducted a short-time Fourier transform (STFT)-based spectrogram of the angular velocity signals to show representative spectrograms of walking trials. For this, we applied 512 frequency bins resulting in 256 frequency scales with a resolution of 0.19 Hz using the TFA STFT Spectrogram VI in LabVIEW.

Spectral analysis metrics followed the assumption that unsmooth movements are more complex in terms of their frequency composition. In other words, lower SPARC values indicate less movement smoothness [16].

Acceleration adjustments (Jerk). The angular velocity time-series was filtered using a low-pass 1st order Butterworth filter at 10 Hz. The filtered angular velocities were derivated to achieve the angular acceleration. The angular acceleration profile was derived to obtain the acceleration variation (jerk). The initial and final frames were removed after each derivation to remove artifacts. To quantify jerk, we counted the number of zero-crossings in the jerk profile.

Gait symmetry and speed. The typical spatiotemporal gait parameters are automatically obtained using the dedicated BTS G-STUDIO software from the acceleration signals. Gait velocity was computed as the mean speed by the ratio of walking distance to duration. Step length was estimated based on the amplitude of vertical pelvic displacement and leg length using a simple inverted pendulum model of walking. It was calculated based on the approach described by the literature [33,34]. The gait symmetry (%) was quantified according to the method described by Robinson [35] as follows:

$$SI = \left[\frac{2(x \; non \; paretic - x \; paretic)}{(x \; non \; paretic + x \; paretic)}\right] x100 \tag{2}$$

where SI is symmetry index in step lengths; x non-paretic is the value of the variable obtained from the non-paretic limb; *x paretic is* the value of the corresponding variable obtained from the paretic limb.

The symmetry index was calculated by the quotient of the difference between step length for paretic and non-paretic limb. The symmetry index should be zero, reflecting a perfectly symmetrical gait pattern. Higher symmetry index values correspond to greater gait asymmetry [35,36].

Statistical analysis

The sample size was determined by G-Power 3.0 software based on previous studies [11,21] adopting 90% power and the alpha value of 0.05 to detect the minimum effect size of 0.7% in

SPARC [21]. A total of 30 participants in each group (stroke and control) was estimated as necessary to this study.

Data were expressed as mean, standard deviation (SD) or 95% confidence intervals (continuous variables) and frequency distribution (categorical variables). Shapiro-Wilk tests were used to evaluate the normality of the continuous variables. Parametric Student t-tests, non-parametric Mann–Whitney, and Chi-square tests were used to compare demographics and stroke-related characteristics between groups. To classify the level of impairment in the stroke group the FMA-LL scores were used: mild/moderate of 20–34 and severe below 19 points. One way-ANCOVA was conducted to compare SPARC and symmetry across three groups (mild/moderate stroke, severe stroke, and control) while controlling for gait speed. Levene's test and normality checks were carried out. One way-ANOVA was used to compare the SD of SPARC throughout the analysis windows. Tukey posthoc test was applied when necessary. The analysis of variation between windows three control subjects was excluded since they had only 1 valid window for analysis (duration $<$ 6 seconds).

A correlational analysis was conducted between the smoothness variables and gait speed, Symmetry index, FMA-LL, and spasticity using the Person's and Spearman's correlation coefficients were used for parametric and nonparametric variables, respectively. We interpreted the strength of correlation as follows: 0.26–0.49 = weak; 0.5–0.69 = moderate; 0.7–0.89 = strong; and 0.9–1.0 = very strong. We used the SPSS statistical software version 21.0 for all analyses. The significance levels were set at $p < 0.05$.

Results

Forty-one individuals with chronic stroke were recruited. Nine participants failed to meet all the eligibility criteria and were excluded from the analysis: incapacity to walk 10 meters (n = 3), musculoskeletal disorders (n = 3), cognitive impairment (n = 2), and significant visual deficit (n = 1). Thus, thirty-two individuals with chronic stroke and thirty-two healthy controls were included. According to the impairment level, post-stroke individuals were divided into two groups: Mild/Moderate (n = 16, 10 men, 55.88 ± 11.42 years), and Severe (n = 16, 12 men; 58.81 ± 6.22 years). The demographic data and clinical characteristics of participants are presented in Table 1.

Stroke individuals presented lower gait speed with higher asymmetry compared with controls. Gait symmetry (%) was of 2.82 (1.55–4.85) [median and 25th to 75th inter-quartile range] for controls, 12.03 (6.43–29.6) for mild/moderate and 7.75 (3.81–27.44) for severe individuals with severe compromise ($U_{(2)} = 23.21$; p<0.001). Subgroup analysis showed no differences between mild/moderate and severe stroke participants (p > 0.05). Gait speed was of 1.22 ± 0.17 m.s^{-1} for controls, 0.68 ± 0.24 m.s^{-1} for mild/moderate and 0.58 ± 0.27 m.s^{-1} for individuals with severe compromise ($F_{(2,61)} = 60.18$, p < 0.001). Posthoc indicated the control group was faster than both mild/moderate and severe stroke groups (p < 0.05). Given the strong influence of velocity over the groups, we decided to account for gait speed as a covariate in our group analysis.

