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GAIT SPEED AND DYNAMIC STABILITY DECLINE ACCELERATES ONLY IN LATE LIFE: A CROSS-SECTIONAL STUDY IN COMMUNITY-DWELLING OLDER ADULTS

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Abstract

Background and Purpose: Incidence of falls increases with age while gait speed declines. The purposes of this study were to examine 1) whether gait speed and center of mass (COM) velocity declined steadily across ages in a linear fashion among community-dwelling older adults, and 2) whether such decline corresponded to the similar decline in dynamic stability, which is governed by the control of their COM position and COM velocity relative to base of support (BOS).

Methods: 184 community-dwelling older adults (≥ 65 yr) participated in the cross-sectional study. The participants were categorized into 5 age groups: 65–69 years, 70–74 years, 75–79 years, 80–84 years, and 85+ years and were asked to walk on the 7-m walkway at their preferred walking speed. Their speed, gait pattern, the relative COM position, and the relative COM velocity were measured.

Results: Very close relationship was confirmed between a clinical gait speed measurement and the COM velocity ($R^2 = 0.875$, $p < 0.05$), which enabled us to use the 2 terms interchangeably. Gait speed decline was not noticeable from 65 to 84 years old ($p > 0.05$), but it accelerated after age 85. This decline was most likely influenced by a reduction in both step length ($p < 0.05$) and cadence ($p < 0.05$). Similarly, dynamic stability against backward loss of balance changed little between 65 and 84 years old ($p > 0.05$). Yet, it declined significantly after 85 years old ($p < 0.05$), primarily affected by the reduction in the COM velocity relative to the BOS, whereby the COM position relative to the BOS remained constant during their walking.

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Conflict of Interest Statement

None declared

Conclusion: Expected steady decline in gait speed and in the control of gait stability cannot be confirmed. Rather, we found that both declined precipitously only after age 85, when the risk of falls is likely to increase correspondingly.

Keywords

Aging; Gait speed; Dynamic stability

INTRODUCTION

Approximately one-third of adults older than age 65 and half of the adults older than age 80 fall annually and half of these falls occur while walking.^{1–3} Falls are a leading cause of serious injury and accidental death in older adults.^{1,4,5} Fall-related injuries can cause devastating outcomes such as hip fracture and traumatic head injury requiring hospitalization and an extended stay in a long-term care facility.^{6,7} Previous research reported that incidence of falls increases with age at the same time as gait speed declines.^{8,9} Statistically, the risk of falls would increase by 7% corresponding to a 0.1 m/s decline in gait speed.⁴ Gait speed decline to below 0.7 m/s corresponds to an increase of the risk by 1.5 fold.⁴

Age and gait speed are negatively correlated with each other in community-dwelling older adults (i.e., in men, $r = -0.35$ and women, $r = -0.42$) from 65 years old to 84 years old; corresponding gait speed range is from 1.5 m/s to 1.0 m/s, respectively.¹⁰ The decline in gait speed with age is reflected differently in different health care settings such as nursing home and hospital.¹¹ Mean gait speed varies from 0.74 m/s in outpatient setting to 0.53 m/s in inpatient setting and to around 0.47 m/s in nursing homes.¹¹ Further, age was thought to be linearly associated with both static and dynamic balance control in older women over 60 years old.⁸ This correlation was $r = 0.31$ in static balance, which was measured by postural sway velocity during quiet standing, and $r = -0.46$ in dynamic balance, which was characterized by limits of stability associated with the maximum excursion of center of pressure while standing.⁸ The inflection point of gait speed decline in older adults who have mild cognitive impairment was at around 83.5 years old.¹²

