Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls

Article *in* Gait & Posture · February 2007

Impact Factor: 2.75 · DOI: 10.1016/j.gaitpost.2006.03.008 · Source: PubMed

4 authors, including:

Rezaul Begg
Victoria University Melbourne

Lisa James
Victoria University Melbourne

Simon Taylor
Victoria University Melbourne

Available online at www.sciencedirect.com
ScienceDirect
Gait & Posture 25 (2007) 191–198
www.elsevier.com/locate/gaitpost

Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls

Rezaul Begg *, Russell Best, Lisa Dell'Oro, Simon Taylor

Biomechanics Unit, Centre for Ageing, Rehabilitation, Exercise & Sport, Victoria University, City Flinders Campus, PO Box 14428, MCMC, Melbourne, Vic. 8001, Australia

Received 30 December 2004; received in revised form 20 March 2006; accepted 20 March 2006

Abstract

This paper models minimum foot clearance (MFC) data during steady-state gait to investigate how the various descriptive statistics of the MFC distribution differ in healthy young and elderly females. A minimum of 20 min of treadmill walking was analysed for 17 young and 16 elderly females using a Peak Motus motion analysis system. The results indicated that none of the 33 participants' MFC data sets were Normally distributed. The deviation from a Normal distribution was systematic (always skewness > 0 and kurtosis > 0). Skewness and kurtosis in MFC data was highly correlated (young: $r = 0.60$, $p = 0.01$; elderly: $r = 0.95$, $p < 0.01$). MFC descriptive statistics provide useful information about basic strategies used by individuals to minimize the likelihood of tripping. Possible strategies to minimize tripping include: (a) increasing MFC height central tendency, (b) reducing MFC variability, and/or (c) increasing right skewness. A low median MFC was often associated with a low IQR or high skewness to compensate. Further research is required to establish how, or if at all, these strategies are modified in populations that are more at risk of falling.

Keywords: Gait; Minimum foot clearance; Descriptive statistics; Tripping

1. Introduction

Falls in the elderly are a major public health issue because of their associated morbidity and mortality rates, social cost and financial cost [1–3]. Most falls in older adults are reported during locomotion and tripping while walking is a commonly reported cause of falls [4,5] responsible for 53% of falls in healthy older adults [6].

Researchers have documented ageing effects on gait with the aim of identifying variables linked to falls. Some research has looked at basic gait variables such as step length, walking speed and stance/swing times [7,8] while others have looked at joint moments/powers [9] to investigate differences between young and old populations. The literature is consistent in supporting the overall slow down in walking performance in the elderly, including reduced step length and walking speed, increased single/double support time, reduced angular range of motion and less propulsive joint power. These gait adaptations are viewed as a safety strategy employed by the elderly during walking [10].

Minimum foot clearance (MFC) is a critical event in the gait cycle as the foot travels with maximum horizontal velocity around this instant [11]. MFC has been reported to be low in young adults (1.29 cm) and Winter [11] recorded a reduced mean MFC = 1.12 cm in healthy elderly. Karst et al. [12] reported a mean MFC = 1.29 cm in elderly participants. Group standard deviation (SD) in MFC has been reported as 0.62 cm for young and 0.5 cm for elderly adults by Winter [9] and 0.68 for elderly adults by Karst et al. [12]. A low mean MFC combined with MFC variability could potentially cause tripping during walking.

In the above studies [9,11,12] the low number of participant trials (5–10) and varying placement of markers may have contributed to the different results. Markers placed on the shoe cannot themselves represent the part of the shoe closest to the ground at MFC. Two- or three-dimensional

* Corresponding author. Tel.: +61 3 9919 1116; fax: +61 3 9919 1110.
E-mail address: rezaul.begg@vu.edu.au (R. Begg).

0966-6362/$ – see front matter
doi:10.1016/j.gaitpost.2006.03.008

foot/shoe modelling techniques are required to accurately represent MFC [13,14].

Mean and group SD only give a basic representation of MFC data and the literature does not report whether MFC data is Normally distributed or not. Moreover, there is neither literature on individual MFC distribution statistics during walking, nor how ageing influences distribution statistics. For a better understanding of MFC central tendency in a sample distribution and MFC variability, other descriptive statistics and longer data sets are required to explore fully the implications of MFC data and how it is controlled for each individual than the 5–10 gait cycles frequently reported [11,12].

The objectives of this research were, firstly, to study MFC variability and, secondly, to investigate ageing effects on MFC statistics and the extent to which ageing affects the risk of tripping. Only female participants were tested because they are more prone to injurious falls [15] and to eliminate gender effects.

2. Method

2.1. Participants

Seventeen young females (age 26.4 $\pm$ 4.9 years) and 16 elderly females (age 72.1 $\pm$ 4.4 years) were studied. Population demographics are presented in Table 1. Participants were free of conditions impairing normal locomotion, as determined from a self-reported health and fitness questionnaire. Participants wore their own flat, comfortable shoes suitable for walking. The study was approved by Victoria University's Human Research Ethics Committee.

