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Foot-ground clearance characteristics in women: A comparison across different ages

Darlan Martins Ribeiro[a,b,*], Guilherme Augusto Santos Bueno[a], Flavia Martins Gervásio[b], Ruth Losada de Menezes[a]

[a] Post-Graduation Program in Health Science and Technologies of the University of Brasília (UnB), Ceilândia Campus, Brasília, DF, Brazil
[b] Movement Analisis Loboratory Dr. Cláudio A. Borges, State University of Goiás (UEG), Goiânia, Brazil

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ABSTRACT

Background: Tripping is a common event leading to falls amongst elderly. Minimum foot clearance (MFC) is a critical swing phase control factor associated with tripping and falls.
Research question: Are there differences in MFC characteristics among three age groups of women and are there association between MFC and lower limb kinematics?
Methods: Cross-sectional observational study. Three-dimensional gait analysis of 55 healthy women. ANOVA was used to compare ($p < 0.05$) MFC characteristics among young, middle-aged and elderly groups. Multiple Linear Regression Analysis was used to test prediction over MFC.
Results: Elderly women walked slower, with lower MFC and lower maximum foot velocity during swing (MFV) than young and middle-aged women. There were more hip flexion and less ankle dorsiflexion during MFC among elderly. There is a strong positive relationship between dorsiflexion and MFC. And ankle dorsiflexion was the most predictive variable over MFC.
Significance: Elderly women walk slower with lower MFC value and less ankle dorsiflexion than gender-matched young controls. Increased hip flexion may represent a gait adaptation to avoid tripping. Gait speed had no effect on those findings.

1. Introduction

Falls in the elderly population are an important public health problem related to morbidity and mortality [1], with tripping during gait been reported as a frequent event leading to falls [1–3].

During swing phase, the lower limb acts like a compound pendulum and its distal point reaches the highest speed of the whole gait cycle at approximately half of the swing phase period [4,5]. Minimum foot clearance (MFC) is defined as the minimum distance between the foot and the ground during swing. Throughout the foot trajectory, the maximum foot velocity (MFV) and MFC are reached simultaneously [5,6]. MFC and MFV are identified as critical swing phase control factors associated with tripping and falls [7,8]. MFC was also associated with frailty [9].

Several authors did not report MFC difference between young and elderly persons [10–13] although none of those investigations have assessed a sample composed exclusively of women.

It was demonstrated that elderly women are at increased tripping risk [10], show lower MFC [14] and fall more frequently than age-matched men [15]. Therefore, studying MFC in women could clarify whether there is difference between age groups within this gender-specific sample. As any changes in MFC are ultimately changes in lower limb kinematics [6] (e.g. ankle, hip and knee motion), any kinematic difference between age groups during MFC could collaborate to understand MFC changes.

Understanding swing phase mechanics between different ages might bring insights that help to develop fall-preventing strategies to groups in greater fall risk, like elderly womem. Thus, the aim of this investigation was to compare MFC across three age groups of healthy women and to explore the associations between MFC and lower limb kinematics.

Our hypothesis is that MFC is lower among elderly women when compared to younger gender-matched groups and that ankle motion has the strongest relationship and predictive value over MTC.

* Corresponding author at: Centro Metropolitano, conjunto A, lote 01, Unidade de Ensino e Docência - UED, 1º andar, sala A1-04/67, Brasília, DF, CEP: 72220-275, Brazil.

E-mail addresses: darlan.ribeiro@hotmail.com (D.M. Ribeiro), fisio.guilhermeaugusto@gmail.com (G.A.S. Bueno), flavia.gervasio@hotmail.com (F.M. Gervásio), ruthlosada@unb.br (R.L.d. Menezes).

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Table 1
Data description and comparison of Young (A), middle-aged (B) and elderly group (C). BMI = body mass index; MFV = maximum foot velocity; MFC = minimum foot clearance; ND = no difference.

