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Synchronized Cyclograms to Assess Inter-Limb Symmetry during Gait in Post-Stroke Patients

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Abstract: The aim of this study was to assess the inter-limb symmetry during gait in post-stroke patients using the synchronized cyclograms technique. In total, 41 individuals with stroke (21 left and 20 right hemiplegic patients; age: 57.9 ± 12.8 years; time stroke event 4.6 ± 1.8 years) and 48 age-, sex-, and height-matched individuals (control group: CG; age: 54.4 ± 12.5 years) were assessed via 3D gait analysis. Raw kinematic data were processed to compute spatio-temporal parameters (speed, stride length, cadence, stance, swing, and double support phases duration) and angle–angle diagrams (synchronized cyclograms), which were characterized in terms of area, orientation, and trend symmetry indices. The results reveal that all spatio-temporal parameters are characterized by abnormal values, with reduced speed, stride length, cadence, and swing phase duration and increased stance and double support phases duration. With respect to inter-limb symmetry, higher values were found in post-stroke individuals for all the considered parameters as patients generally exhibited a cyclogram characterized by larger areas, higher orientation, and trend symmetry parameters with respect to CG. The described alterations of gait asymmetry are important from a clinical point of view as the achievement of symmetry in gait represents a crucial objective in the rehabilitation of hemiplegic people.

Keywords: stroke; gait; kinematics; symmetry; rehabilitation

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1. Introduction

Stroke is the leading cause of long-term disabilities in adults, resulting in a wide range of neurological deficits, affecting mobility and cognitive and communication abilities. Gait deficits, such as asymmetric walking, reduced weight bearing on the paretic limb, and reduced intra- and inter-limb coordination, are widespread among individuals with stroke [1–4], and negatively impact their independence in daily life activities. Thus, improvement of walking function is one of the main goals of rehabilitative treatments. In this context, particular attention is given to restoring the capacity to properly shift weight between the lower extremities during gait and on the equalization of weight bearing through the lower extremities in order to improve gait symmetry. In particular, gait asymmetry has been associated with adverse outcomes such as inefficiency, difficulties in balance control, increased risk of falls and musculoskeletal injuries to the nonparetic lower limb, and loss of bone mass density in the paretic lower limb [5–8]. Because of these aspects, it is necessary to have tools to accurately characterize asymmetry. For example, it could be very interesting to evaluate asymmetry variation following rehabilitation treatments to verify their effectiveness.

Quantitative evaluation of gait symmetry is usually performed according to the differences observed in a subset of spatio-temporal gait parameters commonly analyzed in stroke survivors (e.g., step length, single and double support duration) between the affected and non-affected limb [5,9–14] whilst other kinematic/kinetic variables are considered less frequently [5,12,13,15–20]. However, even though the above-mentioned approach is quite easy to implement, it presents some limitations such as the inability to identify the temporal location of asymmetry or to detect occasional events during the gait cycle and a low sensitivity and lack of standardization due to the arbitrary choice of equation and variables [5,12,15,21,22]. To overcome such drawbacks, new methods allowing for a quantification of gait symmetry have recently been developed. Among them, particular relevance is given to waveform-based methods and statistically-based and nonlinear methods [16]. Although the statistically-based and nonlinear methods rely on the use of consolidate statistical analysis and complex and sophisticated approaches, they are difficult to interpret and generally not usable in a clinical context [16]. On the contrary, waveform-based methods exploiting all the kinematic information of the lower limb joint angles during a complete gait cycle seem to be a valid option to quantify gait symmetry. However, it should be noted that the interpretation of these techniques is not as straightforward as the use of discrete symmetry indexes.

In recent years, several studies have attempted to apply waveform-based analysis to assess inter-limb symmetry during gait in several neurologic and orthopedic conditions [15,16,23–28]. The results of such studies suggest that this approach is sensitive even to relatively low asymmetries and may represent a useful complementary tool to achieve a detailed assessment of gait alterations. Among the waveform-based methods, the most used is based on the so-called "bilateral cyclograms", resulting in the creation of a left-right angle–angle diagram for the joint of interest [29–31]. This method, which was firstly proposed in the late 1960s [32], considers the angular positions of two contralateral joints simultaneously plotted in the same diagram, without considering the time axis of each curve. According to this approach, symmetry quantification can be carried out either by calculating the simple geometric properties of the curve (i.e., such as the area, perimeter, orientation, and shape) or various order moments and trend symmetry [15,16,21,30,33].

