Short bouts of gait data and inertial sensors can provide reliable measures of spatiotemporal gait parameters from bilateral gait data of participants with multiple sclerosis

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Research

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Abstract

Background:

Wearable devices equipped with inertial sensors enable objective gait assessment for persons with multiple sclerosis (MS), with potential use in ambulatory care or home and community-based assessments. However, gait data collected in non-controlled settings is often fragmented and may not provide enough information for reliable measures. We evaluate a novel approach, extracting pre-defined numbers of gait cycles from the full length of a walking task, and their effects on the reliability of spatiotemporal gait parameters.

Methods:

The present study evaluates intra-session reliability of spatiotemporal gait parameters for short bouts of gait data extracted from the full length of the walking tasks to 1) determine the effects of the length of the walking task on the reliability of calculated measures and 2) identify spatiotemporal gait parameters that can provide reliable measures for gait assessments and reference data in different settings.

Thirty-seven participants (37) diagnosed with relapsing-remitting MS (EDSS rage 0 to 4.5) executed two trials, walking 20m each, with inertial sensors attached to their right and left shanks. Previously published algorithms were applied to identify gait events from the medio-lateral angular velocity. Short bouts of gait data were extracted from each trial, with lengths varying from 3 to 9 gait cycles. Twenty-one measures of spatiotemporal gait parameters were calculated. Intraclass correlation coefficients (ICCs) were calculated to evaluate how the degree of agreement between the two trials of each participant varied with the number of gait cycles included in the analysis.

Results:

Spatiotemporal gait parameters calculated as the mean across included gait cycles reach excellent reliability from three gait cycles. Stride time variability and asymmetry, as well as stride velocity variability and asymmetry, reach good reliability from six gait cycles and should be further explored for persons with MS, while stride time asymmetry and step time asymmetry do not seem to provide reliable measures and should be reported carefully.

Conclusion:

Short bouts of gait data, including at least six gait cycles of bilateral data, can provide reliable gait measurements for persons with MS, opening new perspectives for gait assessment using wearable devices in non-controlled environments, to support monitoring of symptoms of persons with neurological diseases.

Trial registration

Not applicable.

Background

Gait impairment is highly prevalent in multiple sclerosis (MS), as the decline on neural control affects motor functions, and consequently gait, balance and mobility (Kamm, Uitdehaag, & Polman, 2014; Kurtzke, 1983). Objective gait measurements enable the assessment of the quality and performance of gait, including gait variability and asymmetry (Lord, Galna, & Rochester, 2013), providing important information to complete the neurological evaluation of persons with MS (Frechette et al., 2019; Vienne-Jumeau, Quijoux, Vidal, & Ricard, 2019). Objective gait assessments are high sensitive to changes in symptoms, supporting early diagnosis and the evaluation of therapeutic interventions (Hubble, Naughton, Silburn, & Cole, 2015; Spain et al., 2012).

Data collected from wearable devices, equipped with inertial sensors, have been demonstrated to be effective in objective gait assessments, offering a portable and cost-effective solution compared to large or fixed installations (Frechette et al., 2019; Simon, 2004; Vienne-Jumeau et al., 2019). However, if wearable devices are suitable for ambulatory care, home assessments and community ambulation, the variety of gait assessment protocols can be considered an obstacle for establishing reference values (Vienne-Jumeau et al., 2019). One challenge is related to the different lengths and durations of mobility tests traditionally used for assessing persons with MS (e.g. 25ft walk, 6 minutes walking test, Timed-Up-and-Go) (Engelhard, Dandu, Patek, Lach, & Goldman, 2016; Greene, Healy, Rutledge, Caulfield, & Tubridy, 2014; Kojima, Obuchi, Henmi, & Iketa, 2008). Moving for non-controlled environments, gait data may be fragmented and non-homogenous (Frechette et al., 2019). The variations and restrictions on gait assessment protocols (e.g. physical space, time), in both controlled and non-controlled settings, may not provide enough gait data for reliable measures.

