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ORIGINAL ARTICLE

Pendular energy transduction and body center of mass levelling at different gait speeds in middle-aged versus young adults

Transdução de energia pendular e nivelamento do centro de massa corporal em diferentes velocidades de marcha em adultos de meia-idade

Transducción de energía pendular y nivelación del centro de masa corporal a diferentes velocidades de marcha en adultos de mediana edad frente a adultos jóvenes

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Keywords:
Gait analysis;
Mechanical energy;
Kinematic study;
Biomechanical modelling.

ABSTRACT

This study examined whether gait mechanics already differ in middle-aged adults respect to young adults. Thirty young (18–30 years) and thirty middle-aged (50–59 years) adults walked at self-selected, slow, and fast speeds. Spatiotemporal variables increased with speed in both groups, but middle-aged adults showed smaller increments in mean speed and dimensionless velocity. At the angular level, differences were most evident at the knee, where middle-aged adults exhibited greater flexion. Energetic analysis revealed lower energy recovery and higher energy congruence, indicating reduced pendular efficiency. These findings suggest that early gait adaptations emerge in midlife, especially under higher mechanical demands.

Palavras-chave:
Análise da marcha;
Energia mecânica;
Estudo cinemático;
Modelagem biomecânica.

RESUMO

Este estudo examinou se a mecânica da marcha já difere em adultos de meia-idade. Trinta adultos jovens (18–30 anos) e trinta adultos de meia-idade (50–59 anos) caminharam em velocidades autosselecionadas, lentas e rápidas. As variáveis espaço-temporais aumentaram com a velocidade em ambos os grupos, mas os adultos de meia-idade apresentaram incrementos menores na velocidade média e na velocidade adimensional. No nível angular, as diferenças foram mais evidentes no joelho, onde os adultos de meia-idade exibiram maior flexão. A análise energética revelou menor recuperação de energia e maior congruência energética, indicando eficiência pendular reduzida. Esses achados sugerem que as adaptações precoces da marcha surgem na meia-idade, especialmente sob maiores demandas mecânicas.

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Palabras clave:
Análisis de la marcha;
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RESUMEN
Este estudio examinó si la mecánica de la marcha ya difiere en adultos de mediana edad. Treinta adultos jóvenes (18-30 años) y treinta de mediana edad (50-59 años) caminaron a velocidades autoseleccionadas, lentas y rápidas. Las variables espaciotemporales aumentaron con la velocidad en ambos grupos, los adultos de mediana edad mostraron incrementos menores en la velocidad media y la velocidad adimensional. A nivel angular, las diferencias fueron más evidentes en la rodilla, donde los adultos de mediana edad exhibieron mayor flexión. El análisis energético reveló menor recuperación de energía y mayor congruencia energética. Estos hallazgos sugieren que las adaptaciones tempranas de la marcha surgen en la mediana edad, especialmente bajo mayores demandas mecánicas.

INTRODUCTION

The onset of alterations in neuromuscular control (Vervoort et al., 2020) and decreases in muscle mass (Muscaritoli et al., 2013) typically begins in the fifth decade of life (Kennis et al., 2014; Chuang et al., 2019). Some evidence suggests that these changes may underlie subtle variations in gait performance (McCrum et al., 2016). Furthermore, a proportion of middle-aged adults report difficulties in performing activities of daily living (Zajacova and Montez, 2018). Such functional decline can have a considerable impact on population health (Case and Deaton, 2015) and social aspects (Meyer and Mok, 2019). However, middle-aged adults also show a strong capacity to recover from functional impairments (Brown and Covinsky, 2020). Despite its potential clinical and public health relevance, this life stage remains largely underrepresented in gait research, which has traditionally focused on comparisons between young and older adults (Herssens et al., 2018). Therefore, studying gait functionality in middle-aged adults may play a crucial role in anticipating and preventing adverse effects later in life.

Regarding functionality evaluation, gait is one of the most frequently analysed aspects (Perry, 2005; Baker, 2006). Spatiotemporal parameters such as mean speed, cycle length, and joint angular values are commonly used in clinical gait evaluations and are important for the diagnosis and treatment of musculoskeletal disorders (Perry, 2005; Baker, 2006; Willems et al., 2012). A review reported that, in healthy adults, most spatiotemporal parameters significantly change across the lifespan (Herssens et al., 2018). However, these differences are mainly observed when comparing young and older adults, as studies focusing on middle-aged individuals are scarce. Alterations in spatiotemporal parameters may compromise key functional outcomes of gait, such as minimizing energy cost and maintaining stability (Perry, 2005).