The control of dynamic stability during walking relies on the control of one's center of mass (COM) position and the COM velocity with respect to this person's base of support (BOS), which is dictated by the foot placement and alterations of the foot placement during volitional movement or protective stepping once balance is disturbed. Dynamic stability can be measured as the shortest distance between the instantaneous COM motion state (which is determined by 2 variables, the COM position and COM velocity relative to base of support) and the dynamic stability limits that simultaneously take into account the changes in both of these 2 variables.¹³ A more anterior COM position and a faster COM velocity enhance dynamic stability.¹³ Dynamic stability is highly correlated to gait speed.¹⁴ While slower gait speed predisposes a person to high risk of backward balance loss, a shorter step length that is often associated with slow gait speed would actually shift the COM closer to the BOS at the toe off (i.e., liftoff), and hence mitigate the risk of falling backward.¹⁵ Indeed, both gait speed and step length are important factors to affect dynamic stability.¹⁴ Overall, whether the effect of age on the decline of gait speed and dynamic stability is progressive and

proportional to advancing age, or whether such declines accelerate at some stage of life is still unclear.

The purposes of this study were, therefore; to examine 1) whether gait speed and COM velocity declined linearly across ages among community-dwelling older adults, and 2) whether the decline in COM velocity corresponded to the similar change in dynamic stability, which is governed by both COM velocity and COM position relative to BOS. Therefore, we hypothesized (Figure 1) that older adults' gait speed would decline slowly and proportionally (Hypothesis 1). We also expected that a similar trend in dynamic stability among older adults would be influenced mostly by their COM position relative to BOS, whereby the COM position relative to BOS remains mostly constant throughout the years (Hypothesis 2).

METHODS

Participants

This study is a sub-study of a large series of studies focusing on slip perturbation training among older adults.^{16–18} Though all participants in the large study later received a slip or repeated slips during their overground walking, this study focused on their regular walking trial prior to their experience of any slip to ensure that perturbation has not directly altered their regular walking pattern.¹⁷ 184 healthy community older adults aged 65 and over (age = 74.1 ± 6.2 , female = 127) participated in the present study. Participants were categorized into 5 age groups: 65–69 years (N = 53), 70–74 years (N = 53), 75–79 years (N = 38), 80–84 years (N = 31), and 85+ years (N = 9). Subjects were recruited from different senior and community-based exercise centers (e.g., YMCAs), independent senior living facilities, the Aging at Northwestern University, or from affiliates of the Department on Aging, City of Chicago. The recruitment and data collection were conducted from March 2009 to July 2015. This study was conducted in the Clinical Gait and Movement Analysis Laboratory in the Department of Physical Therapy of the University of Illinois at Chicago. The participants who are able to walk independently without assistant device such as cane and walker were included in this study. They completed a questionnaire for information on any neurological, musculoskeletal, and cardiopulmonary conditions. These people who are using selected drugs (e.g., tranquilizers), and having the neurological, cardiopulmonary, and other systemic disorders that may alter their control of dynamic stability were excluded. As a safety precaution, older adults who had low bone mineral density score (i.e., T score < -1.5), impaired cognition (i.e., Folstein Mini-Mental Status Exam [MMSE] score < 25), and low functional mobility (i.e., Timed-Up-and-Go test > 12.5 s) were excluded from the study.^{19–21} All participants provided written informed consent. This study was approved by the institutional review board at the University of Illinois at Chicago.

Experimental setup and data collection

All participants walked at their preferred speed across the 7-m walkways, which were surrounded by an 8-camera motion-capture system (Motion Analysis Corporation, Santa Rosa, CA). Each person walked 5 to 7 times to become familiar with the walkway before the trial that was later included in the analysis of the present study. Thirty reflective markers

were placed on the subjects' body bony landmarks and the platforms, and joint kinematics were recorded at 120 Hz capturing each person's walking path. Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters.²² 3-dimensional locations of joint centers, heels, and toes were measured. A 13-segment rigid body model with gender-dependent segmental inertial parameters was used to compute the COM position from the filtered marker positions.²³ A standard numerical method was used to compute the first derivative of the COM position, that is, the COM velocity. Force plates embedded beneath the walkways were used to determine the event time for heel strike and liftoff (i.e., toe off), which was used to compute the step length and cadence.