Despite the importance of a comprehensive assessment of gait symmetry in post-stroke patients, it is quite surprising to observe that just one study has investigated it using the cyclograms so far. Pilkar et al. [23] developed a novel cyclogram-based symmetry method in order to quantify the symmetry of the lower joint and assessed the effect of the use of a foot drop stimulator in a group of 13 stroke patients for 6 months. Their results showed that, as expected, unaffected individuals exhibited a more symmetrical gait at the hip, knee, and ankle joints, and those with stroke did not show any significant changes in symmetry after a 6-month period of foot drop stimulator use at follow-up.

Considering the potentiality associated with the use of cyclograms to investigate inter-limb symmetry and the paucity of existing data, in this paper, we proposed a retrospective study of a group of people with stroke. The aim was to characterize lowerlimb joint kinematics asymmetry during gait in the post-stroke group with respect to unaffected individuals. The bilateral cyclograms provide detailed information that is easy to understand compared with other methods used. So, it is interesting from a clinical point of view to improve knowledge about functional asymmetry and support clinicians in identifying rehabilitation programs.

2. Materials and Methods

2.1. Participants

In total, 41 stroke survivors (21 left and 20 right hemiplegic patients; 16 females, 25 males; age: 57.9 ± 12.8 years; time stroke event 4.6 ± 1.8 years) underwent a computerized 3D gait analysis during a 5-year period at the San Giuseppe Hospital, Istituto Auxologico Italiano, Piancavallo (Verbania), Italy. All patients were assessed according to the classification of Bamford et al. (1991) and showed partial anterior circulation infarct (PACI) features. Inclusion criteria were as follows: age > 18 years, presence of paresis in one lower limb, ability to understand the vocal cues to correctly perform the gait analysis test, and ability to walk 10 m without assistance. Patients with bilateral stroke and the history of other neurological or musculoskeletal disorders unrelated to stroke were excluded.

In total, 48 age-, sex-, and height-matched individuals (19 females, 29 males; age: 54.4 ± 12.5 years) recruited from the University of Cagliari served as a control group (CG). People in the CG were not affected by any neurological or musculoskeletal disorder impacting on their gait abilities. The participants (whose anthropometric and clinical features are reported in Table 1) were required to sign a written informed consent form in which the details of the experimental tests were reported. This study was performed in accordance with the ethics standards of the Institute Auxologico Italiano with the approval of the study by the ethics committee on 20 July 2021 (protocol code 21C130) and with the Declaration of Helsinki 1964 and its latest amendments. Written informed consent was obtained from all participants.

Table 1. Participants' characteristics. Values are expressed as mean ± SD.

	Stroke	**Control Group**
	(*n* = 41)	(*n* = 48)
Gender, *n* (%)		
Male	25 (60.9%)	29 (60.4)
Female	16 (39.1%)	19 (39.6%)
Age (years)	57.9 ± 12.8	54.4 ± 12.5
Height (m)	1.69 ± 0.07	1.68 ± 0.08
Body mass (kg)	77.21 ±16.31	67.92 ± 11.68
Time since stroke (years)	4.6 (1.8)	
Stroke type, *n* (%)		
Ischemic	31 (75.6)	
Hemorrhagic	10 (24.4)	
Affected hemisphere, *n* (%)		
Right	20 (48.8)	
Left	21 (51.2)	

2.2. Data Collection and Processing

A 3D gait analysis examination was performed on the patients at the Movement Analysis Laboratory of San Giuseppe Hospital, Istituto Auxologico Italiano, Piancavallo (VB), Italy, using an optoelectronic system using 6 cameras (VICON, Oxford Metrics Ltd., Oxford, UK; sample rate: 100 Hz) and 2 force platforms (Kistler, Winterthur, CH; acquisition frequency: 500 Hz). The evaluation of the gait kinematics was performed using passive reflective markers attached to the participants' anatomical landmarks according to the literature [34] (Figure 1).