A one-way ANCOVA revealed a significant difference in mean SPARC angular velocity (yaw) ($F_{(2,60)} = 4.317$, p = 0.018) between the groups while adjusting for gait speed. Post-hoc comparisons showed that the mild/moderate (p = 0.015) stroke group presented less smooth gait than the control group (Fig 2a). For the SPARC angular velocity (pitch) there was no significant difference between groups accounting for gait speed as covariate ($F_{(2,60)} = 1.888$, p = 0.160, Fig 2b). There was a significant difference in mean SPARC angular velocity (roll) between the groups ($F_{(2,60)} = 4.413$, p = 0.016). Post-hoc comparisons revealed that mild/moderate (p = 0.024) and severe (p = 0.021) stroke groups presented less smooth gait than the
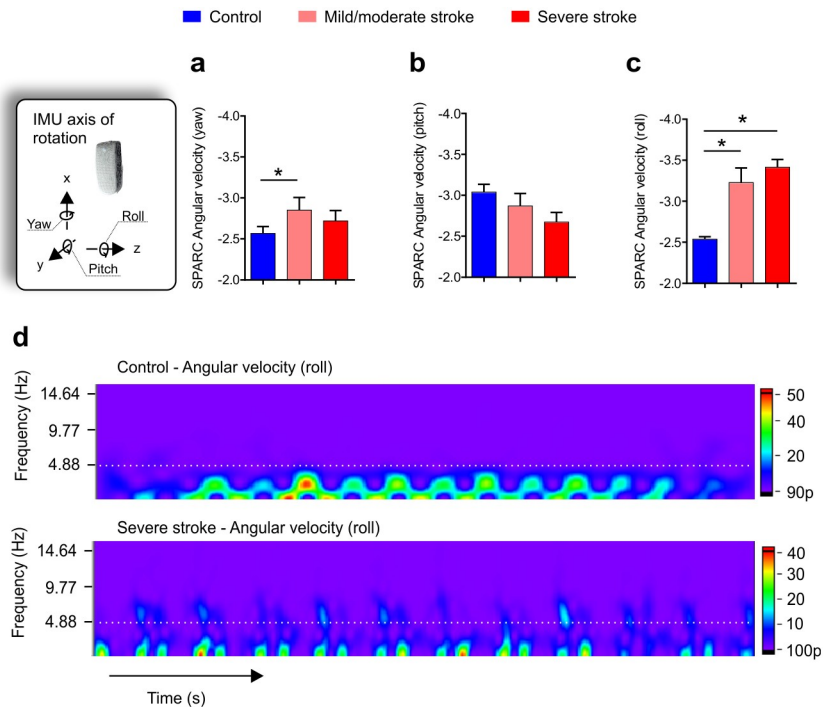
Fig 2. SPARC angular velocities profiles and representative spectral-domain of healthy control and severely impaired stroke participants during the outdoor 10-meters walk test (10 MWT). (a,b,c) Average of yaw, pitch, and roll angular velocities for the control group (blue) and stroke participants with mild/moderate impairment (light red) and severe impairment (dark red). Overall, stroke participants presented greater roll angular velocity than the control group (p <0.001). **(d)** Representative heatmap of power spectral density for roll angular velocity. Note the severely impaired stroke participants presented frequency magnitude peaks above the 5Hz compared with healthy controls (white hashed lines). One-way ANCOVA with Bonferroni posthoc correction, *p < 0.05.

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control group (Fig 2c). Overall, the severely impaired stroke participants presented greater intensity in higher frequencies (i.e., > 5 Hz) compared to controls, as shown in Fig 2d.

When analyzing the variation (SD) of smoothness along the 10 MWT across all the 3-seconds analysis windows, a one-way ANOVA indicated stroke participants presented more variation in smoothness during the walking trial. For SD SPARC angular velocity (pitch), there was a group effect ($F_{(2,59)}$ = 5.931, p = 0.0028, Fig 3a), in which both mild/moderate and severe stroke groups showed greater variability of smoothness during the 10 MWT (p < 0.05). No differences were evident for SPARC variability in the pitch angular velocities [SD SPARC angular velocity (pitch); Fig 3b]. Roll angular velocity smoothness also showed a group effect ($F_{(2,59)}$ = 33.56, p < 0.0001, Fig 3c). This result indicated both stroke groups were more variable in terms of smoothness than controls, but the severe stroke group was more variable than the mild/moderate group. Note the higher frequency amplitude is less constant for the severe stroke group, showing a remarkable high intensity at the end of the walking trial (Fig 3d).

Overall, unlike healthy controls, post-stroke individuals showed a broad spectral range that encompassed several dominant frequencies, not restricted to lower frequencies (Figs 1c, 1d, 2d and 3d). Control individuals displayed lower frequency components, indicating low variability of events generated by stride and step frequencies during walking. A greater number of well-defined higher frequencies in post-stroke individuals was evident—likely reflecting the distinct strategies employed during walking.

