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Research Article

Females Present Reduced Minimum Toe Clearance During Walking As Compared to Males in Active Older Adults

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Abstract

Background: Physical decline due to aging has been associated with the risk of falls. Minimum toe clearance (MTC) is a gait parameter that might play a role in the mechanism of tripping and falling. However, it is unclear if there are any sex-related effects regarding MTC as people age. The present study investigated if there are sex-related differences in MTC in older active adults.

Methods: Twenty-three females and 23 males (F: 65.5 ± 4.8 years; M: 61.9 ± 5.2 years) walked on a treadmill at a preferred walking speed, while kinematic data were obtained at a sampling frequency of 100 Hz and up-sampled to 120 and 240 Hz. MTC was calculated from the kinematics data and evaluated concerning its magnitude (ie, MTC and MTC/leg length), the time between left/right MTC (ie, T-MTC), amount of variability (ie, coefficient of variation [CV] and coefficient of variation modified [CVm]), and temporal structure of variability, that is, the complexity of the time series (ie, MTC α, T-MTC α).

Results: No sex effects were found for MTC/leg length, for the amount of variability (ie, CV and CVm), and for the complexity of the time series (MTC α, T-MTC α). However, females exhibited significantly lower MTC and T-MTC after adjusting for walking speed, mass, and age as covariates.

Conclusions: The reduced MTC in females suggests a potential sex-related disparity in the risk of tripping and falling among active older adults.

Keywords: Balance, Falls, Gait, Tripping, Variability

Physiological decline associated with aging has been linked to the risk of falls. The frequency of falls was suggested to increase threefold in older adults due to loss of muscle mass and strength (1). Falls can cause moderate to severe injuries, compromise mobility, and lead to loss of independence, hospitalizations, and sometimes even death (2,3). Falls frequently occur in the older population during walking, with about 53% of falls emerging when stumbling due to involuntary contact of the foot with the ground or with an obstacle (4,5). As a result, tripping is commonly acknowledged as a significant cause of falls among older adults, and it has been suggested that tripping might be associated with insufficient minimum toe clearance (MTC) to navigate an unseen obstacle (6–8). However, the association between MTC and falls remains uncertain, with some studies suggesting a potential link between minimum foot clearance and the risk of tripping and falling (6–8), while others questioning and challenging this relationship (5,9).

It has been suggested that females show a higher risk of falls than males (10–13). However, it is unclear whether the factors affecting fall risk vary between males and females. MTC is defined as the minimum vertical distance between the anterior part of the foot/shoe and the ground during the mid-swing phase (14). Interestingly, in this phase of gait, some sex-related differences were identified. Specifically, older males showed increased rectus femoris muscle activation during the mid-swing phase, whereas females showed greater lateral gastrocnemius activation (15). Moreover, the duration of dorsiflexion during the initial swing phase of gait increased less abruptly with age for males than for females (16). Among healthy older adults, females were reported to exhibit reduced hip range of motion (ROM) and greater

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ankle ROM compared to males, which was accompanied by an early onset of knee flexion during the preswing phase (16). In addition, pelvic obliquity has also been reported to be greater in older females when compared to older male counterparts (17). Further disparities were observed in hip kinetics, with healthy older females displaying greater hip extension moments, as well as increased external hip adduction and internal rotation when compared to their male counterparts (18). Studies have also reported that healthy older females exhibit higher cadence, shorter stride length, and lower speed compared to males (16,19). These differences can affect MTC and its timing events during the gait cycle (eg, T-MTC). Furthermore, walking speed may also influence patterns of MTC variations (14) and affect MTC (8,20). All this information suggests that MTC could be affected due to sex, however, the answer to this critical question currently eludes us.

Typical MTC analysis includes measures of central tendency (such as mean and median) and measures of the amount of variability like the coefficient of variation (CV) and the coefficient of variation modified (CVm) (5,6). However, it has been noted that such linear metrics fail to capture the full intricacy of the time-evolving properties of signals, potentially overlooking valuable inherent details. Therefore, considering the complex and nonlinear nature of the mechanisms governing human locomotor control (21–23), we also investigated the temporal structure of variability, specifically the complexity of the signal (ie, MTC α and T-MTC α). It is also logical to assume that the large body of knowledge that exists on stride time interval variability can guide our hypotheses development regarding MTC variability purely because of the way they are both acquired, that is, from each stride. Given this potential relationship, it was anticipated that they (ie, MTC α and T-MTC α) would exhibit similar patterns. However, the extent to which these variables align remains uncertain and needs to be explored.

