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The Relationship of the Energetic Cost of Slow Walking and Peak Energy Expenditure to Gait Speed in Mid-to-Late Life

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Abstract

Objective—Peak energy expenditure is highly correlated with usual gait speed, however it is unknown whether the energetic cost of walking is also an important contributor to usual gait speed when considered as a component of peak walking capacity.

Design—The energetic cost of five minutes of slow treadmill walking (0.67 m/s), peak overground walking energy expenditure, and usual gait speed over 6 meters were assessed cross-sectionally in 405 adults aged 33 to 94 in the Baltimore Longitudinal Study of Aging.

Results—Average energy expenditure during slow and peak sustained walking were 8.9 (\pm 1.4) and 18.38 (\pm 4.8) ml/kg/min, respectively. Overall, the energetic cost of slow walking as a percentage of peak walking energy expenditure was strongly associated with usual gait speed ($p < 0.001$), however in stratified analyses, this association was maintained only in those with peak walking capacity below 18.3 ml/kg/min ($p = 0.04$), the threshold associated with independent living.

Conclusions—In older persons with substantially reduced peak walking capacity, the energetic cost of walking is associated with gait speed, particularly when peak walking capacity nears the minimum level considered necessary for independent living. Thus, optimal habilitation in older frail persons may benefit from both improving fitness and reducing the energetic cost of walking.

Keywords

Energy Expenditure; Walking Efficiency; Usual Gait Speed; Physical Function

BACKGROUND

The most consistent age-related change in human gait is a decrease in self-selected usual gait speed¹, beginning near age 60 when usual gait speed averages between 1.1 - 1.3 m/s and escalating near age 80 when the average drops to approximately 0.85 m/s². Accompanying this decline is an increase in the energetic cost of walking^{3,4} and a decrease in peak energy expenditure^{5,6}. Previous research in older adults has estimated the energetic cost of walking per **distance** (ml/kg/m) walked^{7,8} and per **speed** (ml/kg/min) traveled is

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higher for older adults than their younger counterparts^{4,9}, suggesting the speed-aerobic demand association may vary with age. These age-related changes are not clearly understood, but most likely result from a combination of factors including impaired aerobic capacity and reduced movement efficiency. Previous research in older adults has primarily focused on the independent factors affecting either peak aerobic capacity^{7,10-13} or movement efficiency¹⁴, but few studies have examined the combined effect of both peak aerobic capacity and the energetic cost on usual gait speed^{9,12}.

Optimal biomechanics of walking during the gait cycle, including limb motion and displacement of the trunk and pelvis, contribute to minimizing energy expenditure^{15,16}. With age, alterations in these movement related patterns contribute to reduced efficiency⁴ and higher cost of walking. Reduced efficiency of mobility indicates more work is required for a given task⁸ and may suggest higher energy expenditure due to abnormal age-related mobility patterns, including increased step cadence and stride width, and shorter stride length. Although altered gait patterns may improve stability¹⁷ they may also contribute to less efficient mobility and task-dependent energy expenditure, as the oxygen cost per meter of walking has been directly related to the extent of gait disorder¹⁸. Increasing variability in gait patterns and speed with age are common, but is not normal and believed to be influenced by underlying pathology^{1,17} including multi-systems decline and subclinical disease¹⁹⁻²¹. Consequences of these inefficiencies may contribute to reduced activity and slowed movement to conserve energy and minimize fatigue⁵. Such behavior may accelerate age-related deconditioning and thus progressively diminish energetic availability. Reduced energetic availability means a high percentage of capacity must be used to perform everyday functional tasks. Over time, this may contribute to loss of autonomy as the cost of everyday tasks approaches 100% of peak energy availability.

Differences in walking energetics are unlikely to affect behavior in fit individuals, when energy availability is abundant. However, in unfit individuals, when energy availability is scarce, even small incremental increases in the energetic cost of walking may become problematic, lead to increased fatigability, and reduced self-selected, usual gait speed. Accordingly, to better understand loss of gait speed with age it is critically important to evaluate energy availability (peak energy expenditure) while accounting for the energetic cost of walking, which may vary substantially across individuals and with age. Failure to account for both components may underestimate the minimal capacity required to ambulate and live independently. This study examined the energy expended during slow walking as a percentage of peak walking capacity over a wide range. Understanding the composite effect of both components may also help identify intervention strategies aimed at maximizing physical function in older persons.