Table 2 shows correlations between gait speed and asymmetry, clinical variables (FMA-LL and MAS), and SPARC. We found SPARC angular velocity (yaw and pitch) presented a
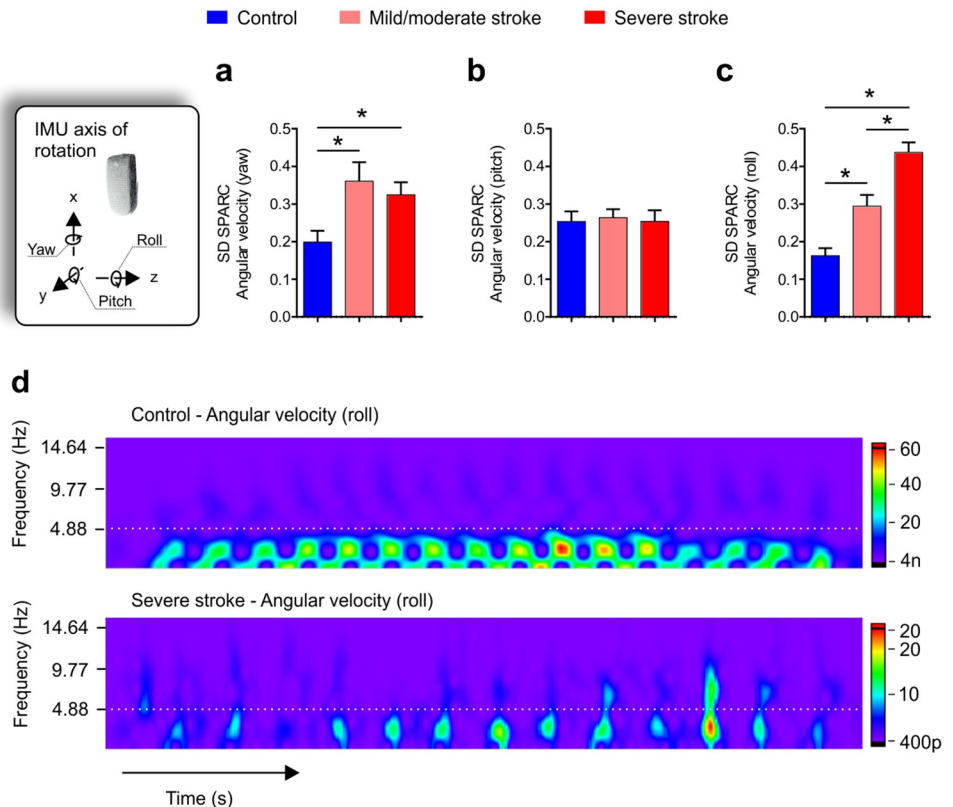
Fig 3. Variability of SPARC angular velocities profiles and representative spectral-domain of the control group and severely impaired stroke participants during the outdoor 10-meters walk test (10 MWT). (a,b,c) Standard deviation (SD) throughout the 3-second analysis windows of yaw, pitch, and roll angular velocities for the control group (blue) and stroke participants with mild/moderate impairment (light red) and severe impairment (dark red). Overall, stroke participants presented greater variability of smoothness during the walking trial for yaw and roll angular velocities than controls ($p < 0.05$). **(d)** Representative heatmap of power spectral density for roll angular velocity. Note the severely impaired stroke participants presented frequency magnitude peaks above the 5Hz compared with controls (white hashed lines). Also, note that the severely impaired stroke participants presented more variable frequency magnitude peaks across the 10 MWT than the control group. One way ANOVA with Tukey's posthoc correction, *$p < 0.05$.

moderate correlation with gait speed. These correlations indicated a negative relation between SPARC and gait speed, where a reduced smoothness was related to faster speeds (Fig 4a and 4b), not evident in controls (Fig 4d and 4e). SPARC angular velocity (roll) was not related to gait speed in both groups (Fig 4c and 4f). FMA-LL and symmetry index were not related to gait smoothness. On the other hand, SPARC angular velocity pitch and yaw displayed a positive and weak/moderate correlation with spasticity of plantarflexors and hip adductors. Also, knee extensors showed a weak negative correlation with SPARC in the roll angular velocity.

Discussion

Individuals with a chronic stroke displayed reduced smoothness while walking in an outdoor environment, indicating movement arrest periods in the yaw and roll angular velocities, and higher spatiotemporal asymmetry compared with control individuals. Severely impaired individuals presented pronounced gait smoothness variability along the walking trajectory, and this greater and variable pattern occurred in the mediolateral roll and yaw angular velocities. These findings are likely associated with mediolateral trunk instability, which is a characteristic

**Table 2. Correlations between clinical parameters and SPARC values in the stroke and control groups.**

		Stroke SPARC Angular velocity (yaw)	Stroke SPARC Angular velocity (pitch)	Stroke SPARC Angular velocity (roll)	Control SPARC Angular velocity (yaw)	Control SPARC Angular velocity (pitch)	Control SPARC Angular velocity (roll)
Gait Speed [#]	R	**-0.47**	**-0.542**	0.211	-0.017	-0.24	0.093
	p-value	**0.007***	**0.001***	0.247	0.927	0.185	0.615
	n	**32**	**32**	32	32	32	32
Gait Symmetry Step Length [¥]	R	0.067	0.264	-0.283	0.065	-0.007	-0.287
	p-value	0.714	0.144	0.199	0.723	0.969	0.111
	n	32	32	32	32	32	32
FMA_LL [#]	R	-0.333	-0.278	0.161			
	p-value	0.067	0.124	0.377			
	n	32	32	32			
Spasticity, MAS [¥]							
Plantiflexors	R	0.313	**0.505**	-0.248			
	p-value	0.081	**0.003***	0.171			
	n	32	**32**	32			
Knee Extensors	R	0.275	**0.324**	**-0.46**			
	p-value	0.128	**0.002***	**0.002***			
	n	32	**32**	**32**			
Adductors	R	**0.385**	**0.437**	-0.321			
	p-value	**0.029***	**0.012***	0.073			
	n	**32**	**32**	32			

Note: FMA-LL, Fugl Meyer Assessment–Lower Limb; MAS, Modified Ashworth Scale; n = number of participants; Pearson's correlations (p < 0.05).

of the stroke gait. Gait smoothness quantified using the SPARC metrics also showed independence of speed in the control group, which indicates SPARC is a good complementary metric to the traditional gait speed assessment in the clinic. Our results also demonstrated that pitch smoothness, which reflects the step-to-step pendular mechanics in the sagittal plane, was positively correlated with plantarflexors, knee extensors, and hip adductors spasticity. It was suggestive of the adaptive use of spasticity in maintaining efficient walking. Conversely, knee extensor spasticity was negatively correlated with smoothness of the roll angular velocity, thus, contributing to the evident gait smoothness deficit in this component. We suggest that gait smoothness extracted from IMUs may represent a complementary outcome measure to the traditional gait speed assessments, often employed in the clinic.