		N	Mean	SD	ANOVA – one way p	post-hoc Tukey		
						A/B	A/C	B/C
Age (Year)	A	20	29.15	5.48	< 0.001	< 0.001	< 0.001	< 0.001
	B	20	48.65	6.07				
	C	15	65.73	4.39				
Weight (kg)	A	20	55.17	7.03	0.025	0.321	0.019	0.317
	B	20	58.71	6.42				
	C	15	62.56	9.83				
Height (m)	A	20	1.58	0.05	0.266	ND	ND	ND
	B	20	1.57	0.05				
	C	15	1.55	0.05				
BMI (kg/m^2)	A	20	21.95	2.60	< 0.001	0.135	< 0.001	0.042
	B	20	23.58	1.91				
	C	15	25.82	3.40				
Gait Parameters								
Cadence (steps/min)	A	20	115.65	7.47	0.009	0.215	0.006	0.237
	B	20	111.42	8.71				
	C	15	107.01	7.13				
Gait Speed (m/s)	A	20	1.25	0.13	0.001	0.052	0.001	0.180
	B	20	1.14	0.16				
	C	15	1.06	0.10				
Step Length (m)	A	40	0.65	0.04	< 0.001	0.033	< 0.001	< 0.001
	B	40	0.62	0.06				
	C	30	0.56	0.05				
MFV (m/s)	A	40	4.32	0.45	< 0.001	0.123	< 0.001	0.037
	B	40	4.11	0.50				
	C	30	3.83	0.46				
MFV Timing (%)	A	40	79.86	2.39	0.689[1]	ND	ND	ND
	B	40	79.32	2.22				
	C	30	79.83	2.18				
MFC (m)	A	40	0.05	0.01	0.044	0.671	0.036	0.197
	B	40	0.04	0.01				
	C	30	0.04	0.01				
Hip Coronal	A	40	3.37	3.11	0.881	ND	ND	ND
	B	40	2.98	4.38				
	C	30	3.38	4.08				
Hip Sagittal	A	40	25.89	9.09	0.031	0.094	0.040	0.861
	B	40	29.53	4.96				
	C	30	30.49	8.49				
Knee Sagittal	A	40	49.97	10.19	0.593[1]	ND	ND	ND
	B	40	52.03	6.01				
	C	30	50.32	11.95				
Ankle Sagittal	A	40	2.83	5.59	0.031[1]	0.789[2]	0.028[2]	0.031[2]
	B	40	2.90	5.65				
	C	30	−1.09	8.27				
Opposite Knee Sagittal	A	40	6.01	5.72	0.243	ND	ND	ND
	B	40	7.76	4.83				
	C	30	8.12	4.97				

Notes: ([1]) Kruskal-Wallis, ([2]) Bonferroni, $p \leq 0.016$. Adopted 95% of confidence. BMI = body mass index; MFV = maximum foot velocity; MFC = minimum foot clearance; ND = no difference.

Since gait speed effect on gait parameters was already demonstrated [16] and elderly usually walk slower [11], the relationship of speed with each gait parameter was assessed.

2. Methods

A cross-sectional study conducted at the State University of Goias gait laboratory, Goiânia, Brazil. Prior to data collection, all participants provided informed consent approved by Human Research Ethics Committee of the Federal University of Goias.

2.1. Participants

A group of healthy women from a community assistance program of the State University of Goias were invited. All participants were part of another study already published [17]. They were assigned to three age groups as proposed by other authors [11]: "Young" (20-39y), "Middle" (middle-age 40-59y) and "Old" (elderly over 60y). All were pain-free, able to walk without assistive devices, had no history of lower limb, pelvis or spine surgery, body mass index (BMI) below 30 kg/m^2, no alcoholic ingestion 24 h prior to data collection. Since fallers are known to have lower MFC values than non-fallers [18] all participants reported no falls in the past 12 months. All over 60-year-old participants scored over 20 on Mini-Mental State Examination [9].