METHODS

Study Design and Subjects

The Baltimore Longitudinal Study Aging is a study of normative human aging established in 1958 and supported by the National Institute on Aging Intramural Research Program (NIA – IRP). A general description of the study has been previously provided²². Briefly, the BLSA constitutes a continuously enrolled cohort study conducted in Baltimore, Maryland of community dwelling volunteers free of major chronic conditions and impairments at the time of enrollment as determined from a comprehensive health and functional screening assessment. Once enrolled, participants remain in the study 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 physical function and gait speed assessments, and tests of walking energy expenditure between July 2007 and June 2010 (n=405). Trained and certified technicians administer all assessments following standardized protocols. The

Internal Review Board of the Medstar Research Institute approved the study protocol and participants provided written informed consent.

Assessment of Usual Gait Speed

Participants stood with their feet behind a taped starting line and were instructed to walk at their “usual, comfortable pace” over a 6-meter course. 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 with the faster used for analysis. Distance covered (6 meters) was divided by number of seconds to derive usual gait speed in meters per second (m/s).

Assessment of the Energetic Cost of Walking

The energetic cost of walking (ml/kg/min) was assessed via indirect calorimetry (Medical Graphics Corp., St. Paul, MN) during 5 minutes of slow walking on a treadmill at 0.67 m/s (1.5 mph) at zero percent grade. A single speed was used for all participants, providing a standardized measure by which to gauge age-related changes in energy expenditure during a slow walking task. Inability to walk at least 0.67 m/s is considered indicative of severe mobility disability²³ and frailty²⁴⁻²⁶. Measurement of expired air was conducted throughout the test and analyzed for oxygen and carbon dioxide content using a standard laboratory metabolic cart (Medgraphics CPX-D). The Medgraphics system utilizes breath-by-breath measurement of gas exchange through a stretch neoprene facemask and a pneumotach for gas collection. Prior to testing, the system was warmed-up for a minimum of 20 minutes and calibrated using reference gases of known concentrations and a 3.0-L syringe for flow.

To calculate the average volume of oxygen consumed per kilogram of body weight (VO₂ ml/kg/min) during standardized slow treadmill walking, energy expenditure readings from the first two minutes of testing were discarded to allow the participant to adjust to the workload and reach stable oxygen consumption. The final three minutes were averaged to derive a single measure of the average VO₂ (ml/kg/min) consumed, or the average energetic cost of a standardized slow walking task.

Assessment of Peak Walking Energy

Peak walking energy expenditure (ml/kg/min) was assessed during the 400 meter segment of the long-distance corridor walk (LDCW), a two-part, self-paced endurance walking test and a validated measure of cardiorespiratory fitness in older adults^{27, 28}. The test was performed on a course in an uncarpeted corridor with the participant wearing a portable metabolic analyzer, the Cosmed K₄b² (Cosmed, Rome, Italy). After the Cosmed was placed on the participant, he/she was seated for 2 minutes, to allow acclimation to the face mask and harness. After two minutes, the participant stood, was escorted to the starting line, and instructed to walk at his/her preferred, comfortable walking speed for 2.5 minutes, the warm-up component of the LDCW. For the second component, the participant was immediately escorted back to the starting line and instructed to walk “as fast as possible, at a pace you can sustain for 400 meters.” The course measured 20 meters, marked by cones at both ends. Standardized encouragement was given with each lap along with the number of laps remaining. Split times for each lap and total time to walk 400m was recorded. The Cosmed remained on the participant for 2 minutes after the completion of the test to ensure adequate breath collection. The Cosmed unit utilizes breath-by-breath measurement of gas exchange through a rubberized facemask and turbine for gas collection. Prior to testing the Cosmed system was warmed-up for a minimum of 20 minutes and calibrated using reference gases of known concentrations and a 3.0-L syringe for flow.