Research has indicated that variability during walking has distinct features in its temporal structure that are related to pathology that should be investigated (21–23). Importantly, it has been suggested that an optimal level of variability is associated with healthy states, whereas too much or too little variability represents an unhealthy and less adaptable system (23). Concerning the temporal structure of gait variability (ie, stride-to-stride variability), it has been predicted that this optimal level is characterized by high complexity. Complexity is defined as highly variable fluctuations in physiological processes resembling mathematical chaos and fractals and expressed as $1/f$ or pink noise. Pink noise because is intermediate between white noise (eg, random with too much variability) and red noise (ie, too rigid and lacking variability), it exhibits both stability and adaptability, properties typical of healthy systems with high complexity (23). Systems exhibiting random and/or rigid behaviors are unstable and lack adaptability having diminished complexity (23). Healthy gait variability has been shown to present high complexity (24–26), whereas the gait variability of older adults (25,27) and neurological patients (28) showed a loss of complexity and a transition toward white noise. Recently, Karmakar, Khandoker Begg, and Palaniswami (14) found more regular patterns in the temporal structure of MTC variability in older adults with a history of falls compared to healthy older and young participants. However, it is unknown if there are any sex-related differences concerning MTC complexity in older adults.

MTC is expected to change due to human movement variability with each step. Thus, besides the magnitude (ie, average) of MTC is essential to understand the amount of MTC variability (ie, CV and CVm) because subjects with low MTC coupled with high MTC variability may be at greater risk of tripping and falling. An increased amount of MTC variability was observed previously in older adults as compared to their younger counterparts, as well as in older fallers as compared to older nonfallers (29). Given that females exhibit a higher risk of falls than males (10–13), it is also important to explore the amount of MTC variability across sexes.

Therefore, the present study aims to fill the above-presented knowledge gaps and investigate sex-related differences in MTC in older active adults. Based on the above-presented literature, we hypothesized that: (1) the magnitude of MTC would be smaller in females than in males, (2) the females would exhibit decreased complexity of MTC variability as compared to males, and (3) the amount of MTC variability would be higher in females than in males.

Method

Participants

Twenty-three females (age = 65.5 ± 4.8 years, mass = 66.1 ± 9.2 kg, height = 1.55 ± 0.06 m, BMI = 27.8 ± 3.7 kg/m^2, cadence = 112.8 ± 9.3 steps/minute) and 23 (age = 61.9 ± 5.2 years, mass = 76.7 ± 8.5 kg, height = 1.70 ± 0.07 m, BMI = 26.7 ± 2.9 kg/m^2, cadence = 105.2 ± 9.6 steps/minute) with White European Ethnic ancestry participated in the study. We used a conventional scale and stadiometer to measure each participant's body mass and height. The participants were physically active and performed exercise sessions of 45 minutes at least twice per week. Both males and females performed the same type of exercise sessions and were from the same class. We controlled through a questionnaire for the following conditions: history of falls during the last 12 months, stroke, recent surgery, myopathy, neuropathy, scoliosis, arterial disease, rheumatoid arthritis, diabetes, lower limb injury in the last 6 months, joint replacement, pulmonary and/or cardiac diseases, asthma, acute pain, foot deformities, and locomotor disorders. Exclusion criteria included the presence of diseases that could directly affect gait, such as neurological, musculoskeletal, cardiovascular, respiratory disorders, rheumatoid arthritis, as well as locomotor disorders. Additionally, all participants provided written informed consent according to the Ethics Committee of the University of Beira Interior procedures.

