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The Role of Energetic Cost in the Age-Related Slowing of Gait Speed

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Abstract

Objectives—Slow walking speed is strongly associated with older age, but mechanisms underlying this relationship are not well-understood. We hypothesize that slow gait represents a compensatory strategy to reduce the energetic cost of walking with age.

Design—Cross-sectional analysis.

Setting—Community-dwelling volunteers from the Baltimore Longitudinal Study of Aging (BLSA).

Participants—420 community-dwelling persons aged 32 to 96 (mean 68.1 ± 12.5) who underwent a physical examination, physical function testing, and energy expenditure assessment.

Measurements—Energy expenditure per minute (ml/kg/min) and per meter (ml/kg/m) during 2.5 minutes of overground walking at customary speed, and usual gait speed over six meters (m/s) were examined. General linear regression models were used to assess the relationship between customary walking energy expenditure and usual gait speed, adjusted for potential confounders including smoking, medical diagnoses, walking-related pain, and balance difficulty.

Results—Usual gait speed was slower with increasing age after age 65. Energy expenditure per minute during customary walking averaged 13.0 ml/kg/min (± 2.8) and was independent of age ($p < 0.01$, $p = .88$). In contrast, energy expenditure per meter walked was progressively higher after age 65 ($p = 0.35$, $p < .001$) and heightened after age 80 ($p = 0.57$, $p < .001$), mirroring the observed pattern of usual gait speed. This relationship remained significant after adjusting for multiple impairments and comorbidities.

Conclusion—These observations support the hypothesis that slower gait at older ages may reflect a compensatory action to offset a greater energetic cost of walking associated with aging and chronic conditions. Future studies should evaluate the specific mechanisms that contribute to this phenomenon as novel targets for clinical intervention.

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Keywords

Energy Expenditure; Gait Speed; Physical Function

INTRODUCTION

Walking is the most common form of physical activity and is central to performing many activities of independent living (1). Walking difficulty, poor walking endurance, and slow gait speed are strongly prognostic of functional dependency and death in older adults (2). Declining cardiovascular fitness with age due to deconditioning and disease processes constitutes a frequent explanation of why older persons walk slower (3–6). Although fitness is an important component of physical function, an increase in the energetic cost of walking with age may also contribute to the decline in walking performance commonly observed in older persons.

Energy expenditure is a critical factor in functional task performance. Across species, preferred level of energy expenditure is associated with speed of movement (7–9). If the energetic cost of an activity is too high, it may be abandoned or performed at a lower level of exertion, in accordance with the energy minimization hypothesis (8, 10, 11). Previous studies in selected populations with impaired mobility have shown higher energy cost associated with activities of daily living (10, 12). Similarly the energetic cost of walking (ml O₂/kg/m) is higher in older adults relative to young-to-middle aged populations, and preferred walking speed has been linked to minimal metabolic cost (9, 13, 14). Accordingly, it is conceivable that individuals inherently select a gait speed that minimizes energetic cost and can be maintained for extended periods (14, 15).

In healthy individuals preferred gait speed remains remarkably constant between 1.1 – 1.3 m/s over much of the adult life span in the absence of disease (16, 17). In unhealthy individuals gait speed is a strong predictor of impending death and disability (16, 18) and may represent the progression of multi-systems decline, and subclinical disease (19). Metabolically demanding conditions, including acute infections, chronic diseases, and gait abnormalities have been shown to reduce activity and slow movement (20, 21) as less energy is available for both essential and discretionary physical activity and more energy is needed to maintain functional status (22). Theoretically, as these compensations become more severe, gait speed may decline further as a means to maintain mobility despite diminishing energetic capacity. In accordance with this interpretation of the energy minimization hypothesis, we assessed the relationships among age, the energetic cost of customary walking and usual gait speed, independent of diseases and conditions in community-dwelling men and women aged 32 to 96 years old participating in the Baltimore Longitudinal Study of Aging (BLSA).

MATERIALS AND METHODS

Participants

The BLSA is a study of normative human aging, established in 1958 and conducted by the National Institute on Aging Intramural Research Program. A general description of the sample and enrollment procedures and criteria has been previously reported (23). Briefly, the BLSA constitutes a continuously enrolled cohort with some targeted recruitment (e.g., women, racial minorities) over its 50-plus year history. All participants are community volunteers and at the time of enrollment must pass a health and functional screening evaluation and be free of major chronic conditions and cognitive and functional impairment.

Once enrolled, participants are followed for life and undergo extensive testing every one to four years depending on age.

