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RESEARCH

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Self-selected speed provides more accurate human gait kinematics and spatiotemporal parameters than overground simulated speed on a treadmill: a cross-sectional study

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Abstract

Background Walking speed, a key element of gait analysis, is essential for evaluating the biomechanics of the musculoskeletal system and is typically assessed on flat surfaces, such as walkways or treadmills. While many authors have compared the differences and similarities between treadmill and overground walking, no studies have yet investigated the differences between treadmill gait analysis at self-selected speed (SS) and overground simulated speed (OS). The hypothesis is that accurate kinematic measurements depend on selecting the correct gait speed; however, a mismatch between the perceived comfortable treadmill speed and actual overground speed may affect the accuracy of treadmill gait analyses. This study aimed to assess treadmill gait in healthy young adults by comparing the SS with the OS. The objectives were to determine whether participants could match SS with OS on a treadmill, examine sex differences in gait kinematics and spatiotemporal parameters (KSP) at different speeds, and identify which speed better reflects natural gait kinematics.

Methods A total of 60 healthy men and 70 healthy women, aged 22–35 years, participated in this cross-sectional study to investigate the gait kinematics and spatiotemporal differences between the SS and OS. Student's t-test, Bonferroni adjustment, Cohen's effect size, and quadratic regression were employed to analyse differences across walking speeds and groups.

Results A discrepancy between OS and SS was observed in 66.4% of the participants. Our findings revealed that the adjusted R^2 values for KSP at SS were consistently greater than those at OS, suggesting that SS offers a more robust and accurate representation of gait kinematics, whereas OS is less reliable.

Conclusions These findings underscore the importance of individualized speed selection in gait analysis, as it significantly impacts the accuracy of kinematic and spatiotemporal measurements. This insight is pivotal for clinicians and researchers to develop more effective rehabilitation strategies and comprehensively understand gait dynamics.

Keywords Gait analysis, Overground speed, Perceived speed, Self-selected speed, Variability, Rehabilitation, Fall risk

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Introduction

Walking speed is considered the 6th vital sign, as it reflects the overall health of a wide range of people [1]. Gait speed is a predictor of gait quality in clinical evaluations and an indicator of negative health events that can lead to disability and hospitalization [2]. Speeds lower than 0.6 m/s are associated with the risk of death, falls, disability, strong reduction in activities of daily living, and inability to manage proper self-care [1]. Gait analysis is an important component of human movement sciences. It reflects the integrity of the musculoskeletal system and brain structures and functions [3] and can be adversely affected by neurological [4–6] and musculoskeletal disorders [7], impacting either the capacity to walk or its functional efficiency. The central nervous system plays an active role in regulating movement variations, allowing diverse movement solutions to be explored until the optimal solution is identified [8].

Treadmills are frequently used by researchers and clinicians as practical alternatives to overground walking, offering the advantages of controlled speed and slope adjustment. However, the comparability between treadmill and overground gait analyses remains debatable. A systematic review by Semaan et al. [9] revealed that biomechanical, electromyographic, and energy expenditure outcomes were largely similar between the two walking modalities. Conversely, a recent meta-analysis reported notable differences in many physiological and biomechanical measures between overground and treadmill walking [10], highlighting the complexity of directly comparing the two methods. Walking on a treadmill requires the brain to adapt to the altered sensory input, recalibrating motor output and increasing neural effort due to the visual-kinesthetic conflict between the fixed visual field and the moving belt [11]. Additionally, the biomechanical response is significantly influenced by changes in gait speed. As speed increases, adjustments in stride length, cadence, and step time affect spatiotemporal parameters across all age groups [12]. Typically, spatiotemporal parameters of healthy adults are used as baselines to identify deviations in various patient populations. For instance, slower gait speeds and altered stride dynamics are often markers of dysfunction in neurological disorders such as Parkinson's disease [13] or musculoskeletal conditions like osteoarthritis [14]. Terrier et al. [15] found that treadmill walking increases dynamic stability while also introducing greater variability in stride interval timing, leading to a less consistent stride pattern, without significantly affecting kinematic variability. At higher speeds, kinematic changes become more pronounced, with joints like the hip, knee, and ankle showing increased angular displacement to accommodate faster movement [16]. These adjustments, such as increased hip flexion and ankle plantarflexion during push-off, require precise coordination to maintain stability and gait efficiency [17], especially during faster locomotion or challenging conditions.

Various instruments and protocols are used in healthcare to evaluate walking speed. Protocols can vary in distance to cover, starting at a static or dynamic position, pace [18], and instruments of evaluation, such as manual stopwatches [19], automatic sensors [20], or treadmills [21]. Differences in gait parameters may arise when the same individual performs overground or treadmill walking, largely owing to variations in the ground reaction force response and visual feedback [22]. In addition, the environment plays a crucial role in the analysis. It is essential to consider these factors to avoid errors during the analysis and to determine whether the assessment occurs on a dedicated walkway, treadmill, or outdoors. While the use of overground speed for treadmill gait analysis has been proposed [23], it remains unclear which type of speed, overground or self-selected, most accurately reflects gait parameters. However, precise evaluation of speed is crucial for effective gait analysis. Variations in speed, whether higher or lower, can alter the spatiotemporal and kinematic characteristics of the gait cycle [24]. Therefore, determining an individualised and comfortable walking speed is crucial for accurate gait analyses.

This study aimed to investigate treadmill gait analyses at two different speeds in a sample of healthy young adults: one self-selected speed (SS) by the participants and one overground simulated speed (OS) identified using inertial measurement unit (IMU) sensors on the feet. The specific goals of the study were to (1) observe whether participants could match their SS with their OS on a treadmill; (2) analyse the sex differences in gait kinematics and spatiotemporal parameters (KSP) at different speeds; and (3) determine which speed (SS or OS) more accurately reflects the natural gait kinematics of the participants.