A slower gait in individuals with stroke was expected, considering that stroke affects walking speed [37]. Poor motor control, reduced intermuscular coordination [38], and gait instability [39] may decrease velocity and smoothness during walking. The severity of the stroke lesion influences gait speed; nonetheless, some patients with mild motor paralysis may still walk slowly [40]. In this line of thought, the movement quality metric presented here may provide additional gait quality indicators in these specific patients with slower gait but mild motor symptoms. Our results indicated that smoothness in the roll angular velocity showed the ability to capture the post-stroke impairment and was not affected by gait speed. As such, it may circumvent these above-mentioned gait speed influences. Individuals with mild motor
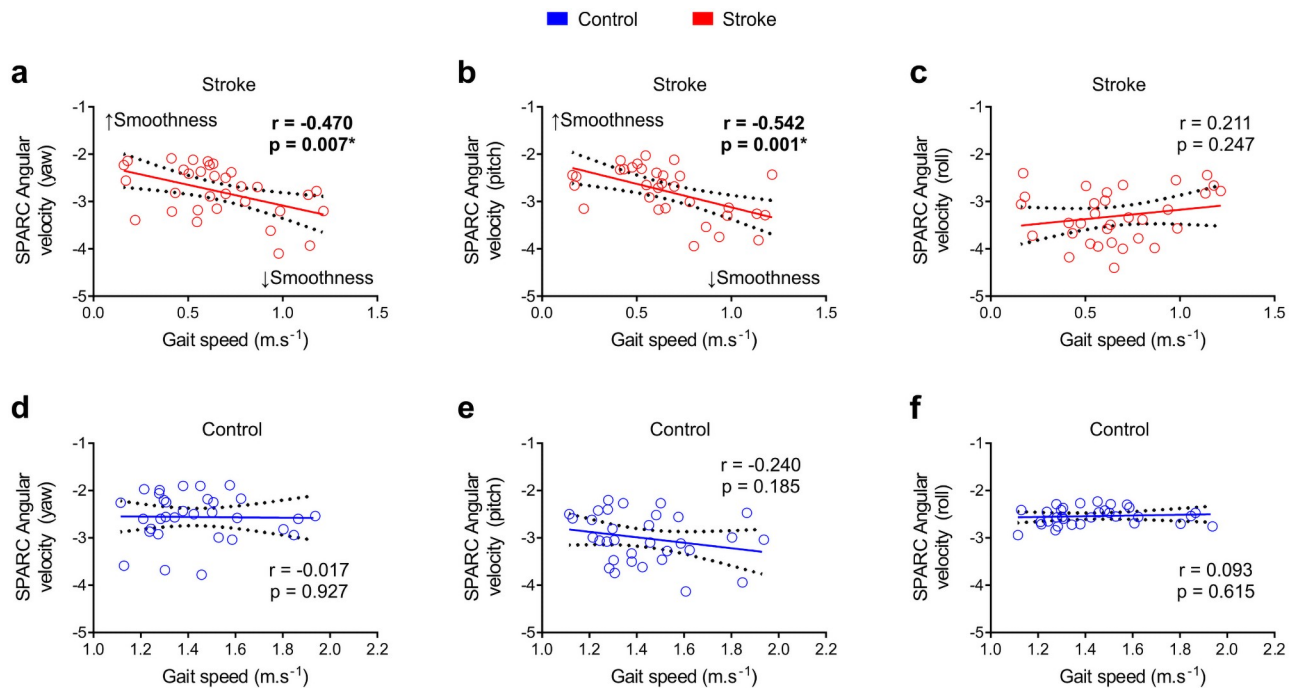
Fig 4. Correlations between SPARC and gait speed for the stroke group indicated faster speeds were associated with reduced smoothness. (a) There was a significant correlation between SPARC angular velocity (yaw) and gait velocity in the stroke group. **(b)** This correlation was also significant between SPARC angular velocity (pitch) and gait velocity in the stroke group. **(c)** The correlation between SPARC angular velocity (roll) and gait velocity in the stroke group was not significant. **(d-f)** Correlations between SPARC angular velocity (yaw, pitch, and roll) and gait velocity were not significant in the control group. The dashed line represents the 95% confidence interval; Pearson correlation, *p < 0.05.

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paralysis and slow walking speed may display reduced trunk stability [40]. The IMU placement used in the present study (waist-mounted) may, therefore, present important advantages in capturing these subtle trunk oscillations. Thus, SPARC is a good metric in assessing gait smoothness because it is less dependent on the duration of the gait, for example, compared to the Jerk metric, which is more susceptible to duration effects (see S1 Table).

Previous research suggests that gains in gait speed are related to improvements in motor control [41]. Gait speed is the leading indicator of function, level of disability, survival and is broadly used to classify ambulation status after stroke [9,42]. In upper limb studies of reach to grasp movements, moving faster can increase rates of muscle activation that controls proximal and distal multi-joint movements [43]. For example, the reach paths are straighter, finger movements are more efficient, and the fingers open wider [43]. Similarly, point-to-point reach movements recover first by regaining the ability to generate submovements, followed by reacquiring the means to combine submovements [44,45]. This impacts upper limb movement smoothness because the submovements become fewer, longer, and faster with recovery [45]. It is thought that, overall, it is hard for humans to execute slow upper limb movements with smoothness and rhythmicity [46]. Here, individuals with a stroke displayed slower gait speed and reduced smoothness than the reference group, corroborating the findings from upper limb studies. Nonetheless, it is essential to highlight the differences between upper and lower limb studies on movement smoothness. Conversely to reach-to-grasp movements, gait involves full body weight support and greater walking speeds are achieved by providing body weight [47]. Dealing with gravity seems to be a major difference between upper and lower limb studies on movement smoothness. It is straightforward to think of a faster and smoother

reach-to-grasp trajectory if performed in a straight line, which would be the shortest path in a point-to-point reach task.