2.2. Experimental set-up and procedure

Each participant's foot clearance data was collected using the Peak Motus system (Peak Technologies, USA) after at least 20 min of steady-state walking at a self-selected speed on an Austradex 683M treadmill (Austradex, Australia). Standard principles for 2D filming were followed [16]. A 50 Hz Panasonic F15 video camera (shutter speed 1/1000 s) positioned 9 m from the treadmill, perpendicular to the plane of treadmill belt motion, recorded unobstructed treadmill walking. Three spotlights were arranged behind the video camera to illuminate reflective markers. Two, 2.5 cm spherical markers were attached to the left shoe at the great toe and fifth metatarsal head (P1 and P2 in Fig. 1). Two markers were also attached to the treadmill (1.6 m apart) as a distance calibration.

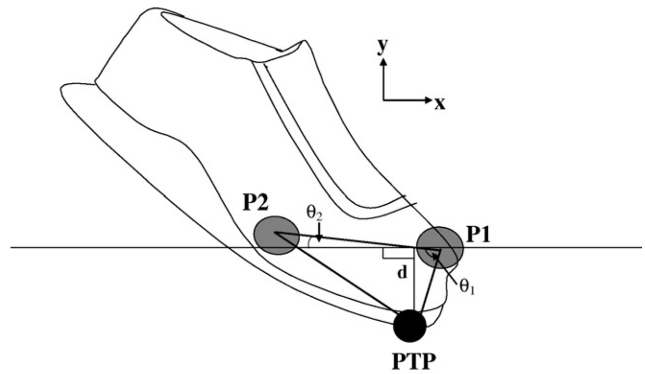

Fig. 1. Geometric model of the foot used to calculate the y coordinate of the lowest point of the shoe (PTP) from great toe (P1) and metatarsal head (P2) markers using constant triangle geometry.

Digital conversion of the location of reflective markers and calculation of 2D marker trajectories were performed using Peak Motus. Raw data was smoothed using a Butterworth filter (cut-off frequency 4–8 Hz).

2.3. Geometric model

Marker positions and shoe dimensions were used to predict the lowest point on the shoe (PTP) using a geometric model (Fig. 1; PTP is a virtual point, the most distal and inferior edge of the shoe at MFC).

The following equations demonstrate how y(PTP) was calculated from the constant geometry triangle in Fig. 1. Mean distances for d_1 (P1–P2), d_2 (P2–PTP) and d_3 (P1–PTP) were calculated for each individual before the main data analysis using Pythagoras and manually digitized

Table 1
Comparison of young and elderly participant demographics, walking speed and relative walking speed

Variables	All ($N = 33$), mean (SD)	Young ($N = 17$), mean (SD)	Elderly ($N = 16$), mean (SD)	p-Value
Age (years)	49.7 (23.0)	26.36 (4.89)	72.10 (4.42)	0.00*
Body mass (kg)	65.39 (8.59)	65.11 (9.91)	65.71 (7.12)	0.84
Stature/height (m)	1.63 (0.07)	1.66 (0.06)	1.59 (0.06)	0.00*
Walking speed (m/s)	1.01 (0.25)	1.15 (0.21)	0.88 (0.19)	0.00*
RWS (statures/s)	0.62 (0.15)	0.69 (0.14)	0.54 (0.13)	0.00*
Strides measured	1295 (581)	1480 (708)	1065 (246)	0.03*

RWS, relative walking speed.
* $p < 0.05$.

x, y coordinates of P1, P2 and PTP at MFC:

$$d_1 = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (1)$$

$$d_2 = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2} \quad (2)$$

$$d_3 = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} \quad (3)$$

The angle θ_1 is constant and calculated using the cosine rule:

$$\theta_1 = \cos^{-1}\left[\frac{d_1^2 + d_3^2 - d_2^2}{2d_1 d_3}\right] \quad (4)$$

During the main trial, the angle θ_2 varies with the motion of the foot:

$$\theta_2 = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \quad (5)$$

The vertical distance, d, also varies with the motion of the foot:

$$d = d_3 \sin(\theta_1 - \theta_2) \quad (6)$$

The vertical coordinate of PTP, y(PTP), is then given by

$$y(\mathrm{PTP}) = y(\mathrm{P1}) - d \quad (7)$$

During the swing phase of gait, the position y(PTP) reaches a minima at MFC, at about mid swing (Fig. 2):

$$\mathrm{MFC}_{(\mathrm{swing\ \ phase})} = y(\mathrm{PTP})_{\min} - y_{\mathrm{ground}} \quad (8)$$

where y_{ground} is the vertical coordinate of the ground reference.

2.4. Data analysis

MFC distribution statistics were determined, including mean, median, mode, standard deviation (SD), interquartile range (IQR), skewness (S) and kurtosis (K). $S > 0$ means skew to the right and $K > 0$ means a leptokurtic/peaked distribution. As MFC data were not Normally distributed, a non-parametric test (Mann–Whitney U-test) was used to test the effect of age on descriptive statistics. Associations between descriptive statistics were determined using Pearson's r.

