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Kinematics predictors of spatiotemporal parameters during gait differ by age in healthy individuals

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A R T I C L E I N F O

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A B S T R A C T

Joint biomechanics and spatiotemporal gait parameters change with age or disease and are used in treatment decision-making. Research question: To investigate whether kinematic predictors of spatiotemporal parameters during gait differ by age in healthy individuals. Methods: We used an open dataset with the gait data of 114 young adults (M = 28.0 years, SD = 7.5) and 128 older adults (M = 67.5 years, SD = 3.8) walking at a comfortable self-selected speed. Linear regression models were developed to predict spatiotemporal parameters separately for each group using joint kinematics as independent variables. Results: In young adults, knee flexion loading response and hip flexion/extension were the common predictors of gait speed; hip flexion and hip extension contributed to explaining the stride length; hip flexion contributed to explaining the cadence and stride time. In older adults, ankle plantarflexion, knee flexion loading response, and pelvic rotation were the common predictors of the gait speed; ankle plantarflexion and knee flexion loading response contributed to explaining the stride length; ankle plantarflexion loading response and ankle plantarflexion contributed to explain the cadence, stride width and stride time. Significance: Our results suggest that the ability of joint kinematic variables to estimate spatiotemporal parameters during gait differs by age in healthy individuals. Particularly in older adults, ankle plantarflexion was the common predictor of the spatiotemporal parameters, suggesting the importance of the ankle for gait parameters in this age group. This provides insight for clinicians into the most effective evaluation and has been used by physical professionals in prescribing the most appropriate exercises to attenuate the effects produced by age-related neuromuscular changes.

1. Introduction

The biomechanical characteristics of a person's gait, such as joint angles and spatiotemporal parameters, are an essential clinical tool to enhance the understanding of gait changes related to either aging or disease [1,2], and has been used in the decision process to prescribe exercise. Reduced walking speed is the most consistent age-related change [3], and several gait parameters play a key role in this change, such as stride length and joint angular displacement [4]. Furthermore, gait speed affected the amplitude of joint kinematics [5]. There is an increase in hip flexion, hip extension, knee flexion, and ankle plantarflexion angles with higher speeds in young adults. Kirtley et al. [6] show a significant correlation between gait speed and knee flexion in stance and swing phases of gait in adults. Lelas et al. [7] found that most peak sagittal plane angles showed significant correlations with gait speed. In older adults, Ko et al. [4] described a decline in speed, stride length, kip extension, ankle plantar flexion, and mediolateral hip control in a longitudinal study. Therefore, spatiotemporal gait parameters, ground reaction forces, joint angles and moments, and muscle activity have all been reported to be affected by gait speed [8,9]. This evidence shows a relationship between joint kinematics variables and spatiotemporal parameters and that these relationships are different with age.

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In typical gait analysis, the gait patterns of joint kinematics of pathological individuals are compared with healthy individuals. However, interpreting the results to list which observed deviations are primary or secondary can be challenging due to the complexity and nature of the process involved in measuring human movement [10]. Relating spatiotemporal parameters with kinematic patterns is crucial to understanding biomechanical changes in elderly gait. Therefore, it is crucial to know the relationships between the joint angles and the spatiotemporal parameters to correct the gait analysis. This article investigates whether kinematic predictors of spatiotemporal parameters during gait differ by age in healthy individuals.

2. Methods

We used an open dataset [11] with the gait data of 242 healthy adults, including 114 young adults (63 females; age, M = 28.0 years, SD = 7.5; height, M = 165.2 cm, SD = 7.8; body mass, M = 59.9 kg, SD = 11.8) and 128 older adults (61 females; age, M = 67.5 years, SD = 3.8; height, M = 159.7 cm, SD = 8.0; body mass, M = 59.0 kg, SD = 9.6), walking at a comfortable self-selected speed. All participants were free of any lower-extremity injury and any orthopedic or neurologic disease that could interfere with their gait patterns. These data were collected by performing a standard three-dimensional gait analysis (Vicon MX, Oxford, UK) with a sampling frequency of 200 Hz, and force plates (AMTI, Watertown, MA, USA) sampled at 1000 Hz, where the subjects walked barefoot on the ground. The lower limb marker-set protocol adopted for this study comprised 23 anatomical reflective markers (Helen Hayes pelvis and Plug-in-Gait marker set). The raw data were digitally filtered using a fourth-order Butterworth filter with zero lag and a cut-off frequency of 6 Hz for the kinematics and 10 Hz for the kinetics. The joint angles data of each gait cycle's hip, knee, and ankle joints were normalized to 0–100 % with a step of 1 %. Visual 3D software version 6.00.33 (C-motion Inc., Germantown, MD, USA) was used to perform all kinematics and kinetics calculations. Data from five right and five left trials were averaged for each condition to obtain an average for each peak joint kinematic and spatiotemporal parameter. The gait determinants are six movements performed in normal gait that combined decrease the vertical and horizontal oscillation of the center of mass to favor an adequate biomechanical pattern and conserve energy. The first determinant is pelvic rotation, the second is pelvic tilt, the third