On the other hand, gait is a cyclic process consisting of several stride cycles used to travel to the endpoint (e.g., here the 10 MWT mark), therefore, should rather be considered in terms of step-to-step transitions. Walking speed would affect the stride cycle submovements, such as stance, double-support, and single support phases. In a sub-acute stroke, walking faster may improve spatiotemporal symmetry in double- and single-support proportions between paretic and nonparetic sides [47]. For example, a greater proportion of single support using the paretic limb was evident when walking faster, suggesting increased usage of this limb during the gait cycle [47]. Several studies assessed movement smoothness in individuals with stroke using a waist-mounted accelerometer [48–52], and pieces of evidence on the effect of speed are lacking. It is known that, in older adults, greater walking speeds may induce less smooth accelerations in ML and AP directions [53]. Here, we suggest that greater spatiotemporal symmetry at faster speeds may be afforded by greater dependence on the paretic lower limb with respectively reduced smoothness.

Smoothness was also correlated with the adaptive use of spasticity in individuals with stroke. We found that greater lower limb spasticity was related to gait smoothness in the pitch component. Prior studies conducted in the upper limbs have demonstrated that increased spasticity affects inter-joint coordination during reaching tasks, causing a reduction in movement smoothness [54–56]. As mentioned earlier, movement intermittency in gait must be considered in terms of step-to-step transitions, conversely to upper limb studies that focus on point-to-point movements. Movements in the pitch direction reflect the body pendular motion in the sagittal plane, where the lower limbs support step-to-step transitions efficiently [57]. In post-stroke individuals, the lower limb is thought to act as a rigid shaft supporting the pendular transduction during walking, which is maintained to some extent despite the motor compromise [5]. We suggest that individuals sustaining a chronic stroke learn to adapt the walking dynamics to maintain an efficient gait. They can maintain a smooth angular velocity profile in the pitch angle, which is likely supported by the adaptive use of spastic muscles. Conversely, spasticity was detrimental to maintaining smoothness in the roll angular velocity and support the importance of the roll component of SPARC in quantifying the gait impairment in stroke.

Another important aspect of our study was the task-specific approach [58,59] since the gait assessments were conducted in an outdoor environment. Our findings suggested that severely impaired stroke subjects displayed more variable gait smoothness during the 10 MWT trial. Although we did not control for intervening factors, such as the number of people or climate/soil conditions, this may indicate that it is difficult for more impaired subjects to deal with real-life constraints to maintaining a smooth gait [58]. These smoothness changes during walking may constitute relevant functional consequences and should be explored in future studies using a similar ecological approach. The use of IMUs allowed researchers to quantify gait in real-life situations, and the use of smoothness measures from IMUs allows the gait assessment in different ways. Since IMU sensors provide abundant information, future studies may also implement an approach using wearable sensors and machine learning techniques to detect subtle gait alterations of stroke survivors, similar to PD [60].

This study has some limitations to be considered, for example, the low sample size of the subgroup analysis. Further research should address the subtle smoothness changes in different levels of post-stroke impairments. Nonetheless, as mentioned above, the results indicated that severe stroke participants displayed greater variability of movement smoothness along the 10 meters of outdoor walking than controls and mild stroke participants. To the best of our knowledge, the present study is the first to evaluate the gait smoothness of post-stroke

individuals walking in a "real context"–i.e. mimicking functional activity challenges during everyday life [41]. Another limitation is the sample heterogeneity, particularly in age and time post-stroke. Nonetheless, we found no relationship between these factors and SPARC. Further studies may analyze the relationship between SPARC and data acquired using scales to assess balance (such as the BERG balance scale) [39] and other functional walking tests (such as the Functional Ambulance Categories [61]). Finally, it is still necessary to investigate if gait smoothness is related to other clinical aspects, such as the risk of falling.

This study demonstrated that the SPARC analysis can be applied to quantify gait smoothness in post-stroke individuals in an outdoor environment. Our results showed that chronic post-stroke participants presented lower SPARC values (i.e. reduced smoothness) than controls. The convergence of results suggests that the reduced gait smoothness saw post-stroke might be due to impaired mediolateral trunk movements with respectively increased instability, as previously described [62]. The independence of SPARC from gait speed and spatiotemporal symmetry suggests that movement smoothness may add information to the traditional gait speed assessment of the 10 MWT. In this line of thought, it is reasonable to think that a rehabilitation program may focus on increasing gait speed and maintaining or reducing unsmooth movements to prevent falls. Nonetheless, further studies are needed to investigate the relationship between gait smoothness, gait symmetry, and risk of falls. In brief, smoothness evaluation adds information about movement quality, and it could be used as an additional measure to help clinicians in quantifying results of gait rehabilitation in post-stroke subjects.

