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Original article

Video-based 2D markerless gait analysis in people with multiple sclerosis

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ABSTRACT

Multiple Sclerosis is a neurodegenerative disease frequently associated with gait impairments that can emerge early and progressively worsen, substantially affecting mobility and independence. The Expanded Disability Status Scale (EDSS) is widely used to quantify overall disability in people with multiple sclerosis. However, gait alterations may present as specific spatiotemporal and kinematic changes that are not explicitly described by the EDSS scoring criteria. In this context, quantitative gait analysis can provide complementary information on motor function. This study investigates the feasibility of a markerless, single-camera two-dimensional video-based approach to extract quantitative gait parameters in people with multiple sclerosis and to examine whether these measures scale with overall disability level as indexed by scores on the Expanded Disability Status Scale. Twenty people with multiple sclerosis were recorded while walking at a comfortable pace using a standard video camera. Spatiotemporal parameters and lower-limb elevation angles (thigh, shank, and foot) were extracted using the position of the keypoints obtained with a pose estimation algorithm. Associations between these measures and disability scores were assessed. Results showed a significant reduction in normalized stride length and stride time with increasing disability level. In addition, the range of motion of shank and foot elevation angles exhibited strong associations with disability scores. These findings suggest that the range of motion of lower-limb elevation angles, particularly at distal segments, might provide sensitive indicators of disability-related gait impairment. The proposed two-dimensional video-based method offers a low-cost, non-invasive, and unconstrained tool for objective gait assessment in people with multiple sclerosis.

1. Introduction

Multiple Sclerosis is a neurodegenerative demyelinating disease that affects the central nervous system, leading to the formation of lesions in the gray and white matter of the brain and, over time, to axonal damage. It is the most common non-traumatic disabling disease in young adults between 20 and 40 years old (Dobson and Giovannoni, 2018). MS comes with a variety of symptoms; among those that most affect the quality of life of persons with MS (pwMS) there are gait impairments and alterations (Heesen et al., 2017), which are present even in the first stages of the disease. Disability in pwMS is measured according to the Expanded Disability Status Scale (EDSS), which goes from 0 (normal neurological examination) to 10 (death due to MS) (Kurtzke, 1983). The EDSS score evaluates the severity of the impairment in different functional systems and considers mainly the distance that the person can walk uninterrupted and the need for ambulatory aids. For example, pwMS with an EDSS score between 0 and 3, while they may be impaired in other functional systems, are considered fully ambulatory without the need for aids or rest (Kurtzke, 1983). Although the EDSS score is certainly valuable for a general characterization of global neurological disability, other parameters that measure specific aspects of gait in a more detailed and quantitative manner can complement and support the standard clinical evaluations. Also, gait alterations may present as specific spatiotemporal and kinematic changes which are not explicitly captured by the EDSS scoring

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criteria and may precede detectable changes in clinical disability scores. Moreover, a consistent body of knowledge shows that even at lower scores, spatiotemporal and kinematic parameters differ from those of unimpaired controls (Carpinella et al., 2021; Greene et al., 2015).

Many studies have assessed such gait characteristics through a variety of devices, among which the most common are inertial sensors (Greene et al., 2014; Lueken et al., 2020; Pau et al., 2017; Voisard et al., 2023), and motion capture systems (Pau et al., 2022; Peebles et al., 2016). For example, Greene et al. (2014) used inertial sensors to assess the reliability of quantitative gait measures in pwMS obtained with inertial sensors placed on both shanks while performing the Timed Up and Go test (Posiadlo and Richardson, 1991); the authors highlighted high levels of variability in spatiotemporal and angular velocity parameters and, when compared to the EDSS score and Multiple Sclerosis Impact Scale (MSIS-29), these parameters were found to be correlated with the disease state. Pau et al. (2017) used an inertial sensor placed on the trunk to assess spatiotemporal parameters and smoothness of gait in pwMS with minimal disability and unimpaired control; they found a significant difference for the smoothness of gait and no difference for the spatiotemporal parameters. Lueken et al. (2020) and Voisard et al. (2023) used data from inertial sensors for the segmentation of gait into stance and swing phases; they then investigated gait parameters, such as stride time variability and average speed.

Optical motion capture systems have also been employed to quantify gait kinematics in pwMS. Pau et al. (2022) analyzed sagittal-plane joint kinematics and spatiotemporal parameters, using joint cyclograms to characterize disability-related differences. Peebles et al. (2016) investigated dynamic stability margins and their relationship with EDSS and other clinical scores. While these approaches provide detailed and accurate measurements, their cost, complexity, and limited portability restrict their routine use in clinical practice.

Recent advances in computer vision have enabled markerless, video-based gait analysis through human pose estimation algorithms, allowing the extraction of spatiotemporal and kinematic parameters from standard RGB videos (Zheng et al., 2020). Within the context of multiple sclerosis, few studies have begun to explore the feasibility of video-based gait assessment. For example, Moro et al. (2025) investigated gait characteristics in pwMS using a multi-camera setup to reconstruct three-dimensional kinematics and examined their relationship with disability level. More generally, Stenum et al. (2024) highlighted the clinical applicability of video-based pose estimation for gait analysis across neurological populations, including multiple sclerosis.