We hypothesized that choosing the correct gait speed is crucial for accurate kinematic measurements. However, there may be a discrepancy between the treadmill walking speed that individuals perceive as comfortable and their actual overground walking speed, which could affect the results of treadmill gait analysis.

Materials and methods

A total of 130 healthy participants, aged 20–30 years, were recruited voluntarily for this cross-sectional study at the Research Center on Motor Activities (CRAM), University of Catania, from April 2022 to June 2022. The study was approved by the Research Center on Motor Activities (CRAM) Scientific Committee (Protocol no. CRAM-03-2020) in accordance with the Declaration of Helsinki. All participants provided informed consent prior to participating in the study. The exclusion criteria were musculoskeletal or neurological disorders and lower limb trauma during the previous six months. The sample size for this study was determined a priori via GPower 3.1 software, with the following parameters: effect size d = 0.6, α = 0.05, power = 0.95, and allocation ratio = 1.

Treadmill system

Gait analysis was performed using the Walker View system (Tecnobody®, Bergamo, Italy), a markerless treadmill equipped with eight load cells and a sampling frequency of 100 Hz, and a 3D Microsoft Kinect v2 camera for motion capture with a sampling frequency of 30 Hz. The validity of the Kinect v2 has been examined in various studies, which show a spectrum of results. Some studies reported low ICCs for kinematic parameters [25], while others demonstrated good to excellent reliability for both kinematic and spatiotemporal parameters when compared to traditional motion capture systems in both healthy [26–28] and pathological participants [29]. The Walker View is equipped with two IMUs, with a weight of 47 g and a sampling frequency of 100 Hz, which are placed on the feet to collect the ankle dorsiflexion and plantarflexion, connected via Bluetooth to the system. Additionally, they can be used to identify ankle kinematics and gait spatiotemporal parameters in isolation without the need for a treadmill. The system records each phase of the gait cycle, and the integrated software (TecnoBody Management System, Bergamo, Italy) reports spatiotemporal parameters (such as step time, cadence, left and right stance and swing times, and left and right step lengths) as well as sagittal plane kinematics (including maximum and minimum angles and the range of motion for the trunk, left and right hips, knees, and ankles). Quaternions for each anatomical landmark are calculated based on the positions of the articular joints and then decomposed into Euler angles following the guidelines of the International Society of Biomechanics for angle calculation [30]. Data were exported from the TecnoBody software as a comma-separated values (CSV) file. For kinematic parameters, we analysed trunk extension and flexion, hip extension and flexion, knee extension and flexion, and ankle dorsiflexion and plantarflexion, all measured in degrees (°). The spatiotemporal parameters included walking speed (km/h), step cycle, step length (cm), and step time (s). Additionally, we calculated the number of steps per minute (spm) using the following formula: D/MSL/T. D represents the distance travelled (m), MSL represents the mean stride length of the left and right feet (m), and T represents the total time of gait analysis (min).

Protocol setup

Before starting the protocol, participants were seated, and an IMU sensor was placed on each foot, secured with a hook-and-loop fastener around their shoes to prevent movement. The researcher initiated the recording phase using the Tecnobody software and instructed the participants to walk along a 20 m indoor pathway as they would during daily activities, completing this task three times [31]. Once finished, the researcher reconnected the IMUs and downloaded the data. The software provided the mean walking speed, which the researcher noted as OS. In the second phase, the participants underwent a 5-minute familiarization period with the treadmill. After a 15-minute rest, the participants returned to the treadmill and used the staircase method to select the most comfortable walking speed within a 5-minute time window. This involved gradually increasing the speed in small increments, with the participants providing feedback at each stage until they reached a comfortable pace. No verbal suggestions were provided during the trials to avoid any discrepancies caused by verbal instructions [32]. Once confirmed by the participant as comfortable speed, the researcher noted it as SS. The participants completed a total of 10 min of familiarization on the treadmill, combining Phases 2 and 3, which included a minimum of 6 min to ensure stable performance [33]. The participants then performed two gait analyses: one at the SS and one at the OS. Speed was set by the researcher for both gait analyses. Each gait analysis, lasting 1 min, was preceded by a 2-minute walking period (not recorded). The order of the two trials was randomly assigned, as shown in Fig. 1. A 10-minute rest period was considered between the two analyses.

Statistical analysis

Data analysis was conducted via the R Project for Statistical Computing (Vienna, Austria) software. We used Student's t-test to analyse the KSP between SS and OS for the entire sample (paired t-test). We also calculated Cohen's effect size (d) to highlight the differences in KSP between the SS and OS groups. Additionally, multiple t-tests were conducted to observe the following specific differences: (1) OS-men vs. OS-women, (2) SS-men vs. SS-women, (3) men-OS vs. men-SS, and (4) women-OS vs. women-SS. We adjusted the p-value via the Bonferroni−Holm method to reduce the probability of obtaining statistical significance by chance. To address the third goal of this study, Pearson's correlation coefficients considering walking speed as independent variable and KSP as dependent variable were calculated for both the SS and OS groups. We addressed the issue of missing data by employing mean imputation. Only significant correlations were considered (p-value < 0.05). Finally, KSP were compared via quadratic regression analyses for both the