One approach to address this challenge is to select short bouts of gait data, representing pre-defined number of gait cycles, from the full length of a walking task. The analysis of the intra-session reliability can show the effects of length of gait data on the reliability of gait parameters, to identify the spatiotemporal gait parameters that can be used to obtain reliable measures according to the number of gait cycles included in the analysis.

The main goal of the present study is to define an optimal length of gait data and identify the spatiotemporal gait parameters that can be used to obtain reliable measures from short bouts of gait data, enabling gait assessments of persons with MS with wearable devices.

Methods

Participants

Participants were recruited from the neurology outpatient department at Saint Vincent’s University hospital, Dublin, Ireland. The inclusion criteria were participants diagnosed with clinically definite relapsing-remitting MS, able to execute two walking trials of 20 metres safely without a mobility aid. All participants provided informed consent and ethical approval was obtained from the hospital research ethics committee.

The present study includes data from 37 participants with MS, mean age 45.1 ± 9.9, height 168.6 ± 9.9 cm, weight 75.5 ± 16.8 kg, 23 females (62%), Mean time since diagnosis was 7.4 ± 7.7 years. Each participant received a comprehensive neurological and physical examination including Expanded Disability Status Score (EDSS). At the time of the assessment, 13 participants had EDSS score 0, 13 had EDSS scores 1 or 1.5, and 11 had EDSS scores 2 or above. Their mean time to complete a TUG test was 7.8 ± 1.7 s, with mean stride velocity 122.2 ± 15 cm/s and mean stride length 136.6 ± 16.9 cm.

Procedures

To include measures representing gait asymmetry, the study protocol was designed to allow data collection representing bilateral gait. Two inertial sensors were attached to the participants' right and left shanks, at the mid-point of the anterior shank using dedicated Velcro straps. Sensors sampled at 102.4 Hz and contained a tri-axial accelerometer and a tri-axial gyroscope. Data were streamed in real time via Bluetooth using dedicated software (Kinesis Gait™, Kinesis Health Technologies Ltd., Dublin, Ireland) and stored for offline analysis.

Participants were instructed to walk at their preferred self-selected pace, starting with their dominant foot (right or left). Each participant completed two trials of 20 m walking task, in the same day, with a short break between trials.

Data extraction

Previously published algorithms were selected for the procedures for calibration, data treatment and artefact rejection (Doheny, Foran, & Greene, 2010; Greene et al., 2012, 2010).

Following the gait event detection, the sequence of Initial Contact (IC) and Terminal Contact (TC) points corresponding to the movements of each leg were used to calculate spatiotemporal gait parameters, as described: mean swing time (TC to IC of the same foot, averaged across both legs, in seconds), mean stance time (IC to TC of the same foot, averaged across both legs, in seconds), stride time (IC to IC of the same foot, averaged across both legs, in seconds). Mean step time represents average of times between IC of one foot to IC of opposite foot, in seconds. Mean single support is the proportion of gait cycle spent in either foot and mean double support is the proportion of gait cycles spent on both feet, averaged across multiple gait cycles, expressed as percentage (%). Mean stride length (m) and mean stride velocity (cm/s) we calculated and averaged across both legs.

For gait variability, the coefficient of variation (CV) was calculated as the standard deviation (SD) divided by mean values within participant across multiple gait cycles, as a percentage.

For gait asymmetry, the Gait Symmetry Index (GSI) represent the difference between right and left divided by average of right and left values, expressed as percentage. Minus values indicate left leg asymmetry.

Data extraction process ignored the first gait cycle (i.e. first step each leg) and included data from the 3rd IC. Figure 1 represents angular velocity signal and the ICs (i.e. heel strike) and TCs (i.e. toe off) for the full length of a walking task.

Participants executed different number of steps to complete the trials. In order to calculate the ICCs for all the spatiotemporal gait parameters, and include all the trials, a minimum number of three and a maximum number of nine complete gait cycles (18 strides, or 9 strides per leg) could be extracted from the full length of the walking tasks. ICCs were then calculated at pre-defined numbers of gait cycles: 3, 4, 5, 6, 7, 8 and 9.