Energy cost during walking is closely associated with the movement of the body center of mass (CoM) (Iida and Yamamuro, 1987; Willems et al., 2012). During gait, the CoM undergoes cyclic changes in potential (Ep) and kinetic (Ek) energy, and two main strategies have been proposed to reduce the energetic cost of walking (Willems et al., 2012). The first strategy is to level the trajectory of the CoM (Saunders et al., 1953; Della Croce et al., 2001), which involves coordinated movements of the lower limbs and pelvis that reduce vertical CoM displacement (Willems et al., 2012). The second strategy describes the legs acting like inverted pendulums in the sagittal plane during each step, enabling conservation and transfer of mechanical energy (Margaria, 1976; Cavagna et al., 1976; Saibene and Minetti, 2003; Peyré-Tartaruga et al., 2021). Neither strategy alone fully explains the complexity of walking; however, a combined kinematic analysis of both aspects can help address this complexity (Kuo, 2007; Kuo and Donelan, 2010). Specifically, the kinematic actions that contribute to levelling the CoM trajectory during gait include pelvis rotation in the transverse and frontal planes, hip abduction/adduction in the frontal plane, knee flexion during mid-stance and swing, and the rolling action of the ankle (Willems et al., 2012). Complementarily, the inverted pendulum mechanism is commonly assessed through the percentage of energy recovery (R) and the congruity percentage (%Cong) (Biewener, 2006; Peyré-Tartaruga et al., 2021). R represents the proportion of external mechanical work saved through the transfer of kinetic (Ek) and potential (Ep) energy, relative to the theoretical work assuming no energy transduction (Cavagna et al., 1977). In contrast, %Cong corresponds to the proportion of the gait cycle in which Ek and Ep fluctuate in the same direction (Biewener, 2006), reflecting the degree of synchrony between these energy components. In healthy young adults, walking is typically characterised by high R (60-60% in optimal speed), low %Cong (<20% in optimal speed) (Cavagna et al., 2002; Gomeñuka et al., 2016) and coordinated angular movements of the lower limbs that level the CoM (Willems et al., 2012; Peyré-Tartaruga et al., 2021). Both energy parameters (R and %Cong) and angular values change systematically with walking speed (Saibene and Minetti, 2003; Willems et al., 2012). Knowing these parameters across different gait speeds in healthy individuals may help interpret potential age-related alterations. Despite their relevance, possible age-related changes in these strategies, particularly considering the effect of different walking speeds, have not yet been systematically described in middle-aged adults

This study aimed to evaluate the impact of ageing on gait mechanics by comparing angular kinematics related to the vertical levelling of the CoM and energy transduction associated with the inverted pendulum mechanism between young and middle-aged adults walking at different speeds. We hypothesised that middle-aged adults would show overall similar gait patterns to young adults, but that early age-related changes could lead to subtle differences in lower-limb angular kinematics and CoM energy parameters, particularly under higher mechanical demands (fast walking).

METHODS

DESIGN

Body movement was recorded during gait at three self-selected speeds slow (Ss), preferred (Sa), and fast (Sf). We implemented a comparative cross-sectional design with a mixed (split-plot) structure, including a between-subjects factor Group (young vs. middle-aged adults) and a within-subjects factor Speed (Ss, Sa, Sf); repeated measures within each participant. The study focused on pendular energy recovery (inverted pendulum mechanism) and lower-limb angular kinematics contributing to the vertical levelling of CoM. The protocol was approved by the CENUR Litoral Norte ethics committee, Universidad de la República (UdelaR) (Exp. Nº 311170-000561-20), and adhered to the Declaration of Helsinki.

SUBJECTS

Sixty healthy adults participated in this study, divided into two groups: thirty young adults (18–30 years) and thirty middle-aged adults (50–59 years). Participants were recruited by convenience. Table 1 summarises their main characteristics. Informed written consent was obtained from all participants prior to data collection. Inclusion criteria for both groups were: (i) no history of neurological, musculoskeletal, or cardiovascular disorders affecting gait; (ii) no acute or chronic pain or injuries at the time of testing; (iii) ability to walk independently without assistive devices; and (iv) normal or corrected-to-normal vision. None of the participants reported taking medications known to affect balance or locomotor performance.