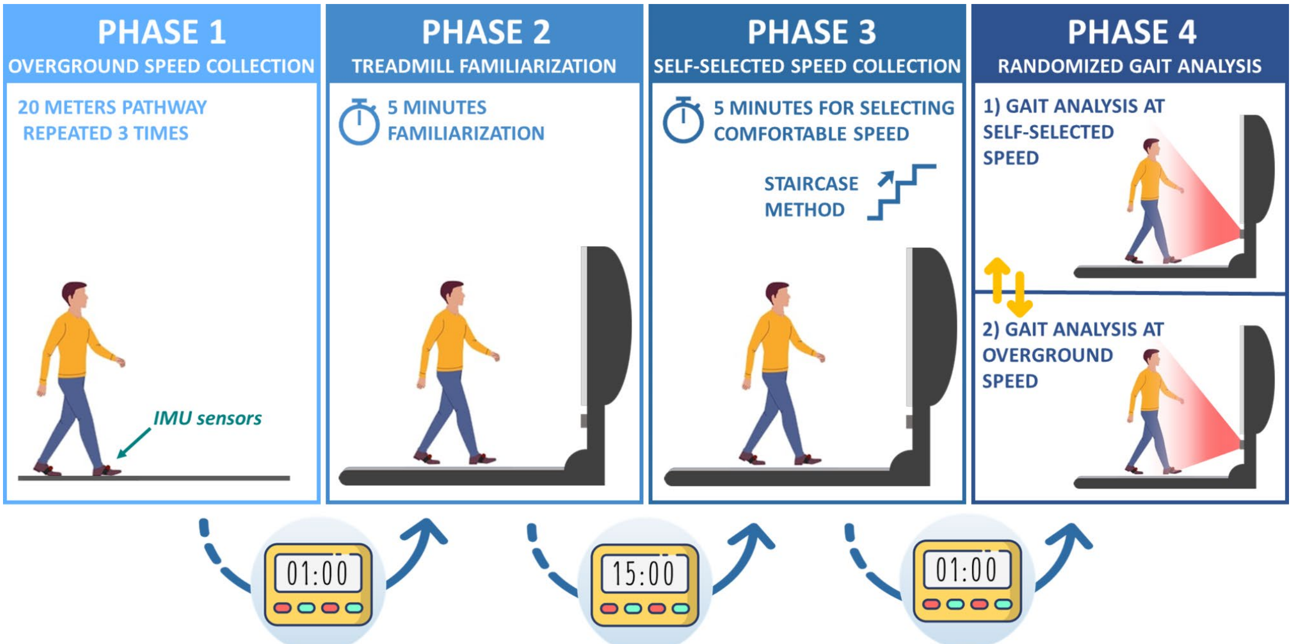

Fig. 1 Graphical Representation of the Research Setup. During Phase 1, the participant walked with the IMUs on, and at the end, the researcher recorded the overground speed. In Phase 2, the participant familiarized themselves with the treadmill for 5 min. During Phase 3, the participant identified their most comfortable speed using the staircase method within a 5-minute time window. In Phase 4, the participant performed two gait analyses at overground and self-selected speeds in a random order

SS and OS to evaluate the potential relationships between walking speed and each peak value.

Results

The means and standard deviations of the characteristics of the participants (60 men and 70 women) are as follows: age (men = 25.4 ± 6.41 years, women = 26.1 ± 5.50 years), height (men = 176.57 ± 7.30 cm, women = 163.54 ± 7.01 cm), and weight (men = 70.38 ± 2.23 kg, women = 55.67 ± 6.30 kg). We first analysed whether the participants correctly matched the SS with the OS. SS and OS were identical for only 33.6% of participants, considering a margin error of ± 0.2 km/h, which was defined as the equal gait group (EG). The unequal gait group (UG), representing 66.4%, was divided between 22.4% of those who favoured a faster speed and 44.0% of those who favoured a slower speed than their own OS. Specifically, the group choosing a faster speed had a 0.75 ± 0.30 km/h mean increase in speed, whereas those choosing a slower speed had a mean decrease in speed of 1.17 ± 0.63 km/h.

Overground vs. self-selected speed

We initially conducted a paired t-test to analyse the KSP of each individual in the SS and OS. The EG results did not significantly differ between the two trials. In contrast, the UG provided statistically significant results. Table 1 presents the means, standard deviations, Cohen's d values, and paired t-test results of the KSP in the UG. Importantly, we compared the results regardless of whether the SS increased or decreased. As revealed by the adjusted p-values, almost all the parameters differed significantly between the two trials. According to Cohen's d, almost all kinematic parameters had a medium effect size (> 0.50), similar to all spatiotemporal parameters.

We then conducted further analyses dividing the UG sample by sex, as shown in Table 2, and performed multiple t-tests comparing (1) OS-men vs. OS-women, (2) SS-men vs. SS-women, (3) men-OS vs. men-SS, and (4) women-OS vs. women-SS, as reported in Table 3. In analyses 1 and 2, we observed that kinematics differed by sex, whereas spatiotemporal parameters did not. In both trials, compared with men, women exhibited increased hip extension, hip flexion, knee flexion, ankle dorsiflexion, and ankle plantarflexion. However, trunk flexion was lower in women than that in men. The step cycle, step length, step time, and spm did not differ between men and women; in other words, the spatiotemporal parameters did not depend on sex.

In contrast, in analyses 3 and 4, the KSP were significantly different. Generally, we observed a greater distribution of records in the SS group, that is, greater variability of the sample expressed in the data by the standard deviation, as reported in Figs. 2 and 3. Furthermore, knee flexion, ankle dorsiflexion, plantarflexion, walking speed, step cycle, length, and step time had narrower distributions in the OS trial than in the SS trial .

Table 1 Mean and standard deviation of KSP for the UG group at OS and SS trials

Variables	OS	SS		
	Mean ±SD	Mean ±SD	Significance +	Effect size (d) ++
Trunk extension (°)	1.9 ± 2.1	1.7 ± 2.1	0.035 *	0.09
Trunk flexion (°)	4.3 ± 2.2	4.1 ± 2.2	0.003 **	0.13
Hip extension (°)	-17.1 ± 3.1	-15.6 ± 4.1	< 0.001 ***	-0.41
Hip flexion (°)	25.9 ± 4.4	23.6 ± 5.2	< 0.001 ***	0.49
Knee extension (°)	5.4 ± 3.2	5.2 ± 3.2	0.132	0.09
Knee flexion (°)	58.7 ± 5.4	55.8 ± 6.6	< 0.001 ***	0.49
Ankle dorsiflexion (°)	18.7 ± 3.6	15.7 ± 6.8	< 0.001 ***	0.56
Ankle plantarflexion (°)	-62.8 ± 5.8	-57.7 ± 10.7	< 0.001 ***	-0.60
Walking speed (km/h)	3.7 ± 0.4	3.1 ± 1.1	< 0.001 ***	0.64
Step cycle	0.9 ± 0.1	0.8 ± 0.1	< 0.001 ***	0.63
Step length (cm)	58.9 ± 4.8	52.6 ± 12.3	< 0.001 ***	0.67
Step time (s)	0.7 ± 0.1	0.8 ± 0.2	< 0.001***	-0.78
Steps per minute	103.5 ± 7.6	97.0 ± 13.7	< 0.001 ***	0.59