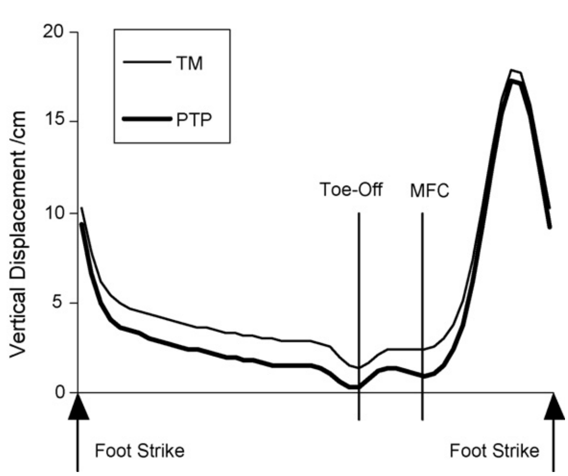

Fig. 2. Vertical displacement (y) of great toe (TM) and PTP markers for one gait cycle.

3. Results

Table 1 shows self-selected walking speed of young participants was significantly higher than the elderly ($p < 0.01$). This remained significant ($p < 0.01$) when walking speed was normalised to body height (RWS). Fig. 2 shows the vertical displacement of the great toe marker (P1) was always greater than PTP throughout the gait stride.

Fig. 3 shows MFC histograms for young and elderly populations as a whole. The histograms share some common characteristics with participants' individual histograms. For example, MFC-values close to zero were rare, and the histograms deviate from a normal distribution; i.e., more data further from the median on the right side than normal and/or more data closer to the median on the left side than normal ($S > 0$; right skewed). The group histograms also indicate that there are 2–3 sub-groups or 'styles' in each group.

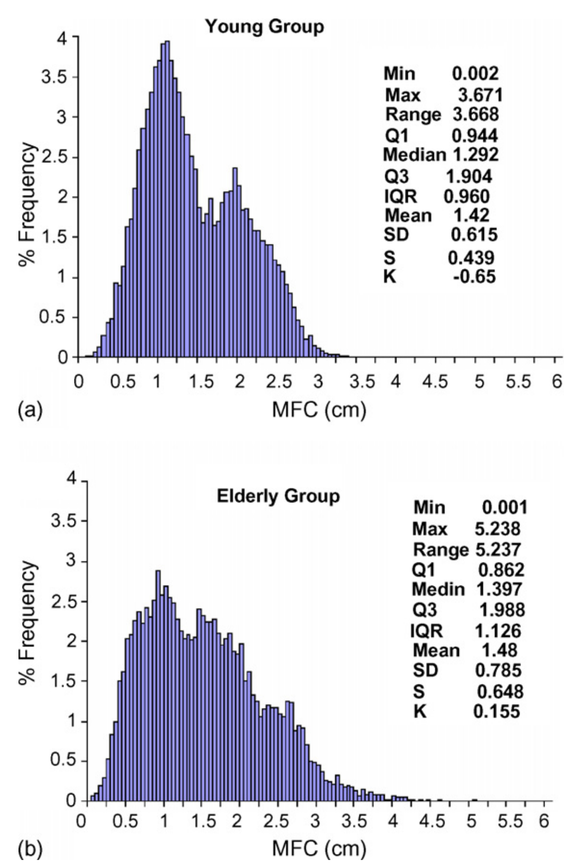

Fig. 3. MFC histogram of the (a) young group (N = 25,633), and (b) elderly group (N = 17,102).

