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Faculteit Revalidatiewetenschappen

master in de revalidatiewetenschappen en de kinesitherapie

Masterthesis

The relationship between gait speed and spatiotemporal parameters in healthy older adults, and the association with physical characteristics

Marlies Mattheeussen
Robbe Van Beers

Scriptie ingediend tot het behalen van de graad van master in de revalidatiewetenschappen en de kinesitherapie, afstudeerrichting revalidatiewetenschappen en kinesitherapie bij musculoskeletale aandoeningen

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ACKNOWLEDGEMENT

We are pleased to present our master's thesis, the culmination of an intensive and educational journey in Rehabilitation Sciences and Physiotherapy education.

We would like to thank our supervisor, Prof. B. Bonnechère, for his expert guidance, constructive feedback, and patience throughout the process. Additionally, we want to express our gratitude for his assistance with the statistical analysis.
We would also like to thank Kirsten Quadflieg, Jolien Robijns, and Kim Daniels for their help and critical proofreading of our work.

CONTEXT

This thesis was written by two master's students, R.V.B. and M.M., majoring in Rehabilitation Sciences and Physiotherapy at the University of Hasselt, in the central format for experimental studies. The following research question was formulated by the two students and in consultation with Prof. B. Bonnechère: 'What is the relationship between gait speed and spatiotemporal parameters in healthy older adults and the correlation with physical characteristics?'.

This study falls under the domain of technology-supported rehabilitation and healthy aging. This study investigates whether spatiotemporal and physical parameters are associated with gait speed in healthy older adults.

Previous research has demonstrated that gait speed strongly predicts functional decline, fall risk, and mortality. Although gait speed has received considerable attention, spatiotemporal gait parameters—such as cadence, step time, stride length, and double support time—are increasingly recognized for their clinical relevance.. Moreover, other studies have investigated the relationship between gait speed and strength parameters, identifying significant associations. The relationship between body composition and gait speed has been established, but the influence of individual characteristics such as height, weight, and gender remains inconclusive. Previous studies demonstrated a relationship between balance and gait speed, specifically dynamic stability. However, the relationship between gait speed and the Timed Up and Go test, often used for assessing balance, has been discussed only briefly. Despite these findings, few studies have systematically examined the combined influence of physical and spatiotemporal parameters on gait speed in a healthy elderly population. This highlights the need to further investigate these relationships and improve mobility outcomes in older adults.

The data collection was part of an ongoing study, called '*Unveiling the digital phenotype: A protocol for a prospective study on physical activity behavior in community-dwelling older adults*', executed by K. Daniels, S. Vonck, J. Robijns, A. Spooren, D. Hansen, and B. Bonnechère. This study aims to design a robust research for the digital phenotypering of physical activity behavior among healthy community-dwelling older adults aged 65 and above by employing a novel measurement approach. The goal is to understand older adults' physical activity behavior.

All the testing took place at the PXL healthcare campus. This is where all tests were set up so that testing could be done in the same way and the same setting throughout the study period. All data were provided to the students in an Excel document. In addition, JMP Pro 17 (SAS Institute Inc., Cary, NC) software was utilized by the two students for the statistical analysis.

The writing of this thesis was improved with the assistance of AI. Self-written text was refined to enhance professionalism and clarity. Further, Grammarly was used to improve the quality of the writing.

ABSTRACT

Background

In older adults, gait speed is a well-established indicator of overall health, fall risk, and functional capacity. Although spatiotemporal parameters and physical characteristics have been individually studied, limited research has explored their combined predictive value in relation to gait speed.

Objectives

This study investigates whether spatiotemporal and physical parameters are associated with gait speed in healthy older adults.

Methods

Digitsoles Pro® insoles were used to measure gait parameters during a six-minute walk test. Grip and quadriceps strength, cardiovascular metrics, anthropometric data, and perceived exertion were also assessed. Statistical analyses included Spearman correlations, t-tests, and multivariate analyses.

Results

108 healthy older adults participated (mean age: 70.11 years; 56% women). The most significant positive correlation with gait speed was observed in stride length (left: $\rho = 0.77$, $p < 0.0001$; right: $\rho = 0.78$, $p < 0.0001$), followed by cadence ($\rho = 0.54$, $p < 0.0001$), and negative associations with stance time ($\rho = -0.62$, $p < 0.0001$), double support phase ($\rho = -0.55$, $p < 0.0001$), flatfoot time ($\rho = -0.53$, $p < 0.0001$), and Timed Up and Go performance ($\rho = -0.60$, $p < 0.0001$). Stride length, cadence, right-side loading time, and rate of perceived exertion fatigue post-exercise were significant predictors of gait speed in the final multivariate model.

Discussion

Stride length, cadence, loading time, TUG-score, and perceived exertion are key predictors of gait speed in healthy older adults. These findings confirm the multifactorial nature of gait and support rehabilitation strategies focusing on these parameters in healthy older adults.

Keywords

Older adults, gait speed, spatiotemporal parameters, physical characteristics, rehabilitation, Digitsoles Pro® insoles

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INTRODUCTION

As the global population continues to age, the proportion of older adults in society is rapidly increasing. By 2030, over 1 billion individuals worldwide are expected to be aged 65 or older [1]. The increase in the aging population presents significant public health challenges [2], given that aging is accompanied by a progressive decline in physical function [3, 4]. Gait characteristics are widely recognized as valuable clinical markers for evaluating an older individual's physical capabilities and general health status [3].