EXPERIMENTAL PROTOCOL

To enable three-dimensional whole-body reconstruction, each participant was fitted with 45 retro-reflective markers placed at anatomical landmarks (marker set and placement as in Fábrica et al. (2019). Participants walked along a flat 10 m × 4 m walkway in a temperature-controlled laboratory (21 °C) at three self-selected speeds: Ss, Sa and Sf. Walking speeds were not externally imposed or paced, in order to capture behaviour representative of activities of daily living. For each speed condition, participants completed ten walking trials; from each trial, two strides from the central walkway section were retained for analysis to avoid acceleration or deceleration artefacts. One-minute seated rests were provided between trials and a 5-minute rest between speed conditions. Motion capture was performed with eight Bonita B10 cameras at 100 Hz, integrated with a Vicon Nexus 2.8 system (Oxford Metrics, Oxford, UK). Heel-strike and toe-off events were identified kinematically from foot markers (heel and toe): heel-strike was defined as the first local minimum of the heel marker vertical position following swing (with the antero-posterior heel velocity crossing zero), and toe-off as the first local minimum of the toe marker vertical position preceding swing. Strides were excluded if there was marker loss for more than three consecutive frames, visible artefacts, turning or acceleration phases, or if instantaneous speed deviated by more than ±10% from the mean speed over the central walkway section.

DATA PROCESSING AND VARIABLE CALCULUS

Data processing and variable calculation were performed in MATLAB R2019a (MathWorks, Inc.). Raw marker trajectories were low-pass filtered using a fourth-order zero-lag Butterworth with a 6 Hz cut-off frequency. Spatiotemporal variables and variables associated with energy transduction in CoM were then computed.

Two types of spatiotemporal variables (global and angular) were considered. The global variables were: mean speed (MS), cycle length (CL) and dimensionless velocity (β) derived from the Froude number ($\beta = \sqrt{Fr} = v/\sqrt{(g \cdot l)}$), where Fr is the Froude number v is the mean gait speed, g the gravitational acceleration (9.8 m / s^2) and l is the height from floor to CoM (hCoM) when the subject is standing in an anatomical stance (Vaughan and O'Malley, 2005). The angular variables were selected based on the combined movements of the lower limb segments and pelvis that contribute to levelling the CoM trajectory (Saunders et al., 1953; Della Croce et al., 2001; Willems et al., 2012). The selected angular variables were: pelvic rotation range (Pr) movement in the transversal plane, maximum pelvic obliqueness

Table 1. Main physical characteristics of the subjects that participated in the study, hCoM represents the height of CoM from the ground when the subject is standing in an anatomical stance.

Group	Age (years)	Body mass (Kg)	Height (cm)	hCoM (cm)
Young adults (n=30)	26.8 (2.5)	70.3 (6.9)	173. 5 (6.6)	92.2 (3.6)
Middle-aged adults (n=30)	56.6 (2.7)	75.6 (6.7)	174.1 (6.5)	95.6 (3.6)

range (Po) movement in the frontal plane, maximum hip adduction/abduction range (H), maximum knee flexion in the sagittal plane, during support (K1), and during swing (K2), ankle dorsiflexion in the sagittal plane, at initial contact (Aci), and maximum during support (Am).

Segmental mass and partial center of mass position and segmental radius of gyration were estimated from anthropometric tables (Winter, 2009), to apply a spatial model used in previous work to determine the variables associated with CoM energy reconversion (Nardello et al., 2011).

R was quantified according to the following equation (Cavagna and Kaneko, 1977):

$$R = \left(\left(Wv + Wh - Wext\right) / \left(Wv + Wh\right)\right) x100 \quad (1)$$

were Wv is the vertical work, Wh is the horizontal work, and Wext is the external work (Saibene and Minetti, 2003; Peyré-Tartaruga et al., 2021). The definitions and computation procedures for Wv, Wh and Wext, are detailed in Willems et al (1995).

The %Cong was determined as the percentage of the gait cycle during which the instantaneous variations in Ep and Ek occurred in opposite directions (Cavagna and Kaneko, 1977).