Data Collection and Analysis

Data collection took place in 2 sessions, 1 week apart. The first session was used to familiarize participants with the laboratory environment and determine their preferred walking speed (PWS) during treadmill walking (h/p/cosmos Mercury 4.0, Munich, Germany). To ensure an adequate number of MTC time series samples and enable a proper observation of system dynamics (30–32), participants were specifically instructed to walk at their PWS for 14 minutes during the second session, following a 3-minute familiarization period. This approach accounted for the natural variation in walking speeds among individuals, as some people may walk at a slower pace and take fewer steps compared to others.

Preferred walking speed

The PWS during treadmill walking was estimated as follows: (1) from 1.5 km/h, the initial speed was increased in intervals of 0.1 km/h every 6 strides until the participant informed that the speed was too high and uncomfortable, the value immediately before this speed was considered the maximum speed; (2) the reverse procedure was then performed by reducing the speed in steps of 0.1 km/h until the participant reported that the speed was too low and uncomfortable, the value immediately before this speed was considered the minimum speed (14). The participants were not aware of the treadmill speeds being applied. This procedure was performed 6 times, and the average of the 6 maximum and 6 minimum speeds was considered the PWS.

Kinematic data

Eight infrared cameras were used to detect the position of retroreflective markers at 100 Hz. It has been suggested that kinematic gait data for detrended fluctuation analysis (DFA) should be sampled at 120 Hz or higher (33,34). Given that up-sampling does not affect measurements of stride correlations (33), we conducted up-sampling at both 120 and 240 Hz. Up-sampling was accomplished using cubic-spline interpolation performed in MATLAB software (MATLAB R 2018a, MathWorks, Inc., Natick, MA). Sixteen retroreflective marks of 9.5 mm were placed on the anatomical landmarks of the right and left sides according to the recommendations of the Plug-in-Gait Lower Body model (Vicon system, Vicon, Oxford, UK). Additionally, each shoe was fitted with 4 half markers each measuring 9.5 mm. These markers were affixed on the forefront of the outsole of the footwear, precisely aligned with the anterior position of the ball of the foot, first, third, and fifth metatarsals (referred to as B1, M1, M3, and M5 respectively, as shown in Figure 1).

Because these real markers may not accurately represent the lowest points of the shoe, they were used to reconstruct virtual markers, namely B1V, M1V, M3V, and M5V to better represent these points. Initially, in the static trial, the *z* coordinates of the real markers were set to 0 to create these virtual markers in the global coordinate system. Then, a transformation matrix was generated using a 3-point method, leveraging the positions of 3 real markers, and was used to compute the local coordinates of the virtual markers during the static trial. To obtain the global coordinates of these virtual markers in the dynamic trial, the inverse process was applied. This involved using a transformation matrix to convert the local coordinates obtained in the static trial into global coordinates for the dynamic trial. This procedure ensured that the virtual markers effectively represented the desired points on the shoe across both static and dynamic trials. For further details on the methodology, refer to Ref. (35).

Identical shoes (SoulCal & Co California, Sunset Lace Canvas, Irvine, California, China) of different sizes were purchased for the study to ensure accurate determination of the MTC and to avoid the effects of different types of shoes (36). Because the M1V marker was found to exhibit on average the smallest MTC value, this marker was selected for the rest of the analysis. During the walking trial, we identified MTC as follows. From each step, the heel-strike (HS) and the toe-off (TO) events were determined through the position-based method proposed by Zeni, Richards, and Higginson (37).

Figure 1. Position of the real (B1, M1, M3, and M5) and virtual (B1V, M1V, M3V, and M5V) retroreflective markers used to determine MTC. The markers were aligned with the anterior position of the ball of the foot, first, third, and fifth metatarsals.

MTC was then estimated by calculating the local minimum between the peaks (A and B) that take place just after the TO and before the HS (Figure 2). After determining MTC for both limbs, T-MTC was calculated by subtracting the instant of MTC between the left and right sides. These procedures were performed with MATLAB software (MATLAB R 2018a). In the very few rare cases where no local minimum existed, the MTC was calculated as the average of the remaining local minimum points.

To avoid affecting the natural walking variability, no data smoothing was performed. MTC was determined from raw data of the markers placed on the shoe because temporal variations in biological signals can exhibit deterministic patterns (besides noise) that can have meaningful implications in human movement interpretation (38).