Among gait parameters, gait speed is particularly important, as it serves as a strong indicator of the musculoskeletal, nervous, and cardiovascular systems [5]. Recognized for its clinical relevance, gait speed is often referred to as the sixth vital sign, alongside heart rate, blood pressure, respiratory rate, temperature, and oxygen saturation [5]. Gait pattern changes progressively with age [6]. Age-related changes in the gait pattern include reduced walking speed, shorter step length, decreased mobility, and a relatively shorter swing phase, compared to younger adults [6]. Such changes in gait can significantly affect the quality of life and independence for older adults [3, 7]. These changes are strongly associated with an increased fall risk, impaired cognitive function [3], reduced mobility, reduced functional capacity [8], and a decrease in muscle mass and strength [9]. For instance, falls occur in approximately 30% of the elderly population above 65 years old once every year [10, 11, 12], and a gait speed lower than 1.0 m/s is a strong predictor for falling [13].

While gait speed has received considerable attention, the spatiotemporal gait parameters such as cadence, step time, stride length, and double support time are increasingly recognized for their clinical relevance. These parameters provide more detailed insights into specific components of the gait pattern, including walking rhythm, symmetry, and stability [14, 15, 16]. As a result, examining the relationship between gait speed and related parameters is of importance. Furthermore, existing literature suggests an association between lower body strength and gait performance [17]. In addition, previous research has identified a significant association between handgrip strength and gait speed [18]. Within the elderly population, muscle weakness is a common phenomenon. Such muscle weakness can affect the gait pattern, for example, by reducing step length and extending the stance phase [19]. Regarding gender differences, the literature mainly highlights variations in muscle mass between men and women, but no strong correlations have been found between gender and gait speed [20]. Furthermore, the literature provides limited evidence regarding the relationship between weight and height, individually, and gait speed. However, a significant association has been observed between body mass index (BMI) and gait speed [20]. In the literature, there are associations found between gait speed and dynamic stability in older adults [21]. The Timed Up and Go (TUG) test is a widely used tool for assessing balance and predicting fall risk in older adults. The association between the TUG and gait speed has been only minimally explored [10]. Moreover, only limited associations have been observed between blood pressure, heart rate, or ratings of perceived exertion (RPE) and gait speed. These parameters give more insight into how physically demanding an activity is and feels, which reflects the physical capacity and endurance [22].

Understanding how these physical and spatiotemporal parameters interact with gait speed can help clinicians better detect early signs of functional decline and develop personalized rehabilitation strategies to promote safe and independent ambulation in older adults [3].

This study aims to investigate the relationship between gait speed and spatiotemporal parameters in healthy older adults, while also examining the correlation of physical characteristics on these relationships. We hypothesize that gait speed will show significant correlations with specific spatiotemporal parameters such as step length, cadence, and double support time in healthy older adults. Furthermore, we anticipate that physical parameters, such as muscle strength, weight, and height, contribute to this relationship. By analyzing these associations, this study aims to identify key gait factors that may support fall prevention and enhance functional mobility in older adults. The aim is to identify specific parameters that rehabilitation programs can target.

METHODS

Study design

This research was an observational study designed to collect comprehensive data, including spatiotemporal parameters and general demographic and physical information, in healthy older adults. The data collection was part of the ongoing digital phenotype study [23] and took place at the PXL-Healthcare facilities. This study was registered at ClinicalTrials.gov (NCT06094374) and was approved by the Ethical Committee of Hasselt University (B1152023000011) on 15/6/23. All participants signed an informed consent before participating in this study.

Participants

Inclusion and exclusion criteria were defined to ensure appropriate participant selection. For inclusion, participants were required to be 65 years of age or older and free of serious illnesses that could restrict their cognitive capability, functional abilities, or mobility. Detailed inclusion and exclusion criteria are presented in *Table 1*. Newspaper advertisements, social media campaigns, presentations at senior citizen organizations, and partnerships with neighborhood community agencies have been used in the recruitment process. In total, 108 participants were included.

Table 1:

Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
65 years or older	Neurological disease
Competent to give informed consent	Cardiovascular disease
Can actively participate in the study	Pulmonary disease
Living independently at home or in a service apartment	Severe metabolic disorder
Dutch as a native Language	Cognitive disorder

Assessments

General measurements

Participants' weight and height were measured without shoes using a calibrated scale and stadiometer, respectively. Based on these measurements, body mass index (BMI) was calculated using the tool provided by Voedingscentrum [24]. Additionally, abdominal circumference was measured at the level of the navel using a standardized tape measure. Blood pressure and heart rate were measured using an automatic blood pressure monitor. Oxygen saturation was measured before and after the walking test using a finger pulse oximeter. Finally, participants rated their perceived leg fatigue and tightness using the RPE scale. This was surveyed on a numerical scale ranging from zero to ten, before and after performing the walking assessment.

Physical parameters

Muscle strength

Muscle strength assessments included measurements of grip strength and quadriceps strength. Each measurement was performed three times. The maximum value was used for analysis. The Kinvent® 2016 handheld dynamometer was employed to measure grip strength, while quadriceps strength was assessed with the K-Force Grip® device. To conduct the grip strength test, the participant was seated on a chair, holding the device at their side with the elbow flexed at 90° and the shoulder and wrist in a neutral position. In this position, the participant was instructed to squeeze the device as forcefully as possible. The quadriceps strength assessment was conducted with the participant seated on a table, their legs hanging freely, and their arms crossed in front of their body, while maintaining 90° of hip and knee flexion. Participants were instructed to generate maximum force while remaining seated and avoiding the use of their arms.

Functional mobility

The TUG test was administered according to standard guidelines. This measurement represents functional mobility and balance [25].

Gait analysis

Gait analysis was performed using Digitsole Pro® insoles equipped with PODOSmart® technology (*Figure 1*). These innovative prosthetic insoles are designed to slide into any regular shoes. These insoles provided detailed measurements of various gait parameters. The system uses a small sensor embedded in the soles that moves with the user, allowing for precise measurements to be taken during action.