DATA ANALYSIS

Variables are reported as mean (SD). For each dependent variable (MS, β, CL; Pr, Po, H, K1, K2, Am, Aci; %Cong, R), we conducted a mixed (split-plot) repeated-measures ANOVA with Group (young vs. middle-aged; between-subjects) and Speed (Ss, Sa, Sf; within-subjects) as factors, using Type III sums of squares. Analyses were performed in SPSS (GLM Repeated Measures / Mixed design) and reproduced in MATLAB for transparency. Statistical significance was set at $\alpha = 0.05$ (two-tailed). Model assumptions were verified as follows. Normality of residuals within each cell was assessed using studentized residuals (extreme $|z| > 3$) and Q–Q plots. Homogeneity of variances across groups was tested with Levene's test. Mauchly's test was used to assess sphericity of the within-subjects factor (Speed) and the Group × Speed interaction; when violated, we applied Greenhouse–Geisser correction if $\varepsilon < 0.75$ or Huynh–Feldt correction if $\varepsilon \geq 0.75$. We reported F, p, and partial η^2 (ηp^2) for all main effects and interactions. When a significant Group × Speed interaction was found, we examined simple effects using Bonferroni-adjusted pairwise comparisons: (i) between-group contrasts at each speed and (ii) within-group contrasts across speeds. Given the balanced design (n = 30 per group), the ANOVA was considered reasonably robust to mild normality or variance deviations. When severe violations were detected, we considered variance-stabilising transformations (e.g., log transformation for positively skewed variables); however, these were not required as conclusions remained unchanged.

RESULTS

Results of mixed-design repeated-measures ANOVA (2×3; Group × Speed) realized to analyse the effects of age group (young vs. middle-aged adults) and walking speed (self-selected, slow, fast) on the spatiotemporal, angular, and energetic variables are presented in Tables 2 to 4.

As shown in Table 2, increasing walking speed produced marked changes in all global spatiotemporal variables, whereas group-related differences were subtle. The Group × Speed interaction reached significance for mean speed (MS), dimensionless velocity (β), and step length (CL), indicating that the progression of these variables across speeds differed between groups. These results are illustrated in Figure 1. At self-selected speed (Sa), mean speed (MS) was 1.10 ± 0.09 m/s in young adults and 1.08 ± 0.07 m/s in middle-aged adults. Dimensionless velocity (β) showed similar values (0.37 ± 0.03 vs. 0.35 ± 0.02), and step length (CL) was also comparable (1.29 ± 0.08 vs. 1.27 ± 0.08 m).

Regarding the angular variables (Table 3), clear main effects of speed were observed from proximal to distal joints. Group effects and Group × Speed interactions were particularly evident for the knee angles (K1, K2), while more proximal segments (pelvis, hip) showed smaller or inconsistent differences between groups. The

Table 2. Results of the 2 × 3 mixed ANOVA (Group × Speed) for spatiotemporal variables (MS, β, CL). F, p, and effect size (ηp^2) values are presented for the main effects of Group, Speed, and their interaction.

Variable	Effect	gl1	gl2	F	p	ηp²
MS	Group	1	58	11.869	0.0011	0.17
	Speed	2	116	561.535	<.0001	0.906
	Group×Speed	2	116	3.277	0.0413	0.054
β	Group	1	58	20.904	<.0001	0.265
	Speed	2	116	558.544	<.0001	0.906
	Group×Speed	2	116	3.463	0.0346	0.056
Cl	Group	1	58	0.789	0.378	0.013
	Speed	2	116	139.106	<.0001	0.706
	Group×Speed	2	116	9.898	0.0001	0.146

Table 3. Results of the 2 × 3 mixed ANOVA (Group × Speed) for the angular variables (Pr, Po, H, K1, K2, Am, Aci). F, p, and effect size (ηp^2) values are presented for the main effects of Group, Speed, and their interaction.

Variable	Effect	gl1	gl2	F	p	ηp^2
Pr	Group	1	58	17.103	0.0001	0.228
	Speed	2	116	467.14	<.0001	0.89
	Group×Speed	2	116	15.12	<.0001	0.207
Po	Group	1	58	11.654	0.0012	0.167
	Speed	2	116	2209.721	<.0001	0.974
	Group×Speed	2	116	23.999	<.0001	0.293
H	Group	1	58	1.21	0.2759	0.02
	Speed	2	116	1527.63	<.0001	0.963
	Group×Speed	2	116	2.353	0.0996	0.039
K1	Group	1	58	226.931	<.0001	0.796
	Speed	2	116	138.57	<.0001	0.705
	Group×Speed	2	116	21.691	<.0001	0.272
K2	Group	1	58	473.502	<.0001	0.891
	Speed	2	116	149.319	<.0001	0.72
	Group×Speed	2	116	69.109	<.0001	0.544
Am	Group	1	58	0.001	0.9792	0
	Speed	2	116	1.688	0.1894	0.028
	Group×Speed	2	116	0.13	0.8779	0.002
	Group	1	58	0.006	0.9386	0
Aci	Speed	2	116	0.856	0.4275	0.014
	Group×Speed	2	116	0.047	0.954	0.001

Table 4. Results of the 2 × 3 mixed ANOVA (Group × Speed) for the energy variables (%Cong, R). The F, p, and effect size (ηp^2) values are presented for the main effects of Group, Speed, and their interaction.