The sample size was calculated after data collecting, based on ANOVA, using G.Power 3.2 software. A confidence interval of 95% and power of 85% for MFC with Cohen Effect Size of 0.481. Total sample size should be 56 participants, considering 10% loss.

2.2. Experimental procedures

A three-dimensional motion analysis system (Peak Performance Technologies, Englewood, Colorado, EUA) was used with 6 cameras (Pulnix® TM 6701 A N). Markers trajectory was sampled at 120 Hz and processed with a fourth order Butterworth filter cut-off frequency of 10 Hz [19]. The conventional gait model was used and, since there appears to be no agreed way to measure MFC [12], the most distal point of the feet was defined as a virtual point located at a volunteer's foot length ahead of the heel marker colinear to the heel and second metatarsal head marker, similar to what was published elsewhere [5,20]. Therefore, our method is not a direct measure of the vertical distance between the floor surface and the segment of the foot that is closer to that surface but gives a simple alternative method to compare amongst groups. Manual event detection technic was used [21] since there is no significant accuracy difference between manual and automated detection technics [22]. All data were normalized by the gait cycle using one hundred time-normalized samples for each stride. MFV was defined as the peak forward foot velocity between foot-off and the subsequent foot contact and MFC was the minimum vertical distance from the foot's distal point to the ground. The swinging limb's hip coronal and sagittal kinematics along with knee and ankle sagittal kinematics and opposite limb knee sagittal kinematics were all collected in synchronicity with the MFV.

Each participant wore a close-fitting stretch short, a sleeveless shirt and walked barefoot, looking straight ahead at a self-selected comfortable speed through an eight meters walkway. Data collection started after three steps and finished three steps before the end of the walkway. Data from both lower limbs were used as done by other authors [9,14] and recently demonstrated as a valid method to match limbs for young and elderly individuals [23]. Height and body mass (BM) were assessed as well as Body Mass Index (BMI) calculated.

2.3. Data analysis

All analyses were performed using SPSS 23.0 (IBM Corp, Armonk NY, USA). Normalcy distribution was tested using Shapiro-Wilk test. Groups were compared using ANOVA with Tukey's post hoc test. The relationship was tested using Pearson and multiple linear regression analysis was performed to test age, gait speed, MFV, hip, knee and ankle kinematics and opposite knee kinematics on predicting MFC ($p \leq 0.05$).

3. Results

A total of 55 women (110 limbs) participated in this study. Young (40 limbs; 29.15y ± 5.48; height 1.585 m ± 0.059; BM 55.17 kg/m^2 ± 7.03), Middle (40 limbs; 48.65y ± 6.07; height 1.57 m ± 0.51; BM 58.71 ± 6.42) and Old (30 limbs; 65.73y ± 4.39; height 1.55 m ± 0.054; BM 62.56 ± 9.83). Table 1 shows the result of ANOVA. Age was different among all groups and height showed no difference ($p = 0.266$).

Between Young and Old, BM and BMI were different ($p = 0.019$ and $p < 0.001$ respectively). Group Old walked slower ($p = 0.001$), with shorter steps ($p < 0.001$) and lower cadence ($p = 0.006$) than group Young.

MFV was higher on group Young than on Old ($p < 0.001$), as well as MFC ($p = 0.036$). MFC and MFV timings were not different among the three groups ($p = 0.689$) and occurred at 79% of the gait cycle.

Hip and ankle range of motion at MFC were different between groups as well. Group Old showed more hip flexion ($p = 0.04$) and less ankle dorsiflexion ($p = 0.028$) than group Young. No difference was found between groups Young and Middle. Coronal hip and sagittal opposite knee kinematics were not different among groups.

Relationship test results (Table 2) showed that age has moderate negative relationship with gait speed ($r = -0.563$; $p < 0.000$) and MFV ($r = -0.490$; $p < 0.000$). Gait speed showed moderate positive relationship ($r = 0.486$; $p < 0.000$) with MFV, weak negative relationship with hip flexion ($r = -0.228$; $p = 0.018$) and no relationship with MFC ($p = 0.107$), knee kinematics ($p = 0.911$) or ankle kinematics ($p = 0.180$).