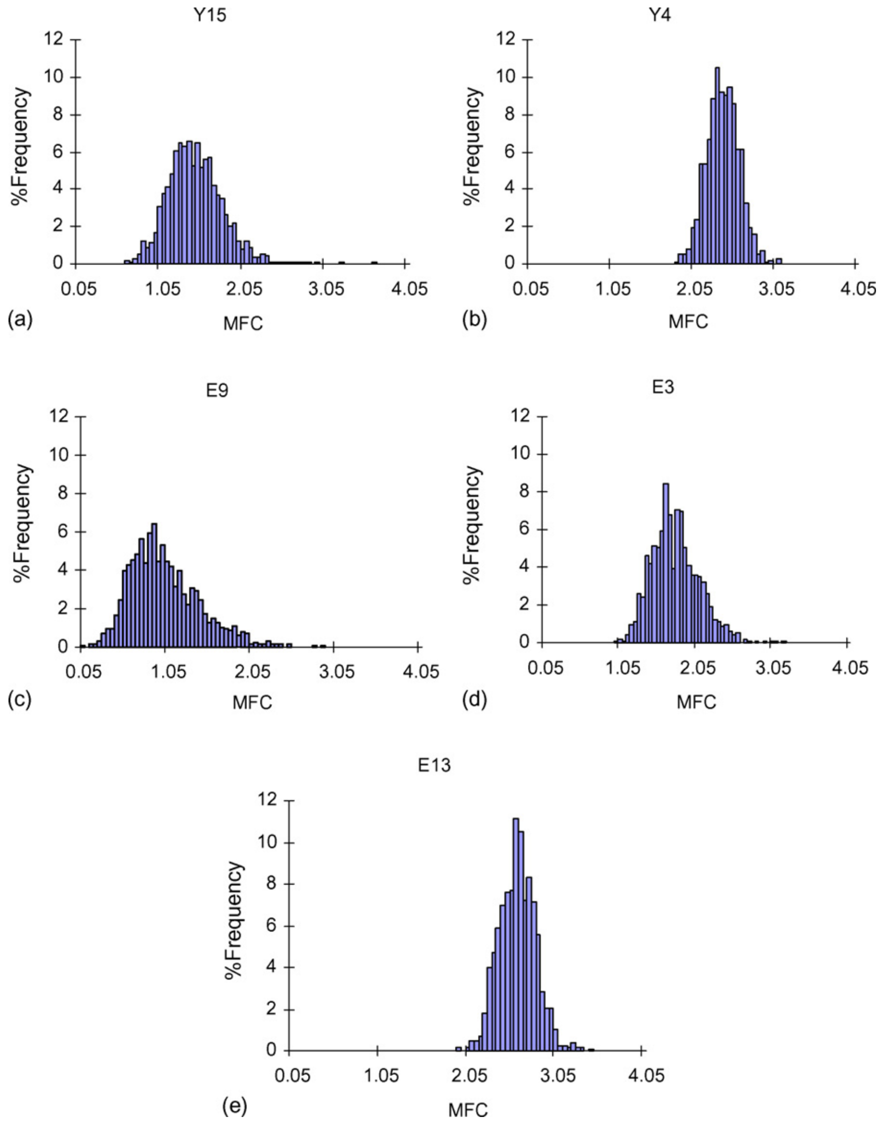

Fig. 4. Representative MFC histogram plots of: (a)–(b) young, and (c)–(e) elderly participants. Y = young; E = elderly.

Fig. 4 shows some individual MFC histograms to illustrate the considerable variation among individuals.

Table 2 presents MFC descriptive statistics for all 33 participants. Results show all but one participant had positive/right skew ($S > 0$) and all had positive/peaked/leptokurtic kurtosis ($K > 0$). One young participant recorded a minimum MFC-value less than 1.2 mm compared to five elderly. One young and one elderly participant recorded an MFC-value of 0.00 cm (the foot touching the ground) which, at >1000 strides measured per individual, corresponds to a <1 in 1000 occurrence. Table 2 shows there were considerable individual variations in walking style.

MFC descriptive statistics for young and elderly groups are presented in Table 3. Elderly mean MFC was lower but not significantly different to the young group (1.48 cm versus 1.56 cm; $p = 0.64$). No significant differences between groups were found for any central tendency measures (mean, median, mode; $p \geq 0.54$). Significantly higher MFC variance in the elderly is evident via both SD and IQR ($p = 0.04$). Analysis of the spread of individual MFC distributions shows the range of values in the fourth quartile (right) was significantly larger in the elderly group ($p = 0.05$) but the first quartile range (left) was not significantly different between groups ($p = 0.71$). Skewness indicated a trend to higher values in the elderly group ($p = 0.07$). Kurtosis was also higher for the elderly group, however, no trend was evident ($p = 0.82$); the large difference between groups was caused by participant E7's $K = 12.60$ (Table 2). Because histograms are skewed, the coefficient of variation (CV) statistic was adapted by using IQR normalised by the median (denoted as CV′). CV′ showed a trend to higher values for the elderly group ($p = 0.09$). The elderly had higher maximum MFC (MAX) and lower minimum MFC (MIN) but the differences were not statistically significant ($p \geq 0.25$).

Table 4(a) and (b) show correlations among descriptive statistics within each group. Mean, median and mode were strongly correlated ($r > 0.99$) for both groups. In the young