Data analysis

The intra-session reliability was calculated using intraclass correlation coefficients (ICC(2,k)) (Koo & Li, 2016; McGraw & Wong, 1996). The ICCs represent the variation in measurements using the same instrument, on the same participant, under the same conditions (test-retest reliability), on the 95% confidence interval (Koo & Li, 2016). Data analysis was conducted offline using MATLAB (version R2019a, MathWorks, VA).

Based on the ICC estimate, the reliability of gait parameters is described as poor (less than 0.5), moderate (between 0.5 and 0.75), good (between 0.75 and 0.9) or excellent (0.9 and greater) (Koo & Li, 2016).

Results

The mean time for all the participants to complete each walking trial was 16.1 ± 3.2 s. Mean stride velocity was 146.2 ± 23.5 cm/s and mean stride length was 135.6 ± 18.5 cm across all trials.

Intra-session reliability of spatiotemporal gait parameters

Spatiotemporal gait parameters representing average values across gait cycles reach excellent reliability from three gait cycles (six strides, three of each leg), as shown in Fig. 2, including mean stance time, mean stride time, mean swing time, mean step time, mean double support, mean single support, mean stride length and mean stride velocity.

Stride length variability reaches good variability from three gait cycles, while all the other parameters describing gait variability show increased reliability when more gait cycles are included in the analysis. Some gait variability parameters, in particular stance time variability, swing time variability, step time variability, and stride velocity variability, reach good reliability after six gait cycles and tend to continue towards an excellent reliability around nine gait cycles, with an exception to the variability of double support, as shown in Fig. 3.

Reliability of parameters describing stride length asymmetry and stride velocity asymmetry reach good reliability from four gait cycles, while stance time asymmetry and swing time asymmetry reach good reliability from seven gait cycles. Step time asymmetry has shown moderate reliability even when nine gait cycles are included in the analysis. In the present analysis, the calculation of stride time asymmetry shows poor reliability. The reliability of gait asymmetry parameters is presented in Fig. 4.

Discussion

In the present study we analysed the intra-session reliability of spatiotemporal gait parameters (means, variability and asymmetry) for assessing gait of participants with MS according to a pre-defined number of gait cycles, representing short bouts of gait data extracted from the full walking trial. The main goal of this analysis is to evaluate a novel approach for gait analysis from data collected with wearable devices, supporting gait assessments in ambulatory care and less controlled settings, such as patients' homes or community ambulation, where gait data is often fragmented (Frechette et al., 2019).

Windowed approach

The analysis of the reliability of spatiotemporal gait parameters followed the extraction of pre-defined numbers of consecutive gait cycles from the full walking trial, representing short bouts of gait data. This approach has been presented in the literature in order to assess the reliability of measures collected from fragmented data (Van Schooten, Rispens, Elders, & Diee, 2014). Another study extracted larger samples of consecutive gait cycles (10 to 60) to compare different conditions of walking trials (e.g. with turns on the ground and straight walk on a treadmill) as well as the effects of the length of gait data collected (Konig, Singh, Beckerath, Janke, & Taylor, 2014). If this second study aimed at recommending an optimal number of strides for reliable measures of gait variability (Konig et al., 2014), on a third study, this approach was used to investigate gait variability over a certain number of gait cycles, in order to determine the length of gait initiation phase (Lindemann et al., 2008).

As different tests conditions can affect the calculated measures (Najafi, Helbostad, Moe-Nilssen, Zijlstra, & Aminian, 2009), there is a need for methods enabling the homogenisation of data extraction and calculation in order to obtain reference values (McKay et al., 2017; Vienne-Jumeau et al., 2019). The analysis of the intra-session reliability for spatiotemporal gait parameters shows that short bouts of gait data could be an effective approach to address this need and support gait assessments in ambulatory care, and should be further explored with the use of wearable devices in controlled and non-controlled environments.

