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Identification of stiff-knee gait in stroke survivors

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Abstract

Background Stiff-knee gait is a common movement disorder in individuals with stroke; however, standardized criteria for its identification remain lacking. This study aimed to examine suitable criteria for identifying stiff-knee stroke survivors to facilitate comparisons across studies. Twenty-four stroke survivors (45.2±13.7 years old) and 24 age- and sex-matched controls (45.5±13.5 years old) with no known gait impairment participated in this study. Participants walked along a 10-m walkway at a self-selected comfortable speed. A motion capture system recorded the trajectories of retroreflective markers placed on specific body landmarks. The following knee flexion parameters during gait cycle were analyzed: (1) peak knee flexion during the swing period, (2) total range of motion (RoM cycle), calculated as the difference between maximum and minimum knee excursion during gait cycle, (3) RoM from toe-off to peak knee flexion ("RoM swing"), and (4) timing of peak flexion. Comparisons were made among control, paretic, and non-paretic limbs.

Results Among the 21 stroke survivors identified with stiff-knee gait, the paretic limb showed reduced peak swing, RoM swing, and RoM cycle compared to both the control and non-paretic limbs, as well as earlier timing compared to the non-paretic limb only.

Conclusions Among the four examined criteria to identify stiff-knee gait in stroke survivors, the most suitable are peak knee flexion during the swing period of less than 40°, and knee range of motion from toe-off to peak knee flexion of less than 12°.

Keywords Kinematics, Walking, Range of motion, Peak knee flexion

Background

Limited knee flexion during the swing period of gait is a common movement disorder in stroke survivors [1–3], often referred to as a stiff-knee gait [4]. The consequences of a stiff-knee gait may include reduced foot clearance [5], leading to tripping, increased risk of falling, compensatory movements (e.g., hip hiking and circumduction) [6], and increased energy expenditure [7]. The causes of stiff-knee gait are not fully understood, but several mechanisms have been proposed, including overactivity of the rectus femoris muscle [8, 9], diminished hip flexion moments [10], diminished plantarflexion moments [11], with multiple mechanisms likely contributing [12].

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Although several studies have explored treatments to alleviate the consequences of stiff-knee gait, such as botulinum toxin injection [13], rectus femoris nerve neurotomy [14], functional electrical stimulation [15], and pedaling exercises [16], standardized criteria for identifying individuals with stiff-knee gait post-stroke are not yet well established.

Among the various criteria used to identify stiff-knee gait in stroke survivors, the most commonly applied quantitative measures include: peak knee flexion during swing of less than 45° [11, 17] or 40°, as suggested in a recent attempt to classify severity [18]; range of motion from toe-off to maximum knee flexion of less than 10° during swing [2]; and a difference in knee range of motion of at least 16° [19] or 20° [8] between the paretic and non-paretic limbs. Subjective criteria have also been used, such as "observable reduced maximum knee flexion during the swing period" [12, 15, 20]. Given the variability in these definitions, it seems essential to first standardize the characterization of stiff-knee gait for stroke survivors before attempting to classify its severity or investigate its underlying causes and treatments strategies.

In children with cerebral palsy, a population in which stiff-knee gait is also common [21], the most widely used criteria for identifying this gait disturbance have included reduced maximum knee flexion during swing [22] and reduced range of knee motion [23, 24] in relation to individuals with no gait impairment. A more comprehensive approach has combined maximum knee flexion during swing, range of motion, and timing of maximum knee flexion during swing either subjectively [21] or in comparison with control subjects [25]. Specifically, Goldberg et al. [25] classified gait as stiff-knee when three or more of these four criteria differed from matched controls (details provided later, in the "Data processing and analysis" section).

Despite important differences between patients with cerebral palsy and stroke survivors, such as secondary impairments in cerebral palsy (e.g., muscle contractures and bone deformities [26]), and variability in gait deviation based on topography (e.g., spastic hemiplegia, spastic diplegia [27, 28]), both groups often experience common neuromuscular deficits such as spasticity, muscle weakness, and reduced selective motor control [29, 30]. Therefore, adapting the four gait parameters identified by Goldberg et al. [25] to help standardize stiff-knee gait characterization in stroke survivors appears to be reasonable and promising approach.

Considering that stiff-knee gait is a common disturbance among stroke survivors, prompting numerous investigations into ways of mitigating its impact on daily life activities, standardizing the criteria for its identification is a feasible approach to enable comparisons across studies. Thus, the aim of this study was to examine suitable criteria for identifying stroke survivors with a stiff-knee gait by assessing the strengths and limitations of the criteria adopted by Goldberg et al. in children with cerebral palsy [25].