To calculate average peak energy expenditure per kilogram of body weight (peak VO₂ ml/kg/min), readings from the first 1.5 minutes of the 400m walk were discarded to allow the participant to adjust to the workload and the remaining readings were averaged to arrive at single measure of the average energy expended (ml/kg/min) during 400 meters of peak sustained overground walking.

Other Measures and Co-Variates

Height and weight were assessed according to standard protocols. Fat mass and lean body mass were obtained from dual energy x-ray absorptiometry (DEXA – GE) and used to compute a ratio of fat-to-lean mass.

Statistical Analysis

Scatterplots and locally weighted regression smoothers were used to assess the study population characteristics and to assess the linear and non-linear associations between age, usual gait speed, the energetic cost of walking, and peak energy expenditure (Figures 1 - 4). We also calculated a cost ratio to examine the energetic cost of slow walking as a percentage of peak walking energy expenditure:

$$\frac{\text{Average slow walking energy expenditure (ml/kg/min)}}{\text{Average peak energy expenditure (ml/kg/min)}}$$

Based on these results, we conducted correlation analyses to assess the magnitude of the relationship between these variables and modeled the relationship between usual gait speed and the cost ratio using general linear models with usual gait speed as the outcome. The final model was adjusted for age, sex, height, and body composition. All analyses were performed using Stata, version 10 (Statacorp, College Station, TX) and p-values of <.05 were considered significant.

RESULTS

All participants were able to complete 5 minutes of slow treadmill walking at 0.67m/sec and 400 meters of peak sustained walking without a walking aid. Participant characteristics are detailed in Table 1. Mean age was 68 (\pm 11.8) years, slightly more than half were men (53.3%) and BMI averaged 26.8 (\pm 4.6) kg/m².

Usual gait speed ranged from 0.6 to 2.0 m/s and averaged 1.2 (\pm 0.2) m/s. Although progressively slower with advancing age, usual gait speed did not vary systematically with age in persons younger than 60 years (β = -0.005, p = 0.08). In persons 60 and older, the magnitude of the slope between age and walking speed was more robust (β = -0.012, p < 0.001, p < .01 for interaction, Figure 1).

The energetic cost of walking (ml/kg/min) ranged from 5.3 to 14.8 ml/kg/min, averaged 8.9 (\pm 1.4) ml/kg/min, and tended to be higher with advancing age (ρ = 0.24, p < 0.001, Figure 2a). Peak walking energy expenditure ranged from 8.9 to 45.0 ml/kg/min, averaged 18.4 (\pm 4.8) ml/kg/min, and was progressively lower with age (ρ = -0.38, p < 0.001, Figure 2b). The cost ratio ranged from 0.2 to 1.1, averaged 0.5 (\pm 0.1), and was strongly associated with both age (ρ = 0.43, p < 0.001) and usual gait speed (ρ = -0.41, p < 0.001, Figure 3).

Given these associations, we fit a general linear model predicting usual gait speed as a function of the cost ratio adjusted for age, sex, height, and body composition (Table 2). The coefficient for the cost ratio showed a significant negative relationship (β = -0.39, p < 0.001) with usual gait speed indicating that as the energetic cost of walking approaches peak

walking energy expenditure, usual gait speed is slower, independent of potential confounders.

Finally, we stratified by peak walking energy expenditure to determine if the relationship between the cost ratio and usual gait speed differed as a function peak capacity. Previous research has identified 18.3 ml/kg/min as the threshold of capacity required for independent function¹³ and other studies have found comparable values^{29,30}. In our sample, 216 (53%) individuals were below the 18.3 ml/kg/min peak threshold and were more likely to be older and female, have a higher BMI, greater fat to lean mass, slower gait speed and a higher cost ratio (Table 3a). In general linear models adjusted for age, sex, height, and body composition the cost ratio significantly predicted gait speed **only** in those with a peak VO₂ below 18.3 ml/kg/min (Table 3b). Age remained a significant contributor in the low-fitness model ($\beta = -0.008$, $p < 0.001$), but in those with a higher level of fitness, neither the cost ratio nor age predicted gait speed.