Variable	Effect	gl1	gl2	F	p	ηp^2
%Cong	Group	1	58	156.673	<.0001	0.73
	Speed	2	116	29.834	<.0001	0.34
	Group×Speed	2	116	4.094	0.0191	0.066
R	Group	1	58	59.064	<.0001	0.505
	Speed	2	116	35.005	<.0001	0.376
	Group×Speed	2	116	2.241	0.1109	0.037

values of the angular variables for both groups at the analyzed speeds are presented in Figure 2. At Sa, pelvic rotation (Pr) was 7.93 ± 0.53° in young adults and 7.83 ± 0.53° in middle-aged adults, while pelvic obliqueness (Po) reached 5.71 ± 0.38° vs. 5.65 ± 0.35°. Knee flexion during support (K1) was 15.35 ± 1.20° in young adults compared with 19.22 ± 1.61° in middle-aged adults, and during swing (K2) it was 50.06 ± 1.62° vs. 59.76 ± 1.62°, respectively.

Finally, the energetic variables (Table 4) also displayed strong effects of speed. Notably, both energy recovery (R) and pendular energy transference (%Cong) differed between groups, with %Cong additionally showing a significant Group × Speed interaction. The values of the pendular energy recovery variables for both groups at the analyzed speeds are presented in Figure 3. At Sa, energy recovery (R) was 64.11 ± 3.47% in young adults and 59.67 ± 3.30% in middle-aged adults, whereas %Cong was 20.42 ± 2.09% vs. 24.98 ± 3.18%, respectively.

DISCUSSION

This study aimed to examine whether age-related changes in gait mechanics already begin to manifest in middle-aged adults. In general terms, mean values appeared broadly similar between groups at each speed condition; however, the mixed-design ANOVA revealed that the progression across speeds differed between young and middle-aged adults. In practical terms, young adults exhibited steeper increments in MS and β when transitioning from slow to fast walking, while middle-aged adults showed comparatively smaller increases in these parameters and slightly longer CL at slow speed. At the

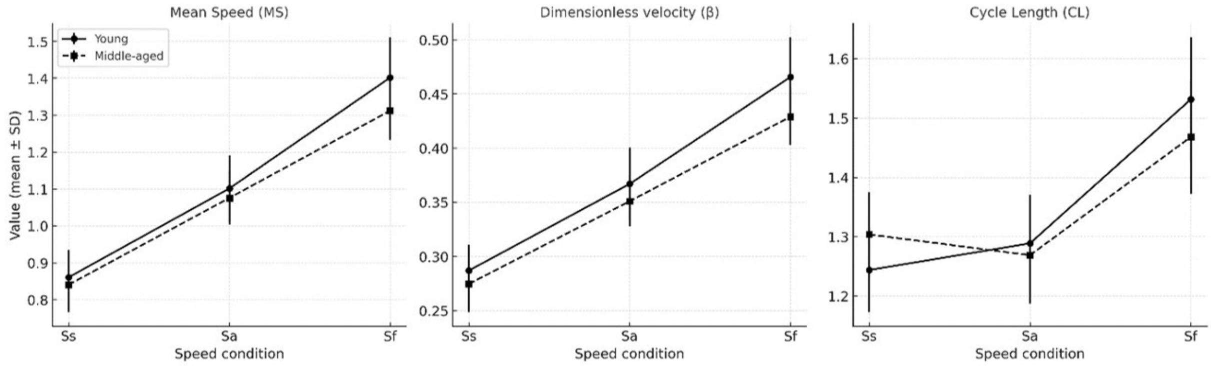

Figure 1. Global spatiotemporal variables by speed condition and group. Mean Speed (MS), Dimensionless velocity (β) and Cycle Length (CL) are shown as mean ± SD across the three speed conditions (Ss, Sa, Sf) for both groups without discriminating by sex. Circles and solid lines represent young adults; squares and dashed lines represent middle-aged adults.