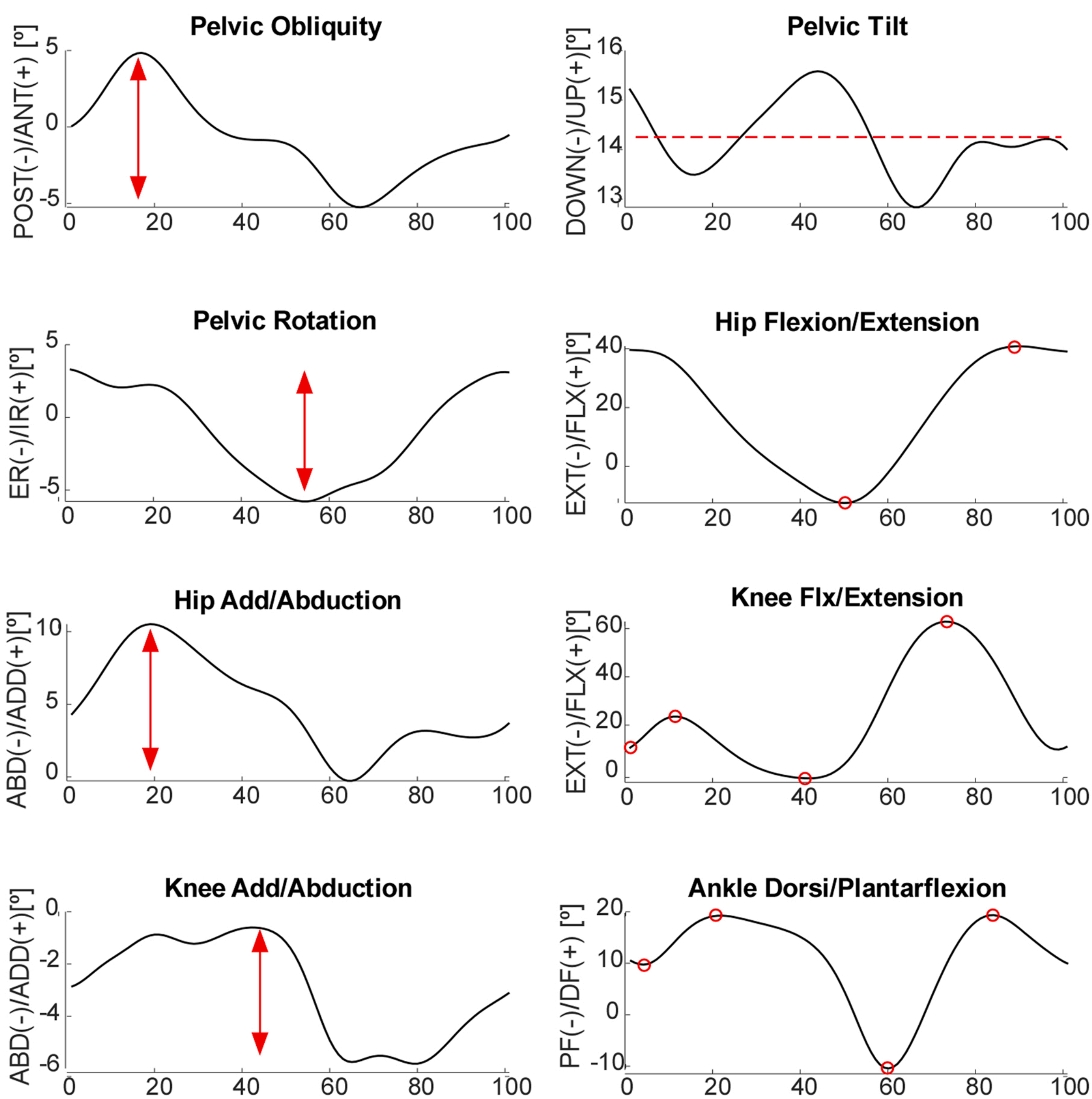

Fig. 1. Representative single trial for the joint angles and the variables of angular kinematics that were calculated. Red arrows and circles indicate the calculated kinematic variables.