DISCUSSION

This study investigated the relationship between the energetic cost of slow walking in relation to peak walking energy expenditure and usual gait speed across a broad age range. In relatively healthy adults in mid- to late-life, the energetic cost of walking contributed to self-selected usual gait speed only in those with fitness levels below the threshold associated with independent living.

It is widely recognized that when oxygen intake during aerobic work does not meet demand, alterations in speed and intensity must occur³¹. The association between the cost ratio and usual gait speed in persons with low fitness indicates that when peak aerobic fitness reaches a critically low threshold, the cost of walking becomes a conditioning factor to speed, either directly, as a strategy to stay within boundaries of energy availability, or because the close match between energy availability and utilization lowers the threshold of fatigue and imposes a behavioral change (Figure 4).

Previous research suggests that rehabilitation to improve timing and coordination of movement may better impact efficiency than efforts to improve aerobic endurance^{32,33}. However, the importance of reserve capacity should not be overlooked. Recent studies evaluating the relative contribution of inefficiency and diminished capacity to slowing gait with age have shown a strong association between usual gait speed, peak aerobic capacity, and perceived exertion¹². The present study builds on this work by simultaneously examining the age-associated upward trend in energetic cost in relation to the downward trend in peak walking energy expenditure in a large cohort of older adults free of mobility limitations. Further, this study delineates the importance of maintaining functional capacity in older adults over 60 when the relationship between the energetic cost of walking and usual gait speed becomes crucial in even healthy older adults without mobility limitations and underscores the importance of evaluating both energetic cost and availability in efforts to understand mechanisms that lead to slowing and in designing effective targets for intervention.

Some limitations to this study should be noted. First, while the speed of the slow walking test (0.67 m/s) was (i) consistent with the minimal demand of functional tasks and (ii) allowed us to include deconditioned and very old individuals in the study, it was likely too slow for younger and more robust participants. Accordingly, the combined effect of walking on a treadmill at a fixed slow rate of speed may have actually increased the energetic cost of walking due to the U-shaped function of the speed-energy tradeoff^{34,35}. Although this phenomenon may tend to inflate the energetic cost of walking in more fit participants and

diminish the correlation between age and energetic cost of walking, it should have minimal impact on the low-fitness analyses since these individuals are more likely to walk at an inherently slower pace. Second, cross-sectional data was used to estimate age-related changes in economy. Confirming these findings in a longitudinal cohort would strengthen these findings. Finally, the energetic cost of walking was estimated using a treadmill. Although utilizing a treadmill ensures a steady rate of speed during individual testing and across age groups, it may alter step cadence and stance times, contributing to higher energy expenditure compared to overground walking³⁶⁻³⁸.

CONCLUSIONS

The mechanisms that underlie reduced gait speed with age are not well understood. Our study points to important connections between peak energy expenditure, energy cost, and usual gait speed. Findings highlight the energetic cost of walking as a looming threat to independence in persons with low fitness – the very old and the deconditioned- and suggest future efforts should target this group and evaluate mechanisms of inefficiency including muscle quality, gait mechanics, and energy-disease interactions.

Acknowledgments

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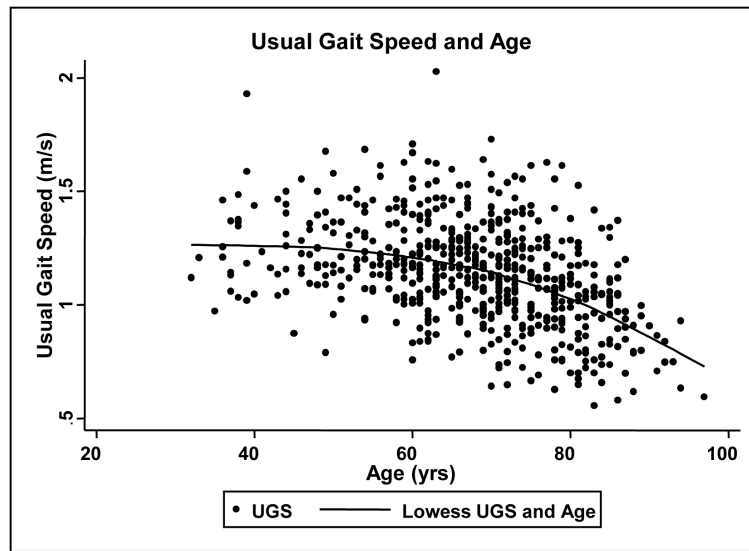