Supporting information

S1 Table. Correlations between clinical parameters and Jerk values in the stroke and control groups.
(TIF)

S1 File.
(XLSX)

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References

1. Kim CY, Choi JD. Comparison between ankle proprioception measurements and postural sway test for evaluating ankle instability in subjects with functional ankle instability. Journal of back and musculoskeletal rehabilitation. 2016; 29(1):97–107. https://doi.org/10.3233/BMR-150603 PMID: 26406221

2. Bohannon RW, Andrews AW. Interrater reliability of hand-held dynamometry. Physical therapy. 1987; 67(6):931–3. https://doi.org/10.1093/ptj/67.6.931 PMID: 3588679

3. Beyaert C, Vasa R, Frykberg GE. Gait post-stroke: Pathophysiology and rehabilitation strategies. Neurophysiol Clin. 2015; 45(4–5):335–55. https://doi.org/10.1016/j.neucli.2015.09.005 PMID: 26547547

4. Roerdink M, Lamoth CJ, Kwakkel G, van Wieringen PC, Beek PJ. Gait coordination after stroke: benefits of acoustically paced treadmill walking. Physical therapy. 2007; 87(8):1009–22. https://doi.org/10.2522/ptj.20050394 PMID: 17553922

5. Balbinot G, Schuch CP, Bianchi Oliveira H, Peyre-Tartaruga LA. Mechanical and energetic determinants of impaired gait following stroke: segmental work and pendular energy transduction during treadmill walking. Biol Open. 2020; 9(7). https://doi.org/10.1242/bio.051581 PMID: 32694152

6. Robinson CA, Shumway-Cook A, Matsuda PN, Ciol MA. Understanding physical factors associated with participation in community ambulation following stroke. Disabil Rehabil. 2011; 33(12):1033–42. https://doi.org/10.3109/09638288.2010.520803 PMID: 20923316

7. Hess RJ, Brach JS, Piva SR, VanSwearingen JM. Walking skill can be assessed in older adults: validity of the Figure-of-8 Walk Test. Physical therapy. 2010; 90(1):89–99. https://doi.org/10.2522/ptj.20080121 PMID: 19959654

8. Perera S, Patel KV, Rosano C, Rubin SM, Satterfield S, Harris T, et al. Gait Speed Predicts Incident Disability: A Pooled Analysis. The journals of gerontology Series A, Biological sciences and medical sciences. 2016; 71(1):63–71. https://doi.org/10.1093/gerona/glv126 PMID: 26297942

9. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al. Gait speed and survival in older adults. Jama. 2011; 305(1):50–8. https://doi.org/10.1001/jama.2010.1923 PMID: 21205966

10. Asai T, Misu S, Sawa R, Doi T, Yamada M. The association between fear of falling and smoothness of lower trunk oscillation in gait varies according to gait speed in community-dwelling older adults. Journal of neuroengineering and rehabilitation. 2017; 14(1):5. https://doi.org/10.1186/s12984-016-0211-0 PMID: 28103907

11. Beck Y, Herman T, Brozgol M, Giladi N, Mirelman A, Hausdorff JM. SPARC: a new approach to quantifying gait smoothness in patients with Parkinson's disease. Journal of neuroengineering and rehabilitation. 2018; 15(1):49. https://doi.org/10.1186/s12984-018-0398-3 PMID: 29914518

12. Balasubramanian S, Melendez-Calderon A, Roby-Brami A, Burdet E. On the analysis of movement smoothness. Journal of neuroengineering and rehabilitation. 2015; 12:112. https://doi.org/10.1186/s12984-015-0090-9 PMID: 26651329

13. Lowry KA, Vanswearingen JM, Perera S, Studenski SA, Brach JS. Walking smoothness is associated with self-reported function after accounting for gait speed. The journals of gerontology Series A, Biological sciences and medical sciences. 2013; 68(10):1286–90. https://doi.org/10.1093/gerona/glt034 PMID: 23689828

14. Duarte E, Marco E, Muniesa JM, Belmonte R, Aguilar JJ, Escalada F. Early detection of non-ambulatory survivors six months after stroke. NeuroRehabilitation. 2010; 26(4):317–23. https://doi.org/10.3233/NRE-2010-0568 PMID: 20555154

15. Brach JS, McGurl D, Wert D, Vanswearingen JM, Perera S, Cham R, et al. Validation of a measure of smoothness of walking. The journals of gerontology Series A, Biological sciences and medical sciences. 2011; 66(1):136–41. https://doi.org/10.1093/gerona/glq170 PMID: 20923910

16. Gulde P, Hermsdorfer J. Smoothness Metrics in Complex Movement Tasks. Frontiers in neurology. 2018; 9:615. https://doi.org/10.3389/fneur.2018.00615 PMID: 30258393

17. Melendez-Calderon A, Shirota C, Balasubramanian S. Estimating Movement Smoothness From Inertial Measurement Units. Front Bioeng Biotechnol. 2020; 8:558771. https://doi.org/10.3389/fbioe.2020.558771 PMID: 33520949

18. Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. Gait & posture. 2003; 18(1):35–46.

19. Latt MD, Menz HB, Fung VS, Lord SR. Walking speed, cadence and step length are selected to optimize the stability of head and pelvis accelerations. Experimental brain research. 2008; 184(2):201–9. https://doi.org/10.1007/s00221-007-1094-x PMID: 17717650

20. Vienne A, Barrois RP, Buffat S, Ricard D, Vidal PP. Inertial Sensors to Assess Gait Quality in Patients with Neurological Disorders: A Systematic Review of Technical and Analytical Challenges. Frontiers in psychology. 2017; 8:817. https://doi.org/10.3389/fpsyg.2017.00817 PMID: 28572784

21. Pinto C, Schuch CP, Balbinot G, Salazar AP, Hennig EM, Kleiner AFR, et al. Movement smoothness during a functional mobility task in subjects with Parkinson's disease and freezing of gait—an analysis using inertial measurement units. Journal of neuroengineering and rehabilitation. 2019; 16(1):110. https://doi.org/10.1186/s12984-019-0579-8 PMID: 31488184