is knee flexion in support, the fourth is the ankle and knee mechanisms, and the fifth and sixth are related to the pelvis and knee in the frontal plane. In gait, movements with a greater range of motion are performed in the sagittal plane. For this reason, we have included peaks of hip and knee flexion and extension. Based on this concept, the kinematic variables were chosen for this study. Variables of angular kinematics were detected at the same specific phases of the gait cycle utilized by Lelas et al. [7], namely (Fig. 1): peak hip flexion, peak hip extension, peak knee extension before initial contact, peak knee flexion loading response, peak knee extension terminal stance, peak knee flexion during the swing, peak ankle plantarflexion loading response, peak ankle dorsiflexion mid stance, peak ankle plantarflexion, peak ankle dorsiflexion swing, mean pelvic tilt, amplitude pelvic obliquity, amplitude pelvic rotation, amplitude hip adduction-abduction, and amplitude knee adduction-abduction. The measurements of the spatiotemporal parameters were: gait speed, cadence, stride length, stride time, and stride width. The stride length was normalized by the height of each participant. To determine the dimensionless gait speed, the Froude number, v*, was calculated based on the participant's average self-selected comfortable speed, v, and leg length, l_0 [12].

Shapiro-Wilk test indicated normal data distribution across dependent variables. Next, MANOVA was analyzed to examine whether groups significantly affect the 15 joint variables and 6 spatiotemporal parameters. Finally, follow-up comparisons between the two groups were made through Student *t*-tests for independent measures. Then, the univariate analyses were used to test which factors (joint kinematics) would be associated with the dependent variables (spatiotemporal parameters). Afterward, to explain the variance of the dependent variables, we included the factors in the linear multivariate analysis using the stepwise model if they presented a *P*-value ≤ 0.10 and a correlation of lower than 0.6 between them to avoid collinearity [13]. Adjustments for multiple comparisons reduce type I errors at the expense of increasing type II errors. Therefore, we decided not to correct for multiple comparisons, as this might lead to false negatives [14]. Statistical procedures were performed using SAS 9.2 (Institute Inc., Cary, NC, USA), and the significance level was set at $P \leq 0.05$ with effect sizes indicated by partial eta squared (η_p^2).

3. Results

Fig. 2 shows the mean and standard error of the joint variables of the two groups. Joint angular variables and spatiotemporal parameters of the two groups are summarized in Table 1.

MANOVA revealed a significant group factor (Wilks' lambda = 0.59, $F_{24,217} = 6.20, p < 0.001$). Table 2 shows the joint angular variables that were statistically significant to explain the spatiotemporal parameters of the two groups according to multiple linear regressions (stepwise method).

4. Discussion

Our results suggest that the joint kinematic variables estimate spatiotemporal parameters during gait differs by age in healthy individuals. For example, in young adults, knee flexion loading response and hip flexion/extension were the common predictors of gait speed; hip flexion and hip extension contributed to explaining the stride length; hip flexion contributed to explaining the cadence and stride time. In older adults, ankle plantarflexion, knee flexion loading response, and pelvic rotation were the common predictors of the gait speed; ankle plantarflexion and knee flexion loading response contributed to explaining the stride length; ankle plantarflexion loading response and ankle plantarflexion contributed to explaining the cadence, stride width and stride time.