Table 2
Major descriptive statistics of individual participants

Participant	Min MFC (cm)	Median (cm)	IQR (cm)	*S*	*K*
Y1	1.17	2.05	0.39	0.57	1.32
Y2	1.34	1.99	0.22	0.11	0.28
Y3	1.41	2.36	0.28	0.20	1.30
Y4	1.84	2.39	0.27	0.11	0.01
Y5	1.24	2.59	0.31	−0.21	1.97
Y6	0.16	0.94	0.39	0.44	0.53
Y7	1.20	2.04	0.27	0.71	2.04
Y8	1.17	1.72	0.25	0.27	0.51
Y9	0.25	0.91	0.31	1.04	2.06
Y10	0.47	1.30	0.36	0.46	1.03
Y11	0.33	1.00	0.31	0.30	0.43
Y12	0.16	0.59	0.29	1.13	1.83
Y13	0.00	0.65	0.37	0.37	0.05
Y14	1.28	1.89	0.27	0.37	0.67
Y15	0.62	1.43	0.42	0.72	1.91
Y16	0.62	1.14	0.26	1.07	2.84
Y17	0.70	1.30	0.36	0.90	1.32
E1	1.11	1.58	0.25	0.92	2.68
E2	1.44	2.00	0.33	1.25	2.53
E3	0.95	1.72	0.41	0.62	0.78
E4	0.34	1.13	0.50	0.69	0.45
E5	0.07	0.61	0.41	0.72	0.44
E6	1.83	3.02	0.69	0.79	0.90
E7	0.12	0.56	0.33	2.81	12.60
E8	0.11	0.72	0.30	0.32	0.24
E9	0.03	0.93	0.54	0.81	0.78
E10	0.00	0.42	0.22	0.85	1.56
E11	1.05	2.09	0.43	1.07	2.84
E12	1.01	2.01	0.55	0.43	0.19
E13	1.92	2.59	0.28	0.21	0.39
E14	0.69	1.46	0.43	1.04	4.28
E15	0.25	0.93	0.30	0.48	0.87
E16	0.44	1.17	0.36	0.37	0.55

Y, young; E, elderly.

group, skewness had a significant negative correlation with median (Q2), Q1 and Q3 ($r = -0.64$, $p = 0.01$) and with MIN ($r = -0.54$, $p = 0.03$). This indicates for the young group that a low median MFC was associated with high positive skewness. For the elderly, correlations between skewness and median, Q1, Q3 and MIN were also negative but not significant ($r \leq -0.23$, $p \geq 0.39$). For the elderly, there was a trend towards a positive correlation between IQR and median ($r = 0.45$, $p = 0.08$), with low median MFC-values associated with a low IQR. This trend was not present for the young group. Within both the young and elderly groups, skewness and kurtosis was significantly correlated ($r_{young} = 0.60$, $p = 0.01$; $r_{elderly} = 0.95$, $p < 0.01$).

4. Discussion

All walking speeds were within the normal range reported by Whittle [10] but older adults walked significantly slower than their young counterparts. This finding is in agreement with other studies documenting ageing effects on walking speed [8]. A slower gait speed might be a safety mechanism adopted by the elderly.

The geometric model used in this study (Fig. 1) gives a more precise representation of the lowest point of the foot at MFC. A comparison of different methods used to calculate MFC (including the method of Startzell and Cavanagh [14]), both in terms of their objectivity and feasibility, would be an important future study.

4.1. Descriptive statistics

MFC descriptive statistics give an insight into the control process occurring at MFC. An important finding from this study is that MFC skewness and kurtosis are non-zero for all participants, and MFC skewness, with one exception, and

Table 3
Comparison of young and elderly group MFC descriptive statistics

Variables	All ($N = 33$), mean (SD)	Young (Y) ($N = 17$), mean (SD)	Elderly (E) ($N = 16$), mean (SD)	*p*-value
Mean MFC (cm)	1.52 (0.68)	1.56 (0.62)	1.48 (0.76)	0.64
Median (Q2) (cm)	1.49 (0.69)	1.55 (0.63)	1.43 (0.76)	0.54
Mode (cm)	1.46 (0.69)	1.50 (0.62)	1.41 (0.78)	0.58
SD (cm)	0.28 (0.08)	0.25 (0.05)	0.32 (0.10)	0.04*
IQR (Q3 − Q1) (cm)	0.35 (0.10)	0.31 (0.06)	0.40 (0.12)	0.04*
Skewness (*S*)	0.66 (0.52)	0.50 (0.38)	0.84 (0.60)	0.07
Kurtosis (*K*)	1.58 (2.22)	1.18 (0.83)	2.01 (3.06)	0.82
CV (%)	29.7 (15.5)	25.1 (14.0)	36.1 (17.2)	0.09
Q1 (cm)	1.33 (0.68)	1.39 (0.64)	1.26 (0.74)	0.47
Q3 (cm)	1.68 (0.70)	1.71 (0.62)	1.65 (0.79)	0.75
Upper quartile range (cm)	1.25 (0.54)	1.06 (0.38)	1.46 (0.70)	0.05*
Lower quartile range (cm)	0.56 (0.20)	0.57 (0.21)	0.55 (0.18)	0.71
Min. MFC (cm)	0.77 (0.59)	0.82 (0.55)	0.71 (0.64)	0.35
Max. MFC (cm)	2.94 (0.87)	2.77 (0.59)	3.11 (1.09)	0.25

Q1, 25th percentile; Q2, median or 50th percentile; Q3, 75th percentile; Q3 − Q1 = IQR, inter-quartile range; SD, standard deviation; CV′, modified coefficient of variation (IQR/Q2 × 100).

* $p \leq 0.05$.