Despite these promising developments, the use of simplified single-camera, two-dimensional (2D) video-based approaches to extract clinically interpretable gait metrics in pwMS remains relatively unexplored, particularly with respect to their relationship with established disability measures such as the EDSS score.

In this work, we study a low-cost, flexible, and non-cumbersome solution for quantifying gait deficits in pwMS based on single-camera 2D video recordings acquired in the sagittal plane. The contribution of the present study is to evaluate the feasibility and clinical relevance of extracting spatiotemporal gait parameters and lower-limb elevation angle (Borghese et al., 1996) kinematics from markerless 2D videos, by examining whether these measures scale with overall disability as indexed by EDSS scores. In this context, the term *markerless* refers to approaches that estimate the motion of body keypoints directly from video recordings using computer vision algorithms. This enables the estimation of body kinematics, without the need for physical markers attached to the person or other wearable sensors, as required in traditional motion capture systems. While similar video-based methodologies have been applied in other neurological conditions *e.g.*, Moro et al. (2020), Rupprechter et al. (2021), Ng et al. (2020), their applicability to MS, characterized by subtle and progressively evolving gait alterations, requires dedicated investigation.

Table 1
Demographic and clinical data of each participant.

ID	Male (M) / Female (F)	Age (years)	Disease duration (years)	EDSS score	Cane
ID1	F	42	0.4	0	no
ID2	F	55	20.0	6	yes
ID3	F	50	12.0	2	no
ID4	F	38	2.2	2	no
ID5	M	30	5.3	1	no
ID6	F	41	14.5	5	no
ID7	F	40	3.0	2	no
ID8	F	36	2.0	5.5	no
ID9	M	37	10.0	2	no
ID10	F	25	0.6	1.5	no
ID11	F	60	4.7	3	no
ID12	F	22	0.7	1	no
ID13	F	27	6.1	1.5	no
ID14	M	31	14.1	2	no
ID15	F	43	21.1	3	no
ID16	F	51	1.6	4	no
ID17	M	31	9.6	1	no
ID18	F	50	17.1	6	yes
ID19	M	30	1.9	1	no
ID20	F	51	21.2	6	yes

To this end, we focused on the estimation of spatiotemporal parameters and thigh, shank, and foot elevation angles (Borghese et al., 1996), and on their range of motion as descriptors of segmental excursion. Sagittal-plane videos of 20 pwMS walking at comfortable speed were acquired, from which spatiotemporal parameters (*i.e.*, normalized stride length, stride time, stance phase, and swing phase) and lower-limb elevation angles were extracted and compared with EDSS scores. By building upon previous multi-camera approaches (Moro et al., 2025), the present study aims to assess whether comparable clinically meaningful information can be obtained using a simplified experimental protocol based on two-dimensional data and lightweight, easy-to-deploy computer vision human pose estimation techniques, thereby improving the accessibility of video-based gait analysis in clinical practice. Given the limited sample size, the present study should be considered exploratory, with the aim of assessing the feasibility and potential clinical relevance of this approach.

2. Materials and methods

2.1. Participants

Twenty people diagnosed with Multiple Sclerosis (pwMS) according to MC Donald criteria 2017 (Thompson et al., 2018) participated in the study. Inclusion criteria included $EDSS score \leq 6$ and adequate vision, with correction using glasses if necessary. Participants who routinely used an assistive device for ambulation ($n = 3$) were allowed to use it during the walking trials. Demographic and clinical information of the participants involved are reported in Table 1. The study was conducted in accordance with the Declaration of Helsinki and approved by the local Institutional Ethical Committee (CER Liguria, approval No. 222REG2017). All participants provided written informed consent prior to participation.

2.2. Experimental protocol

Participants were asked to walk normally in a straight line, at a safe and comfortable pace, in a controlled indoor environment. A RGB video camera recording at 30 frames per second (fps) and with a spatial resolution of $1280x720$ pixels was positioned laterally to the walking path, with the optical axis perpendicular to the direction of progression, to capture motion in the sagittal plane. The camera was placed at approximately 4 m, distance to ensure full-body visibility and to allow capturing at least two consecutive strides. Participants performed up to three trials in each walking direction (left to right and right to left in the image plane), depending on perceived fatigue. Each trial included multiple gait cycles; on average six gait cycles were analyzed per participant, with a minimum of three.