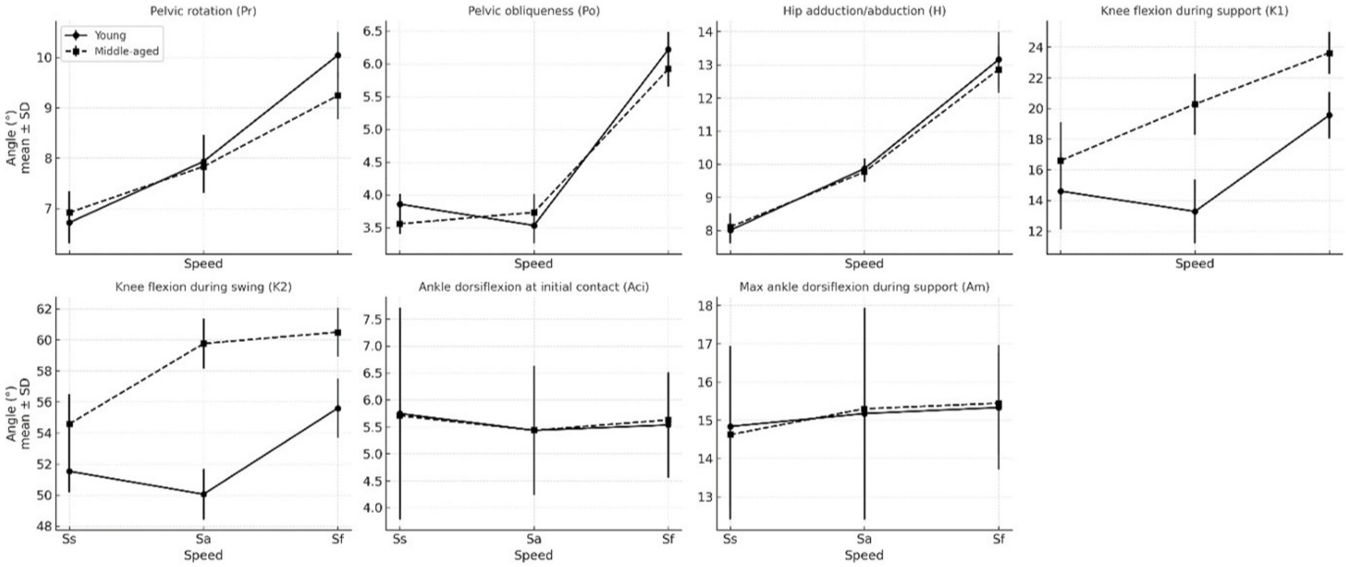

Figure 2. Angular kinematic variables by speed condition and group. Mean ± SD values of Pelvic rotation (Pr), Pelvic obliqueness (Po), Hip adduction/abduction (H), Knee flexion during support (K1), Knee flexion during swing (K2), Ankle dorsiflexion at initial contact (Aci), and Max ankle dorsiflexion during support (Am) across the three speed conditions. Circles/solid lines represent young adults; squares/dashed lines represent middle-aged adults.