The sample for the current study consists of men and women who underwent a physical examination, health history, physical function and gait speed assessment, and tests of walking energy expenditure between July 2007 and March 2009. Participants who required a walking aid or were unable to complete 2.5 minutes of unassisted customary paced walking were excluded from the analysis. Of the 435 participants completing the required testing, 420 achieved a metabolic steady state while walking (see below) and were included in the analysis (24). Trained technicians administered all assessments following standardized protocols. The Internal Review Board of the Medstar Research Institute approved the study protocol and all participants provided written informed consent.

Assessment of Usual Gait Speed

Usual gait speed was assessed by asking participants to walk at their “usual, comfortable pace” over a 6-meter course in an uncarpeted corridor. Participants stood with their feet behind a taped starting line. After a command of “Go,” timing was initiated with the first foot-fall over the starting line and stopped after the last foot-fall over the finish line. Two timed trials were conducted to derive usual gait speed in m/s, with the faster used for analysis.

Assessment of Customary Walking Energy Expenditure

Customary walking energy expenditure (ml/kg/min) was assessed via indirect calorimetry (Cosmed k4b2, Cosmed, Rome, Italy) during 2.5 minutes of overground walking. The 2.5 minute customary walk is the first of two components comprising the BLSA Long Distance Corridor Walk (LDCW). The BLSA version of the LDCW is slightly modified from that developed for the Health, Aging and Body Composition study (25); in place of a 2 minute walk performed as quickly as possible, the BLSA administers a 2.5 minute walk performed at a customary pace to allow assessment of customary walking energy expenditure. Each participant performed the test on a 20-meter course marked by cones at each end of an uncarpeted corridor. Participants stood with their feet behind a taped starting line and were instructed to walk at their “usual comfortable pace” around the course in a continuous loop until directed to stop. After a command of “Go,” timing was initiated with the first foot-fall over the starting line and stopped after 2.5 minutes of customary walking. Distance covered in meters was recorded.

Oxygen consumption and carbon dioxide production were continuously collected and analyzed with breath-by-breath measurement, and averaged over thirty second intervals to reduce variability. VO_2 (ml/kg/min) readings from the first 1.5 minutes of testing were discarded to allow the participant to adjust to the workload and reach stable oxygen consumption. VO_2 (ml/kg/min) values were examined individually for each participant to assure readings between minutes 2.0 and 2.5 had stabilized (varied by less than 15%) and those who failed to achieve a steady rate of oxygen consumption ($n=15$) were eliminated from the analysis. Customary walking energy expenditure was defined as the average volume of oxygen consumed (VO_2 ml/kg/min) during the final minute of the test. To provide a standardized measure of the metabolic cost of customary walking, customary walking energy expenditure was multiplied by 2.5 (the total amount of time walked) and divided by the total number of meters walked in 2.5 minutes to derive energy expenditure per meter (ml/kg/m).

Co-Variate Assessment

Weight (SR Scales 725L) and height were measured according to standard protocols and body mass index (BMI) was calculated as weight in kilograms divided by height in meters squared. The presence of chronic conditions was assessed by trained nurse practitioners combining information from a detailed medical history, medication use, and comprehensive physical examination. Co-morbid conditions included in the analysis comprised cardiovascular disease defined as heart disease (e.g., myocardial infarction, congestive heart failure or angina) or cardiac surgery (e.g., coronary artery bypass graft or angioplasty); cerebral vascular disease defined as stroke or transient ischemic attack; pulmonary disease defined as chronic bronchitis, emphysema, chronic obstructive pulmonary disease or asthma; diabetes as determined from reported diagnosis and current medication use, and osteoarthritis of the hips, knees or feet. Prevalent lower extremity pain defined as reported pain in the knees, hips or feet of at least moderate intensity when walking on a flat surface within the past 30 days was included as an indicator of co-morbidity (26). Smoking status was determined from self-report and current and recent regular smokers (i.e., quit within the past 10 years) were distinguished from never smokers and those who quit over 10 years prior to their clinic visit. Poor standing balance was defined as inability to hold a full-tandem stand for at least 10 seconds and balance difficulty was derived from reported difficulty keeping balance when walking on a level surface.

Statistical Analysis

Unadjusted relationships between variables were explored by scatterplots and summarized by locally weighted regression smoothers. Based on these results, the cross-sectional relationship between customary walking energy expenditure and usual gait speed was modeled using correlation analyses (ρ) and a series of general linear models. To account for the apparent curvilinear relationships between variables: (1) two continuous age-spline terms were used (age-spline 65–80 and age-spline >80), and (2) a quadratic term [(EE per meter)²] was added to capture the curvilinear relationship between energetic cost and walking speed. The knots for the linear spline analysis were determined by inspection of the functional form of the age – gait speed relationship.