2.3. Automatic body keypoints detection and pre-processing

The video dataset was processed with the open-source MediaPipe Pose tool (AI, 2020), which provides pre-trained machine learning models for pose estimation (BlazePose (Bazarevsky et al., 2020)) and other tasks involving human movement. The MediaPipe Pose algorithm detects the (x, y) position in the image plane of 33 landmarks corresponding to keypoints of the human body. For each time instant it provides also the likelihood: a value between 0 and 1, which quantifies the confidence associated with the estimated position of the point. The raw data was then pre-processed through a multi-step filtering pipeline to reduce the effect of keypoint mispredictions and to add spatiotemporal consistency. The first step of the filtering pipeline was to discard (x, y) estimates with a likelihood value lower than 0.7 (Moro et al., 2025). Then, the missing samples were reconstructed using shape-preserving piecewise cubic Hermite interpolation. The trajectories were then smoothed using a zero-phase low-pass Butterworth filter with a cutoff frequency of 7 Hz, following biomechanical considerations related to human motion (Moro et al., 2025). Finally, motion artifacts were identified by computing frame-to-frame displacements (*i.e.*, the temporal derivative of the trajectory) and applying an adaptive threshold proportional to the maximum displacement value. Values exceeding this threshold were replaced using a final interpolation step, as described above. Interpolation was applied only to short gaps; sequences with missing data longer than $1.5s$ were excluded from interpolation. However, no such cases occurred in the present dataset. Overall, the proportion of frames associated with insufficient keypoint likelihood was low, with a median value of 1.9% and an interquartile range of 0–7.6%, indicating minimal loss of tracking even when using a low temporal resolution camera. Instances of low likelihood were typically observed during rapid movements.

2.4. Gait parameters

For each participant, starting from the filtered keypoints trajectories in the image plane, we computed a set of spatiotemporal gait parameters and the elevation angles (Borghese et al., 1996) of the lower limbs on the sagittal plane. For each trial, all parameters were calculated for the leg on the side always visible to the camera during the recording. Spatiotemporal parameters and angular measures were averaged across the left and right legs. Prior to averaging, statistical analysis were performed for each parameter to assess potential asymmetries between sides. No statistically significant differences were observed between the left and right legs for any parameter; therefore, averages were used for subsequent analyses.

2.4.1. Spatiotemporal parameters

After filtering and pre-processing the data, the heel trajectory and velocity were used to identify the heel strike and toe off events in each gait cycle captured in the 2D RGB video (O'Connor et al., 2007). Only complete gait cycles were included in the analysis, excluding the first and last steps present in the videos. The following spatiotemporal parameters were extracted for each gait cycle:

- Stride time (seconds), defined as the time interval between two consecutive heel strikes of the visible foot;
- Normalized stride length, computed in the image plane as the ratio between stride length (in pixels) and leg length (in pixels), following the consideration in Pierrynowski and Galea (2001). Leg length was defined as the maximum distance between the filtered hip and heel landmarks during the gait cycle;
- Normalized average speed ($1/s$), computed as the ratio between normalized stride length and stride time;
- Stance phase duration (%), expressed as the percentage % of the gait cycle from heel strike to toe-off;
- Swing phase duration (%), expressed as the percentage % of the gait cycle from toe-off to the subsequent heel strike.

For each participant, parameters were averaged across all available gait cycles and trials. Both the spatio-temporal parameters and the angles were averaged between left and right legs.

2.4.2. Elevation angles

The elevation angles in the sagittal plane were calculated for each segment of the lower limb (thigh, shank, and foot) with the following equations (Borghese et al., 1996):

$$\theta_{thigh} = arctan\frac{x_{knee} - x_{hip}}{y_{knee} - y_{hip}} \tag{1}$$

$$\theta_{shank} = arctan\frac{x_{knee} - x_{ankle}}{y_{knee} - y_{ankle}} \tag{2}$$

$$\theta_{foot} = arctan\frac{x_{foot\ index} - x_{ankle}}{y_{foot\ index} - y_{ankle}} \tag{3}$$

where x is the horizontal coordinate in the image plane and y is the vertical coordinate in the image plane of each keypoint.

The range of motion (ROM) of each elevation angle was calculated as the difference between the maximum and minimum angle values observed over the gait cycle, thereby quantifying the angular excursion of the corresponding body segment.

2.5. Statistical analysis

Associations between disability level defined by the EDSS score and gait metrics were assessed using Spearman's rank correlation coefficient (ρ), given the ordinal nature of the EDSS score. This approach was chosen to assess monotonic relationships between gait parameters and disability level, in line with the exploratory aim of the study and the ordinal nature of the EDSS score. Given the exploratory scope of the study, correlation analysis was considered appropriate to evaluate whether gait parameters scale with disability level. Correlation analyses were performed separately for each spatiotemporal gait parameters and for each ranges of motion (ROM) of elevation angles. Statistical significance was set at $\alpha = 0.05$. To account for multiple comparisons, p-values were adjusted using the Bonferroni-Holm procedure. All p-values reported in the Results section refer to Bonferroni-Holm-corrected values. Correlation strength was interpreted using conventional thresholds based on the absolute value of Spearman's ρ: weak $\rho \leq 0.30$; moderate $0.30 < \rho \leq 0.60$; strong $\rho > 0.60$ (Akoglu, 2018). Spearman correlation coefficient ρ was interpreted as a measure of association strength, reflecting the strength of the relationship between gait parameters and EDSS score, with its magnitude classified according to established guidelines (Akoglu, 2018).