22. Rech KD, Salazar AP, Marchese RR, Schifino G, Cimolin V, Pagnussat AS. Fugl-Meyer Assessment Scores Are Related With Kinematic Measures in People with Chronic Hemiparesis after Stroke. J Stroke Cerebrovasc Dis. 2020; 29(1):104463. https://doi.org/10.1016/j.jstrokecerebrovasdis.2019.104463 PMID: 31740027

23. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. Stroke. 1995; 26(6):982–9. https://doi.org/10.1161/01.str.26.6.982 PMID: 7762050

24. Tao W, Liu T, Zheng R, Feng H. Gait analysis using wearable sensors. Sensors (Basel). 2012; 12(2):2255–83. https://doi.org/10.3390/s120202255 PMID: 22438763

25. Balasubramanian S, Melendez-Calderon A, Burdet E. A robust and sensitive metric for quantifying movement smoothness. IEEE transactions on bio-medical engineering. 2012; 59(8):2126–36. https://doi.org/10.1109/TBME.2011.2179545 PMID: 22180502

26. Figueiredo AI, Balbinot G, Brauner FO, Schiavo A, Baptista RR, Pagnussat AS, et al. SPARC Metrics Provide Mobility Smoothness Assessment in Oldest-Old With and Without a History of Falls: A Case Control Study. Front Physiol. 2020; 11:540. https://doi.org/10.3389/fphys.2020.00540 PMID: 32587523

27. von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: guidelines for reporting observational studies. International journal of surgery. 2014; 12(12):1495–9. https://doi.org/10.1016/j.ijsu.2014.07.013 PMID: 25046131

28. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. Journal of psychiatric research. 1975; 12(3):189–98. https://doi.org/10.1016/0022-3956(75)90026-6 PMID: 1202204

29. Fugl-Meyer AR. Post-stroke hemiplegia assessment of physical properties. Scandinavian journal of rehabilitation medicine Supplement. 1980; 7:85–93. PMID: 6932734

30. Daly JJ, Zimbelman J, Roenigk KL, McCabe JP, Rogers JM, Butler K, et al. Recovery of coordinated gait: randomized controlled stroke trial of functional electrical stimulation (FES) versus no FES, with weight-supported treadmill and over-ground training. Neurorehabilitation and neural repair. 2011; 25(7):588–96. https://doi.org/10.1177/1545968311400092 PMID: 21515871

31. Lindsay C, Kouzouna A, Simcox C, Pandyan AD. Pharmacological interventions other than botulinum toxin for spasticity after stroke. Cochrane Database Syst Rev. 2016; 10:CD010362. https://doi.org/10.1002/14651858.CD010362.pub2 PMID: 27711973

32. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. Physical therapy. 1987; 67(2):206–7. https://doi.org/10.1093/ptj/67.2.206 PMID: 3809245

33. Bugane F, Benedetti MG, Casadio G, Attala S, Biagi F, Manca M, et al. Estimation of spatial-temporal gait parameters in level walking based on a single accelerometer: validation on normal subjects by standard gait analysis. Computer methods and programs in biomedicine. 2012; 108(1):129–37. https://doi.org/10.1016/j.cmpb.2012.02.003 PMID: 22391334

34. Cimolin V, Capodaglio P, Cau N, Galli M, Santovito C, Patrizi A, et al. Computation of spatio-temporal parameters in level walking using a single inertial system in lean and obese adolescents. Biomed Tech (Berl). 2017; 62(5):505–11. https://doi.org/10.1515/bmt-2015-0180 PMID: 27898396

35. Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. J Manipulative Physiol Ther. 1987; 10(4):172–6. PMID: 2958572

36. Guzik A, Druzbicki M, Perenc L, Podgorska-Bednarz J. Can an Observational Gait Scale Produce a Result Consistent with Symmetry Indexes Obtained from 3-Dimensional Gait Analysis?: A Concurrent Validity Study. J Clin Med. 2020; 9(4). https://doi.org/10.3390/jcm9040926 PMID: 32231065

37. Higginson JS, Zajac FE, Neptune RR, Kautz SA, Delp SL. Muscle contributions to support during gait in an individual with post-stroke hemiparesis. Journal of biomechanics. 2006; 39(10):1769–77. https://doi.org/10.1016/j.jbiomech.2005.05.032 PMID: 16046223

38. Routson RL, Clark DJ, Bowden MG, Kautz SA, Neptune RR. The influence of locomotor rehabilitation on module quality and post-stroke hemiparetic walking performance. Gait & posture. 2013; 38(3):511–7. https://doi.org/10.1016/j.gaitpost.2013.01.020 PMID: 23489952

39. Dean JC, Kautz SA. Foot placement control and gait instability among people with stroke. Journal of rehabilitation research and development. 2015; 52(5):577–90. https://doi.org/10.1682/JRRD.2014.09.0207 PMID: 26437301

40. Mizuta N, Hasui N, Nakatani T, Takamura Y, Fujii S, Tsutsumi M, et al. Walking characteristics including mild motor paralysis and slow walking speed in post-stroke patients. Sci Rep. 2020; 10(1):11819. https://doi.org/10.1038/s41598-020-68905-3 PMID: 32678273

41. Lodha N, Patel P, Casamento-Moran A, Hays E, Poisson SN, Christou EA. Strength or Motor Control: What Matters in High-Functioning Stroke? Frontiers in neurology. 2018; 9:1160. https://doi.org/10.3389/fneur.2018.01160 PMID: 30687217

42. Schmid A, Duncan PW, Studenski S, Lai SM, Richards L, Perera S, et al. Improvements in speed-based gait classifications are meaningful. Stroke. 2007; 38(7):2096–100. https://doi.org/10.1161/STROKEAHA.106.475921 PMID: 17510461