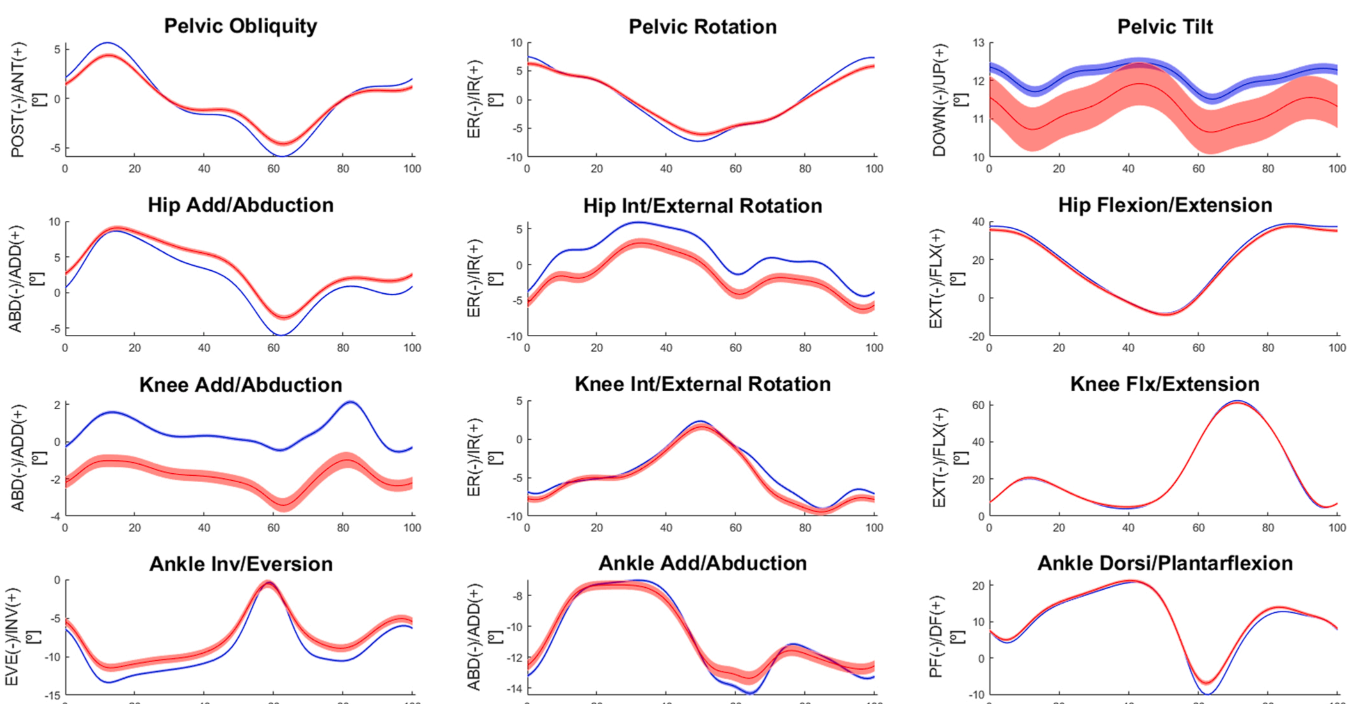

Fig. 2. Mean and standard error of the joint variables of the young (blue) and older (red) adults.

Table 1
Means (standard deviations) and statistical significance (p-value).

	Young	Older	p-value	η_p^2
Peak hip flexion (°)	39.11 (7.62)	38.03 (7.45)	0.267	0.01
Peak hip extension (°)	8.78 (7.78)	9.26 (7.92)	0.639	0.01
Peak knee extension before initial contact (°)	6.99 (3.96)	7.39 (4.14)	0.434	0.01
Peak knee flexion loading response (°)	20.05 (6.61)	20.86 (5.86)	0.317	0.01
Peak knee extension terminal stance (°)	3.26 (4.59)	4.57 (5.10)	0.036*	0.02
Peak knee flexion swing (°)	62.76 (3.94)	61.73 (4.15)	0.048*	0.02
Peak ankle plantarflexion loading response (°)	-3.74 (3.12)	-4.92 (3.53)	0.006*	0.03
Peak ankle dorsiflexion mid stance (°)	21.08 (3.38)	22.03 (3.61)	0.035*	0.02
Peak ankle plantarflexion (°)	11.26 (5.93)	7.52 (6.19)	< 0.001*	0.09
Peak ankle dorsiflexion swing (°)	13.16 (2.67)	14.64 (3.67)	< 0.001*	0.05
Mean pelvic tilt (°)	11.62 (6.52)	11.16 (6.19)	0.579	0.01
Amplitude pelvic obliquity (°)	11.68 (3.09)	9.27 (2.70)	< 0.001*	0.15
Amplitude pelvic rotation (°)	16.10 (4.94)	13.09 (4.84)	< 0.001*	0.09
Amplitude hip adduction-abduction (°)	14.94 (3.08)	13.19 (2.84)	< 0.001*	0.08
Amplitude knee adduction-abduction (°)	5.29 (1.90)	5.15 (2.14)	0.379	0.01
Speed (dimensionless)	3.79 (0.40)	3.63 (0.43)	< 0.001*	0.04
Cadence (strides per minute)	59.68 (4.12)	61.18 (4.73)	0.009*	0.03
Stride length (dimensionless)	0.83 (0.06)	0.81 (0.07)	0.046*	0.02
Stride time (s)	1.01 (0.07)	0.99 (0.08)	0.009*	0.03
Stride width (m)	0.08 (0.02)	0.09 (0.2)	< 0.001*	0.04
Total double support (%)	17.81 (2.29)	18.01 (2.54)	0.509	0.01

* indicates significance.