3. Results

3.1. Spatiotemporal parameters

EDSS score significantly correlated with normalized stride length (moderate negative correlation, $\rho = -0.548$, p = 0.037), stride time (strong correlation, $\rho = 0.646$, p = 0.008), and speed (strong negative correlation, $\rho = -0.765$, $p < 0.001$), indicating that increasing disability was associated with shorter stride length, longer stride time, and reduced walking speed. In contrast, stance phase ($\rho = 0.298$, p = 0.404) and swing phase ($\rho = -0.062$, p = 0.793) expressed as percentages (%) of the gait cycle duration were not significantly correlated with EDSS score (Fig. 1)

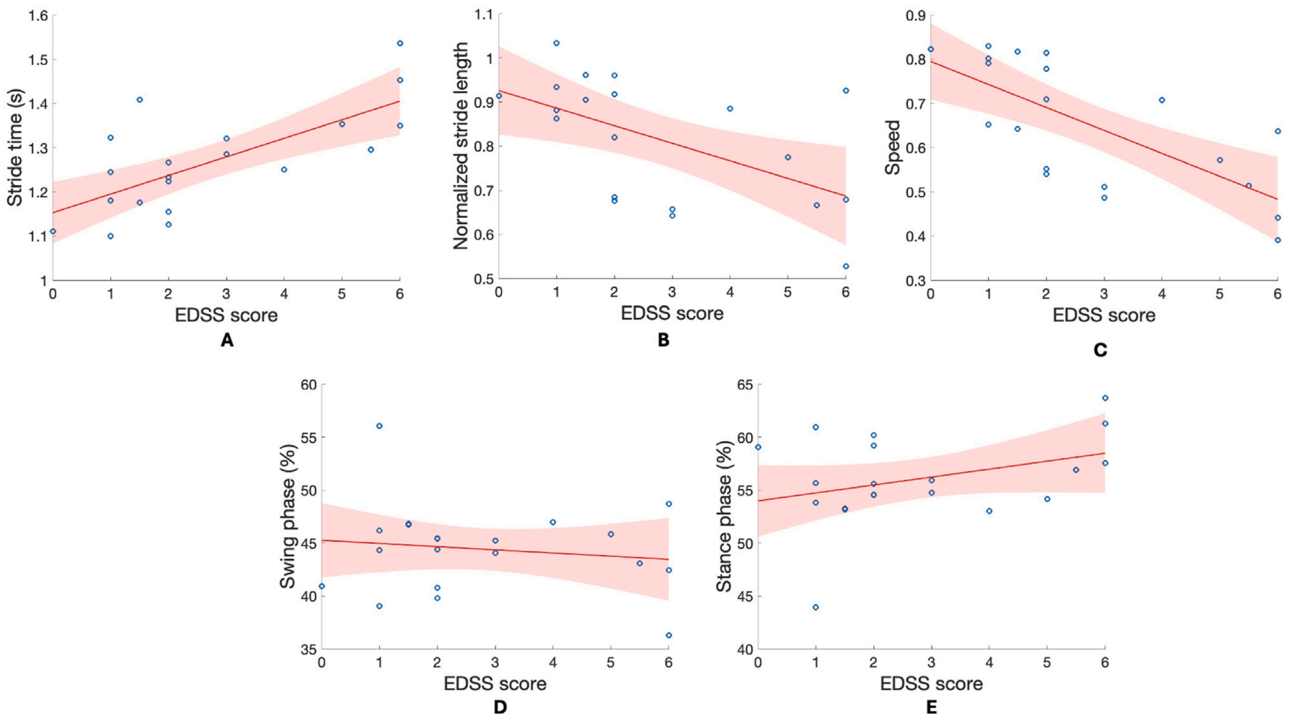

Fig. 1. Linear regression analysis between spatiotemporal gait parameters and EDSS scores. Blue dots denote the mean value for each participant, while red lines represent the corresponding fitted linear regression models and shaded areas indicate the 95% confidence intervals. These changes reflect reduced walking efficiency and altered temporal organization of gait with increasing disability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Range of motion analysis

For all participants, the elevation angles in the sagittal plane followed the expected cyclic patterns characteristic of physiological gait (see Fig. 2). Visual inspection of the curves revealed modest differences between people with different EDSS scores in terms of waveform shape. Higher EDSS scores were associated with reduced ROMs, especially in the shank and foot, indicating a decrease in angular excursion during gait. This reduction was most evident during the swing phase and suggests impaired control of distal segments associated with higher levels of disability.

The shank ROM (Fig. 3B, $\rho = -0.688$, p = 0.002) and the foot ROM (Fig. 3C, $\rho = -0.604$, p = 0.006) exhibited a strong significant negative correlation, while the thigh ROM (Fig. 3A) was not significantly correlated with EDSS score ($\rho = -0.200$, p = 0.400).

4. Discussion

The present study explored whether gait parameters obtained from markerless 2D RGB video recordings were associated with clinical disability, as reflected by EDSS scores, in people with multiple sclerosis. The main findings indicate that, while conventional spatiotemporal parameters capture global alterations in gait, the range of motion of shank and foot elevation angles may provide more sensitive indicators of disability-related gait impairment.

4.1. Interpretation of gait parameters

Consistent with previous literature, participants with higher EDSS scores walked with shorter normalized stride length and higher stride time, reflecting reduced walking speed and diminished propulsive capacity as disability increases.