43. DeJong SL, Schaefer SY, Lang CE. Need for speed: better movement quality during faster task performance after stroke. Neurorehabilitation and neural repair. 2012; 26(4):362–73. https://doi.org/10.1177/1545968311425926 PMID: 22140198

44. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, et al. Movement smoothness changes during stroke recovery. J Neurosci. 2002; 22(18):8297–304. https://doi.org/10.1523/JNEUROSCI.22-18-08297.2002 PMID: 12223584

45. Dipietro L, Krebs HI, Fasoli SE, Volpe BT, Hogan N. Submovement changes characterize generalization of motor recovery after stroke. Cortex. 2009; 45(3):318–24. https://doi.org/10.1016/j.cortex.2008.02.008 PMID: 18640668

46. Park SW, Marino H, Charles SK, Sternad D, Hogan N. Moving slowly is hard for humans: limitations of dynamic primitives. J Neurophysiol. 2017; 118(1):69–83. https://doi.org/10.1152/jn.00643.2016 PMID: 28356477

47. Lamontagne A, Fung J. Faster is better: implications for speed-intensive gait training after stroke. Stroke. 2004; 35(11):2543–8. https://doi.org/10.1161/01.STR.0000144685.88760.d7 PMID: 15472095

48. Mizuike C, Ohgi S, Morita S. Analysis of stroke patient walking dynamics using a tri-axial accelerometer. Gait & posture. 2009; 30(1):60–4. https://doi.org/10.1016/j.gaitpost.2009.02.017 PMID: 19349181

49. Buckley C, Mico-Amigo ME, Dunne-Willows M, Godfrey A, Hickey A, Lord S, et al. Gait Asymmetry Post-Stroke: Determining Valid and Reliable Methods Using a Single Accelerometer Located on the Trunk. Sensors (Basel). 2019; 20(1). https://doi.org/10.3390/s20010037 PMID: 31861630

50. Osaka H, Shinkoda K, Watanabe S, Fujita D, Kobara K, Yoshimura Y, et al. Association between trunk acceleration during walking and clinically assessed balance in patients with stroke. NeuroRehabilitation. 2017; 41(4):783–90. https://doi.org/10.3233/NRE-172171 PMID: 29254113

51. Isho T, Usuda S. Association of trunk control with mobility performance and accelerometry-based gait characteristics in hemiparetic patients with subacute stroke. Gait & posture. 2016; 44:89–93. https://doi.org/10.1016/j.gaitpost.2015.11.011 PMID: 27004638

52. Yen CL, Chang KC, Wu CY, Hsieh YW. The relationship between trunk acceleration parameters and kinematic characteristics during walking in patients with stroke. J Phys Ther Sci. 2019; 31(8):638–44. https://doi.org/10.1589/jpts.31.638 PMID: 31528001

53. Huijben B, van Schooten KS, van Dieen JH, Pijnappels M. The effect of walking speed on quality of gait in older adults. Gait & posture. 2018; 65:112–6. https://doi.org/10.1016/j.gaitpost.2018.07.004 PMID: 30558916

54. Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. Brain. 1996; 119 (Pt 1):281–93. https://doi.org/10.1093/brain/119.1.281 PMID: 8624689

55. Tsao CC, Mirbagheri MM. Upper limb impairments associated with spasticity in neurological disorders. Journal of neuroengineering and rehabilitation. 2007; 4:45. https://doi.org/10.1186/1743-0003-4-45 PMID: 18047660

56. Bensmail D, Robertson JV, Fermanian C, Roby-Brami A. Botulinum toxin to treat upper-limb spasticity in hemiparetic patients: analysis of function and kinematics of reaching movements. Neurorehabilitation and neural repair. 2010; 24(3):273–81. https://doi.org/10.1177/1545968309347682 PMID: 20067949

57. Saibene F, Minetti AE. Biomechanical and physiological aspects of legged locomotion in humans. Eur J Appl Physiol. 2003; 88(4–5):297–316. https://doi.org/10.1007/s00421-002-0654-9 PMID: 12527959

58. Donovan K, Lord SE, McNaughton HK, Weatherall M. Mobility beyond the clinic: the effect of environment on gait and its measurement in community-ambulant stroke survivors. Clin Rehabil. 2008; 22 (6):556–63. https://doi.org/10.1177/0269215507085378 PMID: 18511535

59. Yang S, Zhang JT, Novak AC, Brouwer B, Li Q. Estimation of spatio-temporal parameters for post-stroke hemiparetic gait using inertial sensors. Gait & posture. 2013; 37(3):354–8. https://doi.org/10.1016/j.gaitpost.2012.07.032 PMID: 23000235

60. Reches T, Dagan M, Herman T, Gazit E, Gouskova NA, Giladi N, et al. Using Wearable Sensors and Machine Learning to Automatically Detect Freezing of Gait during a FOG-Provoking Test. Sensors (Basel). 2020; 20(16). https://doi.org/10.3390/s20164474 PMID: 32785163

61. Mehrholz J, Wagner K, Rutte K, Meissner D, Pohl M. Predictive validity and responsiveness of the functional ambulation category in hemiparetic patients after stroke. Archives of physical medicine and rehabilitation. 2007; 88(10):1314–9. https://doi.org/10.1016/j.apmr.2007.06.764 PMID: 17908575

62. Van Criekinge T, Saeys W, Hallemans A, Velghe S, Viskens PJ, Vereeck L, et al. Trunk biomechanics during hemiplegic gait after stroke: A systematic review. Gait & posture. 2017; 54:133–43. https://doi.org/10.1016/j.gaitpost.2017.03.004 PMID: 28288334