To account for the possible influence of height on results, MTC was normalized by leg length (ie, MTC/leg). Leg length was measured according to the specifications of the Vicon Plug-in Gait model (Vicon system), spanning from the Anterior Superior Iliac Spine marker to the medial malleolus while passing through the knee joint.

In addition, the coefficient of variation (CV = *SD*/Mean × 100) and the coefficient of variation modified (CVm = IQR/Q2 × 100) were obtained after determining the interquartile range (IQR = Q3 – Q1) and the median (ie, Q2), as suggested by Begg, Best, Dell'Oro, and Taylor (6).

Detrended fluctuation analysis

The temporal structure of the MTC variability and the complexity of the time series were assessed through DFA using MATLAB software (MATLAB R2018a). Briefly, DFA is used

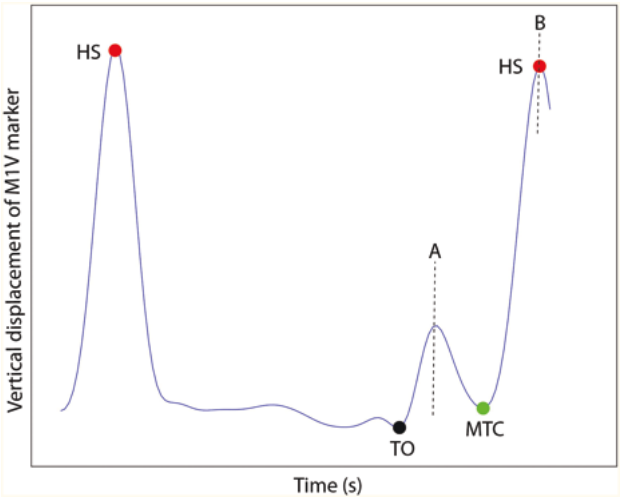

Figure 2. Illustration depicting the vertical displacement of the M1V marker throughout the gait cycle, highlighting the minimum toe clearance (MTC) occurring between toe-off (TO) and heel-strike (HS) within the mid-swing phase.

to identify fractal-like (ie, self-similar) processes by integrating data over time, where each time series integrated will be self-similar if the fluctuations at different time windows [$F(n)$] scale as a power-law with window size n. A linear relationship on a double-log graph will denote self-similarity with $F(n) \approx n^{\alpha}$, while the slope of the gradient, relating the log $F(n)$ to the log n, will determine the self-similarity scaling parameter α (39). The size of the DFA windows used in our study was 16 to $N/9$, while the N was 600 (31). When the α-value is lower than 0.5, the long-range correlation is termed antipersistent, suggesting that decreases are expected to be followed by increases and vice versa. Although an α value greater than 0.5 denotes a persistent long-range correlation implying that decreases and increases are likely to be followed by decreases and increases, respectively. If the α value is ≈ 1.0 (ie, pink noise or 1/f noise), the structure of the signal denotes a fractal-like complexity and an optimal state of adaptability in motor performance. In contrast, a highly variable signal with a low α value (eg, white noise with α ≈ 0.5) would indicate a loss of complexity suggesting unconstrained variability and unstable motor performance (32). When the α value is greater than 1.0 (ie, brown noise), the signal represents a deterministic structure. Using the above procedures, we calculated MTC α and T-MTC α from the MTC time series of the right foot. MTC α was computed using the time series of the MTC values between 2 consecutive instances of MTC of the right foot, whereas T-MTC α was determined using the time series of the values of the time interval between 2 consecutive instances of MTC of the right foot.

Statistical analysis

After the dependent variables (ie, MTC, MTC/leg, T-MTC, MTC α, and T-MTC α) were tested for assumptions, a 1-way MANCOVA (A) was run to determine sex-related differences while controlling for age, PWS, and mass. The first hypothesis of the present study focused on the variables MTC, MTC/leg, and T-MTC, whereas the second on MTC α and T-MTC α. Sex-related differences in PWS and cadence were also evaluated by another 1-way MANCOVA (B) while controlling for age and mass.