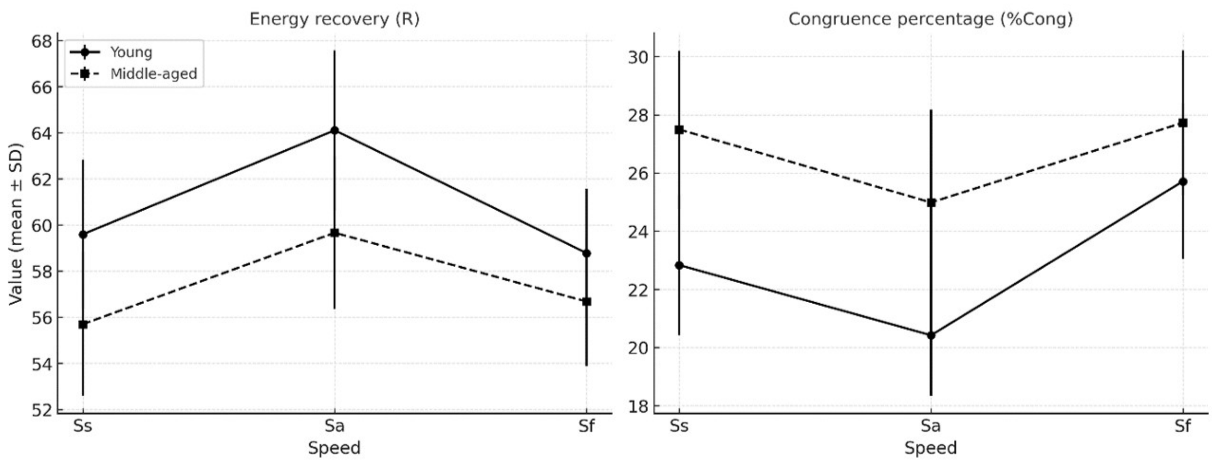

Figure 3. Energetic variables associated with transduction of mechanical energy at center of mass (CoM) level considering the inverted pendulum model by speed condition and group. Mean ± SD values of Energy recovery (R) and Congruence percentage (%Cong) across the three speed conditions. Circles/solid lines represent young adults; squares/dashed lines represent middle-aged adults.

angular level, group effects and interactions were most evident at the knee, where middle-aged adults displayed higher flexion values than young adults, particularly under faster speeds, suggesting early alterations in joint strategies that contribute to the vertical levelling of the CoM. Regarding energetics, middle-aged adults also demonstrated lower R and higher %Cong compared with young adults, indicating a reduced efficiency in pendular energy transduction. Taken together, these results suggest that neuromuscular (Vervoort et al., 2020) and structural (Muscaritoli et al., 2013) changes that begin in the fifth decade of life (Kennis et al., 2014; Chuang et al., 2019) imply detectable variations in gait, which become more evident as locomotor demands increase. An important methodological aspect of this study is that walking speeds were not externally imposed but self-selected. This approach allowed us to capture gait performance within the natural range chosen by each participant, thereby reflecting conditions closer to daily living activities. For this reason, the comparisons provide a valuable reference framework. In the following sections, we discuss the results in three domains: (I) global spatiotemporal variables, (II) angular kinematic variables, and (III) energetic variables associated with CoM energy transduction.

(I) For the global spatiotemporal variables (MS, β and CL), a marked increase with speed was observed in both groups ($\eta p^2 > 0.70$), confirming that these variables consistently respond to the proposed speed manipulation. Although mean values at each condition were broadly comparable between young and middle-aged adults, the Group × Speed interaction indicated that the progression across speeds differed: young adults exhibited steeper increases in MS and β, while middle-aged adults showed comparatively smaller increments and slightly longer CL at slow speed. MSa mean values for both groups were similar to those established as optimal in most of the works (4 Km/h or 1,11 m/s) (Saibene and Minetti, 2003; Willems et al., 2012; Peyré-Tartaruga et al., 2021). The same occurred with CL, whose mean values closely matched with the corresponding graphs presented in Willems et al. (2012), which were made based on data from Schepens et al (2004). The same absolute MS does not necessarily indicate the same mechanical task, but actions can be compared if two individuals walk at the same β (Vaughan and O'Malley, 2005). This effect has been discussed when comparing adults with children (Vaughan et al., 2003), or with groups of adults with short height (Minetti et al., 1994, 2000; Saibene and Minetti, 2003). Dimensionless velocity β is the product of dimensionless step length and frequency. All three parameters increase from 18 months of age and reach values that are thought to remain relatively stable in adulthood (Vaughan et al., 2003). Our mean values support this notion; however, the way in which speed influenced these parameters differed between groups. To conclude this point, it should be noted that although we considered hCoM instead of lower limb length, as done in some previous studies (Saibene and Minetti, 2003; Vaughan et al., 2003), calculating β based on lower limb length would have resulted in only a 0.01 increase in the values. Therefore, our previous discussion remains valid. We opted to calculate dimensionless velocity relative to hCoM because we believe it aligns better with the assumptions of the inverted pendulum model on which the calculations of R and %Cong are based.