Methods

Participants

Twenty-four stroke survivors and 24 individuals matched by age and sex (control group), were conveniently sampled and included in this cross-sectional study. The inclusion criteria for stroke survivors having experienced stroke (either ischemic or hemorrhagic) more than 6 months prior, ability to walk at least 10 m with no assistance, ability to follow verbal instruction, absence of any orthopedic or neurological impairment other than stroke, and no surgical intervention, including botulinum toxin injection, within the previous 6 months. For the control group, the inclusion criterion was the absence of any known neurological or orthopedic impairment or musculoskeletal injury that could compromise gait.

Procedures

Following the recommendations of the International Society of Biomechanics (ISB) [31], retroreflective markers and rigid clusters were placed on specific body anatomical landmarks and lower limb segments, as described in previous studies [32, 33]. A calibrated anatomical system technique (CAST) was employed to record the three-dimensional kinematics of the lower extremities [34].

A t-pose kinematic calibration trial was performed with all retroreflective markers placed on anatomical landmarks. Subsequently, markers from the anterior and posterior superior iliac spine, medial and lateral epicondyles of the femur, tibialis tuberosity, medial and lateral malleoli, and intermalleolus were removed.

Each participant walked in their own shoes at a self-selected comfortable speed on a 10-m extension walkway equipped with two embedded force plates (Kistler, model 9286BA) covered with a thin rubber carpet. Prior to data acquisition, the participants practiced a few trials until they felt comfortable with the experimental setup. Each participant underwent a minimum of five trials. A computerized gait analysis system (VICON, Inc.) with eight infrared cameras was used to synchronously acquire all the marker positions and force plate data at a frequency of 100 Hz.

Stroke survivors were clinically examined using the Fugl-Meyer test [35], functional independent measurements (motor domain) [36], and functional ambulation category [37]. These data were solely used for characterizing these individuals.

Data processing and analysis

We analyzed two consecutive steady-state strides (paretic and non-paretic for stroke survivors, and right and left for the control group) per trial, for a total of five trials for each participant. Foot contact and toe-off events were identified for each stride using force plate signals and foot vertical velocity [38]. These events were used to define each stride and the stance and swing periods [4].

The knee joint angle was calculated using a commercial algorithm (Visual3D; C-Motion, Inc.). Further analyses were conducted using custom algorithms (MATLAB; MathWorks, Inc.), as it follows.

Kinematic data were digitally filtered using a low-pass 4th order, and zero-lag Butterworth filter with a 6 Hz cut-off. The gait cycle (i.e., two consecutive foot contacts of the same limb) was defined, and its durations were time-normalized and averaged to obtain the mean cycle for each participant.

We quantified four parameters (1) peak knee flexion during the swing period of gait, identifying the maximum value of knee flexion ("peak swing"), (2) knee range of motion from toe-off to peak flexion, calculated as the difference between maximum knee angle and knee angle at toe-off ("RoM-swing"), (3) total knee RoM across the entire gait cycle, calculated as the difference between maximum and minimum knee angles ("RoM cycle"), and (4) timing to peak knee flexion during the swing ("timing"), expressed as a percentage of the stance period duration, as in previous investigation [25]. Figure 1 illustrates each of these four parameters. It important to note that for the stroke survivors who exhibited two peaks of knee flexion during swing ($n = 9$), only the first peak was considered.

Subsequently, we replicated the procedures adopted by Goldberg et al. [25] to calculate the average value of each parameter for the control group ("normal values") and used the values to identify the "stiff-knee", as the stroke survivors presented the values greater than two standard deviations either below (for parameters 1–3) or above (for the parameter 4) the observed average normal value. A limb was classified as "stiff-knee" if at least three of these four parameters met the established criteria [25].