Outcome measure

The gait speed was obtained with the simple formula of distance/time. Also, the COM velocity was obtained via differentiation of the COM position. The 2 measures were computed over the middle 5-meter distance of the 7-meter walkway using a digital stopwatch and used to demonstrate reliability of the gait speed obtained clinically with that obtained computationally. The *step length* was calculated as the distance of heel to heel markers, normalized by body height. The average length of 2 steps (from the first left foot to the second right foot and the second right foot to the third left foot) was used for the step length. The *cadence* (number of steps in a minute) was obtained from the division of the gait speed by the step length.

The *dynamic stability* was determined collectively by 2 factors, the *COM position relative to BOS* and the *COM velocity relative to BOS*, which were also each quantified to examine the contribution of different factors to any changes in dynamic stability (Figure 2). When computing the dynamic stability, the relative COM position was normalized by full base of support (i.e., $X_{\text{COM/BOS}} / \text{BOS}^{-1}$), and the relative COM velocity was normalized by the square root of the acceleration due to gravity that was multiplied by body height (i.e., $V_{\text{COM/BOS}} (g \times bh)^{-1/2}$).^{13,24} The dynamic stability thus was a dimensionless measurement, and was calculated by the shortest distance from the COM motion state (that is, instantaneous position and velocity of the COM) to the stability limits.²⁴ Higher dynamic stability values indicate greater stability against backward balance loss.^{13,24}

Statistical Analysis

Pearson's correlation analysis was performed to assess the degree of association between the gait speed and COM velocity and between relative COM velocity and COM velocity. In order to examine the gender difference in gait speed and dynamic stability, independent t-tests were used. Intraclass correlation (ICC) model was used to evaluate the test-retest reliability of 2 trials of COM velocity and dynamic stability and coefficient of variation (CV) was calculated as follows: $\text{CV \%} = 100 (\text{SD/mean})$ of COM velocity and dynamic stability of the 2 trials.²⁵ We have tested across different models to find out the best-fit model. First, curvilinear regression was conducted to appreciate the overall trend of the gait speed and dynamic stability. Second, linear regression using 5 age categorical variables was used to examine the changing point of the COM velocity (or gait speed) and dynamic stability based on the age. The primary dependent variables included COM velocity (or gait speed) and

dynamic stability. The 4 age groups, 70–74 years, 75–79 years, 80–84 years, and 85+ years, were compared to the first age group, 65–69 years (reference), in the regression model based on the age group order. In order to explore the mechanism of the age effect on COM velocity (or gait speed) and dynamic stability, we also applied the second regression analysis on secondary dependent variables, step length and cadence, and COM velocity relative to BOS and COM position relative to BOS. Cohen's *d* effect sizes were calculated to determine the strength of the association between the age groups. All analyses were conducted using SAS 9.4 (SAS Inc., Cary, NC), and a *p*-value below 0.05 was considered statistically significant.

RESULTS

Participants' demographic information is shown in Table 1. The gait speed related closely with the COM velocity derived by motion-capture system ($R^2 = 0.875$, $p < 0.05$, Figure 3a). These results enable us to use these 2 terms interchangeably. Also, COM velocity related closely with the relative COM velocity ($R^2 = 0.879$, $p < 0.05$, Figure 3b). Gait speed was significantly different between male and female ($p < 0.05$); however, normalized gait speed (i.e., gait speed was divided by body height) was not significantly different (Figure 4a, $p > 0.05$). In addition, dynamic stability was not significantly different between gender ($p > 0.05$).

There were curvilinear relationships between age and gait speed, and between age and dynamic stability ($p < 0.05$, both, Figure 4b and 4c, respectively). Categorical linear regression model showed that there were no significant differences in gait speed (COM velocity) of 3 age groups, 70–74 years, 75–79 years, 80–84 years, compared to that of the first age group, 65–69 (reference, $p > 0.05$, Figure 5a). The decline, however, was significant after age 85 ($B = -0.133$, $p < 0.05$, $d = 0.58$, Table 2). The gait speed for adults after age 85 was about 0.13 m/s slower than those aged 65–69 and became 0.76 m/s. The decline in gait speed in this age group (85+) was affected by a reduction in the step length ($p < 0.05$, Figure 5b, Table 3) and cadence ($p < 0.05$, Figure 5c, Table 4). On average, step length for adults aged 85 or over was about 0.08 m (or 0.04 body height) shorter ($p < 0.05$) and cadence was about 8 steps/min slower ($p < 0.05$) than those aged 65–69.