Once equipped with the marker set, the participants were asked to walk barefoot at their natural gait speed along an 8-m-long walkway, embedding the force platforms in its central part. Each participant was asked to perform at least 5 trials in order to guarantee the reproducibility of the collected kinematic and kinetic data. The raw 3D markers' trajectories were then processed using dedicated software (Polygon Application, version 2.4, VICON, Oxford Metrics Ltd., Oxford, UK) to obtain the following variables:

- Spatio-temporal gait parameters (i.e., gait speed, cadence, stride length, stance, swing, and double support phase duration);
- The dynamic range of motion (ROM) for hip and knee flexion-extension and ankle dorsi-plantarflexion, computed as the difference between the maximum and minimum angle value recorded during the gait cycle.

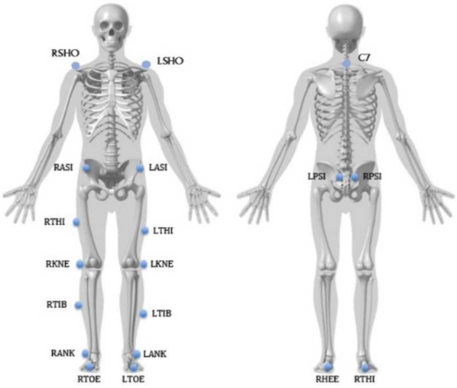

Figure 1. Graphic representation of marker placement.

2.3. Inter-Limb Symmetry Quantification by Means of the Waveform-Based Method

Bilateral cyclograms were obtained using a dedicated Matlab routine based on the procedure proposed by Goswami [31], allowing for the creation of left-right angle diagrams from which the following parameters were calculated (Figure 2):

- Cyclogram area (degrees2), defined as the area enclosed by the curve obtained from the left-right angle diagram [33]. A hypothetical symmetrical gait would lead left and right joints to assume the same angular position during the gait cycle. In this way cyclogram points would lie on a 45° line in the diagram, with a null area;
- Cyclogram orientation (degrees), expressed as the absolute value of the angular difference φ between the perfect symmetry line (45° line) and the orientation of the principal axis of inertia [30,31], which is the direction of the eigenvector of the inertial matrix for the cyclogram points in the x-y (left vs. right joint angle) reference system. Low φ angles indicate higher interlimb symmetry;
- Trend symmetry index (dimensionless), calculated to assess the similarity of two waveforms (i.e., right and left leg angular trend across the gait cycles, for each joint) by means of an eigenvector analysis. The trend symmetry value is calculated by taking the ratio of the variability about the eigenvector to the variability along the eigenvector, and is expressed as a percent. A value of 0% indicates perfect symmetry and interlimb asymmetry results in high trend symmetry values [21].