The 1-way MANCOVA assumption of normality was evaluated with the Kolmogorov–Smirnov (K–S) test for all dependent variables. When the assumption of normality was violated, the data were log-transformed (ie, for MTC and MTC/leg). There was homogeneity of covariances, as assessed by Box's M test. There were some univariate outliers, as evaluated by standardized residuals, but none influenced the model estimated (maximum Cook's distance less than 0.5). Residuals were normally distributed, as assessed by the K–S test. When significant multivariate differences were detected, univariate 1-way ANCOVAs were used to determine where the differences lay.

To test the third hypothesis, we conducted both the independent-samples t test and the Mann–Whitney U test. These tests were run to investigate potential significant differences in the amount of MTC variability between males and females, specifically focusing on the CV and the CVm, respectively. The nonparametric Mann–Whitney U test was used because the normality of data was violated. The distributions of the CVm for males and females were similar, as assessed by visual inspection. An alpha level of $p < .05$ was considered statistically significant. Statistical analysis was performed using SPSS (IBM SPSS Statistics 28.0.1.0, Chicago, IL).

The statistical tests formerly explained were applied to raw and filtered data obtained at 100, 120, and 240 Hz. The results obtained were similar across all the frequencies analyzed and between raw and filtered data. Therefore, only the raw 120 Hz results were reported.

Results

We hypothesized that: (1) the magnitude of MTC would be smaller in females than in males and (2) females would exhibit decreased complexity of MTC variability compared to males. We tested these 2 hypotheses through the 1-way MANCOVA (A) and the results revealed significant differences between sex on the combined dependent variables (ie, MTC, MTC/leg, T-MTC, MTC α, and T-MTC α; Table 2) after controlling for PWS, mass, and age, $F(5,37) = 6.84$, $p < .001$, Wilks' $\Lambda = 0.52$, partial η^2 (%) = 48, power = 0.99. The follow-up univariate 1-way ANCOVAs (Tables 1 and 2) provided further support for our first hypothesis by revealing significantly smaller MTC, and T-MTC in females than males. However, the second hypothesis was not supported, as females showed a similar level of complexity (ie, MTC α and T-MTC α) of MTC variability to males (Tables 1 and 2).

Regarding our third hypothesis and to examine potential differences in the amount of MTC variability (ie, CV) between males and females, we conducted an independent-sample t test. However, no significant differences were found between males (27.2 ± 8.22) and females (25.79 ± 4.49) in the amount of MTC variability, $t(34.04) = 0.72$, $p = .48$, 95% CI [–2.57, 5.37], Cohen's $d = 0.21$. Additionally, we evaluated the amount of MTC variability using the modified coefficient of variation (ie, CVm) with a Mann–Whitney U test. Again, no significant differences were observed between males (36.76 ± 12.08) and females (34.82 ± 6.97) in the amount of MTC variability, $U = 250$, $z = -0.32$, $p = .75$.

To understand the combined effects of PWS and cadence between sexes, a 1-way MANCOVA (B) was performed while controlling for age: $F(2, 41) = 4.29$, $p = .02$, Wilks' $\Lambda = 0.83$, partial η^2 (%) = 17.3, power = 0.72. However, the follow-up

Table 1. Descriptive Statistics for Male and Female Participants

Variables	Males (n = 23)		Females (n = 23)	
	Mean (*SD*)	$Mean_{adj}$ (*SE*)	Mean (*SD*)	$Mean_{adj}$ (*SE*)
MTC (mm)	16.37 ± 5.1	—	13.38 ± 4.27	—
MTC/leg length	0.02 ± 0.01	—	0.02 ± 0.01	—
Median MTC (Q2) (mm)	15.84 ± 4.96	—	13.09 ± 4.18	—
IQR (Q3 – Q1) (mm)	5.64 ± 2.05	—	4.69 ± 2.49	—
CV (%)	27.20 ± 8.22	—	25.79 ± 4.49	—
CVm (%)	36.76 ± 12.08	—	34.82 ± 6.97	—
T-MTC (s)	0.69 ± 0.06	0.69 ± 0.01	0.64 ± 0.05	0.64 ± 0.01
MTC α	0.86 ± 0.12	0.86 ± 0.03	0.76 ± 0.13	0.77 ± 0.03
T-MTC α	0.82 ± 0.18	0.8 ± 0.04	0.76 ± 0.12	0.79 ± 0.04
PWS (k/h)	3.79 ± 0.45	3.83 ± 0.1	3.73 ± 0.44	3.7 ± 0.1
Cadence (steps/min)	105.22 ± 9.62	105.39 ± 2.25	112.78 ± 9.34	112.61 ± 2.25