A key contribution of this study lies in the analysis of lower-limb elevation angles derived from 2D video data. While the time-normalized elevation angle waveforms were preserved across disability levels, participants with higher EDSS score exhibited a marked reduction in the shank and foot range of motion, indicating decreased angular excursion during gait. This pattern indicates that alterations in distal segment kinematics are more consistently captured by the present measures, while changes at more proximal segments may also be present, but were not detected as significant, potentially due to greater inter-person variability and the limited sample size. Distal kinematic alterations may be related to changes in ankle control and push-off mechanics and may influence swing-phase clearance, even in the absence of marked modifications in the overall temporal structure of gait. Although these changes do not substantially alter basic spatiotemporal organization, they nonetheless have functional implications. The strong correlations observed between shank and foot ROM and EDSS score further support the potential of these kinematic measures as quantitative markers of disability severity, complementing traditional clinical scales.

From a clinical perspective, the observed reduction in shank and foot range of motion may reflect impairments in ankle control and push-off mechanics, which are essential for efficient propulsion and adequate foot clearance during gait. These alterations could contribute to an increased risk of instability, reduced walking efficiency, and fatigue, even in individuals who are still able to walk independently. The ability to quantitatively assess distal segment kinematics may therefore provide clinically relevant information that is not captured by conventional scales such as the EDSS score. These measures could support the identification of subtle gait impairments, enable more precise monitoring of disease progression over time, and inform targeted rehabilitation interventions aimed at improving distal motor control and gait efficiency. Moreover, the simplicity of the proposed video-based approach makes it suitable for repeated assessments, potentially enabling longitudinal monitoring in clinical or home-based settings.

4.2. Implications for clinical gait assessment

From a clinical perspective, the results highlight that a simple, non-invasive, and low-cost 2D video-based approach can extract gait

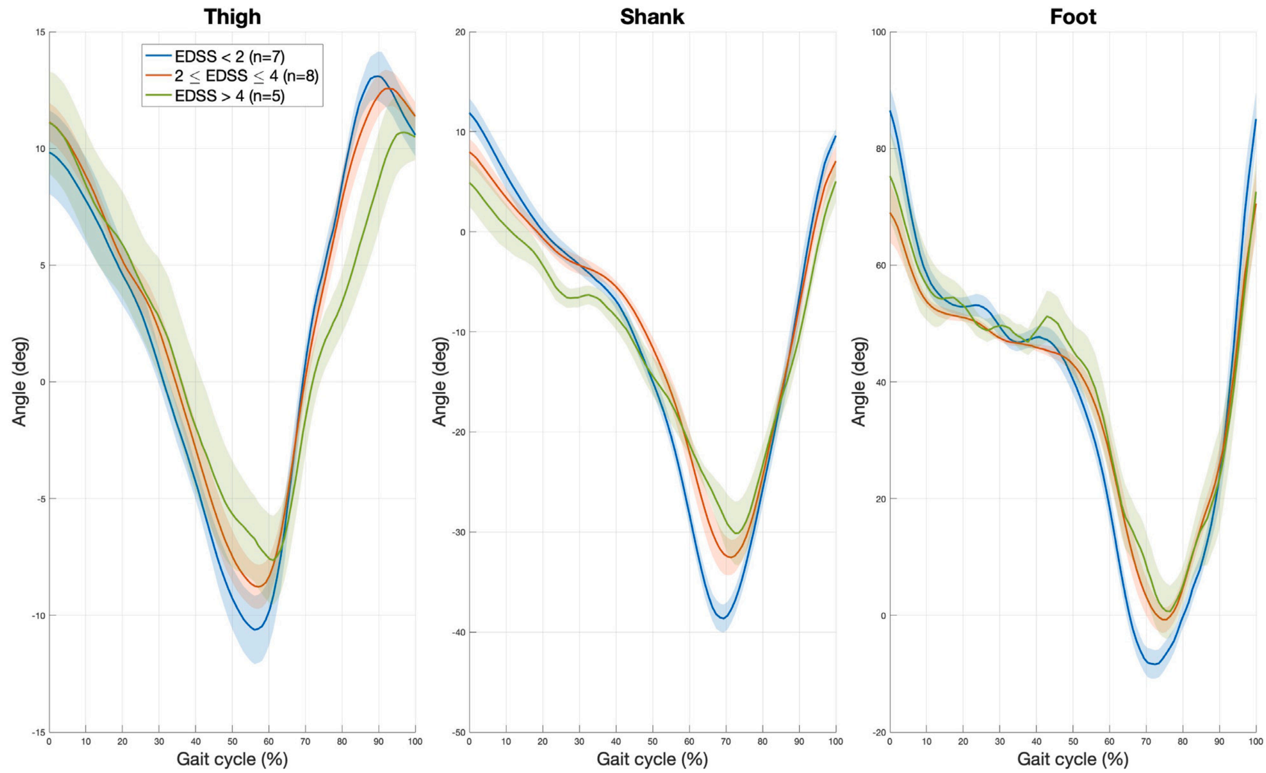

Fig. 2. Thigh (left panel), shank (middle panel) and foot (right panel) elevation angles. We report the mean and the standard error (shadow area) of individuals with $EDSSscore < 2$ (blue), $2 \leq \text{EDSS}score \leq 4$ (red), and $\text{EDSS}score > 4$ (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