OS = overground speed; SS = self-selected speed; SD = standard deviation; + according to t-test for normal data and Mann–Whitney U for non-normal data, ++ according to Cohen's d, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2 Mean and standard deviation of KSP for the UG group by sex at OS and SS trials

Variables	Mean ± SD		Mean ± SD	
	Women		Men	
	OS	SS	OS	SS
Trunk extension (°)	1.4 ± 2.3	1.2 ± 2.1	2.3 ± 1.9	2.3 ± 2.0
Trunk flexion (°)	3.9 ± 2.3	3.5 ± 2.1	4.8 ± 1.9	4.7 ± 2.1
Hip extension (°)	-18.0 ± 3.0	-16.4 ± 4.3	-16.0 ± 2.9	-14.7 ± 3.6
Hip flexion (°)	28.5 ± 3.6	25.6 ± 5.0	23.1 ± 3.3	21.3 ± 4.5
Knee extension (°)	5.3 ± 3.3	5.1 ± 3.1	5.6 ± 3.1	5.3 ± 3.2
Knee flexion (°)	61.4 ± 5.0	58.1 ± 6.4	55.9 ± 4.4	53.3 ± 5.9
Ankle dorsiflexion (°)	20.4 ± 3.2	17.3 ± 6.9	17.2 ± 3.3	14.2 ± 6.4
Ankle plantarflexion (°)	-64.4 ± 5.7	-60.4 ± 9.6	-61.3 ± 5.6	-55.1 ± 11.2
Walking speed (km/h)	3.7 ± 0.5	3.1 ± 1.1	3.6 ± 0.4	3.2 ± 1.1
Step cycle	0.9 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
Step length (cm)	59.0 ± 4.9	52.2 ± 11.9	58.8 ± 4.8	53.0 ± 12.8
Step time (s)	0.7 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.2
Steps per minute	104.3 ± 7.3	96.1 ± 13.8	102.8 ± 7.9	97.9 ± 13.7

OS = overground speed; SS = self-selected speed; SD = standard deviation

Table 3 P-values of the different multiple t-tests analyses

Variables	OS (Men vs. Women)	SS (Men vs. Women)	Men (OS vs. SS)	Women (OS vs. SS)
Trunk extension (°)	0.123	0.068	0.123	0.433
Trunk flexion (°)	0.111	0.039 *	0.018 *	0.273
Hip extension (°)	0.008 **	0.050 *	< 0.001 ***	0.032 *
Hip flexion (°)	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.007 **
Knee extension (°)	1.000	1.000	1.000	0.699
Knee flexion (°)	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***
Ankle dorsiflexion (°)	< 0.001 ***	0.049 *	0.010 **	0.007 **
Ankle plantarflexion (°)	0.043 *	0.043 *	0.030 *	0.010 **
Walking speed (km/h)	0.841	0.841	< 0.001 ***	0.046 *
Step cycle	0.762	0.411	0.036	0.002 **
Step length (cm)	1.000	1.000	< 0.001 ***	0.013 *
Step time (s)	0.226	0.722	< 0.001 ***	0.011 *
Steps per minute	0.742	0.742	0.002 **	0.069

OS = overground speed; SS = self-selected speed; + according to t-test for normal data and Mann–Whitney U for non-normal data * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Correlation and quadratic regression analyses of walking speed

Both the SS and OS groups were subjected to Pearson's correlation coefficient (r) analysis. The SS group showed high correlations between walking speed and step length ($r = 0.95$), step time ($r = -0.88$), steps per minute ($r = 0.87$), step cycle ($r = 0.88$), ankle dorsiflexion ($r = 0.84$), ankle plantarflexion ($r = -0.79$), hip extension ($r = -0.69$), and hip flexion ($r = 0.66$). In contrast, the OS group presented high correlations only between walking speed and step length ($r = 0.79$), step time ($r = -0.66$), and steps per minute ($r = 0.70$) and moderate correlations for ankle dorsiflexion ($r = 0.53$) and ankle plantar flexion ($r = -0.45$).

We then conducted a quadratic regression to evaluate the goodness of fit for the KSP in both the SS and OS groups, as presented in Table 4. Quadratic regression provided an excellent fit for many of the KSP parameters when SS was considered the dependent variable, with spatiotemporal parameters showing a mean adjusted R^2 greater than 0.80. For the kinematic parameters, only trunk flexion and extension demonstrated a poor fit. In contrast, quadratic regressions using OS as the dependent variable resulted in a poor fit for all KSP parameters except for step length. The fitted curve plots of each KSP for both speeds are shown in Figs. 4 and 5, respectively.