Table 4
Correlations (*r*-values) for (a) young group and (b) elderly group (*p*-values in bracket)

	MIN	MAX	Q1	Median (Q2)	Q3	IQR	*S*	*K*	Lower QR
(a) Young group									
MAX	0.63 (0.01)								
Q1	0.95 (0.00)	0.76 (0.00)							
Median (Q2)	0.94 (0.00)	0.78 (0.00)	1.00 (0.00)						
Q3	0.93 (0.00)	0.80 (0.00)	1.00 (0.00)	1.00 (0.00)					
IQR	−0.49 (0.04)	0.19 (0.46)	−0.37 (0.15)	−0.33 (0.20)	−0.29 (0.27)				
S	−0.54 (0.03)	−0.33 (0.20)	−0.64 (0.01)	−0.64 (0.01)	−0.64 (0.01)	0.16 (0.54)			
K	−0.14 (0.60)	0.28 (0.28)	−0.04 (0.89)	−0.04 (0.87)	−0.04 (0.88)	0.03 (0.92)	0.60 (0.01)		
Lower QR	−0.55 (0.02)	0.24 (0.36)	−0.45 (0.07)	−0.42 (0.09)	−0.39 (0.12)	0.76 (0.00)	0.54 (0.03)	0.49 (0.05)	
Upper QR	0.29 (0.26)	0.68 (0.00)	0.57 (0.02)	0.59 (0.01)	0.60 (0.01)	0.17 (0.51)	−0.54 (0.03)	0.24 (0.35)	0.06 (0.83)
(b) Elderly group									
MAX	0.67 (0.00)								
Q1	0.98 (0.00)	0.73 (0.00)							
Median (Q2)	0.96 (0.00)	0.75 (0.00)	1.00 (0.00)						
Q3	0.94 (0.00)	0.77 (0.00)	1.00 (0.00)	1.00 (0.00)					
IQR	0.23 (0.39)	0.58 (0.02)	0.39 (0.13)	0.45 (0.08)	0.52 (0.04)				
S	−0.17 (0.52)	0.35 (0.19)	−0.23 (0.39)	−0.23 (0.39)	−0.22 (0.41)	−0.07 (0.79)			
K	−0.16 (0.56)	0.35 (0.19)	−0.23 (0.40)	−0.23 (0.38)	−0.24 (0.37)	−0.19 (0.48)	0.95 (0.00)		
Lower QR	−0.02 (0.95)	0.69 (0.00)	0.02 (0.96)	0.03 (0.90)	0.06 (0.82)	0.31 (0.24)	0.80 (0.00)	0.81 (0.00)	
Upper QR	0.42 (0.11)	0.58 (0.02)	0.61 (0.01)	0.64 (0.01)	0.69 (0.00)	0.79 (0.00)	−0.32 (0.23)	−0.35 (0.18)	0.12 (0.65)

Abbreviations represent: MIN, minimum MFC; MAX, maximum MFC; Q1, 25th percentile; Q2, median or 50th percentile; Q3, 75th percentile; IQR, interquartile range; *S*, skewness; *K*, kurtosis; lower QR, lower quartile range = range of MFC-values from MIN to Q1; upper QR, upper quartile range = range of MFC-values from Q3 to MAX.

kurtosis were always positive. This means MFC data was not Normally distributed and there was a systematic deviation from the Normal distribution. This then questions the appropriateness of the descriptive statistics commonly used in the literature to describe central tendency and variance in MFC data, namely mean and SD.

4.1.1. Measures of central tendency (intention of the locomotor system)

Since MFC histograms are not Normally distributed, mean MFC may not be the best statistical descriptor of central tendency and, more importantly, the mean may not represent the intention of the locomotor system. Mode, median and mean occurred in ascending order (Table 3) with the histograms being sufficiently skewed to produce significantly higher mean values compared to median and mode in both age groups ($p < 0.05$). Median was also significantly higher than the mode in the young group ($p = 0.02$). All three measures were, however, highly correlated ($r > 0.99, p < 0.01$) and the maximum within-group difference between the three measures was functionally small (<1 mm).

Mean is the most commonly used central tendency measure. Its advantage, and disadvantage, is that all data are used in its calculation. The mode and median are better descriptors of central tendency in skewed distributions where a constraint affects one end of the distribution. In this case, the ground constraint affects the locomotor system's intention in performing MFC.

Mode represents the most frequently occurring, or most often achieved, MFC height and is theoretically the best central tendency measure for this study's, non-Normal, unimodal distributions. However, mode is not a robust measure and its value can vary considerably depending on *N* and the bin size used in its calculation. From a statistical perspective, mode should only be used when a rough estimate of central tendency is required, or if the robustness of the measure is demonstrated.