Reliability of spatiotemporal gait parameters

In the literature, many authors investigated the reliability of spatiotemporal gait parameters, in particular for measures of gait variability, recommending calculated measures should be carefully reported together with the length of the walking tasks and the test conditions (Hausdorff, 2005; Hollman et al., 2010; Van Schooten et al., 2014). Different approaches have been used to estimate reliability, including sampling methods (i.e. bootstrapping) (Bruijn, van Dieën, Meijer, & Beek, 2009), thresholds around the mean values (Owings & Grabiner, 2004) analysis of variance of calculated measures (Lindemann et al., 2008), and other specific methods estimating measurement errors through intraclass correlation coefficients (Kang &

Dingwell, 2006; Konig et al., 2014; Riva, Bisi, & Stagni, 2014; Van Schooten et al., 2014). In the present study, the ICCs were calculated to highlight differences according to the number of gait cycles included in the analysis and identify which gait parameters enable reliable measures for gait assessment of persons with MS when a restricted number of gait cycles are available.

The analysis showed that spatiotemporal gait parameters calculated as average across gait cycles, and representing bilateral gait collected from inertial sensor data, can reach excellent reliability from as few as three gait cycles. This result is in line with the literature, describing good test-retest reliability for mean stride length, mean stride velocity, mean stance time, mean swing time and mean double support for participants with MS (Craig, Bruetsch, Lynch, Horak, & Huisinga, 2017).

The present analysis of the reliability of parameters describing gait variability presents stride time variability, stride length variability and stride velocity variability reaching good and excellent reliability with fewer strides than previous results reported in the literature (Hausdorff, 2005; Hollman et al., 2010). Including bilateral data, and the selected algorithm for data acquisition and gait event detection might have facilitated this result (Doheny et al., 2010; Greene et al., 2010, 2015). This is an important outcome in light of the use of gait variability measures to determine and characterize gait impairment, as well as the potential of sensor-based data to facilitate diagnosis and intervention for persons with MS (Spain et al., 2012).

Objective gait assessment for persons with MS

One goal of the present study is to determine which spatiotemporal gait parameters can provide reliable gait measurements for short bouts of gait data collected from wearable devices.

While stride time asymmetry and step time asymmetry have poor reliability, results show that gait asymmetry estimated from stance time, swing time, stride length and stride velocity should be further explored, since they provide reliable measures for short bouts of gait data and have a potential to diagnosis and monitoring symptoms of persons with MS (Frechette et al., 2019). This is a promising result that shows that measures describing gait variability and gait asymmetry, in particular of stride length and stride velocity, should be further investigated for their potential of completing neurological assessment of participants with MS and other neurological conditions.

Conclusion

The present study shows that short bouts of gait data, representing bilateral gait data collected using inertial sensors, can provide reliable measures for objective gait assessment of persons with MS.

Gait parameters representing average values across gait cycles reach excellent intra-session reliability from three gait cycles, while parameters describing gait variability and asymmetry tend to reach higher ICCs when more gait cycles are included in the analysis.

From six gait cycles, stride length variability and asymmetry, as well as stride velocity variability and asymmetry, show good reliability and should be further explored to their potential contribution to the early diagnosis and monitoring symptoms of persons with MS. Stride time asymmetry and step time asymmetry do not seem to provide reliable measures and should be reported carefully.

The main contribution of the present study is to demonstrate that short bouts of gait data, including at least six gait cycles of bilateral data, can provide reliable gait measurements for persons with MS, opening new perspectives for gait assessment using wearable devices in non-controlled environments, to support monitoring of symptoms of persons with neurological diseases.

Declarations

Ethics approval and consent to participate

All participants provided informed consent and ethical approval was obtained from St Vincent's hospital research ethics committee.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to data protection regulations in order to protect individual participant's privacy. Data and supplementary material can be available from the corresponding author on reasonable request.