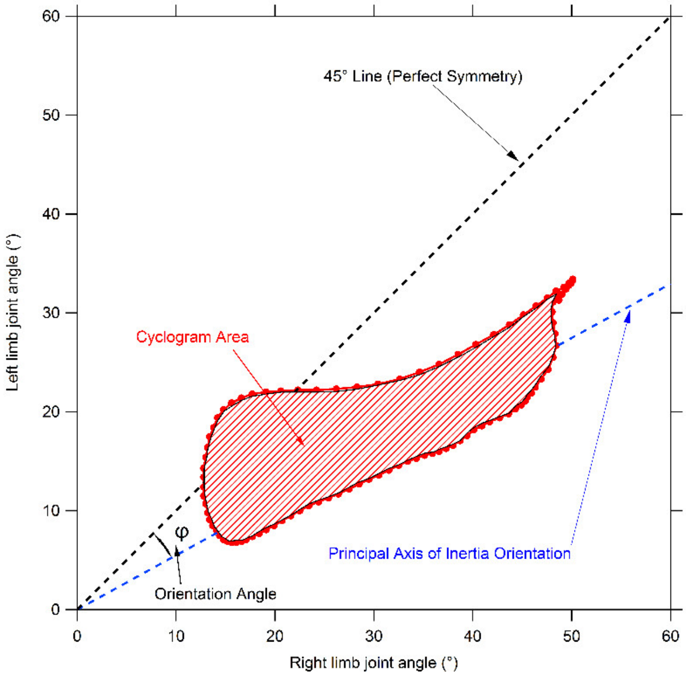

Figure 2. Graphic representation of a cyclogram and its main features considered for the present study.

2.4. Statistical Analysis

Parametric statistical analysis was adopted after preliminarily checking the data for normality (Shapiro–Wilk's test) and homogeneity of variance (Levene's test). The existence of possible differences in symmetry introduced by the presence of stroke was investigated using distinct one-way multivariate analysis of variance (MANOVA). The first one, which investigated the differences between the spatio-temporal parameters of people with stroke and unaffected individuals, was performed by considering the participant's status (i.e., unaffected and with stroke) as the independent variable and the seven spatio-temporal parameters previously mentioned (speed, stride length, cadence, step width, stance, swing, and duration of double support phases) as dependent variables. For dynamic ROMs, a t-test was carried out considering the affected limb vs. CG and unaffected limb vs. CG. Then, we analyzed the effect of stroke on the symmetry parameters; in this case, the independent variable was once again the participant's status while the dependent variables were the three previously listed symmetry indexes calculated at the hip, knee, and ankle joints. Univariate ANOVA was carried out as a post-hoc test by reducing the level of significance to $p = 0.008$ (0.05/6) for the spatio-temporal parameters and $p = 0.017$ (0.05/3) for the symmetry indexes after a Bonferroni correction for multiple comparisons. All the analyses were performed using the IBM SPSS Statistics v.20 software (IBM, Armonk, NY, USA).

3. Results

The results of the comparison between people with stroke and unaffected individuals in terms of the spatio-temporal parameters of gait, ROM, and symmetry indexes are summarized in Tables 2–4.

Table 2. Comparison between the spatio-temporal parameters of the gait of people with stroke and unaffected individuals (control group). Values are expressed as mean ± SD.

	Stroke	**Control Group**
Gait speed (m s^{-1})	0.55 ± 0.18 *	1.23 ± 0.19
Stride length (m)	0.79 ± 0.24 *	1.31 ± 0.11
Cadence (steps min^{-1})	79.9 ± 21.5 *	111.6 ± 10.7
Stance phase (% of the gait cycle)	67.36 ± 5.73 *	59.49 ± 1.73
Swing phase (% of the gait cycle)	32.63 ± 5.73 *	40.41 ± 1.46
Double support (% of the gait cycle)	33.17 ± 13.58 *	19.58 ± 3.08

The symbol * indicates significant difference vs. control group.

The statistical analysis revealed a significant effect of the individual's status (F (7,81) = 65.53, $p < 0.001$, Wilks $\lambda = 0.15$, $\eta2 = 0.85$) on the spatio-temporal gait parameters. In particular, the follow-up analysis detected the existence of significant differences between the groups in all the investigated parameters. In particular, individuals living with stroke are characterized by reduced speed, stride length, cadence, and swing phase duration and by increased stance and double support phase duration.

Regarding dynamic ROM, the results indicated that stroke individuals were characterized by significantly reduced dynamic hip, knee, and ankle ROM of the plegic and non-plegic limb with respect to the control group. These reduced ROMs are displayed in the kinematic curves for the three lower limb joints in Figure 3.