The median (50th percentile or Q2) could also be argued as the intention of the locomotor system because it represents 50% of MFC-values above and 50% below this point. The median, like the mode, is not affected by the magnitude of outliers. When data is skewed and when mode is not robust enough, median is often used as the best estimate of central tendency. This is partly because the median is closer to the mode than the mean in a skewed, unimodal distribution. We conclude, for MFC data, that the mode best represented the intention of the locomotor system but, since the mode is not sufficiently robust, median is the most appropriate central tendency measure.

4.1.2. Measures of MFC variance

The group variance (the SD of the group mean in brackets in the first row of Table 3) is frequently presented in the literature and the individual's variance (the mean of the individuals' SD in the fourth row of Table 3) has not been presented previously.

The systematically positive-skewed individual MFC histograms and the use of median as a measure of the individual's MFC central tendency means IQR is arguably a better estimate of the MFC variance about an individual's planned MFC height, rather than the SD which is affected by extreme/outlier values (i.e., IQR is a better variance measure than SD for systematically skewed distributions). As with the central tendency measures, IQR and SD were highly correlated ($r > 0.9$; $p < 0.01$) but SD gives an overestimate of the variance on the left side and/or an underestimate of the variance on the right side of positively skewed MFC distributions.

4.1.3. Ageing effects

The elderly had lower median MFC-values compared to young adults (elderly, 1.43 cm; young, 1.55 cm; difference = 0.12 cm) but this difference was not significant ($p = 0.54$). Previous studies report group means and group SD only. Winter [9] reported lower mean MFC-values in the elderly (E, 1.12 cm; Y, 1.29 cm; difference = 0.17 cm) and also found no significant difference between the groups. Although the group SD values were similar between this and previous studies [9,12] and the difference between young and elderly mean MFC-values were similar in this, and Winter's study [9]. The mean MFC-values in the present study were generally higher than those reported by Karst et al. [12] and Winter [9]. This could be due to differences in methods between studies, overground versus treadmill.

An important finding from this study is the significantly higher MFC variance in the elderly group ($p = 0.04$). An increase in variance in the locomotor system due to ageing has also been found for temporal parameters of the gait cycle and has been recognized as a predictor of falls in elderly populations [15,17].

The spread of MFC-values within the lower quartile range (lower QR; Q1—MIN) was not significantly different between the young and elderly groups ($p = 0.71$). This suggests that the elderly were able to display a similar degree of control in the critical lower quartile of the MFC distribution. Furthermore, upper quartile range (upper QR; MAX—Q3) was significantly higher in the elderly group ($p = 0.05$) suggesting that the significant difference in IQR between groups was a result of upper QR differences.

4.2. Strategies for minimizing tripping risks

Possible strategies to minimize tripping risk include:

(i) *Increasing median MFC height*. This, by itself, should result in a higher energy cost of gait. The results suggest that the elderly did not use this strategy since the median MFC was less for the elderly group compared to the young group. The lower median (and lower Q1 and MIN) in the elderly group would suggest an increased likelihood of tripping.

(ii) *Reducing MFC variability*. This strategy effectively exerts greater 'control' on MFC by reducing variability. This strategy would seem inefficient since it would exert unnecessarily excessive 'control' on the relatively unimportant right side of the distribution. The group data suggest that the elderly do not use this strategy to minimize the likelihood of tripping as the elderly group had a significantly higher IQR ($p = 0.04$). This suggests that they exerted less control on MFC than the young group. The significantly higher IQR in the elderly group suggests an increased likelihood of tripping.

(iii) *Increasing skewness and kurtosis*. This is perhaps the most logical since it does not necessarily exert 'control' on the relatively unimportant right side of the distribution. There was a high correlation between skewness and kurtosis values both in the young ($r = 0.60$, $p = 0.01$) and elderly ($r = 0.95$, $p < 0.01$), suggesting they may relate to the same strategy. The locomotor system errs on the side of safety by reducing the spread of values in the lower quartile range (lower QR is significantly less than upper QR for both groups; $p < 0.01$) to reduce the risk of ground contact at MFC. Skewness in the elderly was higher ($p = 0.07$) which would, by itself, suggest a reduced likelihood of tripping compared to young adults.

(iv) *Combined strategies*. This involves individual-specific interactions between the former three strategies to reduce the likelihood of tripping. For example, for the young group, skewness had a significant negative correlation with Q2 (and MIN and Q1), which demonstrates a combined strategy (low median compensated by a high skewness; *S*/median strategy). There was no significant correlation between skewness and median for the elderly group but, alternatively, there was a positive trend between median and IQR ($p = 0.08$), which demonstrates a different strategy in the elderly group (low median compensated by a low IQR; IQR/median strategy).

(v) *Other strategies*. There are many other strategies that can be used to avoid the possibility of a trip and consequent fall, e.g., careful foot placement before/after obstacles [18], obstacle avoidance strategies [19] or walking more slowly.