Through the application of modified AI, the algorithms used allowed for the evaluation of walking and running dynamics in various contexts. It gathered data on foot placements, walking patterns, and the quantity of steps taken. Quantifiable spatiotemporal, kinematic, and biomechanical frameworks within an AI system were computed using all the data gathered. Along with knowledge of how the musculoskeletal system works, this ensured the gait analysis was both accurate and reliable [26, 27]. The software required less than three minutes to analyze the walking pattern, and since participants walked for six minutes, sufficient data was collected. The different spatiotemporal parameters [15] that were measurable using this technology and relevant to the study are described in *Table 2*. Furthermore, foot kinematics and advanced parameters were also examined, as presented in *Table 3*.

Table 2:

Spatiotemporal Parameters

Parameter	Definition
Speed (km/h)	The rate at which the person covers a distance over time.
Step length (cm)	The distance measured in the anterior-posterior direction between the heel of one foot and the heel of the opposite foot.
Stride length (cm)	The distance between the heels of the same foot during two steps in the anterior-posterior direction.
Stride duration (ms)	The time interval between the two following initial contacts of the same foot.
Swing time (ms)	The time between the initial swing and just before the subsequent initial contact of the same foot
Stance time (ms)	The time interval between the initial contact and the pre-swing phases of the same foot, during which the body's weight is supported by the foot in question.
Cadence (steps/min)	The number of steps taken in one minute.
Double contact (%)	The period during which both feet are in contact with the ground
Loading time (ms)	The duration during which only the heel of the foot going to stance phase is in contact with the ground.
Flat foot time (ms)	The duration during which the foot is in the stance phase is fully flat on the ground.
Propulsion time (ms)	The duration of the push-off phase, during which only the toes of the foot preparing for the swing phase remain in contact with the ground.
Single stance time (ms)	The time only one foot remains in contact with the ground, from the moment the opposite foot is raised until it is lowered again

Note. Km/h; kilometers per hour; cm = centimeters; ms = milliseconds; min = minute; % = percentage

Table 3:

Foot Kinematics and Advanced Parameters

Parameter	Definition
Foot kinematics	
Clearance (cm)	The lowest distance between the toes and the ground during the foot's swing phase.
Pronation/supination angle (°)	The angles of the foot, in pronation and supination, are determined when the foot is in the stance phase.
Circumduction (cm)	The lateral distance the foot moves during the swing phase.
Step progression angle (°)	The angle formed by the foot concerning the direction of walking during a step.
Step page heel (°)	The hook of the foot makes contact with the floor when the heel touches the ground during initial contact.
Step page toe (°)	The hook the foot makes with the floor when the toes touch the ground during the push-off phase.
Advanced parameters	
Symmetry (%)	The percentage indicates the balance of stance time between both feet, reflecting how evenly time and weight are shared during the stance phase of the gait cycle.
Propulsion rate (%)	The proportion of how much a person uses the hip flexors compared to the plantar flexors of the foot.

Note. Cm = centimeters; ° = degrees; % = percentage

The Digitsole insoles were placed in the participants' shoes and connected to the software. Participants then completed the Six-Minute Walk Test (6MWT), walking as fast as possible along a 30-meter corridor [28]. Spatiotemporal gait analysis was conducted during the 6MWT, as this study was part of a larger investigation that utilized the results of the 6MWT.

Figure 1

Podosmart Digitsoles

Note. Ziagkas, E., Loukovitis, A., Zekakos, D. X., Chau, T. D., Petrelis, A., & Grouios, G. (2021). A Novel Tool for Gait Analysis: Validation Study of the Smart Insole PODOSmart(®). Sensors (Basel), 21(17). https://doi.org/10.3390/s21175972

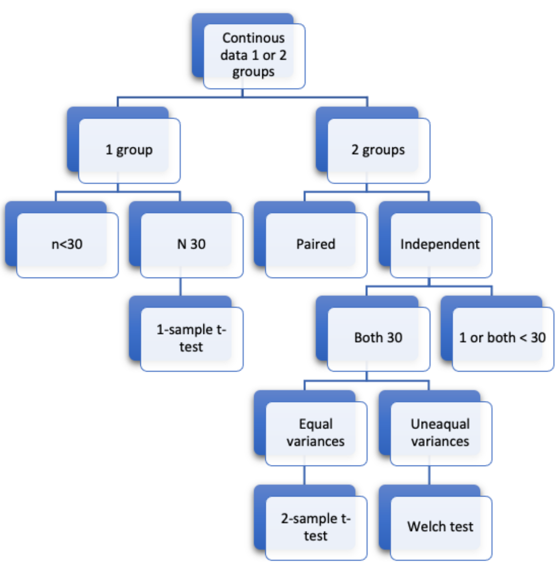
Statistical Analysis

All statistical analyses were conducted using JMP Pro 17. To check the normality of the data, the Shapiro-Wilk tests and histograms were used. To investigate the relationships between gait speed and other spatiotemporal and physical characteristics, Spearman correlation coefficients (p) were calculated. A Spearman correlation was used because the assumptions for parametric tests were not met for all variables. The strength of the correlations was categorized as no correlation ($0 < r < 0.3$), weak ($0.3 < r < 0.5$), moderate ($0.5 < r < 0.7$), strong ($0.7 < r < 0.9$), or very strong ($0.9 < r < 1$) [28]. Statistical significance was set at $p < 0.05$; both correlation coefficients and corresponding p-values were reported. Welch's tests and t-tests were conducted to see if there were significant differences between the left and right sides and to investigate potential gender differences (*Figure 2*). Multivariate correlation analysis was used to identify additional parameters associated with gait speed. This was divided into a demographic/physical part and a spatiotemporal part. Afterward, the residuals were checked for normality using the Shapiro-Wilk tests, the linearity of the residuals and the homoscedasticity were checked graphically. For all the characteristics in both the multivariate correlations, a linear model was developed to further explore these associations together (*Figure 3*). In these models, gait speed was designated as the dependent variable, while the identified spatiotemporal and physical parameters served as independent variables.