The variables selected for this study included the four described knee flexion parameters and the mean walking

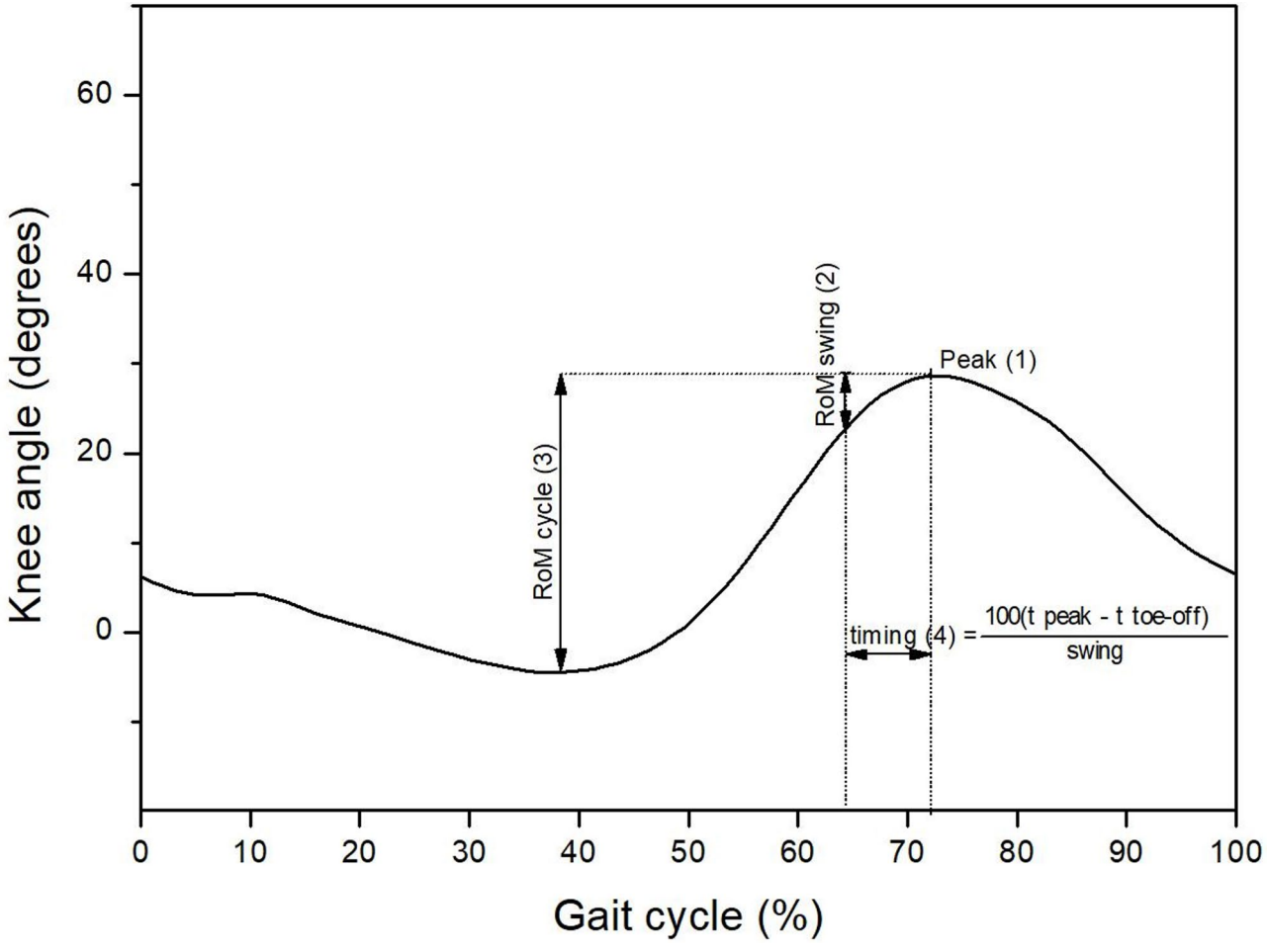

Fig. 1 Time series profile of knee angle and the four gait parameters used to identify stiff-knee gait

speed. Notably, no limb effects were observed in the control group; therefore, data from the right and left limbs were combined and treated as a single "control limb" [32].

Statistical analyses

We examined the normality of distribution and homogeneity of variance, and both assumptions were met for the use of parametric tests. To characterize participants in both the stroke and control groups, three one-way univariate analyses of variance (ANOVAs) were conducted to compare age, body mass, height, and mean walking speed between groups. Since a group effect was observed for walking speed, the mean walking speed was used as covariate in the analysis of the criteria for identifying stiff-knee gait among participants who met at least three of the four parameters [25]. A multivariate analysis of covariance (MANCOVA) was performed with limb (control, paretic, and non-paretic) as factor and the following dependent variables: peak swing, RoM swing, RoM cycle, and timing.

Univariate analysis and post-hoc pairwise comparisons with Bonferroni adjustments were conducted as needed. The alpha level was set at 0.05 for all statistical tests, which were performed using SPSS software.