The first model confirmed the well-established relationship between age and usual gait speed (18, 27) adjusting for sex, height, and an interaction between sex and height to account for sex and leg-length differences in the energy-speed relationship. The second model included terms to assess the relationship between customary walking energy expenditure and usual gait speed (EE per meter and EE per meter²). Finally, the third model included terms to adjust for smoking, medical diagnoses, walking-related pain, and balance difficulty. Tests for interaction between age and sex, age and energy expenditure, and sex and energy expenditure were not statistically significant and were not included in the models presented. Weight was not included in any of the models, as the measure of energetic cost (VO₂ (ml/kg/m)) was standardized per kilogram of body weight. All analyses were performed using Stata MP, version 10 (Statacorp, College Station, TX) and p-values of <.05 were considered significant.

RESULTS

Participant characteristics are detailed in Table 1. The mean age was 68.1 ($\pm$ 12.5) years, slightly more than half were men (51.9%) and BMI averaged 27.1 ($\pm$ 5.0) kg/m². Only five percent were current smokers or quit within the past ten years. The most common chronic condition was lower extremity osteoarthritis with a prevalence of 44 percent. All other medical conditions were relatively rare with no more than 15 percent having prevalent pulmonary or heart disease. Usual gait speed ranged from 0.5 m/s to 1.9 m/s and averaged

1.1 ($\pm$ 0.2) m/s. In cross-sectional analyses, gait speed did not vary systematically with age before 65 ($\rho = -.10$, $p = .23$), but was on average slower in those over 65 ($\rho = -.43$, $p < .001$), and even slower in those 80 and over ($\rho = -.60$, $p < .001$, Figure 1A).

Energy expenditure for customary walking averaged 13.0 ($\pm$ 2.8) ml/kg/min and was constant across age ($\rho < 0.01$, $p = .88$). As illustrated in Figure 1B, the energetic cost of walking per meter was also constant up to the age of 65 ($\rho = -0.02$, $p = .81$), sloped upwards from age 65 until 80 ($\rho = 0.18$, $p = .01$), with an even steeper increase after age 80 ($\rho = 0.57$, $p < .001$).

In further analyses, three linear models were used to investigate the hypothesis that older persons slow down to maintain energy expenditure at a constant level. Sex, height and the interaction between sex and height were significant independent predictors of usual gait speed and were included in all models (Table 2 – Model 1). When energy expenditure terms (EE per meter and EE per meter²) were added to Model 2, the quadratic term for energy expenditure per meter walked was inversely related ($\beta = -10.578$, $p < .001$; Table 2 - Model 2) to gait speed, indicating that as energy expenditure per meter increases, gait speed is exponentially slower. To evaluate the extent to which co-morbidity and other health-related factors may confound the relationships between age, energy expenditure and gait speed, measures of prevalent disease, pain-related symptoms, balance difficulties, and smoking were added to Model 3 as covariates (Table 2 - Model 3). In this adjusted model the magnitude of the coefficients for age remained relatively constant, and the energy expenditure variables diminished to some extent, but remained significant ($p < .01$). Diabetes and balance difficulty were also independently associated with usual gait speed.

Finally, the association between energy expenditure and gait speed as a function of age was evaluated separately in participants <80 years and $\geq$ 80 years based on the apparent steepening of both the age-walking speed and age-energy expenditure curves near age 80 (Figure 1, A & B). In persons 80 and older, the slope of the linear relationship between energy expenditure and walking speed was substantially steeper than in those younger than age 80 as revealed by a significant interaction between age and walking efficiency in those over 80 ($p = .004$).

DISCUSSION

In healthy individuals aged 32 to 96 years energy expenditure per minute during customary walking on a flat course averaged 13.0 ml/kg/min independent of age. This finding supports the hypothesis that older adults slow down to maintain an inherent level of energy expenditure. Further, graphical findings that portray the energetic cost of customary walking per meter as a mirror image of the decline in walking speed (Figure 1) suggest that older persons may slow down to minimize energy expenditure in the face of age-related inefficiencies that cause the cost of walking per meter to rise exponentially. Our findings also suggest that independent of aging and the energetic cost of walking, specific conditions including diabetes and walking related balance difficulties may play an important role in modifying gait speed, providing targets for clinicians to monitor that may help preserve mobility and independence in late life.