Figure 1. Usual Gait Speed (m/s) & Age (yrs)
A lowess fit curve displays the curvilinear relationship between usual gait speed (m/s) and age (yrs).

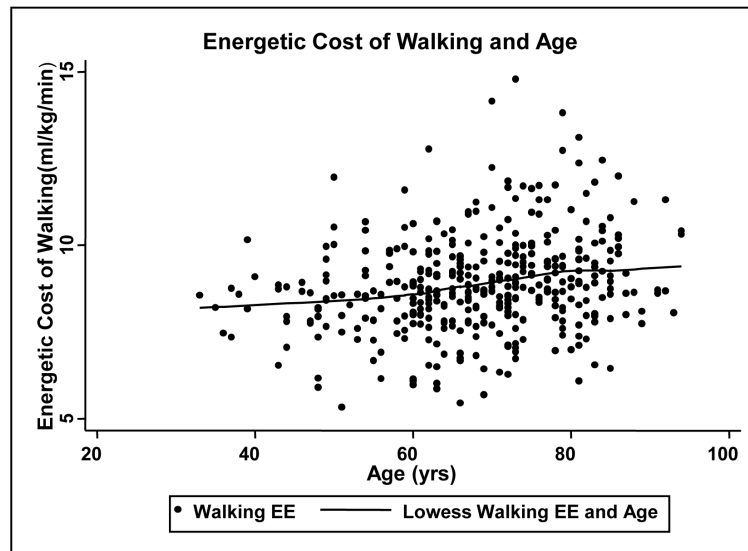


Figure 2a.
Energetic Cost of Walking (ml/kg/min) & Age (yrs)
A lowess fit line displays the linear relationship between the average energetic cost of slow walking (ml/kg/min) and age.

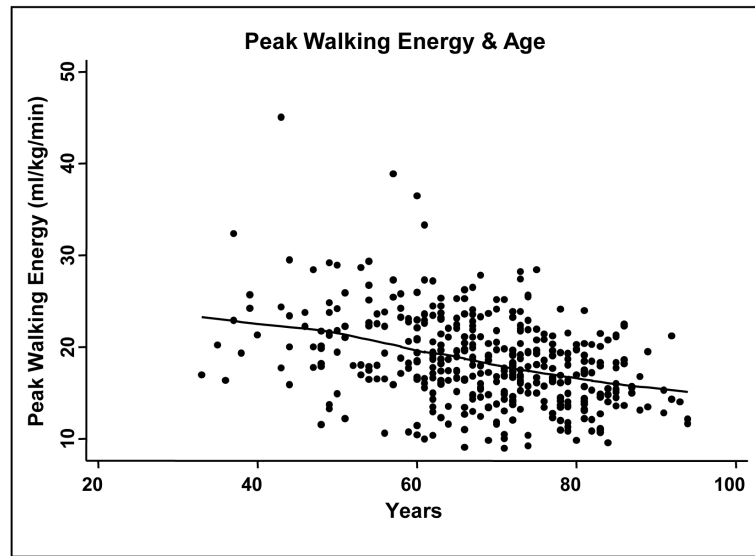


Figure 2b.
Peak Walking Energy Expenditure (ml/kg/min) & Age (yrs)
A lowess fit curve displays the relationship between average peak walking energy expenditure (ml/kg/min) and age.