Note: CV = coefficient of variation (*SD*/Mean × 100); CVm = coefficient of variation modified (IQR/Q2 × 100); MTC = average of minimum toe clearance for all steps; MTC/leg length = minimum toe clearance normalized by leg length; median MTC (Q2) = median of minimum toe clearance for all steps; PWS = preferred walking speed; Q3 – Q1 = inter-quartile range (IQR); Q1 = 25th percentile; Q2 = median or 50th percentile; Q3 = 75th percentile; T-MTC = time between MTC of the right and left foot; MTC α = scaling exponent α computed using MTC values between 2 consecutive MTC of the right foot; T-MTC α = scaling exponent α computed using time interval between 2 consecutive MTC of the right foot.

Table 2. One-Way MANCOVA (A) Considering the Effect of Gender on Several Dependent Variables (ie, MTC, MTC/leg, T-MTC, MTC α, and T-MTC α) While Controlling for Age, Preferred Walking Speed, and Mass. One-way MANCOVA (B) Considers the Effect of Gender on Dependent Variables (ie, PWS and Cadence) While Controlling for Age and Mass

One-Way MANCOVA (A)					
Variables	**Gender Effect**				
	Males-Females Mean Difference	***F* Value**	***p* Value**	**ES Partial η^2 (%)**	**Power**
MTC (mm)*	0.25 (0.04, 0.47)	$F(1, 41) = 5.74$	**.021**	12.3	0.65
MTC/leg length*	0.18 (–0.04, 0.4)	$F(1, 41) = 2.63$	.112	6.0	0.35
T-MTC (s)	0.06 (0.02, 0.09)	$F(1, 41) = 9.33$	**.004**	18.5	0.85
MTC α	0.09 (–0.01, 0.19)	$F(1, 41) = 3.44$	.071	7.7	0.44
T-MTC α	0.01 (–0.11, 0.12)	$F(1, 41) = 0.03$	.865	0.1	0.05
One-Way MANCOVA (B)					
PWS (km/h)	0.13 (–0.2, 0.45)	$F(1, 42) = 0.61$	.441	1.4	0.12
Cadence (steps/min)	–7.22 (–14.29, –0.15)	$F(1, 42) = 4.25$	**.046**	9.2	0.52

Notes: MTC = minimum toe clearance for all steps; MTC/leg length = minimum toe clearance normalized by leg length; T-MTC = time between MTC of the right and left foot; PWS = preferred walking speed; MTC α = scaling exponent α computed using MTC values between 2 consecutive MTC of the right foot; T-MTC α = scaling exponent α computed using time interval between 2 consecutive MTC of the right foot. Bold values indicate statistically significant differences (p <.05).
*Log-transformed for MANCOVA.

univariate 1-way ANCOVAs (Table 2) only showed a significantly higher cadence for females than males.

Discussion

This study aimed to investigate sex-related differences in MTC among active older adults. Three hypotheses were formulated based on prior research: (1) females would exhibit smaller MTC magnitude compared to males, (2) females would demonstrate decreased complexity of MTC variability compared to males, and (3) the amount of MTC variability will be higher in females than in males.

However, only the first hypothesis was supported by the findings. Males showed significantly higher mean MTC (16.4 ± 5.1 mm), than females (13.4 ± 4.3 mm) even after adjusting for age (Tables 1 and 2). In general, mean MTC values can vary depending on the population and methodology employed, typically falling within the range of 8.5 to 22.4 mm (40,41). Previous studies on older individuals during treadmill walking at self-selected speed reported similar mean MTC values. For instance, Karmakar, Khandoker, Begg, and Palaniswami (14) reported MTC values of 12.5 mm for older females, whereas Sparrow, Begg, and Parker (42) reported foot-ground clearance values of 15.95 mm for