Results

Based on the four stiff-knee criteria [25] applied to the paretic limb, three stroke survivors did not meet at least three of these criteria and were therefore excluded from the analysis, along with their matched control participants. Among the remaining stroke survivors ($n=21$), the following numbers did not meet the respective criteria for the paretic limb: peak knee flexion during swing ($n=1$), knee RoM swing ($n=2$), knee RoM cycle ($n=1$), or the timing of peak knee flexion ($n=20$). For the non-paretic limb, the numbers were: peak knee flexion during swing ($n=4$), knee RoM swing ($n=10$), knee RoM cycle ($n=11$), and timing of peak knee flexion ($n=20$).

Table 1 General characteristics of participants analyzed

Characteristics	Stroke	Control	*p* value
Sex (female/male)	14/7	14/7	-
Age (years)[a]	46.4±13.8	46.5±13.8	0.951
Body mass (kg)[a]	77.0±20.4	67.6±10.3	*0.043*
Height (m)[a]	1.67±0.09	1.65±0.10	0.599
Mean walking speed (m/s)[a]	0.64±0.28	1.26±0.13	*< 0.001*
Time poststroke (months)[a]	84.6±40.5	-	-
Type of lesion (ischemic/hemorrhagic)	12/9	-	-
Hemiparesis side (right/left)	12/9	-	-
Fugl-Meyer score (maximum, 84)[a]	63.9±5.9	-	-
Functional independence (maximum, 91)[a]	81.7±4.1	-	-
Functional ambulation category (0–5)[b]	4[4–5]	-	-

[a]Mean±standard deviation; [b]Median [Interquartile interval]

Table 1 presents the general characteristics of the 21 participants in each group (stroke and control) included in the final analysis. ANOVAs revealed no group effect for age ($F_{1,40}=0.004$) or height ($F_{1,40}=0.28$). However, stroke survivors presented higher body mass ($F_{1,40}=4.39$) and walked at slower pace ($F_{1,40}=90.36$) compared to controls. All stroke survivors were in the chronic stage of recovery and, as shown by clinical assessments (Table 1), most demonstrated high levels of motor function and walked with minimal limitation.

Figure 2 presents the mean (±SD) values of peak swing, RoM swing, RoM cycle, and timing across the control, paretic, and non-paretic limbs. MANCOVA revealed a limb effect (Wilks' Lambda = 0.33, $F_{8,112}=10.38$, $p<0.001$). Follow-up univariate analysis revealed differences in peak swing ($F_{2,59}=48.97$, $p<0.001$), RoM swing ($F_{2,59}=14.28$, $p<0.001$), RoM cycle ($F_{2,59}=19.83$, $p<0.001$), and timing ($F_{2,59}=7.02$, $p=0.002$). Post hoc comparisons revealed that the paretic limb had reduced peak swing, RoM swing, and RoM cycle values relative to both the non-paretic and control limbs. Additionally, the timing of peak knee flexion occurred earlier in the paretic limb compared to the non-paretic limb (Fig. 2).

Discussion

In this study, we investigated suitable criteria for identifying stiff-knee gait in stroke survivors. Among the four criteria adopted by Goldberg et al. [25], peak knee flexion during swing emerged as the most distinctive feature in this population (only one stroke survivor did not meet this criterion), followed by the RoM during swing (only two stroke survivors did not meet this criterion). In contrast, RoM during the gait cycle and the timing of peak knee flexion appear to be less reliable indicators and should be interpreted with caution, as discussed below.

First, regarding the RoM cycle, it is important to note that the knee excursion patterns observed in stroke survivors differed from those reported in individuals with cerebral palsy [25]. Specifically, while individuals with cerebral palsy often exhibit either a crouched or jump gait during the stance period [39, 40], most stroke survivors in our study presented with knee hyperextension. These behavioral differences affect the total knee RoM and could lead to a misleading conclusion when using RoM cycle as a criterion for identifying stiff-knee gait in stroke survivors. Thus, the RoM cycle does not appear to be a suitable criterion in this population.