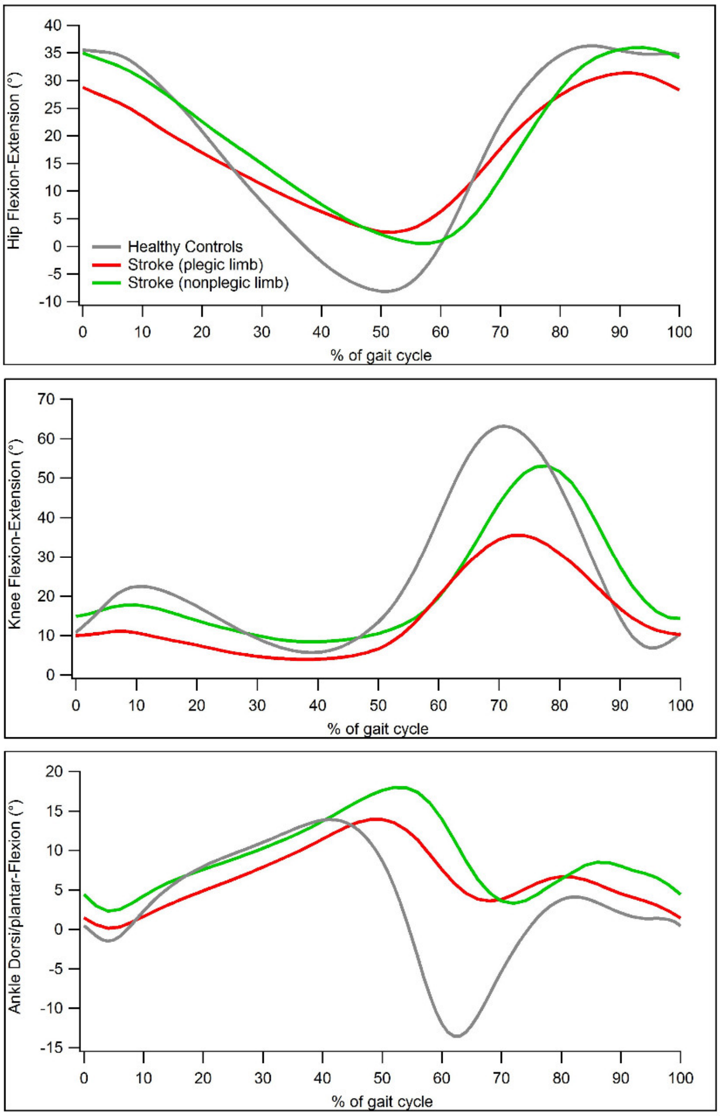

Figure 3. Gait kinematics in the sagittal plane for stroke individuals (plegic and non plegic limb) and for healthy controls. From top to bottom: hip flexion-extension, knee flexion-extension, and ankle dorsi-plantar-flexion angles during the gait cycle.

MANOVA also detected a significant effect of the presence of the disease on the symmetry indexes in all the three investigated joints, in particular, for hip (F (3,85) = 14.88, $p < 0.001$, Wilks $\lambda = 0.66$, $\eta 2 = 0.34$), knee (F (3,85) = 33.42, $p < 0.001$, Wilks $\lambda = 0.46$, $\eta 2 = 0.54$), and ankle (F (3,85) = 20.54, $p < 0.001$, Wilks $\lambda = 0.58$, $\eta 2 = 0.42$). From the post-hoc analysis, it was observed that individuals with stroke generally exhibit cyclograms characterized by larger areas, higher orientation, and trend symmetry parameters with respect to unaffected individuals. However, the magnitude of such differences was found to be dependent on the considered joint in some cases. For instance, individuals with stroke exhibited cyclogram areas about two and half times larger than controls at the hip joint, but such difference was reduced to 73% for the knee joint and 45% for the ankle joint. In contrast, the magnitude of change concerning the orientation and trend symmetry was substantially similar regardless of the considered joints. In this case, individuals with stroke were found to be characterized by values 5 to 11 times higher with respect to unaffected individuals.

Table 3. Comparison between dynamic ROM of the control group and stroke individuals. Values are expressed as mean (SD).

		Stroke		**Control Group**
		Plegic Side	**Non Plegic Side**	
ROM (°)	Hip	31.62 ± 10.30 *	39.06 ± 5.84 *	45.88 ± 4.57
	Knee	36.94 ± 16.85 *	52.80 ± 9.19 *	59.76 ± 4.27
	Ankle	17.92 ± 7.11 *	25.03 ± 8.15 *	28.60 ± 6.02

The symbol * indicates significant difference vs. control group.