older males. Our values are within the ballpark of these previous results providing confidence in our procedures and methods. Several studies have reported sex-related differences in gait patterns (15,43,44). For instance, greater preferred and faster walking speed was associated with males (45), and an increase in MTC was linked to faster walking speeds (8,20). Although other studies did not find sex-related differences in walking speed (43,44). In line with these latter studies, our results also indicate no significant differences in PWS between sexes (Table 2). Consequently, speed didn't influence the variations in MTC between males and females. As outlined in the methods section, the average age of females (65.5 ± 4.8 years) was higher than that of males (61.9 ± 5.2 years). The impact of age on MTC has yielded conflicting findings in previous studies. For instance, while Killeen, Easthope, Demko, Filli, Lorincz, Linnebank, Curt, Zorner, and Bolliger (46) reported no significant MTC differences across various age groups, Nagano, Sparrow, Mizukami, Sarashina, and Begg (47) found significant variations. To account for this potential influence, we controlled for age as a covariate. However, no changes in the results were observed, suggesting that age does not affect our outcomes, at least within the age range examined in our study (Table 2). Height can affect gait measurements (29), and females generally have shorter height and leg length compared to males (48). To address this discrepancy, we normalized MTC to leg length (MTC/leg length). Interestingly, after this normalization, no significant differences for MTC were found between the sexes (Table 2). Therefore, based on the overall results, the differences in MTC are related to body structure. Studies have indicated that shorter stride length and stride time are related to lower MTC (49). In this context, we evaluated the time between MTC (ie, T-MTC) across sexes. As shown in Tables 1 and 2, T-MTC was significantly lower in females than in males. This observation can be attributed to the well-established fact that females generally have shorter heights and leg lengths, resulting in shorter step lengths (16,44). The shorter steps and higher cadence of females enable them to achieve walking speeds equivalent to males (16,44). On average, females took approximately 113 steps per minute, whereas males took about 105 steps per minute (Table 1). With females taking more steps in the same time interval, each step must be completed in less time than those of males. Given that the occurrence of the MTC is inherently tied to every step taken, it is only natural to expect a decrease in the time interval between each MTC, as corroborated by our results, specifically in the context of T-MTC. This empirical evidence solidifies the connection between sex-specific differences in cadence and their direct impact on the time interval between MTC occurrences, reinforcing the findings reported in Tables 1 and 2.

Regarding the second hypothesis, although females showed lower complexity results than males (ie, MTC α and T-MTC α), no significant differences were found across sexes (Tables 1 and 2). Complexity relates to the level of adaptability that a system can achieve. A biological system that shows too little or too much variability is characterized by a loss of complexity, indicating that the system is too rigid or unstable and, therefore, less adaptable and healthy (23). As shown in Table 1, the complexity results for MTC α were (M: 0.86 ± 0.12 and F: 0.76 ± 0.13) and for T-MTC α were (M: 0.82 ± 0.18 and F: 0.76 ± 0.12). Older adults and unhealthy populations generally exhibit lower values of the scaling exponent α compared to their younger and healthy counterparts, which indicates a decrease in long-range correlations associated with aging and disease. In a systematic review by Ravi, Marmelat, Taylor, Newell, Stergiou, and Singh (32), the authors reported that a threshold of 0.86 [2 standard errors (0.76, 0.96)] for the average scaling exponent α effectively differentiated between young and older adults. Furthermore, in the same systematic review, a threshold of 0.82 [2 standard errors (0.72, 0.92)] was identified to differentiate between Parkinson's disease and healthy asymptomatic individuals. Considering these established thresholds, both male and female participants in our study fall within these intervals, suggesting that they can be categorized as healthy individuals. Therefore, it is possible that the lack of differences with respect to complexity is due to the quite healthy sample that was used in the present study. It's important to recognize the distinct nature of the analyzed MTC variability, where one is based on displacement (MTC α), and the other on time (T-MTC α). MTC occurs for every step we take. In this fashion, both measurements are related to stride time interval variability (the so-called stride-to-stride variability in the literature), as both metrics are derived from individual strides. Given this inherent relationship, it was expected that MTC α and T-MTC α would demonstrate comparable complexity patterns. To delve deeper into this issue, we conducted additional step-to-step analyses on MTC α and T-MTC α. The MTC α values obtained were (M: 0.87 ± 0.1 and F: 0.79 ± 0.12), whereas the T-MTC α values were (M: 0.71 ± 0.17 and F: 0.64 ± 0.11). Expanding upon these findings and considering our previous results regarding stride parameters [specifically, for MTC α (M: 0.86 ± 0.12 and F: 0.76 ± 0.13) and for T-MTC α (M: 0.82 ± 0.18 and F: 0.76 ± 0.12)], it appears that MTC α exhibits greater consistency across different time scales (steps vs strides), as evidenced by the closer results observed for MTC α, whereas T-MTC α demonstrates more variation.