Discussion

The findings of this study confirmed our hypothesis that most participants would choose a different walking speed on the treadmill compared with their OS and that

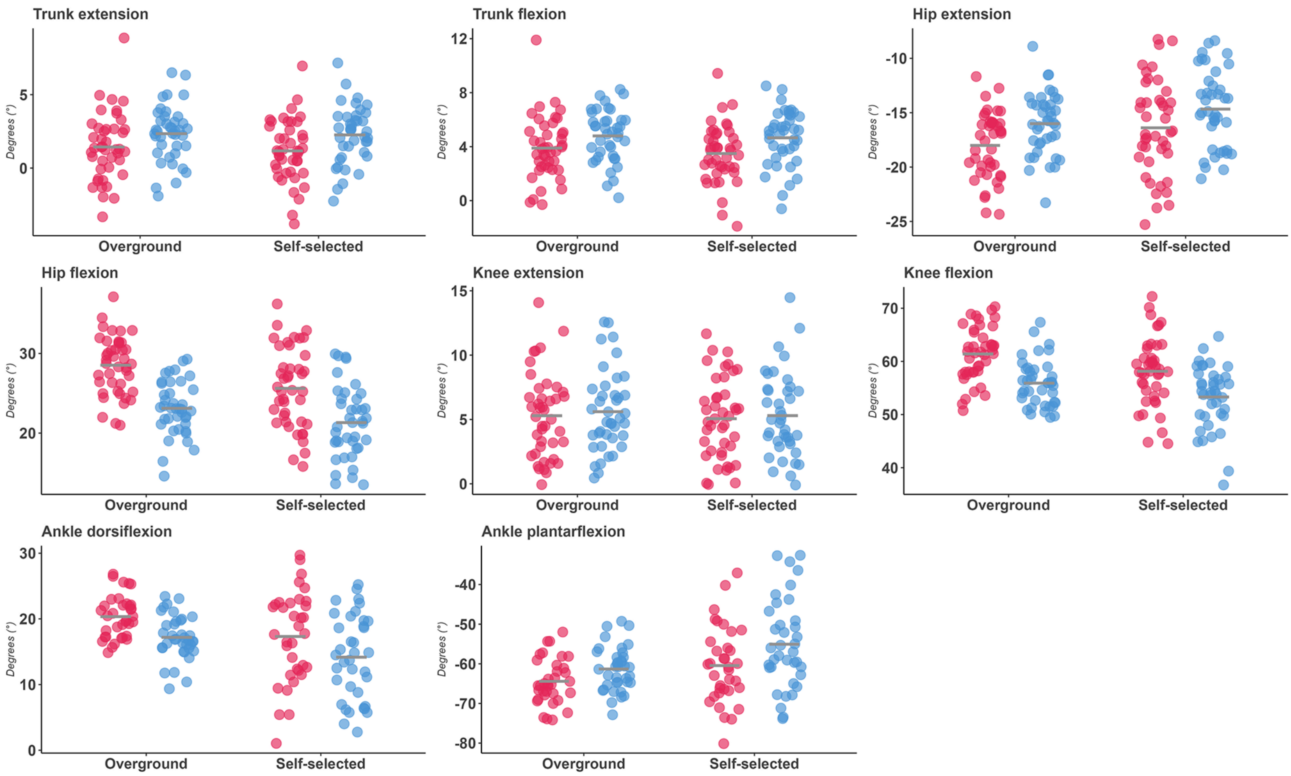

Fig. 2 Jitter plot differences in men (blue) and women (red) gait kinematics between OS and SS

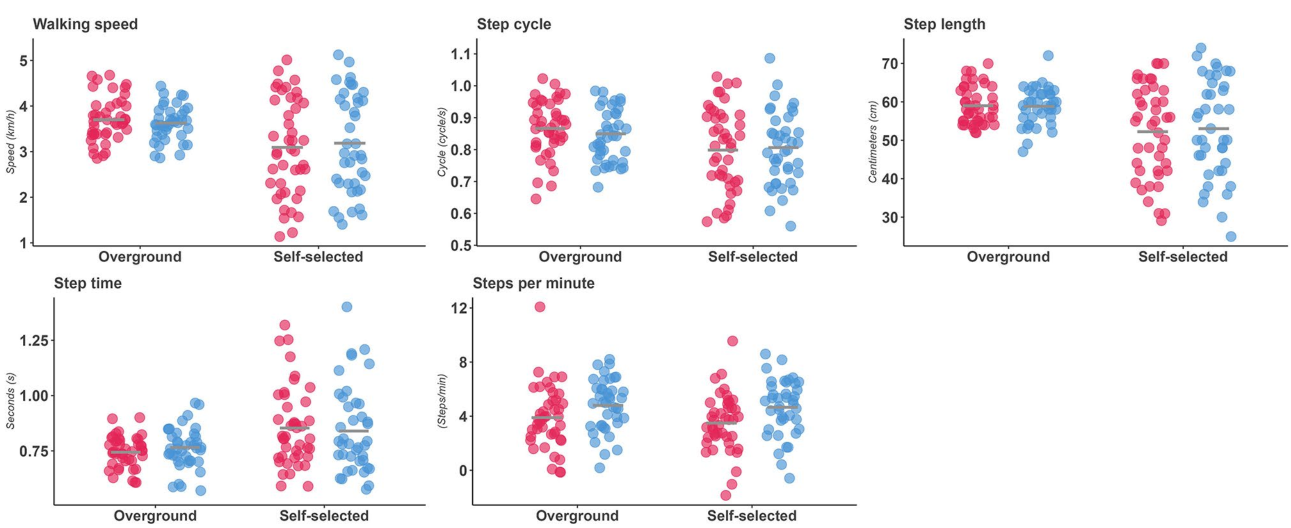

Fig. 3 Jitter plot differences in men (blue) and women (red) gait spatiotemporal parameters between OS and SS

imposing the overground simulated speed would poorly correlate with gait KSP. Notable differences between men and women were observed in kinematic parameters but not in spatiotemporal parameters. Furthermore, KSP was moderately to highly predictive of SS gait speed rather than OS.