Competing interests

B.R.G. is a director of Kinesis Health Technologies Ltd, a company with a license to commercialize Kinesis Gait™. B.R.G. and K. McM. are employees of Kinesis Health Technologies. The rest of the authors declare that there are no competing interests.

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Author's contributions

The authors contributions and their responsibilities in the research are as follows. L.G.M.A. produced the original draft, and contributed to the conceptualization, analysis and interpretation of the data. B. R. G. contributed to the conceptualization, data collection and curation, methodology, analysis and manuscript preparation. K. McM. contributed to the data analysis and manuscript preparation. N. T. contributed to the study design, data collection and manuscript review. B. C. contributed to conceptualization, methodology and manuscript review. All authors read and approved the final manuscript.

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Figures

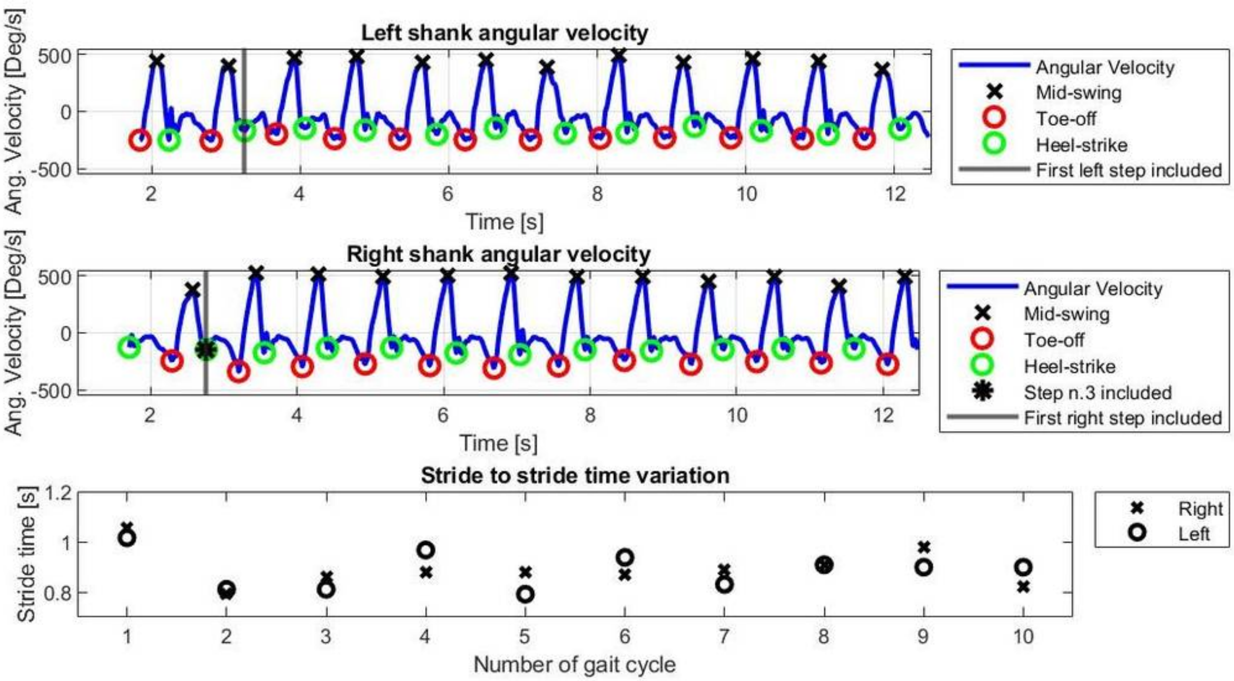

Figure 1

Top panel: medio-lateral angular velocity from left and right shank over time for a 20m walk trial. Bottom panel: stride to stride time variation for one participant (age 49, female, 165cm height, 60 kg, EDSS 3)