Categorical linear regression model showed that there were no significant differences in dynamic stability of 3 age groups, 70–74 years, 75–79 years, 80–84 years, compared to that of the first age group, 65–69 (reference, $p > 0.05$, Figure 5d). Yet, it declined significantly after 85 years old ($B = -0.268$, $p < 0.05$, $d = 0.73$, Table 5). The changes in the dynamic stability were attributable to the decline in the COM velocity relative to BOS ($p < 0.05$, Figure 5e, Table 6). In contrast, there were no significant changes in COM position relative to BOS during walking at all ages from 65 years to 85+ ($p > 0.05$, Figure 4f). Intraclass correlation coefficient for inter-trial reliability was 0.724 in gait speed and 0.700 in dynamic stability measurements with coefficient of variation 0.089 in gait speed and 0.084 in dynamic stability indicating good reliability and low-variance.

DISCUSSION

We found that gait speed had little change between ages 65 and 84, but declined significantly at age 85+, which did not support the hypothesis that gait speed would proportionately decline across age groups. Further, this decline in speed was mostly affected by both step length and cadence reduction. In addition, we found a similar trend in the decline of the dynamic stability that was affected primarily by the COM velocity relative to the BOS, whereby the COM position relative to the BOS during walking remained mostly unchanged across age groups. Again to our surprise, dynamic stability against backward balance loss had little change between ages 65 and 84, but the steeper decline occurred after age 85.

Gait speed is an important indicator of mobility in older adults living in long term care,²⁶ and age-related decline in gait speed is associated with morbidity, mortality, and risk of falls.²⁷ Our findings were similar to those of Buracchio et al., who found a pronounced decline in gait speed at 83.5 years old in 204 healthy older adults.¹² Most often in everyday living, the regulation of the step length and cadence is controlled subconsciously; hence such alteration in gait pattern is most unlikely reflecting conscious choice by the older adults. The rationale for such late-age gait pattern alteration is an interesting topic, yet it is also beyond the scope of the present study.

The dynamic stability is determined by both COM velocity and COM position relative to BOS during walking. A higher walking velocity gives a person a higher momentum to carry the person forward against backward balance loss.²⁸ Thus, everything else being equal, a higher COM velocity provides greater resilience against a perturbation-induced backward balance loss such as what happens following a slip, because higher COM velocity makes the COM easier to catch up with the forward traveling BOS.¹³ While slips are especially dangerous often leading to hip fracture or traumatic head injury, trip is another common cause of forward falls. In that case, a slower walking speed would provide a better alternative against the ensuing forward loss of balance.²⁹ Weighing these 2 risks (forward fall versus backward fall), human anatomical structures inherently favor forward mobility and forward protective stepping, hence the slower walking speed could reduce the likelihood of forward balance loss induced forward falls than the backward fall.³⁰

According to Alcock et al., a decrease in plantar flexor moments which is associated with advanced age may impair propulsive impulse of the leg during walking forward in older women.³¹ Along with the decreased propulsive impulse, reduced hip extension, increased anterior pelvic tilt, and reduced swing phase cause reduced step length which affects decrease in gait speed.³¹ On the other hand, a more forwardly COM position with respect to the BOS also gives a person better reserve against backward balance loss.³² The present study showed dynamic stability change by age is mainly due to the decline in the COM velocity rather than the COM position relative to the BOS during walking, which can be strongly influenced by trunk posture. Therefore, age-related decline in gait speed will likely predispose older adults to a greater risk of backward balance loss. These findings have clinical implications, which suggest future intervention may focus on teaching older adults

how to properly shift their COM position in order to compensate for or offset the natural decline in their gait speed and the associated stability against backward loss of balance.