4.3. Gait is a constrained optimisation problem

Gait can be described as an optimisation problem with the overall goal of reaching a destination with minimum energy cost [20,21]. Gait is actually a constrained optimisation problem with penalties associated with violating the constraint. One constraint is the ground (MFC = 0 cm), and the penalty for violating the ground constraint is tripping and, potentially, falling. The systematic positive skewness and significantly smaller lower QR compared to upper QR in the MFC distribution indicates that the trip constraint is operational at MFC for the swinging foot, i.e., the ground was actively being avoided.

5. Conclusions

An individual's MFC data is not Normally distributed. The deviations from a Normal distribution are systematic (almost always skewness > 0 and always kurtosis > 0) and describe a real strategy to minimise the likelihood of the foot hitting the ground. Median MFC is a better indicator of the 'intention of the locomotor system' than the mean, whereas IQR is better than SD as a variability measure for the systematically non-Normal MFC distributions. Based on MFC data alone, there are three possible strategies for avoiding tripping: (a) increase median MFC; (b) reduce MFC variability; (c) increase skewness. Individuals with a low median MFC appear to compensate by having either a low IQR or a high positive skewness. Furthermore, a median/*S* strategy was dominant in the young group whereas a median/IQR strategy was dominant in the elderly group. The elderly seemed to be more prone to tripping with, for example, lower median MFC-values (not significantly lower) and significantly higher MFC variability. The results show that important information is lost in group-based analysis and only an individual-based approach will show which individuals are at risk of tripping. Future research could focus on MFC strategies used to minimise the likelihood of tripping while walking. Group histograms suggest there may be two or three sub-groups or 'walking styles' within each group and cluster analysis on a larger sample size may yield further information.

References

[1] Fildes B. Injuries among older people: falls at home and pedestrian accidents. Melbourne: Dove Publications; 1994.
[2] NIPAC. Directions in injury prevention. Report 1: research needs. A report from the National Injury Prevention Advisory Council. In: Elkington J, editor. Commonwealth of Australia. Canberra: Commonwealth Department of Health and Aged Care; 1999.
[3] NIPAC. Directions in injury prevention. Report 2: injury prevention interventions – good buys for the next decade. A report of the National Injury Prevention Advisory Council. In: Elkington J, editor. Commonwealth of Australia. Canberra: Commonwealth Department of Health and Aged Care; 1999.
[4] Hill K, Schwarz J, Flicker L, Carroll S. Falls among healthy, community-dwelling older women: a prospective study of frequency, circumstances, consequences and prediction accuracy. Aust New Zealand J Pub Health 1999;23:41–8.
[5] Overstall PW, Exton-Smith AN, Imms PJ, Johnson AL. Falls in the elderly related to postural imbalance. BMJ 1977;1:261–4.
[6] Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SBJ, Arie THD, et al. Falls by elderly people at home: prevalence and associated factors. Age Ageing 1988;17:365–72.
[7] Judge JO, Õunpuu S, Davis RB. The effects of age on the biomechanics and physiology of gait. Clin Ger Med 1996;12:659–78.
[8] Ostrosky KM, VanSwearingen JM, Burdett RG, Gee Z. A comparison of gait characteristics in young and old subjects. Phys Ther 1994; 74:637–46.
[9] Winter DA. The biomechanics and motor control of human gait Waterloo. Canada: University of Waterloo Press; 1991.
[10] Whittle MW. Gait analysis: an introduction. Oxford: Butterworth-Heinemann; 1991.
[11] Winter DA. Foot trajectory in human gait: a precise and multifactorial motor control task. Phys Ther 1992;72:45–56.
[12] Karst GM, Hageman PA, Jones TF, Bunner SH. Reliability of foot trajectory measures within and between testing sessions. J Gerontol 1999;54:343–7.
[13] Best RJ, Begg RK, James L. The probability of hitting an unseen obstacle while walking. In: Proceedings of the international society of biomechanics XVII congress; 1999. p. 234.
[14] Startzell JK, Cavanagh PR. A three dimensional approach to the calculation of foot clearance during locomotion. Hum Move Sci 1999;18:603–11.
[15] Hausdorff JM, Edelberg HK, Mitchell SL, Goldberger AL. Increased gait unsteadiness in community-dwelling elderly fallers. Arch Phys Med Rehab 1997;78:278–83.
[16] Bartlett RM. Biomechanical analysis of performance in sport. Leeds: British Association of Sport and Exercise Sciences; 1992.
[17] Maki B. Gait changes in older adults: predictors of falls or indicators of fear? J Am Ger Soc 1997;45:313–20.
[18] Begg RK, Sparrow WA. Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls. J Gerontol 2000;A55:147–54.
[19] Patla AE, Prentice SD, Robinson C, Newfold J. Visual control of locomotion: strategies for changing direction and for going over obstacles. J Exp Psychol 1991;17:603–34.
[20] Pandy MG, Anderson FC. Three-dimensional computer simulation of jumping and walking using the same model. In: Proceedings of the VII international symposium on computer simulation in biomechanics; 1999. p. 92–5.
[21] Anderson FC, Pandy MG. Dynamic optimisation of human walking. J Biomech Eng 2001;123:381–90.