On average, OS was faster than SS. This finding aligns with a previous study [34], which reported that the OS speed was faster than the SS speed when there was no visual flow stimulation and that the two speeds were similar only when participants were placed in a virtual reality environment. Notably, 66.4% of participants in this study selected a different speed on the treadmill compared to their OS, with 44% opting for an SS that was lower than their OS. These findings contrast with those of Hutchinson et al. [35], who noted that self-selected walking speeds tended to increase when individuals were aware of being recorded. During data collection, participants

Table 4 Quadratic regression results of the sagittal plane kinematic parameters

Variables	Self-selected speed		Overground speed	
	Adjusted R^2	p-value	Adjusted R^2	p-value
Trunk extension (°)	0.008	0.673	0.007	0.651
Trunk flexion (°)	0.029	0.596	0.014	0.999
Hip extension (°)	0.477	0.006 **	0.141	0.026 *
Hip flexion (°)	0.427	0.012 *	0.132	0.563
Knee extension (°)	0.005	0.539	0.003	0.143
Knee flexion (°)	0.299	< 0.001 ***	0.052	0.012 *
Ankle dorsiflexion (°)	0.705	< 0.001 ***	0.278	0.724
Ankle plantarflexion (°)	0.642	< 0.001 ***	0.192	0.152
Step cycle	0.789	< 0.001 ***	0.079	0.193
Step length (cm)	0.921	< 0.001 ***	0.512	0.047 *
Step time (s)	0.825	< 0.001 ***	0.454	0.002 *
Steps per minute	0.759	< 0.001 ***	0.478	0.141

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

were aware that they were being recorded, suggesting that this effect may not have occurred when walking on a treadmill.

Various studies have investigated factors that may contribute to the preference for a lower SS speed. One significant factor is the psychological impact of the treadmill environment. Treadmill walking can evoke feelings of constraint and reduce spatial awareness, leading individuals to feel less confident in their movements [36]. This psychological discomfort may prompt participants to select a speed they perceive as safer or more manageable. Furthermore, biomechanical differences between treadmill and overground walking also play a role in speed selection. Treadmill walking often involves a different gait pattern, where individuals may subconsciously adjust their speed to accommodate the lack of environmental interaction [10]. This adjustment may result in participants feeling that a slower speed is more appropriate when walking on a treadmill.

Understanding the discrepancy between OS and SS may be particularly important for older adults and gait-impaired individuals, as these populations are often the focus of gait analysis studies. The implications of these findings are significant for older adults and gait-impaired patients. Research indicates that older adults frequently experience declines in gait mechanics and balance, which increases their risk of falls [37]. The discrepancy between OS and SS could reflect these challenges, suggesting that older adults may prefer slower speeds to enhance their stability and reduce fall risk. This tendency could be further pronounced in gait-impaired patients, who may have increased concerns about their mobility and safety [38].

In the comparison between the two trials, we found differences controlling for sex, for both kinematic and spatiotemporal parameters. Specifically, knee flexion, ankle dorsiflexion, ankle plantarflexion, walking speed, step cycle, length, and step time, which presented a narrower distribution in the OS trial than in the SS trial. This could be due to the intrinsic variability that characterizes biological systems when performing repetitive tasks [39]. Strategic and execution variability affect different strategies, and conscious and unconscious adjustments are adopted while a movement is performed [40]. Therefore, another possible factor that might elicit a difference between the OS and the SS is the difference in the balance required by the two tasks [9]. This could be explained by the reduced step length and trunk extension that we found in the SS gaits, in line with the findings of Yang et al. [41], who compared overground and treadmill gaits in a similar population. Furthermore, the correlation analysis revealed that SS speed had greater correlations with step length, step time, steps per minute, step cycle, ankle dorsiflexion and plantarflexion, hip extension, and flexion than OS.

To determine which speed (SS or OS) more accurately reflected the natural gait kinematics of the participants, we followed the approach suggested by Lelas et al. [42], who assessed the relationship between gait speed and kinematic parameters via regression analyses. Our findings revealed that the adjusted R^2 values for KSP at SS were consistently greater than those at OS. This suggests that, in treadmill gait analyses, the SS offers a more robust and accurate representation of gait kinematics, whereas the OS is less reliable. Previous studies have investigated the association between gait speed and KSP in overground trials, often finding a weak predictive relationship [42, 43]. Although direct comparisons with our results are challenging, the factors contributing to their poor results may be the same as those in our study, considering the gait analysis at an overground speed. This instruction might lead individuals to adopt a gait that does not accurately reflect their true kinematics because it may be influenced by habitual movement patterns. In contrast, when participants are encouraged to find a comfortable speed (SS trial), the body may engage more naturally in the task, leading to a more authentic representation of their gait kinematics. Therefore, the SS appeared to be more representative of physiological walking because the variance in walking speed explained by the dependent variables was better captured in the SS group than in the OS group. This finding indicates that the SS more effectively reflects the true kinematic patterns and relationships between gait variables and walking speed. These results could be due to the feedback from the treadmill, which is different from that given by the ground, mainly because the ground remains still and the person walks towards it, whereas on treadmills, it is the belt that moves towards the individual. The sensory system can receive altered signals from the foot while walking on a moving surface, especially at the first heel strike and during