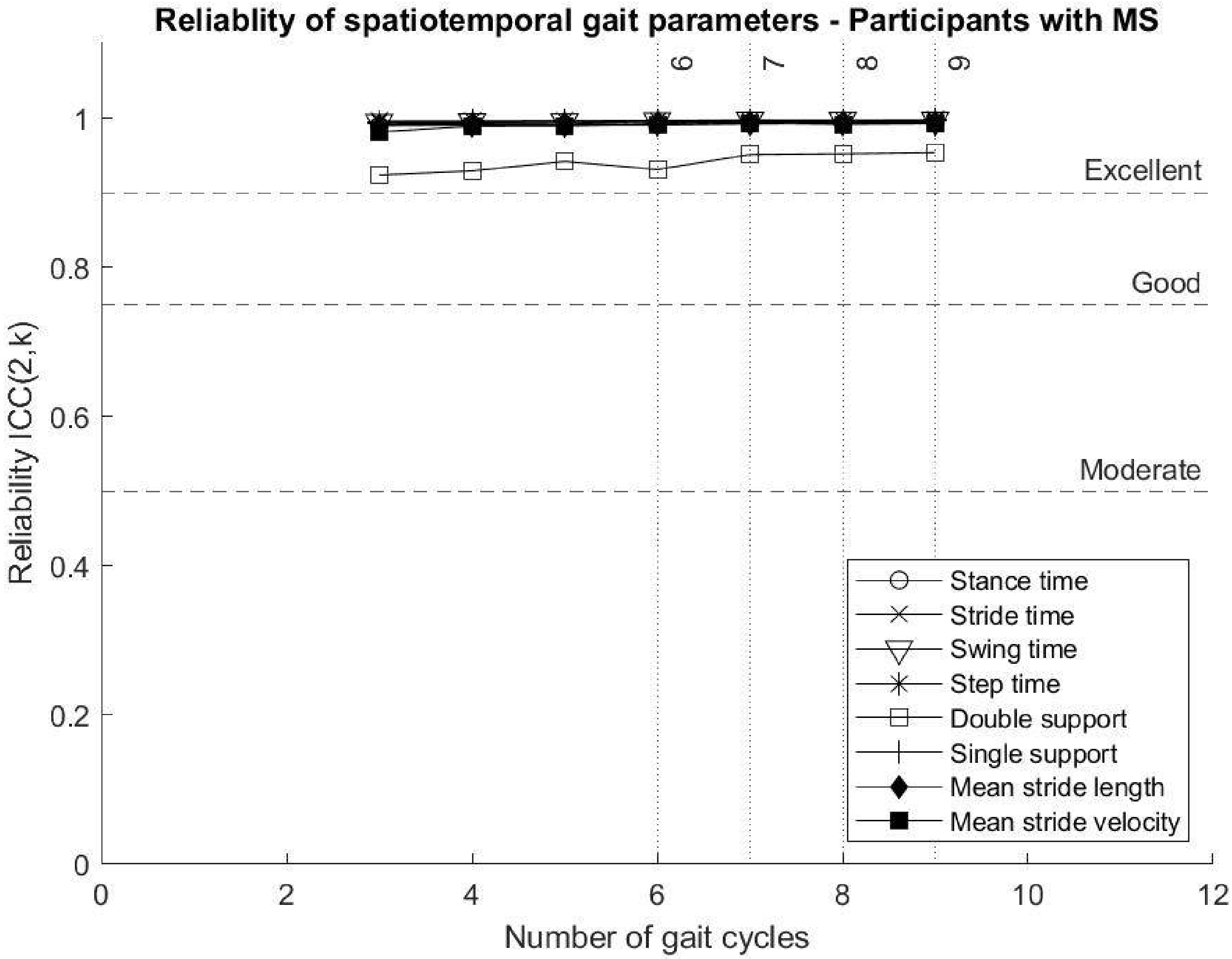

Figure 2

Variation of the reliability (ICCs) of spatiotemporal gait parameters for participants with MS according to the number of gait cycles included in the analysis