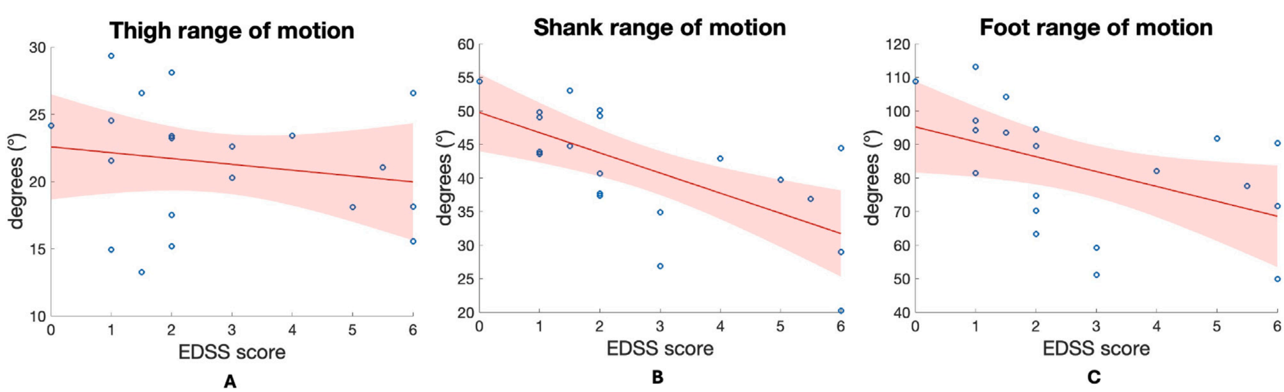

Fig. 3. Linear regression analysis between ROM's elevation angles and EDSS scores. Left panel (A): thigh ROM, middle panel (B): shank ROM, right panel (C): foot ROM. Blue dots denote the mean value for each participant, while red lines represent the corresponding fitted linear regression models and shaded areas indicate the 95% confidence intervals. The observed reductions in shank and foot range of motion with increasing EDSS score suggest impaired distal segment control associated with higher levels of disability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

parameters that are meaningfully related to neurological disability in pwMS. Unlike motion capture systems or wearable sensors, the proposed method requires no specialized equipment and minimal setup, making it well-suited for routine clinical assessments or longitudinal monitoring. Importantly, the observed correlations between elevation angle ROM and EDSS scores suggest that markerless video analysis may provide complementary information on gait alterations beyond what is captured by EDSS scores alone, particularly in the early or intermediate stages of the disease.

The observed correlations with EDSS scores are expected, given that EDSS score is partially based on ambulatory function. However, EDSS score provides an ordinal measure of disability with limited granularity, particularly at lower disability levels. Quantitative gait metrics may therefore capture subtle functional alterations that are not reflected in ordinal EDSS categories. The proposed approach provides a more detailed, objective, and quantitative characterization of gait alterations beyond the limited granularity of EDSS score, by enabling the analysis of specific spatiotemporal and kinematic features. In particular, the range of motion of distal segments, such as the shank and foot, emerged as sensitive indicators of disability-related changes. These segment-specific alterations are not explicitly captured by EDSS scoring criteria and may reflect more subtle impairments in motor control. This suggests that video-based kinematic analysis may offer complementary information and could be particularly valuable for detecting early or subclinical gait alterations, which may not yet result in measurable changes in EDSS score.

4.3. Methodological considerations and limitations

First, gait analysis was performed using a single sagittal-plane camera, which restricts the analysis to two-dimensional kinematics. Since human gait is inherently a three-dimensional process, this approach does not capture movements occurring in the frontal and transverse planes, such as pelvic rotations or mediolateral dynamics. In addition, 2D video-based analysis may be affected by perspective distortions, particularly if the person deviates from the sagittal plane, as well as by occlusions or inaccuracies in keypoint detection during rapid or complex movements. Despite these limitations, the choice of a simplified 2D approach was motivated by the aim of maximizing accessibility. Importantly, several clinically relevant gait features, including spatiotemporal parameters and sagittal-plane kinematics, can still be reliably extracted and have been shown to reflect functional impairment in people with multiple sclerosis. Therefore, while less comprehensive than full 3D motion capture systems, the proposed method represents a practical compromise between accuracy and applicability in real-world clinical and home-based settings.

Another important limitation of the present study is the absence of an unimpaired healthy control group. The current analysis is therefore focused on the relationship between gait parameters and disability level within the MS population, rather than on comparisons with normal gait patterns. Nevertheless, previous studies have consistently reported differences in spatiotemporal and kinematic gait parameters between people with multiple sclerosis and unimpaired people, even at early stages of the disease, supporting the interpretation that the alterations observed in this study are likely related to disease progression (Akbari et al., 2026; Martin et al., 2006; Kaipust et al., 2012).