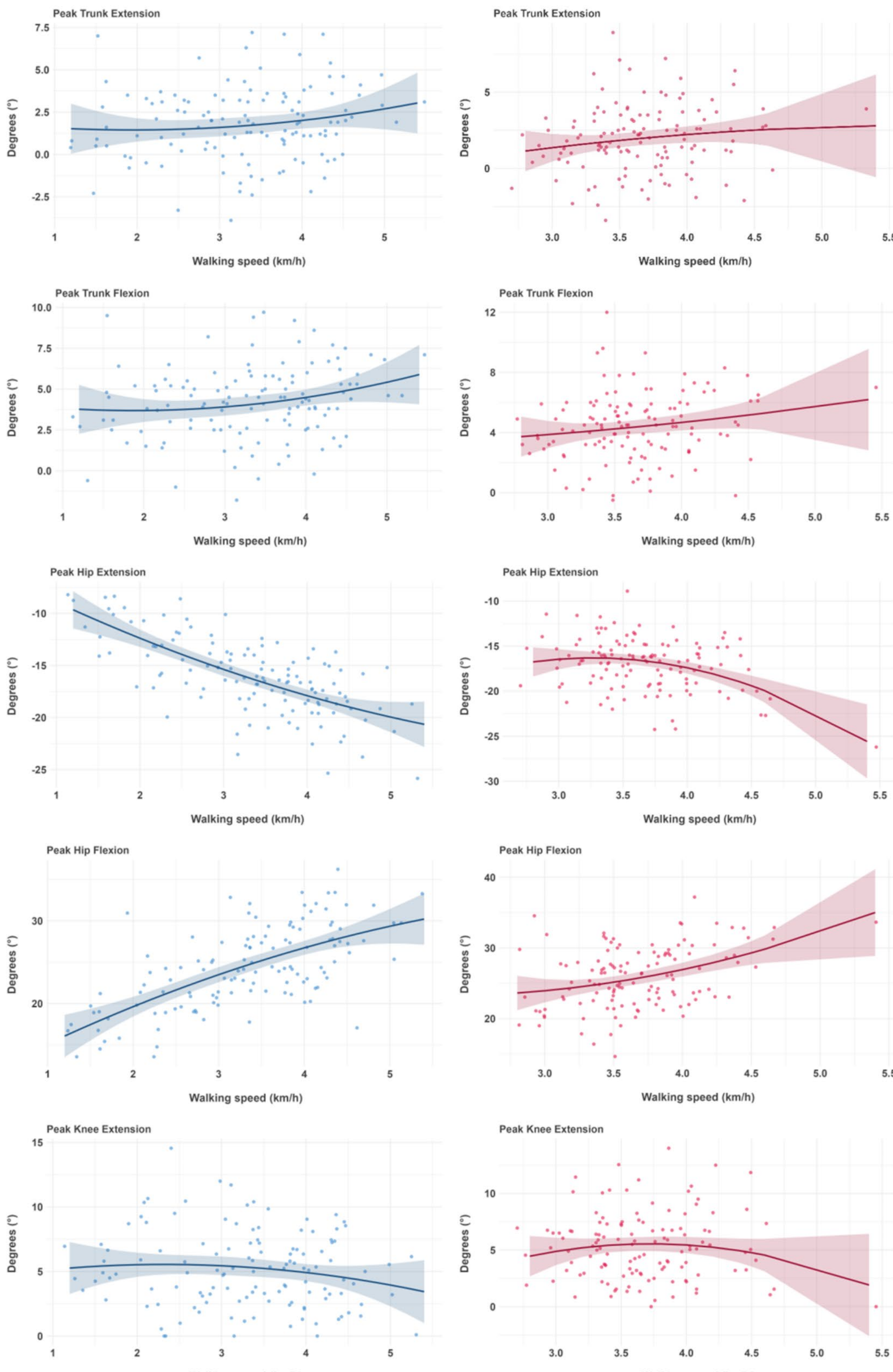

Fig. 4 The fitted curves of the kinematic and spatiotemporal parameters illustrate that the self-selected speed (blue plots) provides a better goodness of fit, with data points more closely aligned to the regression curve and narrower confidence intervals, than the overground speed (red plots)