(II) Mean angular values associated with levelling the trajectory of the CoM in this study were within the range established as normal for adult subjects at self-selected speed (Sa) (Willems et al., 2012). In agreement with Willems et al. (2012), actions at the pelvis, hip, and knee (Pr, Po, H, K1 and K2) showed clear effects of speed, with amplitudes increasing from slow to fast walking. Group effects and interactions, however, were most evident at the knee. Middle-aged adults consistently exhibited higher knee flexion values both during support (K1) and swing (K2), and the progression of these variables with speed differed from that of young adults. These findings suggest that knee joint strategies contributing to the vertical levelling of the CoM may already begin to change in middle age. Such alterations are consistent with previous evidence showing that young adults display greater knee extension at heel strike and during swing when compared under speed-matched conditions (Boyer et al., 2017). The functional implications of the observed knee values in middle-aged adults are noteworthy, as knee flexion during mid-support reduces the elevation of the CoM precisely when it passes over the supporting limb (Willems et al., 2012). Consequently, angular values reflecting the knee's contribution to vertical levelling of the CoM appear to change significantly within this age range. By contrast, more proximal segments showed smaller or inconsistent group differences: pelvic rotation and obliqueness (Pr and Po) increased with speed in both groups but with only subtle between-group variations, while hip adduction/abduction (H) followed a parallel pattern in young and middle-aged adults. Finally, ankle dorsiflexion at initial contact (Aci) and maximum dorsiflexion during support (Am) remained virtually unchanged across speeds and between groups, indicating that distal control at the ankle is preserved in middle-aged adults. Taken together, these results highlight those early age-related changes in gait mechanics manifest preferentially at the knee, whereas proximal adjustments remain broadly comparable to young adults and distal control appears unaffected.

(III) Clear effects of speed were observed for both energy recovery (R) and congruence (%Cong). Beyond this expected modulation, group differences were also evident: middle-aged adults displayed lower R values and higher %Cong than young adults, indicating a reduced efficiency in pendular energy transduction. Importantly, the interaction effects suggest that discrepancies between groups became more pronounced as walking speed increased. From a functional perspective, these findings imply that, although middle-aged adults walk at absolute speeds similar to young adults, they utilise CoM mechanical energy less effectively. This aligns with previous reports establishing that R values in young adults at self-selected pace typically range between 60–65% (Saibene and Minetti, 2003; Peyré-Tartaruga et al., 2021), whereas the values observed here for middle-aged adults (59.6) fell below this benchmark. Moreover, for efficient walking, the duration during which the potential and kinetic energies of the CoM fluctuate in the same direction should be low (Biewener, 2006). %Cong values in healthy young adults are generally below 20% at optimal speeds (Gomeñuka et al., 2016) as observed here (20.42 in MSa), whereas middle-aged adults in our sample exceeded this threshold (24.98 in MSa), suggesting a greater mismatch in the synchrony of kinetic and potential energy fluctuations. Together, these results reinforce the notion that age-related alterations in locomotor energetics emerge already in middle age, even in the absence of marked reductions in self-selected walking speed, and may precede more evident declines typically reported in older adults.

This study has some limitations that should be acknowledged. First, the cross-sectional design precludes establishing causal relationships between age and the observed gait differences. Second, walking speeds were self-selected rather than imposed, which enhances ecological validity but may limit comparability with studies using strictly controlled speeds. Third, dimensionless velocity was normalised to hCoM instead of leg length; although theoretically consistent with the inverted pendulum model, this choice complicates direct comparisons with Froude-based reports. Finally, the absence of additional neuromuscular or structural measures (e.g. muscle strength or EMG) restricts our ability to directly link the observed gait alterations with underlying mechanisms.

Future studies should address these aspects by including broader age groups, longitudinal designs, and integrated neuromuscular assessments to better characterise the onset and progression of age-related gait adaptation. In addition, the differences observed in K1 may indicate that relevant alterations occur at specific moments within the gait cycle. Because R and %Cong values are averaged over the entire cycle, complementary analyses focusing on pendular energy transduction within-cycle could provide further insight. One option is the instantaneous recovery of mechanical energy in equal time intervals (Gomeñuka et al., 2016), a method previously applied to study gait at different slopes and speeds in young adults (Dewolf et al., 2017) and in asymmetric gait (Fábrica et al., 2019). Applying this approach to middle-aged adults could help clarify the mechanisms underlying the differences reported here.

CONCLUSION

Middle-aged adults maintain a broadly similar spatiotemporal gait pattern to that of young adults; however, differential effects emerge when speed increases, with smaller increments in MS and β and a slightly longer CL at slow speed. The main age-related manifestations in angular variables occur at the knee, becoming more evident at higher speeds. Finally, middle-aged adults exhibit a gait pattern that is slightly less economical, as reflected by lower R and higher %Cong values, and this inefficiency becomes more pronounced with increasing speed.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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