The present study has limitations. Because this is a subset of a large study in which perturbation training was applied, we recruited community-dwelling older adults who had no acute symptoms of neurological, cardiopulmonary, or other systemic disorders that may affect their ability to tolerate with subsequent perturbation training, and did not use selected drugs (e.g., tranquilizers) that may alter their control of stability.¹⁸ Such criteria will inevitably introduce its own sampling bias. Also, the sample size of the age group over 85 years old is relatively low (N = 9, Female = 5) compared to the total sample size (N = 184) for the whole study. To assess its potential impact, we performed a second analysis by dividing the total sample into 3 age groups (65–69 years [N = 53], 70–79 [N = 91], and 80+ [N = 40]). All results showed the same trend, with the only exception that the accelerated decline now began at age 80. Based on the Cohen's d effect sizes that were higher in 5 age groups than in 3 age groups, the results derived from 5 age groups may in fact provide a finer temporal resolution on the onset of the rapid decline in gait speed and gait pattern. Still, a bigger sample size is certainly necessary to provide conclusions with greater representation or greater certainty.

CONCLUSIONS

In conclusion, the present study found that gait speed in adults age 85 and over decreased precipitously, and dynamic stability exhibited a similar trend which was due to the decline in the COM velocity rather than any change in the COM position relative to the BOS during walking. Gait speed, easily obtainable in the geriatric clinic setting, may be routinely collected along with blood pressure or weight and height measurements for long-term monitoring to detect a rapid decline in physical function leading to increased risk of falls.

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Figure 1.

Conceptual model illustrating age-related declines in gait speed and dynamic stability. Interactions between age and gait speed (Hypothesis 1), and between dynamic stability, COM velocity relative to base of support (BOS), and COM position relative to BOS (Hypothesis 2).

Figure 2.

Schematic illustration of the feasible stability region (FSR) involving 2 boundaries: the limits of stability (LOS) against backward balance loss and LOS against forward balance loss. The dynamic stability indicates the magnitude of the instantaneous stability of the center of mass (COM) against backward balance loss, and is defined as the shortest distance from the instantaneous COM motion state to the corresponding LOS. The x-coordinates represent the COM anteroposterior position and y-coordinates represent the COM velocity. The COM position and the COM velocity relative to base of support (BOS) are dimensionless as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents for full base of support during double stance, g represents the gravitational acceleration, and bh represents the body height.

Figure 3.

The correlative relationships between COM velocity and gait speed a), and COM velocity and relative COM velocity, i.e., the COM velocity relative to the base of support (BOS) normalized by full base of support (l_{BOS}) and $\sqrt{g \times bh}$ [i.e., the g represents the gravitational acceleration and the bh represents the body height], b) measured by motion-capture system.

Figure 4.

Gait speed and normalized gait speed (i.e., gait speed divided by body height) between male and female [*bh* represents the body height] a), scatter plot exemplifying curvilinear relationship between age and gait speed b), and age and dynamic stability c). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 5.

Gait speed [and COM velocity] a), step length b), and cadence c), dynamic stability d), COM velocity relative to BOS e), and COM position relative to BOS f) by age groups (Age 65–69, Age 70–74, Age 75–79, Age 80–84, Age +85). Both the COM position and the COM velocity were relative to the base of support (BOS) and respectively normalized by full base of support (I_{BOS}) and $\sqrt{g \times bh}$ (i.e., the g represents the gravitational acceleration and the bh represents the body height). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 1.

Demographic information

Age group	65–69		70–74		75–79		80–84		85+	
	F	M	F	M	F	M	F	M	F	M
Sample Size (N)	36	17	40	13	27	11	19	12	5	4
Height (m)	1.64 (0.06)	1.73 (0.08)	1.64 (0.06)	1.69 (0.11)	1.61 (0.06)	1.75 (0.06)	1.62 (0.08)	1.74 (0.07)	1.55 (0.08)	1.68 (0.06)
Weight (kg)	73.5 (14.2)	85.8 (12.1)	71.4 (13.9)	79.5 (11.1)	65.1 (10.8)	76.0 (9.9)	64.8 (11.4)	78.6 (14.2)	62.5 (9.8)	65.6 (8.5)
Normalized Gait Speed (Gait Speed/bh)	0.53 (0.08)	0.54 (0.12)	0.52 (0.06)	0.55 (0.07)	0.51 (0.07)	0.57 (0.08)	0.50 (0.10)	0.51 (0.12)	0.39 (0.08)	0.56 (0.10)

Note. F = female, M = male, bh = body height.