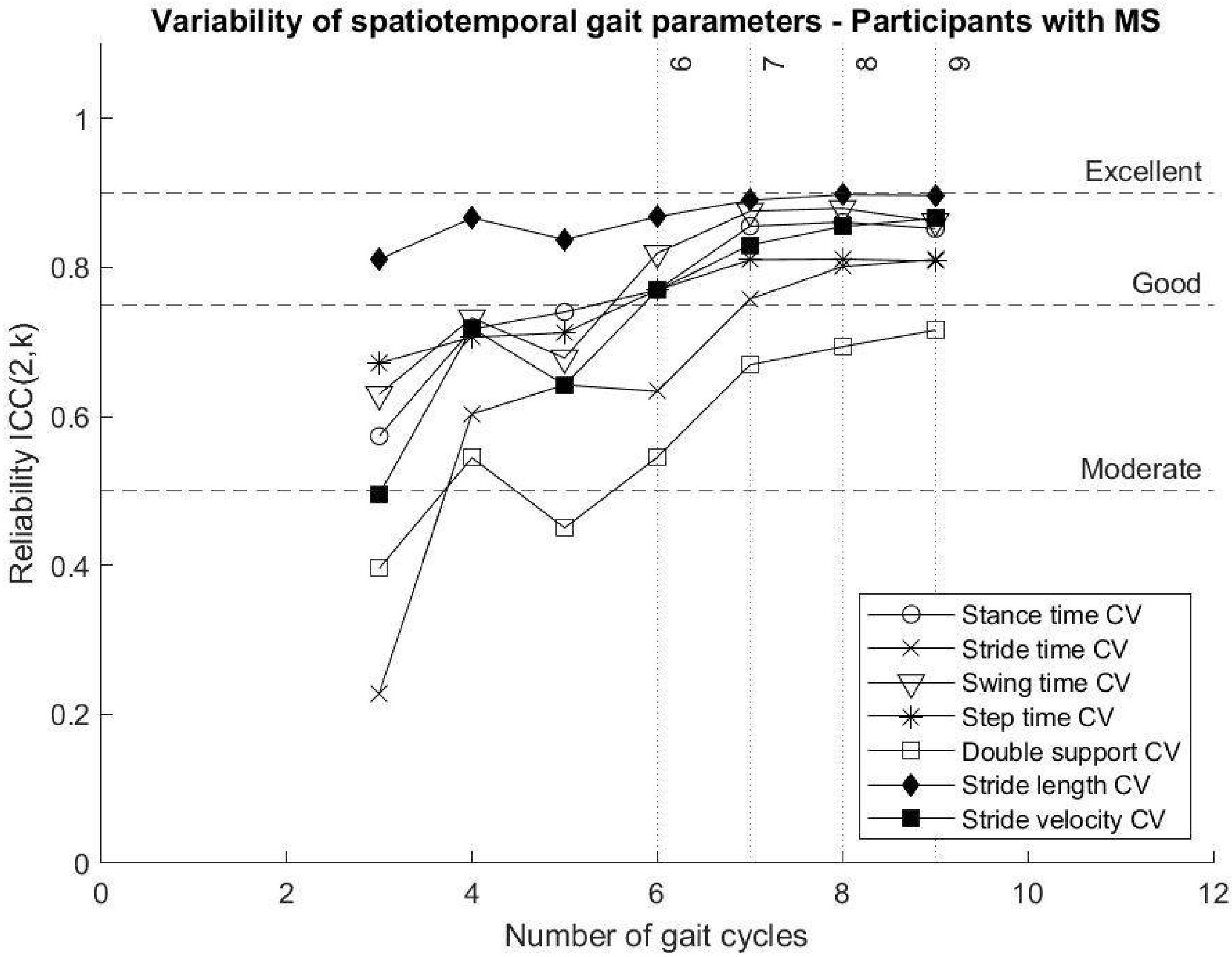

Figure 3

Variation of the reliability (ICCs) of variability of spatiotemporal gait parameters for participants with MS according to the number of gait cycles included in the analysis