A stepwise selection approach was applied to identify the most relevant predictors. A potential multicollinearity among independent variables was assessed. The required model assumptions – homoscedasticity, linearity, and normality of residuals – were evaluated to ensure the validity of the models. Variance Inflation Factors (VIFs) were examined to assess multicollinearity within the models. A VIF value below five indicates that multicollinearity is not a concern. Values between five and ten suggest potential multicollinearity, and results should therefore be interpreted with caution. A VIF exceeding ten is indicative of a multicollinearity issue, in which case it is advisable to either remove or combine the affected variable.

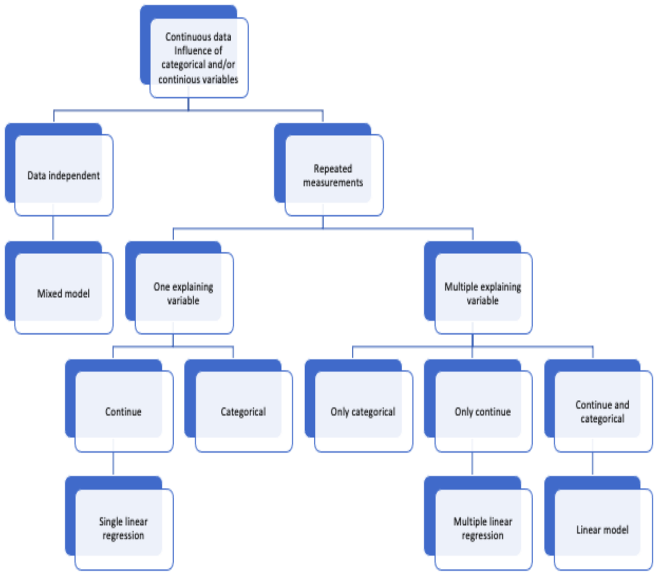
Multicollinearity was assessed using Variance Inflation Factors (VIFs). A VIF lower than five indicates no problematic multicollinearity. A VIF between five and ten indicated a possible multicollinearity; results should be interpreted with some caution. A VIF higher than ten indicates a multicollinearity problem, it is best to remove or merge the variable.

Figure 2



Flow Chart Statistics Welch's test and T-test

Figure 3



Flow Chart Statistics Multivariate

RESULTS

Descriptive analyses

The study included 108 participants, 56% of whom were women. The descriptive characteristics and physical characteristics of the participants are shown in *Table 4*. Significant gender differences were observed in height, weight, abdominal circumference, and all strength parameters. Gender-specific differences in these parameters were accounted for in further analyses. The spatiotemporal characteristics of the participants are shown in *Table 5.* Several parameters also showed significant asymmetries between the left and right sides, including pronation-supination angle for both heel ground contact and toe lift, step progression angle, circumduction, clearance, step page toe, stride duration, stride length and, swing time. These side-specific differences were also considered in subsequent analyses. Overall values were included in the tables to support additional statistical analyses where appropriate.

Table 4:

Descriptive Characteristics and Physical Characteristics of the Participants According to Gender

Parameter	Overall (n = 108)		Female (n = 61)		Male (n = 47)		Difference
	Md	IQR	Md	IQR	Md	IQR	P-value
Age (years)	69	67-72	70	67-74	68	66-71	0.0707
Length (cm)	166.00	159.63-173.88	161.00	157.50-165.00	175.00	169.50-179.50	<0.0001*
Weight (kg)	74.40	63.38-84.65	69.00	57.70-75.10	79.40	75.00-90.20	<0.0001*
BMI (kg/m^2)	26.30	22.93-28.45	25.30	22.30-28.31	26.60	25.00-28.70	0.2319

Circumference (cm)	95.00	86.00-103.00	89.00	82.00-100.00	99.00	93.00-105.00	0.0002*
BPS (mmHg)	134.00	125.00-148.00	131.50	123.00-146.00	141.00	127.00-153.00	0.0607
BPD (mmHg)	81.00	74.00-88.00	80.50	75.00-88.00	82.00	73.00-89.00	0.6002
Heart rate (beats/min)	67	59-73	69	62-69	63	57-71	0.0542
Saturation pre (%)	98	97-98	98	97-99	98	97-99	0.9447
Saturation post (%)	98	97-99	98	97-99	98	97-99	0.5552
RPE fatigue pre (score/10)	0	0-1	0	0-1	0	0-1	0.5610
RPE tightness pre (score/10)	0	0-3	1	0-2	0	1-3	0.6549
RPE fatigue post (score/10)	1	0-0.5	0	0-0.25	1	0-1	0.4137
RPE tightness post (score/10)	2	1-3	1	1-3	2	1-3	0.9388
TUG (sec)	5.96	5.51-6.78	6.00	5.64-6.99	5.93	5.16-6.75	0.1702
Grip strength L (N)	22.00	18.00-30.00	19.00	17.00-21.00	30.00	27.00-34.00	<0.0001*

Grip strength R (N)	24.50	20.00-32.00	21.00	18.00-23.00	34.00	29.00-38.00	<0.0001*
Quadriceps strength L (N)	27.00	21.00-35.00	22.00	18.50-27.50	35.00	29.00-44.00	<0.0001*
Quadriceps strength R (N)	29.00	22.25-36	23.00	20.00-30.00	36.00	31.00-46.00	<0.0001*

Note. Md = median; IQR = interquartile range; p-value* <0.05 = significant effect; RPE = rating of perceived extortion; TUG; timed up and go; N = newton; sec = seconds; BPS = blood pressure systolic, BPD = blood pressure diastolic

Table 5:

Spatiotemporal Characteristics of the Participants

Parameter	Mean		Left		Right		Difference
	Md	IQR	Md	SD	Md	SD	P-value
Speed (m/s)	5.90	5.40-6.40					
Symmetry (%)	98.00	95.50-99.00					
Cadence (steps/min)	127	118-131					
Double support phase (%)	9.50	8.70-10.60					