Table 2.

Linear Regression Analysis of Gait Speed by Age (as categorical variable).

Gait Speed (m/s)	Age 65–74		
	B	SE	p
Intercept	0.865	0.014	<.0001
Age 65–69 (reference)			
Age 70–74	0.009	0.026	0.721
Age 65–84			
Intercept	0.873	0.021	<.0001
Age 65–69 (reference)			
Age 70–74	0.001	0.030	0.970
Age 75–79	–0.002	0.033	0.961
Age 80–84	–0.033	0.035	0.356
Age 65–94			
Intercept	0.893	0.022	<.0001
Age 65–69 (reference)			
Age 70–74	–0.018	0.031	0.559
Age 75–79	–0.021	0.034	0.538
Age 80–84	–0.052	0.036	0.150
Age 85+	–0.133	0.058	0.022*

Note. B= unstandardized regression coefficient; SE=Standard error of the coefficient;

* p < 0.05: statistical significance of the independent variables.

Table 3.

Linear Regression Analysis of Step Length by Age (as categorical variable).

Step Length (/bh)	Age 65–94		
	B	SE	p
Intercept	0.339	0.007	<.0001
Age 65–69 (reference)			
Age 70–74	–0.003	0.010	0.773
Age 75–79	–0.004	0.011	0.746
Age 80–84	–0.018	0.012	0.140
Age 85+	–0.039	0.019	0.043 [*]

Note. B= unstandardized regression coefficient; SE=Standard error of the coefficient;

^{*} p < 0.05: statistical significance of the independent variables.

Table 4.

Linear Regression Analysis of Cadence by Age (as categorical variable).

Cadence (steps/min)	Age 65–94		
	B	SE	p
Intercept	103.641	1.531	<.0001
Age 65–69 (reference)			
Age 70–74	1.773	2.165	0.414
Age 75–79	1.379	2.369	0.561
Age 80–84	–2.889	2.520	0.253
Age 85+	–8.473	4.018	0.036 *

Note. B= unstandardized regression coefficient; SE=Standard error of the coefficient;

* p < 0.05: statistical significance of the independent variables.

Table 5.

Linear Regression Analysis of Dynamic Stability by Age (as categorical variable).

Dynamic Stability	Age 65–74		
	B	SE	p
Intercept	1.683	0.025	<.0001
Age 65–69 (reference)			
Age 70–74	0.039	0.046	0.4023
Age 65–84			
Intercept	1.692	0.036	<.0001
Age 65–69 (reference)			
Age 70–74	0.030	0.053	0.568
Age 75–79	0.022	0.058	0.711
Age 80–84	–0.062	0.062	0.322
Age 65–94			
Intercept	1.730	0.038	<.0001
Age 65–69 (reference)			
Age 70–74	–0.009	0.054	0.875
Age 75–79	–0.017	0.059	0.772
Age 80–84	–0.101	0.063	0.111
Age 85+	–0.268	0.100	0.008*

Note. B= unstandardized regression coefficient; SE=Standard error of the coefficient;

* p < 0.05: statistical significance of the independent variables.

Table 6.

Linear Regression Analysis of COM Velocity relative to BOS (normalize to $\sqrt{g \times bh}$, where g is the acceleration due to gravity, and the body height [bh]) by age (as categorical variable).

COM Velocity relative to BOS [$V_{\text{COM/BOS}} (g \times bh)^{-1/2}$]	Age 65–94		
	B	SE	p
Intercept	0.252	0.007	<.0001
Age 65–69 (reference)			
Age 70–74	–0.002	0.009	0.803
Age 75–79	–0.005	0.010	0.605
Age 80–84	–0.019	0.011	0.080
Age 85+	–0.049	0.018	0.005*

Note. COM: center of mass; BOS: base of support; B= unstandardized regression coefficient; SE=Standard error of the coefficient;

* p < 0.05: statistical significance of the independent variables.