Second, concerning the timing of peak knee flexion during the swing period, our findings indicated that stroke survivors tended to exhibit earlier peak knee flexion (20 stroke survivors did not meet this criterion, with values ranging from 8 to 29% of the swing period), which contrasts with the pattern observed in individuals with cerebral palsy, who had presented an average value of

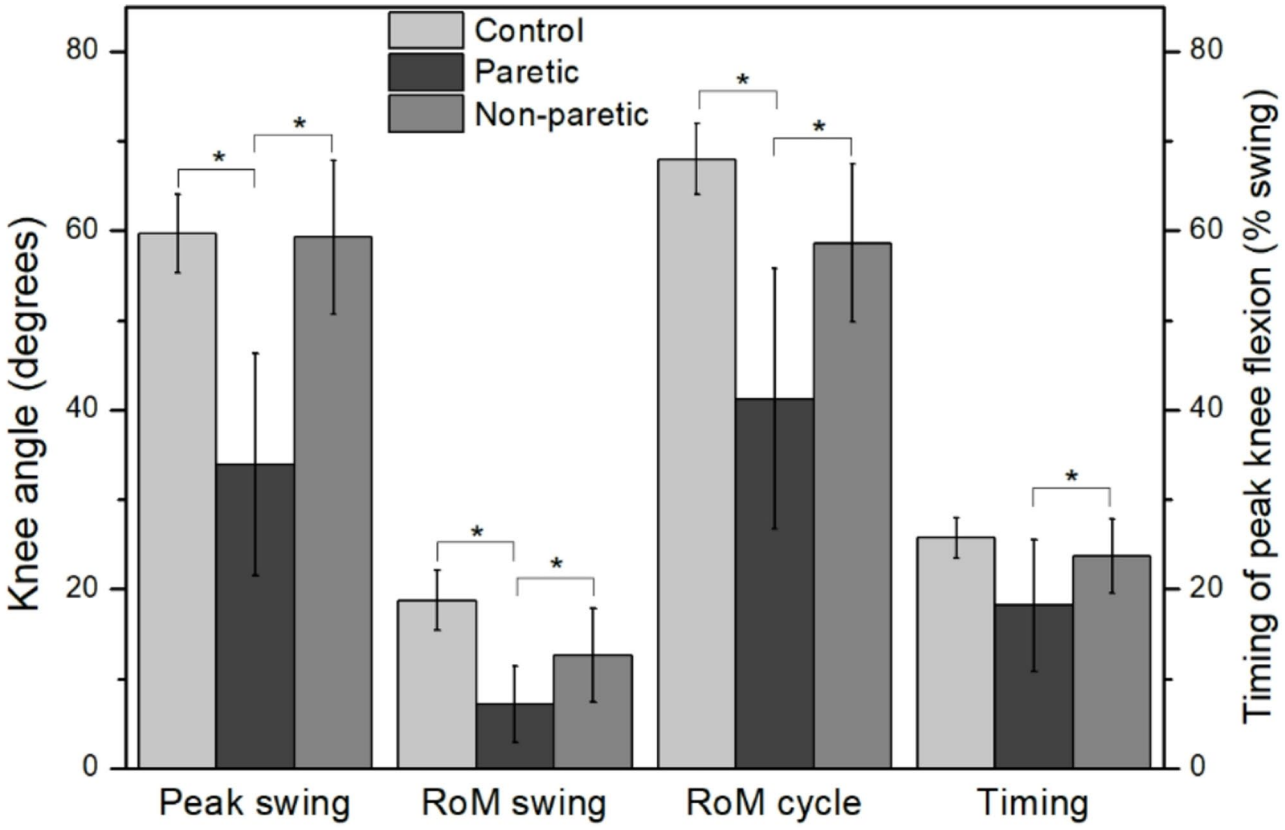

Fig. 2 Mean (±SD) values of peak knee flexion during the swing period, range of knee flexion from toe-off to peak flexion (RoM swing), range of knee flexion during the gait cycle (RoM cycle), and timing of peak knee flexion (Timing) for the control, paretic, and non-paretic limbs

45% of the swing period [25]. Moreover, after accounting for the gait speed, the only difference in the timing of peak knee flexion was found between the paretic and non-paretic limbs (Fig. 2). Unlike knee angle measurements, which reflect the relative excursion between the thigh and shank, timing metrics are directly related to locomotor coordination, which is frequently impaired after stroke [41, 42]. Furthermore, differences in the relative timing of the stance and swing periods have been observed both between stroke survivors and non-disabled individuals [41], and between paretic and non-paretic limbs [41, 43]. Notably, disturbances in locomotor coordination may arise from factors unrelated to stiff-knee gait itself, such as slow walking speed or balance impairments. Therefore, the timing of peak knee flexion does not seem to be a reliable criterion for identifying stiff-knee gait in stroke survivors.