Propulsion duration (ms)	235.75	216.63-252.38	238.00	219.00-255.00	233.00	218.50-256.50	0.3499
Flatfoot time (ms)	253.5	231.50-283.38	250.00	227.50-279.50	255.00	232.50-290.50	0.0243
Loading time (ms)	79.50	68.63-86.88	81.00	69.50-91.00	77.00	65.00-85.00	0.005
Propulsion ratio (%)	9.25	5.50-14.00	9.00	4.00-14.50	10.00	6.00-15.00	0.9275
Pro-sup angle heel ground (°)	-17.75	-20.63--14.50	-18.00	-20.00--13.50	-18.00	-22.00--15.50	0.0004*
Pro-sup angle flatfoot (°)	-10.75	-14.00--7.50	-10.00	-13.50--7.00	-11.00	-13.50--8.00	0.1464
Pro-sup angle heel lift (°)	-8.75	-11.50--6.50	-9.00	-12.00 --6.00	-9.00	-12.00--7.00	0.7975
Pro-sup angle toe lift (°)	-2.50	-5.50- -0.50	-3.00	-6.00- -1.00	-2.00	-5.00-1.00	0.0003*
Step progression angle (°)	8.90	5.85-11.43	7.30	4.60-9.90	9.90	6.22-13.35	<0.0001*
Circumduction (cm)	3.60	2.50-2.28	3.40	2.10-4.30	3.70	3.00-4.80	<0.0001*
Clearance (cm)	1.23	0.90-1.75	1.30	0.90-1.80	1.10	0.80-1.70	0.0011*

Step page heel (°)	63.20	59.20-67.70	63.70	59.55-67.70	63.10	58.85-68.35	0.1575
Step page toe (°)	22.20	20.10-24.63	23.00	20.75-25.00	21.70	19.00-24.25	0.0001*
Stride duration (ms)	946.00	917.75-1009.25	946.00	918.00-1009.00	946.00	916.50-1009.50	0.0281*
Stride length (m)	1.57	1.44-1.69	1.57	1.45-1.69	1.56	1.44-1.69	<0.0001*
Swing time (ms)	382.00	366.50-405.25	384.00	367.50-405.50	380.00	364.00-405.00	0.0285*
Stance time (ms)	571.00	545.50-600.75	573.00	539.00-602.00	569.00	545.50-602.00	0.3215

Note. Md = median; IQR = interquartile range; p-value* <0.05 = significant effect; m/s = meters/seconds; min = minute; ms = milliseconds; m = meter

Univariate correlation analyses

Strong and statistically significant positive correlations were observed between gait speed and stride length on both the left side ($\rho = 0.77$, $p < 0.0001$) and the right side ($\rho = 0.78$, $p < 0.0001$). Furthermore, a moderate and statistically significant negative correlation was identified between gait speed and stance time ($\rho = -0.62$, $p < 0.0001$).

Cadence also demonstrated a moderate positive correlation with gait speed ($\rho = 0.54$, $p < 0.0001$). Additionally, moderate and statistically significant negative correlations were found between gait speed and the double support phase ($\rho = -0.55$, $p < 0.0001$) as well as flatfoot time ($\rho = -0.53$, $p < 0.0001$).

Weak but statistically significant correlations were observed for step page heel (ρ = 0.45, $p < 0.0001$) and stride duration (left: ρ = -0.47, $p < 0.0001$; right: ρ = -0.48, $p < 0.0001$).

Among physical characteristics, a moderate negative correlation was found between gait speed and the TUG test (ρ = –0.60, $p < 0.0001$). Several weak but statistically significant negative correlations were also identified between gait speed and circumference (male: ρ = –0.40, p = 0.0083; female: ρ = –0.34, p = 0.0123) between gait speed and right-hand grip strength in females (ρ = –0.30, p = 0.0294) and between gait speed and BMI (ρ = -0.30, p = 0.030). Moreover, a significant positive correlation was observed between gait speed and RPE fatigue post (ρ = 0.30, p = 0.0039). The complete results of the correlation analysis can be found in Appendix 1.

Multivariate analysis

Multivariate analyses were then performed to further investigate these associations. Multivariate modelling was used to examine which spatiotemporal parameters contribute to the prediction of gait speed in healthy older adults. Three different models were tested: one only using demographic and physical characteristics, one using only spatiotemporal parameters, and a final model incorporating all variables. For the three models, a multivariate analysis was performed using the stepwise method with a p-value threshold <0.05.

<u>Demographic and physical characteristics</u>

The final model consists of the following characteristics: TUG (β = -0.4451, p = <0.0001), RPE tightness pre-exercise (β = -0.1914, p = 0.0220), and RPE fatigue post-exercise (β = 0.0817, p = 0.0342). These factors were found to be significant predictors of gait speed (F = 34.49, $p <0.0001$).

<u>Spatiotemporal characteristics</u>

The final model consists of the following characteristics: cadence (β = 0.0480, $p <0.0001$), loading time right (β = 0.0012, $p < 0.0001$), and the stride length (left: β = 1.9348, $p <0.0001$, right: β = 1.7765, $p <0.0001$). These factors were found to be significant predictors of gait speed (F = 4559.60, $p <0.0001$).

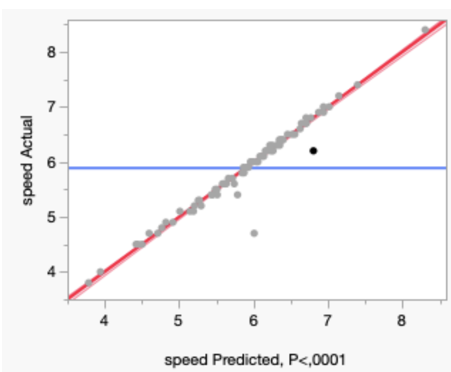
Complete model

A final model was constructed considering both the physical characteristics and the spatiotemporal characteristics from the multivariate analysis.