Another limitation of the present study is that potential confounding variables, such as age and disease duration, were not explicitly controlled for in the statistical analysis. These factors may influence gait characteristics and could partially contribute to the observed associations with EDSS score. However, given the relatively small sample size and the exploratory nature of the study, the inclusion of multiple covariates in the analysis could lead to overfitting and unstable estimates.

Finally, the relatively small sample size (n = 20) represents a limitation of this study, as it may reduce statistical power and limit the generalizability of the findings. For this reason, the present work should be considered exploratory. Although the observed trends and correlations were consistent, further studies on larger and more heterogeneous cohorts are needed to confirm the robustness and clinical applicability of these results.

4.4. Future directions

Future studies should investigate the longitudinal sensitivity of elevation angle ROM to disease progression and rehabilitation-induced changes, as well as validate the proposed approach in larger and more heterogeneous cohorts. Integration with automated clinical workflows and remote assessment protocols could further enhance the applicability of video-based gait analysis in real-world settings. The use of correlation-based analyses allowed us to investigate whether gait parameters scale with disability level; however, future studies could further explore predictive or multivariate relationships in larger cohorts. In addition, complementary group-wise comparisons between different disability levels (reported in the Appendix) provide further support for the observed trends. Future studies on larger cohorts should investigate the independent contributions of clinical and demographic variables using multivariate approaches.

CRediT authorship contribution statement

Lea Turolla: Writing – original draft, Methodology, Formal analysis, Data curation, Software. **Matteo Moro:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Giacomo Boffa:** Writing – original draft, Methodology, Data curation. **Francesca Odone:** Writing – review & editing, Methodology, Conceptualization. **Matilde Inglese:** Writing – review & editing, Methodology, Conceptualization. **Luca Giulio Brayda:** Writing – review & editing, Methodology, Conceptualization. **Maura Casadio:** Writing – review & editing, Methodology, Conceptualization.

Institutional review board statement

The study adhered to the principles of the Declaration of Helsinki and it was approved by the Institutional Ethical Committee (CER Liguria, approval No. 222REG2017). Informed consent was obtained from all participants prior to their involvement in the study.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

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Appendix

To enable a group-wise comparison of gait characteristics across clinically distinct levels of disability, participants were divided into two groups based on their Expanded Disability Status Scale (EDSS) score: a low-disability group ($EDSSscore < 3$) and a high-disability group ($EDSSscore \geq 3$). The threshold was selected based on previous literature (equal to Moro et al., 2025 and similar to Pau et al., 2017) and in consultation with the clinicians at the recruitment facility to reflect clinically meaningful differences in gait function and ensure a more balanced distribution of participants between groups. Demographic and clinical characteristics of the participants are reported in Table 2. As expected, participants in the high-disability group exhibited higher EDSS scores and, on average, were older and had a longer disease duration than those in the low-disability group, as higher EDSS score values are more frequently observed in cross-sectional cohorts of individuals with a longer clinical history of the disease.

The normality of the spatiotemporal and ROM elevation angles parameters was assessed using the Shapiro–Wilk test. Parameters that satisfied normality assumptions were compared between groups using independent-samples t-tests, while non-normally distributed variables (stance and swing phases % duration and speed) were analyzed using the Mann–Whitney U test. To account for multiple comparisons, p-values were adjusted using the Bonferroni–Holm procedure, and