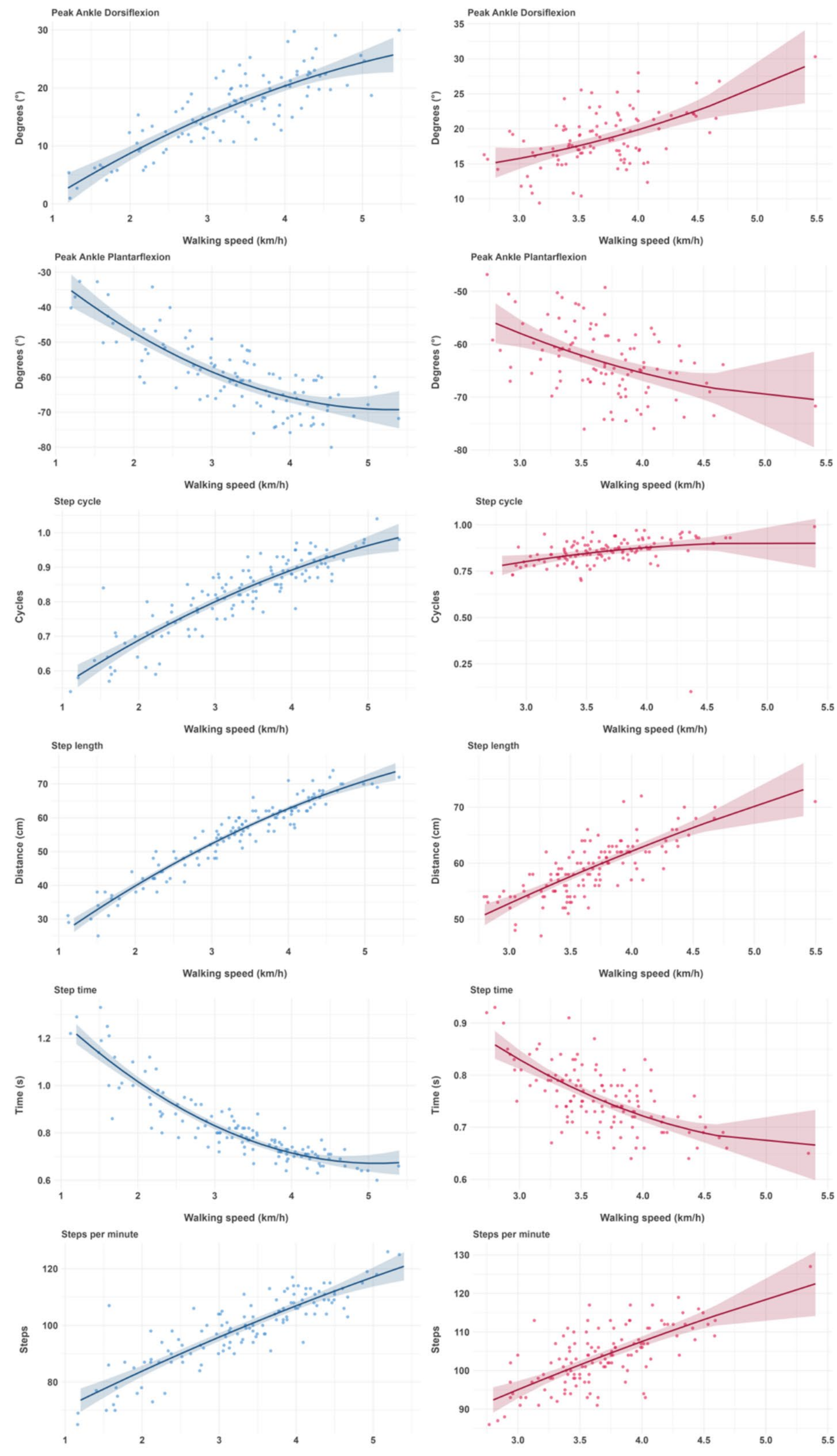

Fig. 5 The fitted curves of the kinematic and spatiotemporal parameters illustrate that the self-selected speed (blue plots) provides a better goodness of fit, with data points more closely aligned to the regression curve and narrower confidence intervals, than the overground speed (red plots)

single-limb support [44, 45]. Given these findings, selecting the OS as a reference for treadmill walking may not be appropriate, as it could result in inaccurate representations of the natural gait of the participants. Therefore, analysis of the relationship between the walking speed and kinematic variables via the SS appears to be more effective and indicative. This condition provides a better understanding of how kinematic factors influence walking speed and supports the validity of the results derived from self-selected speeds.

When comparing the gait analysis of men and women controlled for speed, we identified various significant differences in kinematics. In line with the literature on comparable samples for age and health status, we found that, compared with men, women presented increased knee flexion [46], hip extension, hip flexion [47], and ankle plantarflexion [48]. These differences may be due to different reasons, such as greater ligamentous laxity and flexibility [49] and differences in the pelvic anatomy of women, which are broader and wider [50] with an increased Q angle [51]. Conversely, statistically significant differences were not found for the spatiotemporal parameters. In line with our results, a previous study by Bruening et al. [52] revealed that spatiotemporal parameters did not differ between males and females. In contrast, Cho et al. [53] reported that stride length and step width were lower in women than in men.

In the field of human movement analysis, a variety of methods exist for assessing gait, each with distinct strengths and weaknesses that can influence the accuracy and applicability of the results obtained [54]. In this study, we employed a system equipped with a Microsoft Kinect v2, whose validity for gait analysis has been thoroughly investigated, highlighting both its advantages and limitations. While Bravi et al. [25] found lower ICCs for kinematic parameters during walking and running in their studies, Usami et al. [55] argue that the Kinect v2 is a reliable device for assessing gait velocity, cycle time, step length, and the minimum and maximum flexion angles of the hip and knee joints, with strong correlation coefficients compared to traditional motion capture systems. Supporting this perspective, studies by Latorre et al. [29], Eltoukhy et al. [26], and Dolatabadi et al. [28] have reported very high ICCs and correlations between the Kinect v2 and Motion capture systems. Consequently, as supported by Otte et al. [56], the Kinect v2 can be regarded as a reliable and valid tool for clinical measurements, underscoring its utility in both research and clinical contexts.

The findings of this study highlight the significance of speed selection in gait analysis, a critical factor in diagnosing and treating musculoskeletal conditions, as well as in fall risk assessment. On the basis of the quadratic linear regression of each gait parameter, this study supports the notion that SS may yield a more accurate KSP during treadmill gait analyses. The use of the SS can enable clinicians to identify gait abnormalities and balance issues more precisely, facilitating the development of more effective intervention strategies. This approach underscores the importance of a patient-centered methodology in gait analysis, which is crucial for creating personalized rehabilitation programs and improving patient outcomes in both orthopedic care and fall prevention.

This study has several limitations. First, it involved young adults, whose characteristics may limit the generalizability of the findings to older adults. Additionally, young adults may have difficulty accurately gauging their actual walking speed. Second, we did not account for psychological factors, such as stress or depression, which can influence walking speed. Third, the familiarization period on the treadmill consisted of two phases. Fourth, our analysis was limited to sagittal kinematics using a 3D markerless system, which may impact the quality of the results. Future studies should specifically target older adults and gait-impaired patients to test this hypothesis and determine whether these populations also exhibit a discrepancy between overground speed and self-selected speed. Additionally, it is important to understand if, for these groups, the KSP may be better represented by self-selected speed rather than overground speed.

Conclusions

Analysis of human walking can provide important information about the health status of an individual. Therefore, it is essential to understand the best approach for assessing gait while minimizing potential confounding factors that may affect the evaluation. Our study highlights the significance of walking speed in influencing kinematic and spatiotemporal parameters in treadmill gait analysis. We recommend allowing participants to choose their own walking speed to ensure a more authentic representation of their natural gait. This approach could greatly benefit clinicians and researchers by enabling more precise gait analyses on treadmills, thereby enhancing the understanding and treatment of various health conditions.

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Author contributions

FR and GM conceptualized the study. FR, BT, and MS conducted the investigation. MV and GM supervised the investigation and ensured adherence to the study protocol. GM handled the project administration and funding acquisition. All the authors contributed to the writing and review process.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Signed informed consent was obtained from all the subjects involved in the study. The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Center on Motor Activities (CRAM) Scientific Committee (Protocol no. CRAM-03-2020).

Consent for publication
Not applicable.

Competing interests
Dr. Federico Roggio is an Editorial Board Member of BMC Sports Science, Medicine and Rehabilitation.

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