The model consists of the following characteristics: RPE fatigue post-exercise (β = 0.0249, p = 0.0018), cadence (β = 0.0482, p <0.0001), loading time right (β = 0.0014, p < 0.0001) and the stride length (left: β = 2.0785, p <0.0001, right: β = 1.6548, p = 0.0002), were significant predictors of gait speed speed (F = 3496.91, p <0.0001).

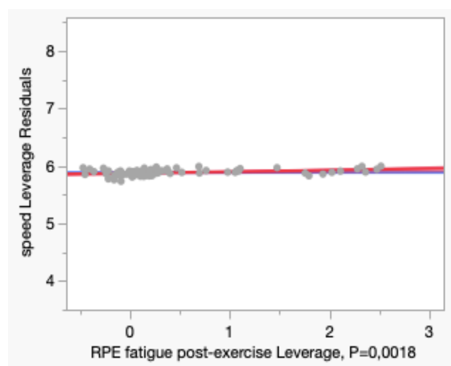
The scatter plot (*Figure 4*) shows a clear positive linear relationship between actual and predicted gait speed. The regression model explains 95% of the variance in actual gait speed ($R^2 = 0.99$) and has a low prediction error (RMSE = 0.0518). The model fit was statistically significant ($p < 0.0001$), indicating a strong agreement between predicted and actual gait speed. The visualization of the different parameters is presented in *Figure 5-9*.

Figure 4



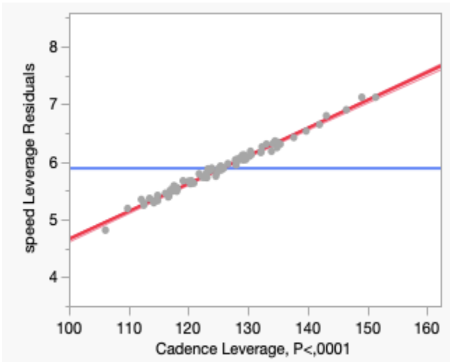
Scatter Plot Complete model

Figure 5



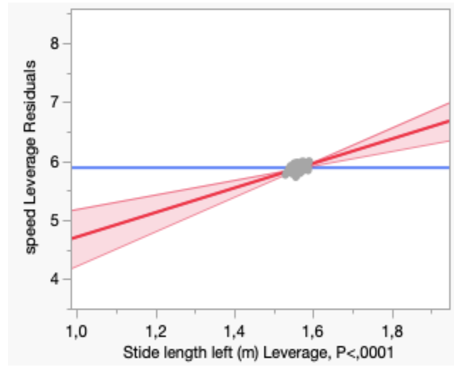
Scatter Plot RPE Fatigue Post-Exercise

Figure 6



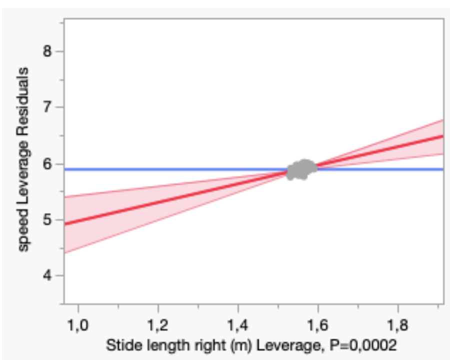
Scatter Plot Cadence

Figure 7



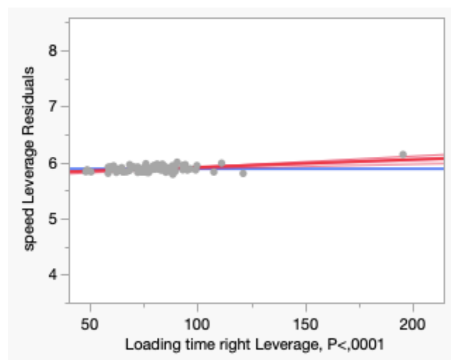
Scatter plot Stride Length Left

Figure 8



Scatter plot Stride Length Right

Figure 9



Scatter Plot Loading Time Right

The VIFs of all parameters in the models were below five, indicating no concerns regarding multicollinearity. An exception was noted for stride length on the left and right sides, which exhibited high VIFs due to their strong interdependence. However, they were included separately in the model due to significant side-specific differences observed among participants.

Table 6 provides a summary of the univariate and multivariate analyses of the final parameters.

Table 6:

Summary of the Final Parameters

Parameter	Univariate	Model 1	Model 2	Model 3
TUG	β = - 0.4844 p < 0.0001	β = -0.4451 p = <0.0001		
RPE tightness pre-exercise	β = 0.1214 p = 0.0197	β = 0.081 p = 0.0342		
RPE fatigue post-exercise	β = -0.3145 p = 0.0047	β = 0.0817 p = 0.0342		β = 0.0249 p = 0.0018
Cadence	β = 0.0527 p < 0.0001		β = 0.0480 p <0.0001	β = 0.0482 p <0.0001
Loading time	Not significant		β = 0.0012 p < 0.0001	β = 0.0014 p < 0.0001
Stride length	Left: β = 3.7777 p < 0.0001 Right: β = 3.8217 p = <0.0001		Left: β = 1.9348 p <0.0001 Right: β = 1.7765 p <0.0001	Left: β = 2.0785 p <0.0001 Right: β = 1.6548 p = 0.0002

DISCUSSION

This study aimed to investigate the relationship between gait speed and spatiotemporal parameters, as well as the influence of physical characteristics, in healthy older adults. The results of the study confirm and extend existing knowledge about the relationship between gait speed and spatiotemporal and physical parameters in healthy older adults. The most impactful correlations with gait speed were those with stride length (left: $\rho = 0.77$, $p < 0.0001$; right: $\rho = 0.78$, $p < 0.0001$). These findings are consistent with previous studies showing that older adults take shorter steps as walking speed decreases [3, 6]. Additionally, there was also a significant negative correlation for gait speed with the double support phase ($\rho = -0.55$, $p < 0.0001$) and with standing time ($\rho = -0.62$, $p < 0.0001$). This suggests that older adults with slower gait speeds spend more time in the double support phase, potentially as a compensatory strategy for balance deficits [30].