The findings from the first and second hypotheses suggested that the magnitude of MTC is predominantly influenced by biomechanical factors that vary between sexes, such as body structure. These differences can result in fluctuations in the average height of foot clearance during the swing phase of gait. In contrast, MTC complexity may be more influenced by factors associated with neuromuscular control or adaptability to environmental conditions, which could vary independently of sex.

Regarding the third hypothesis, the evaluation of MTC variability using both CV and CVm indicated no significant differences between males (CV: 27.20 ± 8.22%; CVm: 36.76 ± 12.08%) and females (CV: 25.79 ± 4.49%; CVm: 34.82 ± 6.97%) as reported in Table 1. Notably, both CV and CVm values are within the range reported in published research. For example, Karmakar, Khandoker, Begg, and Palaniswami (14) and Sparrow, Begg, and Parker (42) observed CV values of 25.6% and 30.4% (average of both legs), respectively, in older populations. Additionally, Begg, Best, Dell'Oro, and Taylor (6) reported a CVm value of 36.1% for older females. The similar CV and CVm values in both females and males suggest that the amount of MTC variability may not be a relevant factor in the incidence of trips and falls across sexes. These findings align with Killeen, Easthope, Demko, Filli, Lorincz, Linnebank, Curt, Zorner, and Bolliger (46), who also found no significant sex differences in MTC variability in their studies.

Gait data were acquired on a treadmill, a limitation of the study. Treadmill walking tends to produce relatively stable

gait patterns due to consistent speed and surface, whereas overground walking involves diverse environmental conditions, potentially leading to greater variability in gait patterns (49). Given this limitation, it is prudent to consider whether treadmill walking versus overground walking could affect our study results. However, given that our analysis is primarily centered on exploring sex differences in the magnitude of MTC, which is predominantly influenced by biomechanical factors such as leg length, we anticipate consistent findings across different walking conditions. Regarding MTC complexity, it's noteworthy that treadmill walking has been reported to worsen the long-range correlation of stride intervals evaluated by DFA (50). For instance, in treadmill walking, α values of 0.66 were reported, whereas in overground walking, the α values were 0.81, indicating a 22% increase in α value during overground walking compared to treadmill walking. Adjusting for this 22% in our results (ie, 0.86 and 0.76) would yield α-values corresponding to ~1 and 0.92 for males and females, respectively. This would indicate fractal-like complexity and an optimal state of adaptability in motor performance for both sexes. Regarding CV, no differences were observed between the 2 walking conditions in the same study (50).

We acknowledge the lack of EMG or muscle strength data in our study, limiting direct assessment of their impact on MTC values, especially concerning sex differences. Therefore, we advocate for their inclusion in future research to enhance understanding of MTC and gait dynamics.

Conclusion

In summary, the study aimed to investigate sex-related differences in MTC among older adults based on 3 hypotheses. The first hypothesis was supported by the findings, showing that females had significantly lower MTC values than males. However, the second and third hypotheses were not supported, as no significant sex differences were found in MTC complexity or amount of MTC variability. The reduced MTC in females suggests a potential sex-related disparity in the risk of tripping and falling among active older adults.

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Conflict of Interest

None.

Author Contributions

A.F., T.S., and R.G. provided the concept and experimental design of the work. A.F., T.S., and N.S. wrote the manuscript. A.F., T.S., J.R.V., R.G., J.G., and N.S., provided data collection, analyses, interpretation, and reviewed the manuscript. N.S. and A.F. obtained funding for the study.

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