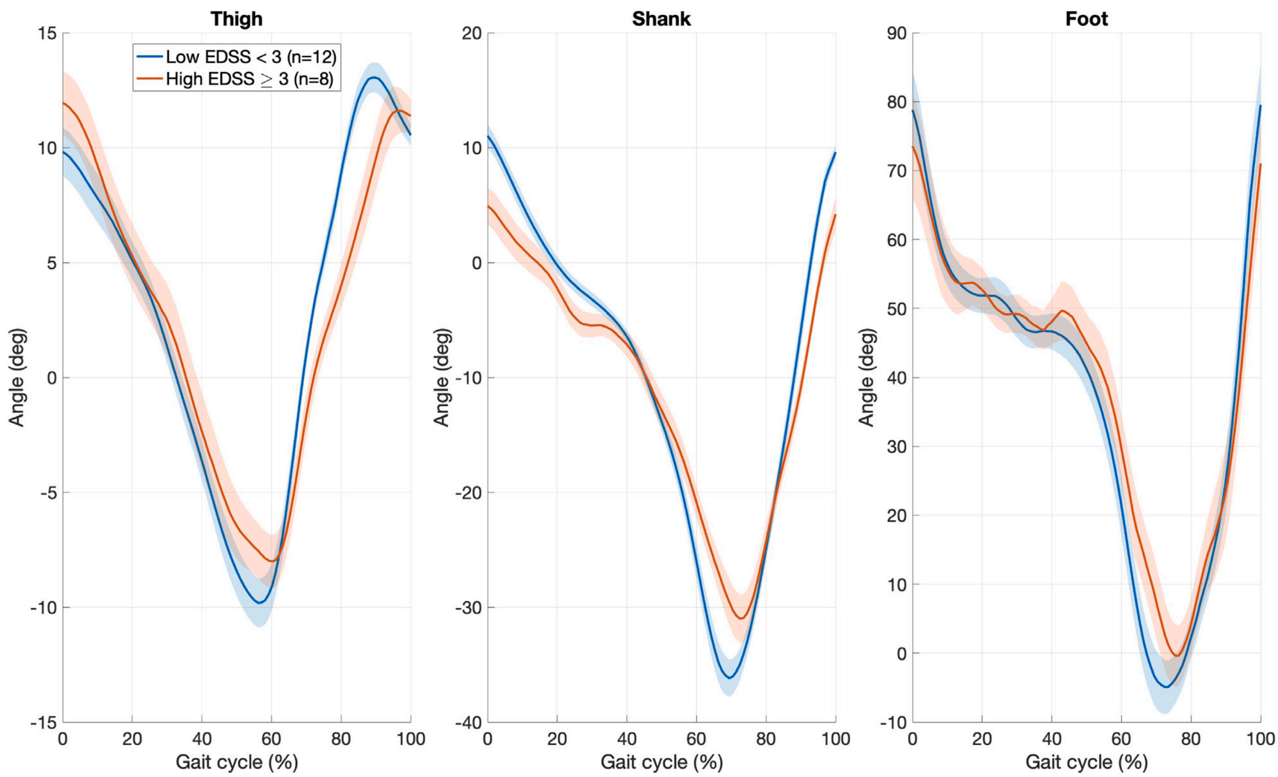

Fig. 4. Thigh (left panel), shank (middle panel) and foot (right panel) elevation angles. We report the mean and the standard error (shadow area) of individuals with $EDSS score < 3$ (blue), $EDSS score \geq 3$ (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Demographic and clinical data of participants. Age and duration of the disease are reported as mean value ± standard deviation. EDSS score is reported as median value [minimum – maximum].

Group	Participants (females)	Age (years)	Disease duration (years)	EDSS score
Low ($EDSS score < 3$)	12 (7)	33.6 ± 8.0	5.5 ± 4.8	1.5 [0.0 – 2.0]
High ($EDSS score \geq 3$)	8 (8)	48.4 ± 7.9	12.8 ± 8.6	5.0 [3.0 – 6.0]

Table 3
Mean ± standard deviation of spatiotemporal parameters divided for high and low EDSS groups. The last two rows report the statistical test and the p-values for the comparison between the two groups (high and low EDSS). MW test: Mann–Whitney U test.

Group	Normalized stride length	Stride time (s)	Stance phase(%)	Swing phase (%)	Speed
Low ($EDSS score < 3$)	0.88 ± 0.11	1.21 ± 0.09	59.3 ± 4.5	40.7 ± 4.5	0.73 ± 0.11
High ($EDSS score \geq 3$)	0.72 ± 0.13	1.35 ± 0.10	60.2 ± 8.3	39.8 ± 8.3	0.53 ± 0.10
Test	ttest	ttest	MW test	MW test	MW test
p-value	0.043	0.018	0.836	0.836	0.012
Cohen's d	1.36	1.49	0.14	0.14	1.88

Table 4
Mean ± standard deviation of the range of motion (ROM) of the elevation angles (thigh, shank, foot) divided for high and low EDSS groups. The last two rows report the statistical test and the p-values for the comparison between the two groups (high and low EDSS).

Group	Thigh ROM	Shank ROM	Foot ROM
Low ($EDSS score < 3$)	21.8 ± 5.4	46.1 ± 5.7	90.4 ± 15.4
High ($EDSS score \geq 3$)	20.7 ± 3.5	34.4 ± 8.4	71.7 ± 16.7
Test	ttest	ttest	ttest
p-value	0.586	0.015	0.047
Cohen's d	0.23	1.70	1.18

all p-values reported in the Appendix section refer to Bonferroni–Holm–corrected values.

Statistical comparison between groups revealed a significant reduction in normalized stride length (p =0.043) in the high-EDSS group, indicating progressively shorter steps with increasing disability. Furthermore, high-EDSS group showed a significant increase in stride time (p = 0.018) and speed (p = 0.012). No significant differences were observed for the stance phase, or the swing phase % duration (p = 0.836), although greater inter-individual variability was observed in the high-EDSS group (see Table 3). Group-wise comparisons revealed large effect sizes for normalized stride length (d = 1.36), stride time (d = 1.49), and speed (d = 1.88), indicating substantial differences between low- and high-disability groups. In contrast, stance and swing phase durations showed small effect sizes (d = 0.14), consistent with the lack of significant differences between groups. Effect sizes were interpreted according to Cohen conventions, with values of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively (Brydges, 2019).

In both groups, the elevation angles followed the expected cyclic patterns characteristic of physiological gait (see Fig. 4). As for the range of motion of the elevation angles (see Table 4), participants in the high-EDSS group showed a significantly reduced shank (p = 0.015) and foot ROM (p = 0.047), indicating a decreased angular excursion during gait. No significant difference between groups was observed for the thigh. Large effect sizes were observed for shank (d = 1.70) and foot (d = 1.18) range of motion, confirming pronounced reductions in distal segment excursion in the high-disability group. In contrast, the thigh range of motion showed only a small effect size (d = 0.23), suggesting more limited involvement of proximal segments.

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