In addition, this study also examined the combination of spatiotemporal parameters in a multivariable model. In the multivariate model, stride length, cadence, and loading time emerged as the strongest predictors of gait speed. This multifactorial approach gives more insight into how multiple aspects of gait pattern work together to specify final speed, as shown by the fact that loading time, a relatively less frequently reported parameter, also made a significant contribution in combination with the other parameters. This result suggests that the role of the early support phase, the moment when the foot just makes contact with the ground, may have been underestimated in previous research. This phase has been found to make a significant contribution to the speed of locomotion of older adults. Whereas previous studies focused on univariate associations, the current model highlights that a combination of multiple parameters yields more accurate predictions.

Further, among the physical characteristics, the results confirm the negative relationship between gait speed and TUG score ($\rho = –0.60$, $p < 0.0001$). This result is to be expected given the relationship between the gait speed and the balance function [21]. Additionally, individuals with slower gait speeds tend to perform worse on the TUG, indicating reduced functional mobility.

Furthermore, a significant association was seen between RPE fatigue and gait speed (ρ = 0.30, p = 0.0039 This suggests that perceived exertion may be an important, yet often overlooked, factor in predicting functional capacity in older adults. Clinical practice may benefit from this.

Additionally, there were weak negative associations found between BMI and gait speed (ρ = –0.30, p = 0.030) and circumference and gait speed (male: ρ = –0.40, p = 0.0083; female: ρ = –0.34, p = 0.0123). These results are in line with earlier studies showing that being overweight can impair physical performance and mobility [31]. However, the relatively weak correlation coefficients indicate that these associations with gait speed are modest.

In contrast, correlations between gait and strength-related parameters were not or only one weakly correlated (right-hand grip strength in females (ρ = –0.30, p = 0.0294)) This was unexpected, given the initial hypothesis and previous research [17, 18] that muscle strength would have a more substantial influence on gait speed especially lower limb strength.

The multivariate analysis with physical parameters identified the TUG test, RPE tightness before exercise, and RPE fatigue after exercise as significant predictors of gait speed. The strongest negative predictor was the TUG test (β = -0.4451, p < 0.0001). This confirms that functional mobility as evaluated by the TUG is a vital determinant of gait speed among older adults. Moreover, a negative relationship was observed with perceived muscle stiffness before exercise and gait speed (β = -0.1914, p = 0.0220), suggesting that participants who perceive greater muscle stiffness before walking exercises tend to be slower. This could be suggestive of restricted motion or discomfort influencing the gait. In addition, post-exercise perceived fatigue (RPE fatigue post) was found to positively influence gait speed (β = 0.0817, p = 0.0342). It may be that higher walking speed is associated with greater effort during the measurements of perceived effort, leading to greater fatigue afterward. This suggests there may be little correlation between walking faster and reduced effort, while in fact, doing so indicates a greater level of exertion.

The final multivariate model, which incorporated both physical and spatiotemporal parameters, confirmed the previously identified predictors of gait speed. In this model, post-exercise RPE fatigue ($\beta = 0.0249$, $p = 0.0018$), cadence ($\beta = 0.0482$, $p < 0.0001$), loading time right ($\beta = 0.0014$, $p < 0.0001$), and stride length on both sides (left: $\beta = 2.0785$, $p < 0.0001$; right: $\beta = 1.6548$, $p = 0.0002$) serve as significant predictors of gait speed. Here, the angle and stride length as cadence have been shown to impact the speed of walking in healthy older adults. The importance of the early support phase during gait is marked ($\beta = 0.0014$, $p < 0.0001$) as a significant predictor, which shows how this phase contributes to gait speed. This means that the efficiency and the speed of walking are governed by the way the body mechanics interact with the ground at the very beginning of a new step. Also, the nuance of fatigue after exercise underlines the fact that gait performance is governed by the blend of biomechanical efficiency and the relative effort involved in the movement. In brief, evidence indicates that in aged healthy adults, there is a multisystem coordination involving energy balance along with stride length and rhythm, which modulates gait speed.

Several limitations should be acknowledged. Firstly, the cross-sectional nature of this study makes it more difficult to determine causal correlations. Secondly, the participants are healthy elderly, so the result cannot be generalized to the general population over 65. Thirdly, technology may be accompanied by malfunctions resulting in missing data, therefore, some missing data points were also present in this study.

Testing procedures were conducted by eight different examiners, which may have introduced variability despite efforts to standardize assessments. All tests were gone over together to highlight the points of interest and how to perform the tests correctly. The advantage of this is a better reliability and less chance of bias. In addition, it does increase the risk of assessment variation and different interpretations of assessment criteria.

Future research should focus on collecting longitudinal data to observe changes in walking speed and spatiotemporal parameters over time, to objectify the changes during aging. In addition, future studies could examine the effect of a strength training intervention on gait speed, given the unexpected result here. Furthermore, integrating cognitive functions and detailed balance measurements can broaden this outcome to provide a complete picture of all aspects of the older adults' lives.

From a clinical viewpoint, enhancing gait speed in healthy older adults requires increasing stride length, cadence, and loading time. Clinical strategies such as verbal cues, use of metronomes, and phase-specific gait training may assist in achieving these improvements.

In conclusion, this study highlights the relevance of specific spatiotemporal parameters, specifically step length, cadence, and loading time, concerning gait speed in healthy older adults. In addition, the study also shows that of the physical parameters, TUG-score an influencing factor is in gait speed as well as RPE tightness pre exercise as RPE fatigue post exercise. It therefore can be inferred that these factors can be worked on to improve walking speed in healthy older people.