Knee flexion loading response and hip flexion/extension appear to be the best universal measures to estimate spatiotemporal parameters in young adults. Knee flexion-extension predicts older adults' static and dynamic balance performance [15]. A reduced rate of torque of quadriceps may contribute to loss of stability and balance, leading to falls [16]. When matched for gait speed, differences in knee kinematics in young adults are more apparent when compared to older adults [17]. Our results show that the hip is a predictor of spatiotemporal parameters only in young adults, not in older adults. These results are supported by evidence showing that hip extensor moment was associated with a longer step length and lesser cadence in young adults [18]. Age-related changes may occur in the joints, as a stiffening periarticular connective tissue and can limit movement [19].

In older adults, ankle plantarflexion was the common predictor of the spatiotemporal parameters, suggesting the importance of the ankle for gait parameters in this age group. Gait performance in older adults may be limited by ankle plantarflexor concentric weakness [20,21], with propulsive angle kinetics being diminished [17]. Hip and knee kinetics compensate for this reduction of ankle power generation with age [17]. During gait, moments before initial contact, the lower limb is in the air at the end of the swing phase. Therefore, an adequate range of motion of hip flexion, full knee extension, and neutral ankle position is necessary for the hindfoot to receive the abrupt transfer of body weight. Studies have shown that age-related neuromuscular changes alter gait parameters and decrease joint range of motion, thus compromising the pre-positioning of the lower limb in the initial contact [1,17]. The initial contact and the next moment, load response, are important subphases in the human gait. The plantarflexion movement acts together with the first knee flexion peak. It is a mechanism used by the body to absorb impact and stabilize the lower limb initiating a gait cycle. Changes in this mechanism may represent variations in gait stability, which requires individuals to adjust gait parameters, including step width, to

Table 2
Linear multiple regressions (stepwise method) with included factors and spatiotemporal parameters as dependent variables.

Spatiotemporal parameters	Young			Older		
	Joint angular variables	*Partial R^2*	*Model R^2 Change*	Joint angular variables	*Partial R^2*	*Model R^2 Change*
Speed	Knee flexion loading response	0.15	0.15	Ankle plantarflexion	0.15	0.15
	Hip flexion	0.07	0.22	Knee flexion loading response	0.13	0.28
	Hip extension	0.05	0.27	Pelvic rotation	0.12	0.40
	Ankle dorsiflexion mid stance	0.03	0.30	Ankle dorsiflexion swing	0.04	0.44
	Knee flexion initial contact	0.02	0.32	Knee flexion terminal stance	0.03	0.47
Stride length	Hip flexion	0.33	0.33	Ankle plantarflexion	0.09	0.09
	Hip extension	0.15	0.48	Knee flexion loading response	0.06	0.15
	Pelvic rotation	0.03	0.51	Pelvic obliquity	0.03	0.18
	Knee flexion swing	0.02	0.53	Knee flexion swing	0.03	0.21
	Pelvic tilt	0.02	0.55			
Cadence	Hip flexion	0.10	0.10	Ankle plantarflexion loading response	0.14	0.14
	Ankle dorsiflexion mid stance	0.07	0.17	Ankle plantarflexion	0.09	0.23
	Knee flexion loading response	0.07	0.24	Pelvic rotation	0.03	0.26
Stride width	Knee flexion swing	0.06	0.06	Ankle plantarflexion	0.06	0.06
	Hip add/abduction	0.04	0.10	Ankle plantarflexion loading response	0.03	0.10
Stride time	Hip flexion	0.11	0.11	Ankle plantarflexion loading response	0.13	0.13
	Knee flexion loading response	0.06	0.17	Ankle plantarflexion	0.10	0.23
	Ankle dorsiflexion mid stance	0.05	0.22	Pelvic rotation	0.03	0.26
	Knee flexion initial contact	0.03	0.25	Knee flexion initial contact	0.03	0.29

maintain the body's center of mass within the support base [22].

A further limitation to this study is that other kinematic variables may be important to estimating spatiotemporal parameters, such as those that occur during a swing. Finally, factors other than age and sex may influence gait mechanics. In conclusion, older adults walk with different spatiotemporal parameters and joint kinematics compared to young adults. This study could benefit future clinical assessments and exercises methods by showing which joint kinematic variables are important for the spatiotemporal parameters of gait according to age. In addition, future studies are needed to understand alterations in the biomechanics of gait in fallers and identify appropriate interventions.

Conflict of interest statement

Authors declare to have no actual or potential conflict of interest including financial, personal or other relationships which might influence results and their interpretation.

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