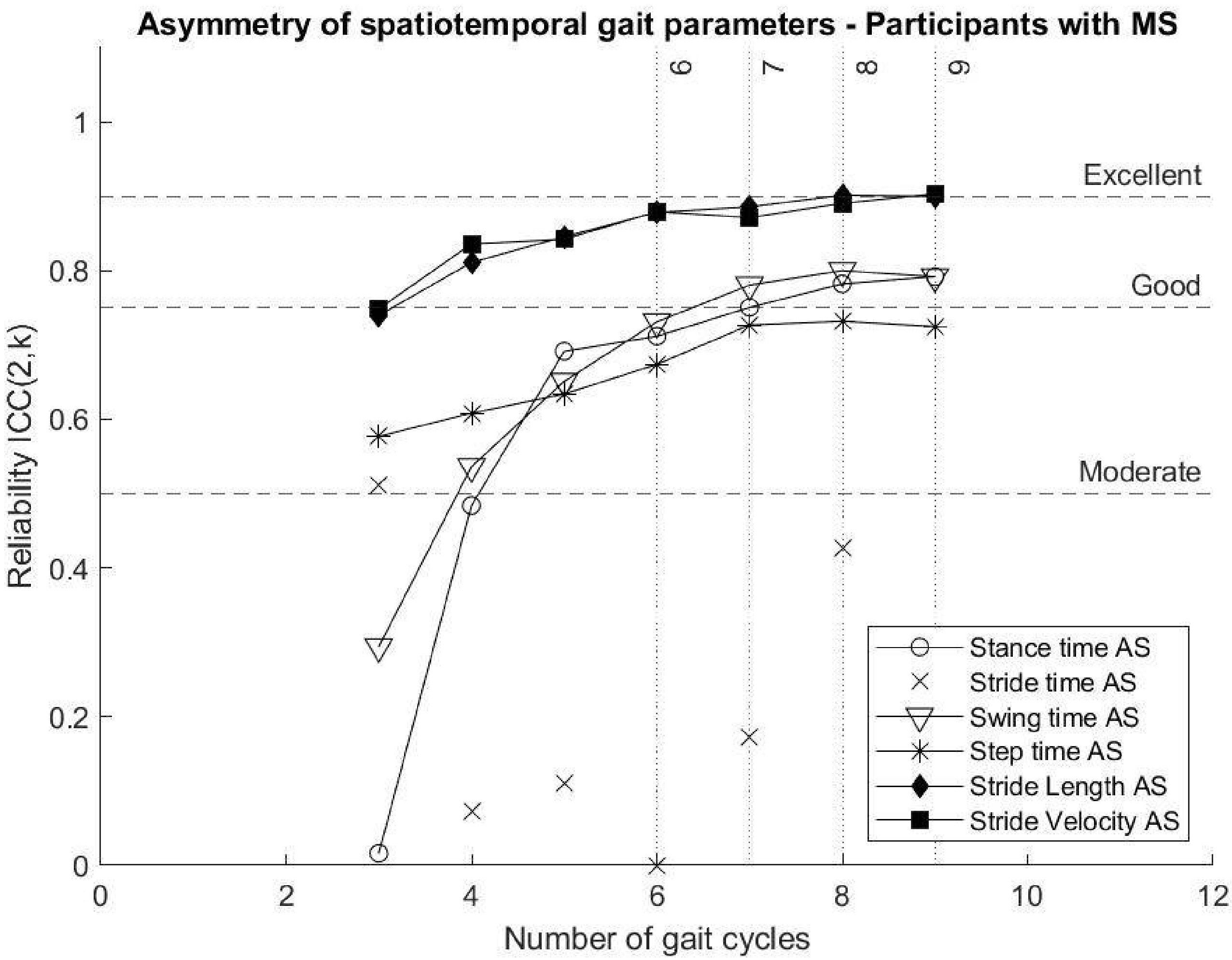

Figure 4

Variation of the reliability (ICCs) of asymmetry of spatiotemporal gait parameters for participants with MS according to the number of gait cycles included in the analysis