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APPENDICES

Appendix 1: Univariate Spearman correlations

Table

Univariate Spearman Correlations: Biomechanical Parameters

Variable x	Variable y	Spearman (ρ)	Prob>p
Gait speed	Symmetry	-0.1510	0.1398
Gait speed	Cadence	0.5442	<0.0001*
Gait speed	Double support phase	-0.5501	<0.0001*
Gait speed	Propulsion duration L	-0.0295	0.7745
Gait speed	Propulsion duration R	-0.1229	0.2306
Gait speed	Flatfoot time L	-0.5420	<0.0001*
Gait speed	Flatfoot time R	-0.4958	<0.0001*
Gait speed	Loading time L	-0.2922	0.0037*
Gait speed	Loading time R	-0.2360	0.0199
Gait speed	Propulsion ratio L	0.0925	0.3674
Gait speed	Propulsion ratio R	0.0186	0.8563
Gait speed	Pro-sup angle heel ground L	0.1265	0.2099
Gait speed	Pro-sup angle heel ground R	0.1207	0.2391
Gait speed	Pro-sup angle flatfoot L	0.0564	0.5833
Gait speed	Pro-sup angle flatfoot R	0.0385	0.7082
Gait speed	Pro-sup angle heel lift L	0.0240	0.8158
Gait speed	Pro-sup angle heel lift R	-0.0509	0.6208
Gait speed	Pro-sup angle toe lift L	0.2101	0.0388*
Gait speed	Pro-sup angle toe lift R	0.1551	0.1293

Gait speed	Step progression angle L	-0.1498	0.1430
Gait speed	Step progression angle R	-0.1073	0.2957
Gait speed	Circumduction L	-0.1147	0.2633
Gait speed	Circumduction R	-0.1492	0.1446
Gait speed	Clearance L	-0.0939	0.3651
Gait speed	Clearance R	-0.0196	0.8490
Gait speed	Step page heel L	0.4051	<0.0001*
Gait speed	Step page heel R	0.3960	<0.0001*
Gait speed	Step page toe L	0.2709	0.0073*
Gait speed	Step page toe R	0.3469	0.0005*
Gait speed	Stride duration L	-0.4794	<0.0001*
Gait speed	Stride duration R	-0.4831	<0.0001*
Gait speed	Stride length L	0.7654	<0.0001*
Gait speed	Stride length R	0.7794	<0.0001*
Gait speed	Swing time L	-0.1783	0.0873
Gait speed	Swing time R	-0.1561	0.0995
Gait speed	Stance time L	-0.6236	<0.0001*
Gait speed	Stance time R	-0.6181	<0.0001*
Gait speed	Propulsion duration mean	-0.0745	0.4684
Gait speed	Flatfoot time mean	-0.5330	<0.0001*
Gait speed	Loading time mean	-0.2916	0.0038*
Gait speed	Propulsion ratio mean	0.0639	0.5342

Gait speed	Pro-sup angle heel ground mean	0.1393	0.1735
Gait speed	Pro-sup angle flatfoot mean	0.0362	0.7248
Gait speed	Pro-sup angle heel lift mean	-0.0238	0.8170
Gait speed	Pro-sup angle toe lift mean	0.1781	0.0809
Gait speed	Step progression angle mean	-0.1660	0.1042
Gait speed	Circumduction mean	-0.1214	0.2363
Gait speed	Clearance mean	-0.0608	0.5544
Gait speed	Step page heel mean	0.4458	<0.0001*
Gait speed	Step page toe mean	0.3419	0.0006*
Gait speed	Stride duration mean	-0.4844	<0.0001*
Gait speed	Stride length mean	0.7728	<0.0001*
Gait speed	Swing time mean	-0.1719	0.0995
Gait speed	Stance time mean	-0.6181	<0.0001*

Note. L = left; R = right; pro-sup = pronation-supination; p-value* <0.05 = significant effect

Table:

Univariate Spearman Correlations: Physical Parameters

Variable x	Variable y	Spearman (ρ)	prob>p
Gait speed	Age	-0.2103	0.0387*
Gait speed	Gender	-0.2653	0.0086*
Gait speed	Length (male)	-0.0183	0.9072
Gait speed	Length (female)	0.2863	0.0358*
Gait speed	Weight (male)	-0.2290	0.1396
Gait speed	weight (female)	-0.2503	0.0679

Gait speed	BMI	-0.2981	0.0030*
Gait speed	Circumference (male)	-0.3974	0.0083*
Gait speed	Circumference (female)	-0.3384	0.0123*
Gait speed	Blood pressure systolic	-0.0118	0.9090
Gait speed	Blood pressure diastolic	-0.0352	0.7332
Gait speed	Heart rate	-0.1631	0.1123
Gait speed	Saturation pre	0.1603	0.1169
Gait speed	Saturation post	-0.0032	0.9753
Gait speed	RPE fatigue pre	-0.0485	0.6693
Gait speed	RPE tightness pre	-0.1768	0.1076
Gait speed	RPE fatigue post	0.3012	0.0039*
Gait speed	RPE tightness post	0.1308	0.2042
Gait speed	TUG	-0.6042	<0.0001*
Gait speed	Kg handgrip L (male)	-0.0075	0.9621
Gait speed	Kg handgrip R (male)	-0.0695	0.6577
Gait speed	Kg handgrip L (female)	0.2776	0.0421*
Gait speed	Kg handgrip R (female)	0.2966	0.0294*
Gait speed	Kg quadriceps L (male)	-0.0150	0.9239
Gait speed	Kg quadriceps R (male)	0.0897	0.4674
Gait speed	Kg quadriceps L (female)	0.1574	0.2557
Gait speed	Kg quadriceps R (female)	0.1743	0.2075

Note. L = left; R = right; BMI = body mass index; Kg = kilogram; p-value* <0.05 = significant effect