In a previous investigation, Chantraine et al. [18] proposed a novel classification system for stiff-knee gait of stroke survivors using cluster analysis. To assess the construct validity of the resulting clusters, they compared their classification with two existing approach: (1) an experienced observer's categorization using the chronic hemiparesis gait classification [44], and (2) the criteria adopted in the present study [25]. While this prior work represents a valuable contribution toward understanding subtypes and severity levels of stiff-knee gait, it presupposes the identification of individuals who exhibit this gait disturbance. Therefore, we argue that the present study offers an important complementary step by addressing the initial identification of stiff-knee gait. Establishing standardized identification criteria may serve as a prerequisite for subsequent classification and for tailoring treatment strategies accordingly.

It is well stablished that mean walking speed influences gait parameters [45], and specifically among stroke survivors, slower walking speeds are associated with greater gait impairment [e.g., 46, 47]. In the present study, stroke survivors walked slower than their matched controls; however, even after accounting for walking speed in our analyses, the paretic limb continued to differ from both non-paretic and control limbs across all four evaluated parameters. Similar findings were reported by Chantraine et al. [18], who observed that although their control group walked at speed comparable to that of the stroke survivors, no knee flexion impairments were identified.

Another important aspect to consider is the behavior of the non-paretic limb. Although previous studies [8, 19, 48] have compared knee flexion RoM between the paretic and non-paretic limbs to identify stiff-knee gait in stroke

survivors, our findings revealed that the non-paretic limb also frequently met the stiff-knee criteria: peak swing ($n = 17$), RoM swing ($n = 11$), RoM cycle ($n = 10$), and timing of peak knee flexion ($n = 1$). These results may be explained by compensatory adaptation in the non-paretic limb in response to impairments in the paretic limb. Therefore, relying solely on differences between the paretic and non-paretic limbs may not be sufficient to accurately identify stiff-knee gait in stroke survivors.

Altogether, the findings of this study suggest that the most suitable criteria for identifying stiff-knee gait in stroke survivors are a maximum knee flexion < 40° and ROM of knee flexion from toe-off to peak flexion at swing < 12°. Nevertheless, if the the timing of peak knee flexion during the swing period is to be used as a criterion, the threshold value should be < 21%. Furthermore, our results indicate that it is inappropriate to use the non-paretic limb as a reference for identifying stiff-knee gait in stroke survivors, as has been done in previous investigations [8, 19, 48]. We observed that several stiff-knee criteria were also observed for the non-paretic limb in some stroke survivors. This finding is likely due to motor compensation [49], which may lead to misclassification if the non-paretic limb is used as a reference.

Although the present study provides valuable insights toward standardizing the criteria for identifying stiff-knee gait in stroke survivors, several limitations should be acknowledged. First, the sample size was limited to 24 stroke survivors with a high level of independence, most of whom were younger than 55 years ($n = 16$), which may reflect the increasing incidence of stroke among younger individuals [50]. Second, this study focused solely on identifying suitable criteria for recognizing stiff-knee gait in stroke survivors. Future studies should apply these criteria to a broader range of stroke survivors, considering variations in independence level and age, and further investigate the underlying causes of stiff-knee gait, which were beyond the scope of the present study.

Conclusion

In summary, based on our findings, the most suitable criteria for identifying stiff-knee gait in stroke survivors are a peak knee flexion during the swing period of < 40° and a knee RoM from toe-off to peak knee flexion of < 12°. Importantly, our results highlight that comparing the paretic and non-paretic limbs may not be reliable for identifying stiff-knee gait, as compensatory strategies can affect the non-paretic limb. These findings contribute to the standardization of stiff-knee gait identification, which is crucial for improving diagnosis, treatment planning, and guiding future research in stroke rehabilitation.

Abbreviations

CAST	Calibrated anatomical system technique
RoM	Range of motion
ANOVA	Univariate analyses of variance
MANCOVA	Multivariate analyses of covariance

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Not applicable.

Author contributions
OB contributed to the acquisition, analysis, and interpretation of data, and have drafted the work; MLC and JAB contributed to the interpretation of data and substantively revised the work; AMFB contributed to the conception of the work, analysis and interpretation of data, and substantively revised it. All authors read and approved the submitted version.

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Data availability
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with Brazilian legislation governing human research. The experimental protocol was approved by the Ethics Committee of Cruzeiro do Sul University, Plataforma Brasil (CAAE: 02887518.2.0000.8084). Informed consent was obtained from all participants prior to any experimental procedures.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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