Previous research on the energetic cost of walking has been limited to smaller samples with younger participants or confined to laboratory settings and the use of a treadmill (5, 28), which can affect gait mechanics and may not accurately reflect energy expenditure while walking overground (29, 30). The current study examined the relationship between energy expenditure during customary overground walking and usual gait speed over a broad age spectrum. This approach provides a more realistic assessment of the energetic cost of

independent living as reflected by energy expenditure during customary walking, a key component of daily activity in community-residing adults. Further, the results indicate that the speed-energy association is curtailed in those over 80 relative to those younger than 80. The steeper slope in this age group indicates that with age, the typical positive speed energy relationship is diminished as more energy is needed per meter walked. The factors underlying this phenomenon have yet to be clearly delineated and should be further examined as they may provide novel targets for intervention.

This study has several potential limitations. First, due to the demands of attending a clinic visit and test eligibility criteria (e.g., ability to walk 2.5 minutes without stopping and without a walking aid), the study population is healthier than the general population, particularly the oldest participants. Thus, the observed age-gait speed slope may underestimate true age-related reductions. Although the findings may not apply to the general aging population, the health status of participants serves to reduce the confounding of co-morbidity and age. Second, the study uses cross-sectional data to estimate age-related change. Confirming these findings using longitudinal data is an important next step. Third, although 2.5 minutes is less than the time typically used to assess steady state energy expenditure, all participants included in the analysis achieved evidence of a metabolic steady state after 1.5 minutes of customary walking. Finally, because testing is performed overground, there is no guarantee participants walk at a uniform pace throughout the entire 2.5 minutes. Although the distance covered during each 30 second time period was not measured, the time to complete each 40 meter lap during the 400m component of the LDCW was remarkably consistent despite a longer walking time and more intensive effort. Further, individuals tend to walk at a speed that minimizes energy consumption (13, 28), which logically translates to a nearly constant rate on a flat, unchanging surface.

Loss of mobility with age poses a substantive threat to life quality and seriously impacts the capacity to live independently. Slow or slowing gait speed frequently precedes mobility limitations and disability (2, 18). Accordingly, efforts to delay or prevent mobility loss should be aimed both at increasing fitness and minimizing energetic cost. Identifying these sources could lead to targeted clinical interventions aimed at preventing the burden of mobility decline that affects many older individuals.

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Data for these analyses were obtained from the Baltimore Longitudinal Study of Aging (BLSA), a study performed by the National Institute on Aging.

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Data for these analyses were obtained from the Baltimore Longitudinal Study of Aging, a study performed by the National Institute on Aging.

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Figure 1A. Usual Gait Speed (m/s) and Age

A lowess fit curve displays the curvilinear relationship between usual gait speed (m/s) and age UGS (m/s).

UGS (m/s) = $1.383 + (-.003) \text{ Age} + (-.004)\text{Agespline1} + (-.017)\text{Agespline2}$ ($p > .05$ for Age and Agespline1, $p = .002$ for Agespline2)

Abbreviations: Agespline1 = age 65 – 80; Agespline2 = age > 80

Figure 1B. Customary Walking Energy Expenditure per meter (ml/kg/m) and Age

A lowess fit curve displays the curvilinear relationship between the energy expended per meter during customary walking (ml/kg/m) and age.

Energy Expenditure per Meter (ml/kg/m) = $.085 + (1.05e^{-06})\text{Age} + (.001)\text{Agespline1} + (.001)\text{Agespline2} + (2.840)\text{EEM}^2 + (-.033)\text{Agespline1}*\text{EEM}^2$ ($p=.983$ for Age, $p<.001$ for all other variables)

Abbreviations: Agespline1 = age 65 – 80; Agespline2 = age>80; EEM^2 = Energy expenditure per meter²

Table 1**Participant Characteristics**

Characteristics	N = 420
Age (years), mean (SD)	68.1 (12.5)
Distribution, No. (%):	
<65	157 (37.4)
65 – 79	187 (44.5)
80 +	76 (18.1)
Male sex, No. (%)	218 (51.9)
Body Mass Index (kg/m ²), mean (SD) ^a	27.1 (5.0)
Smoker, No. (%) ^b	22 (5.2)
Usual Gait Speed (m/s), mean (SD)	1.1 (0.2)
Customary Energy Expenditure (ml/kg/min), mean (SD)	13.0 (2.8)
Customary Energy Expenditure per meter (ml/kg/m), mean (SD)	.18 (0.04)

Comorbid conditions	No. (%)
Cardiovascular disease ^c	53 (12.6)
Cerebral vascular disease ^d	22 (5.2)
Pulmonary disease ^e	62 (14.8)
Diabetes ^f	33 (7.9)
Lower Extremity Arthritis ^g	189 (44.0)
Lower extremity pain ^h	36 (8.6)
Poor standing balance ⁱ	33 (7.9)
Balance difficulty ^j	59 (14.1)

^aCalculated as weight in kilograms divided by height in meters squared.