Ankle dorsiflexion showed strong positive relationship with MFC ($r = 0.68$; $p < 0.000$).

Multiple linear regression analysis (Table 3) revealed that ankle dorsiflexion has the highest predictive value over MFC (R^2ajusted 0.457; $p < 0.000$) followed by knee kinematics (R^2ajusted 0.076; $p = 0.002$), age (R^2ajusted 0.056; $p = 0.008$) and MFV (R^2ajust 0.046; $p = 0.015$).

4. Discussion

This investigation aimed to compare minimum foot clearance, maximum foot velocity and lower limb joint kinematics during MFC amongst three age groups of healthy women.

As found by other authors [11,24], the central tendency measures of gait speed and step length were lower in elderly and no difference was found between the young and middle-aged group or between middle-aged and elderly. In this study, it was expected to find differences between young and middle-aged that could be early indicators of age-related gait changes, although no tested variable was different between those groups. That might indicate that the onset of gait functional decline is only detectable after 60 years of age and, following Gillain [14], increases after 70 years of age.

As shown by some investigators [7,14], our data showed that the elderly group had lower MFC values than young. Other authors did not find any difference between those age groups [10–13,25]. One investigation reported higher MFC in older vs. younger adults [21] during walking with several shoe conditions but no barefoot data were analysed. That could explain those contradicting results, since our data collection were conducted barefoot. Moreover, none of those above-mentioned studies assessed a sample that was exclusively women composed.

MFC and MFV are known to be critical swing control factors that can lead to tripping and falls [4,26]. This study investigated MFC control assessing lower limb joint kinematics in time synchronicity with MFV. It is known that ankle joint movement has an important role on MFC [6,20,27]. Those authors suggest that ankle dorsiflexion is a critical factor in MFC control, which is confirmed by our data. The multiple linear regression analysis demonstrated that ankle dorsiflexion was the main MFC predicting variable, while knee movement, age and MFV had much lower predicting capacity (Table 3).

It was demonstrated that gait speed has a positive relationship with MFC [6,27]. Those authors did not assess gender influence as well. Our data did not reproduce those findings whereas, in this investigation, gait speed had no relationship with MFC ($p = 0.107$). Alcock [15] had stated that swing phase mechanics changes in elderly women cannot be fully explained only by gait speed and age. It is possible that MFC is influenced by the typical ageing motor decline process [28] or mediated by declines in muscular strength, flexibility and postural control, common in the elderly [29,30].

The elderly group had more hip flexion during MFC than younger group ($p = 0.04$) and walked slower ($p = 0.001$). Schwartz [16] tested the influence of gait speed on lower limb kinematics and had demonstrated that hip flexion during swing phase decreases with slower gait speeds. In contrast, our data showed weak negative relationship (R -0.228; $p = 0.018$) between speed and hip flexion during MFC. The observed hip flexion increase could provoke higher MFC and might indicate a gait adaptation to the MTC decrease in order to reduce the likelihood of tripping over the swinging foot trajectory.

A limitation of this investigation is that the elderly group is relatively young (65.73y ± 4.39) and does not include participants over 80-year-old. An older sample could highlight those differences um swing phase mechanics. The chosen method to define toe position led to higher MFC values than those reported by other authors, pointing out the importance of defining an agreed method to measure MFC. The eight meters long walkway does not allow the collection of a sufficient number of strides to address variability which is known to be a critical factor when investigating MFC control [3,8].

Table 2
Pearson's relationship test. (Spearman for Ankle Sagittal).