Table 4. Comparison between stroke and unaffected individuals (control group). Values are expressed as mean ± SD.

Parameter	**Joint**	**Stroke**	**Control Group**
Cyclogram area (degrees^2)	Hip	248.23 ± 241.47 *	96.79 ± 84.74
Cyclogram orientation ϕ (degrees)		12.08 ± 14.92 *	1.63± 1.24
Trend Symmetry		14.38 ± 21.09 *	1.66 ± 1.26
Cyclogram area (degrees^2)	Knee	474.05 ± 356.90 *	273.43 ± 177.67
Cyclogram orientation ϕ (degrees)		12.89 ± 12.83 *	1.37 ± 1.39
Trend Symmetry		15.85 ± 13.51 *	1.35 ± 1.39
Cyclogram area (degrees^2)	Ankle	98.68 ± 69.07 *	67.84 ± 49.72
Cyclogram orientation ϕ (degrees)		15.48 ± 12.87 *	3.17 ± 2.95
Trend Symmetry		18.65 ± 16.63 *	2.89 ± 2.67

The symbol * indicates significant difference vs. control group.

4. Discussion

The aim of the present study was to quantify and characterize interlimb asymmetry during gait in post-stroke hemiparetic patients using the so-called "bilateral cyclograms" method. Compared with the control group, statistically significant differences were shown considering the three main geometric properties of the curve: area, orientation, and trend symmetry. Such information is considered relevant in the analysis of motor impairment associated with hemiparetic individuals because of their proved symmetry alteration [12,13,23,35,36]. As symmetry is one of the domains significantly impacting on gait quality and efficiency, clinical interest in investigating this aspect in hemiparetic patients is evident.

At first, our results confirm that the main spatio-temporal parameters significantly differ among patients and controls, as previously reported in similar studies [12,37–39]. Taken together, such alterations suggest the adoption of compensatory strategies aiming to increase the stability and efficiency of locomotion and preserve the residual balance and stability capabilities. The prolonged stance and double support phase duration are expected, in fact, to reduce the risk of instability and falls [10,13,37,39,40]. In the hemiparetic, to increase stability when body weight is transferred from limb to limb during gait, both feet need to be in contact with the ground for a longer time. Then, to maintain balance, the paretic pre-swing is prolonged and body weight is supported by the non-paretic limb for a longer time before paretic limb toe-off [5,12,13,41]. Therefore, the low gait speed, typical of hemiparetic patients, is likely due to the strong instability originating from muscular weakness, which characterizes the paretic side.

The outcome of the inter-limb symmetry analysis showed a well-defined trend characterized by larger asymmetry for all the joints in people with stroke, as the values of all the selected parameters were found to be significantly higher with respect to those of the control group. This is likely due to the specific nature of the gait impairments in hemiparetic patients. These subjects show alteration not only in spatio-temporal parameters but also in kinematics. For example, due to the drop foot on the paretic side, the following might occur: decreased hip flexion at the time of initial contact, limited hip excursion, lack of knee flexion in the swing phase, and decreased ankle dorsiflexion, as demonstrated by the reduced dynamic ROMs of the lower limb joints, too [38,42,43]. Although one of the main gait impairments after stroke could be a lack of ankle dorsiflexion, the compensatory knee movement reduces the range of motion of the knee itself on the affected side, thus resulting in a less asymmetrical gait pattern. The asymmetries observed in these patients could be associated with the alterations in the amplitudes of the bilateral knee angles due to impaired flexion on the paretic side. Together with the reduced walking speed and longer stance phase duration, such alterations might indicate the adoption of a pattern that aims to reduce the articular stress and compensate for the reduced muscular strength and altered joint proprioception. A somatosensory deficit is common after stroke, occurring in up to 89% of stroke survivors [44]. Proprioception and tactile somatosensorial are impaired in the leg post stroke, with the frequency increasing with the increasing level of weakness and stroke severity. Leg somatosensory impairment negatively influences balance and gait. These deficits may lead to reduced weight-bearing and contribute to balance impairment and falls post stroke. It was demonstrated that impaired load detection may also contribute to gait asymmetry, particularly in the push-off phase [45,46]. Lower limb proprioception could influence the variance in the stride length, gait velocity, and walking endurance in stroke survivors [47,48]. It is important to note that all symmetry indexes of people with stroke were markedly different from the control group from a statistical point of view. For example, the trend symmetry values were found to be 8–9 times higher at the hip, 11–12 times higher at the knee, and 6–7 times higher at the ankle than those of the control group. A comparison with previous studies is difficult because the bilateral cyclogram approach is never used in stroke patients. To provide a term of comparison, previous studies on other pathological states that present an asymmetrical gait pattern, i.e., hip osteoarthritis, reported lower increases in trend symmetry with respect to the controls.