^bSelf-reported regular smoking within the past 10 years

^cSelf-reported history of heart disease or cardiac surgery, including myocardial infarction, congestive heart failure, angina, coronary artery bypass graft, and angioplasty.

^dSelf-reported history of stroke or transient ischemic attack.

^eSelf-reported history of pulmonary disease.

^fSelf-reported past diagnosis and current medication for diabetes.

^gSelf-reported diagnosis of lower extremity arthritis.

^hSelf-reported lower extremity pain of at least moderate intensity walking on a flat surface within the past 30 days.

ⁱUnable to hold a full-tandem stand for at least 10 seconds.

^jReported difficulty keeping balance when walking on a level surface.

Table 2
Association Between Age, Usual Gait Speed & the Energetic Cost of Walking (ml/kg/meter)

Dependent Variable: Usual Gait Speed (m/s)	Model 1		Model 2		Model 3	
Independent Variables:	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Age Slope:						
<65	-.002	.126	-.003	.111	-.001	.316
65 – 80	-.009	<.001	-.009	<.001	-.008	<.001
80+	-.023	<.001	-.020	<.001	-.017	<.001
Male sex	1.207	.007	1.124	.011	1.030	.018
Height (cm)	.005	.027	.004	.029	.004	.041
Male sex*height (cm)	-.007	.012	-.006	.018	-.006	.028
Intercept	.571	.106	.210	.568	.308	.390
EE per meter (ml/kg/m)			4.143	.001	3.414	.005
EE per meter ² (ml/kg/m) ²			-10.578	<.001	-8.376	.005
Current or recent smoker ^a					-.025	.530
Cardiovascular disease ^b					.013	.644
Cerebral vascular disease ^c					.015	.723
Pulmonary disease ^d					-.021	.397
Diabetes ^e					-.137	<.001
Lower Extremity Arthritis ^f					-.024	.214
Lower extremity pain ^g					-.052	.110
Poor standing balance ^h					-.046	.250
Balance difficulty ^k					-.093	.001

Abbreviations: EE, energy expenditure.

Model 1: UGS (m/s) = $\beta_0 + \beta_1 \text{ Age} + \beta_2 \text{ Agespline1} + \beta_3 \text{ Agespline2} + \beta_4 \text{ male} + \beta_5 \text{ height} + \beta_6 \text{ male*height}$

Model 2: UGS (m/s) = $\beta_0 + \beta_1 \text{ Age} + \beta_2 \text{ Agespline1} + \beta_3 \text{ Agespline2} + \beta_4 \text{ male} + \beta_5 \text{ height} + \beta_6 \text{ male*height} + \beta_7 \text{ EEM} + \beta_8 \text{ EEM}^2$

Model 3: UGS (m/s) = $\beta_0 + \beta_1 \text{ Age} + \beta_2 \text{ Agespline1} + \beta_3 \text{ Agespline2} + \beta_4 \text{ male} + \beta_5 \text{ height} + \beta_6 \text{ male*height} + \beta_7 \text{ EEM} + \beta_8 \text{ EEM}^2 + \beta_9 \text{ smoke} + \beta_{10} \text{ cardiovascular disease} + \beta_{11} \text{ cerebral vascular} + \beta_{12} \text{ pulmonary disease} + \beta_{13} \text{ diabetes} + \beta_{14} \text{ arthritis} + \beta_{15} \text{ lower extremity pain} + \beta_{16} \text{ poor standing balance} + \beta_{17} \text{ balance difficulty}$

- ^aRegular smoking within the past 10 years
- ^bHistory of heart disease (myocardial infarction, congestive heart failure or angina) or cardiac surgery (coronary artery bypass graft or angioplasty).
- ^cHistory of stroke or transient ischemic attack.
- ^dHistory of chronic bronchitis, emphysema, chronic obstructive pulmonary disease or asthma.
- ^eDiagnosed with and currently taking medication for diabetes.
- ^fHistory of lower extremity (hips, knees or feet) arthritis.
- ^gReported moderate lower extremity pain while walking on a flat surface within the past 30 days.
- ^hUnable to hold a full-tandem stand for at least 10 seconds.
- ⁱReported difficulty keeping balance when walking on a level surface