		Cadence (steps/min)	Gait Speed (m/s)	Step Length (m)	MFV (m/s)	MFC (m)	Hip Coronal	Hip Sagittal	Knee Sagittal	Ankle Sagittal
Age (years)	r	−0.461**	−0.563**	−0.593**	−0.490**	−0.255**	−0.043	0.263**	−0.039	−0.242*
	p	0.000	0.000	0.000	0.000	0.008	0.660	0.006	0.690	0.012
Weight (kg)	r	−0.164	−0.178	−0.192*	−0.273**	−0.246*	0.121	0.093	0.038	−0.183
	p	0.086	0.063	0.045	0.004	0.010	0.214	0.338	0.694	0.058
Height (m)	r	0.336**	0.407**	0.353**	0.095	0.068	0.127	−0.145	0.071	0.033
	p	0.000	0.000	0.000	0.327	0.482	0.191	0.136	0.465	0.738
BMI (kg/m^2)	r	−0.355**	−0.409**	−0.402**	−0.357**	−0.297**	0.054	0.181	−0.004	−0.213*
	p	0.000	0.000	0.000	0.000	0.002	0.578	0.062	0.969	0.027
Cadence (steps/min)	r	1	0.856**	0.517**	0.485**	0.230*	0.085	−.0230*	0.064	0.138
	p		0.000	0.000	0.000	0.017	0.382	0.016	0.511	0.154
Gait Speed (m/s)	r	0.856**	1	0.772**	0.486**	0.156	0.160	−.0228*	0.011	0.130
	p	0.000		0.000	0.000	0.107	0.099	0.018	0.911	0.180
Step Length (m)	r	0.517**	0.772**	1	0.453**	0.227*	0.260**	−0.250**	0.017	0.234*
	p	0.000	0.000		0.000	0.018	0.007	0.009	0.865	0.015
MFV (m/s)	r	0.485**	0.486**	0.453**	1	0.234*	−0.011	−0.256**	0.079	0.032
	p	0.000	0.000	0.000		0.015	0.908	0.008	0.419	0.740
MFC (m)	r	0.230*	0.156	0.227*	0.234*	1	0.021	−0.167	0.291**	0.680**
	p	0.017	0.107	0.018	0.015		0.828	0.085	0.002	0.000
Hip Coronal	r	0.085	0.160	0.260**	−0.011	0.021	1	0.102	0.202*	0.075
	p	0.382	0.099	0.007	0.908	0.828		0.293	0.036	0.443
Hip Sagittal	r	−0.230*	−0.228*	−0.250**	−0.256**	−0.167	0.102	1	0.340**	−0.167
	p	0.016	0.018	0.009	0.008	0.085	0.293		0.000	0.085
Knee Sagittal	r	0.064	0.011	0.017	0.079	0.291**	0.202*	0.340**	1	0.350**
	p	0.511	0.911	0.865	0.419	0.002	0.036	0.000		0.000
Ankle Sagittal	r	0.138	0.130	0.234*	0.032	0.680**	0.075	−0.167	0.350**	1
	p	0.154	0.180	0.015	0.740	0.000	0.443	0.085	0.000	

** $p < 0.01$ (2 tails).
* $p < 0.05$ (2 tails).

Table 3
Multiple Linear Regression Analysis: Ankle and knee sagittal, age and maximum foot velocity (MFV) predicting minimum foot clearance.

MFC / Variables	R	R^2	R^2 adjusted	Standard error	p value
Ankle sagittal	0.680	0.462	0.457	0.012	< 0.001
Knee sagittal	0.291	0.084	0.076	0.016	0.002
Age (year)	0.255	0.065	0.056	0.016	0.008
MFV (m/s)	0.234	0.055	0.046	0.016	0.015

5. Conclusion

This study endorses previous literature reports indicating that elderly women walk slower and show lower minimum foot clearance than young. Our findings confirm that ankle dorsiflexion critically influences foot clearance and that gait speed may have no effect on these parameters.

Increased hip flexion in the elderly group might indicate a gait adaptation to avoid tripping.

Further investigations assessing factors like muscle strength, postural balance and proprioception with older elderly groups are needed and might yield new insights on the underlying mechanisms of swing phase motor control.

Conflict of interest statement

All authors declare that they have no conflict of interest.

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