In addition, we noted that several parameters of the stroke individuals displayed high values of standard deviation, revealing high data variability. The control group showed, in fact, lower variability in the symmetry parameter values with smaller standard deviations compared to the stroke group. These results could be related to the heterogeneity in terms of motor deficit severity and temporal distance from the stroke event. In addition, both males and females were pooled, not disaggregating by gender; however, combining male and female subjects introduces a source of potential variability. However, with our sample, it was not possible to consider them separately; thus, potential differences in movement characteristics between males and females require further study.

The results obtained in this study confirm what has been previously reported in terms of gait pattern and asymmetry, although the latter was assessed with different discrete methods [5,12,13,23,36]. To this author’s knowledge, no previous studies have investigated the inter-limb symmetry of lower limb joint kinematics in hemiparetic individuals with the bilateral cyclogram technique. The possibility of assessing hemiparetic gait during the whole gait cycle using this method may provide useful insights to better understand the impairments in motor control associated with this pathological state, supporting clinics in the identification of the best rehabilitation program for post-stroke patients. These results support the necessity of defining a rehabilitative program focused on both lower limbs, aiming to equalize weight bearing through the lower extremities and the capacity to shift weight between the lower extremities during gait and to reduce the gait alteration of the paretic limb and the motor compensation patterns of the non-paretic limb.

In addition, it should not be forgotten that the achievement of symmetry in gait represent a crucial point in the rehabilitation of hemiplegic people and that it is often used to measure the effectiveness of a treatment [38]. Furthermore, gait symmetry could be a crucial parameter in the outcome of the rehabilitation path and in the monitoring of the rehabilitation process, as asymmetric gait can be resistant to intervention and may even worsen over time [49]. Thus, the results of this study can be used to update rehabilitation training, with the aim of improving symmetry and limiting the negative outcomes in stroke survivors.

However, this study presents some limitations. Firstly, the applied method was developed to only explore interlimb symmetry. However a similar approach could be used to explore intralimb coordination by taking into account a different combination of joints (i.e., hip vs. knee, knee vs. ankle, etc.) and such an approach may be effective in providing relevant data on the possible impact of the coordination/incoordination degree between the two limbs/joints, thus allowing for assessment of the existence and type of compensatory mechanisms. Further, in the present study, right and left hemiparetic individuals were pooled in a single group; however, it could be interesting to investigate the presence of some differences due to the different sides of the lesion. In addition, further studies could be conducted considering hemiparetic individuals as homogenous in terms of motor deficit severity and temporal distance from the stroke event. At last, the progress of inter-limb asymmetry after rehabilitative programs could be considered.

5. Conclusions

In this retrospective study, the assessment of post-stroke hemiparetic inter-limb asymmetry was conducted with an innovative method, the so-called "bilateral cyclogram". This technique considers the entire gait cycle, providing detailed information compared to other methods. Although this study has some limitations, the results obtained are in line with previous ones, and the bilateral cyclogram shows great potential in supporting clinicians in identifying the best rehabilitation program for post-stroke patients and evaluating its efficacy over time.

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Data Availability Statement: Data available on request due to restrictions, e.g., privacy or ethical.

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