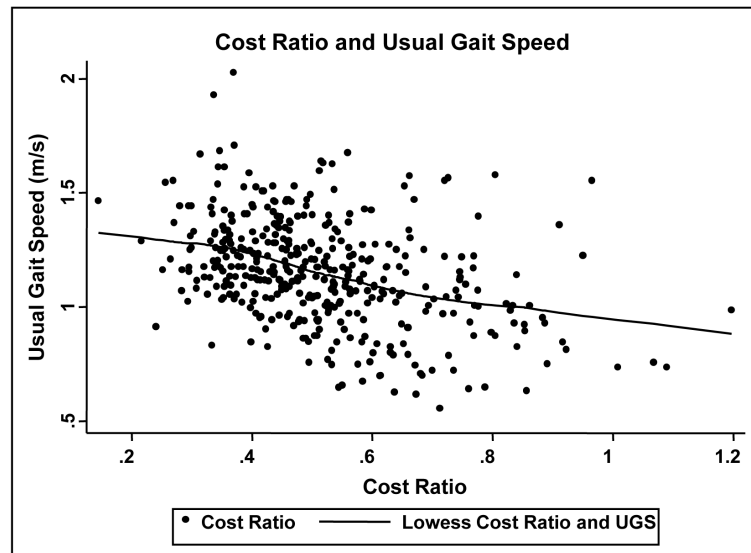


Figure 3.
Cost Ratio and Usual Gait Speed (m/s)
A lowess fit line displays the relationship between the ratio of slow walking energy expenditure to peak energy expenditure and usual gait speed (m/s).

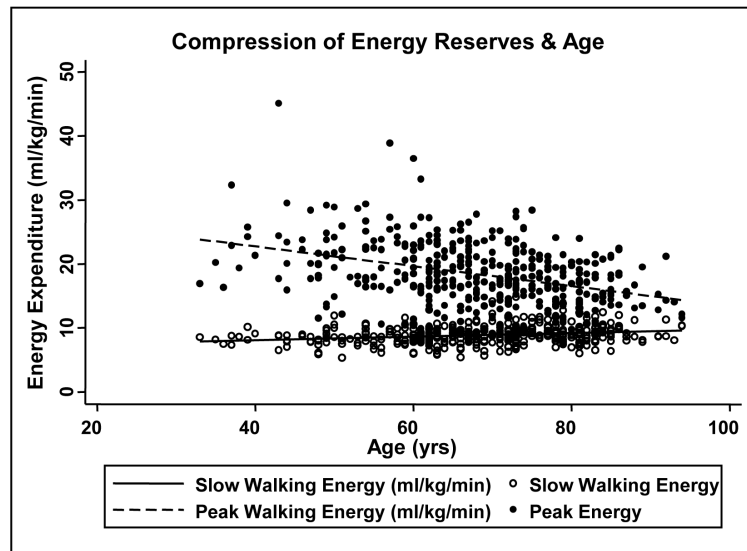


Figure 4.
 Compression of Energy Reserves and Age
 A linear fit graph displays the compression of energy availability (peak walking energy expenditure) and energy utilization for basic tasks (slow walking energy) and age.

Table 1

Participant Characteristics:

Characteristics (<i>n</i> = 405)	<i>n</i> / mean	% / \pm SD
Sex, % male	216	53.33
Age, yrs	68.09	11.84
BMI, kg/m ²	26.80	4.59
Ratio of fat-to-lean mass	0.57	0.23
UGS, m/s	1.15	0.23
ECW, ml/kg/min	8.87	1.39
Peak Energy Expenditure, ml/kg/min	18.38	4.83
Cost Ratio	0.51	0.15

Values are means \pm SD; *n*, no. of subjects. BMI, body mass index; UGS, usual gait speed; ECW, energetic cost of slow walking; Cost Ratio, ratio of ECW to peak energy expenditure.

Table 2

Parameter estimates for generalized linear regression model:

Association Between the Cost-to-Availability Ratio and Usual Gait Speed (m/s)			
Regression Variable	Coefficient (β)	Std Err	p-value
Cost Ratio	-0.387	0.072	<0.001 *
Age	-0.005	0.001	<0.001 *
Male sex	-0.057	0.032	0.080
Height	0.003	0.002	0.097
Ratio of fat-to-lean mass	-0.120	0.052	0.021 *
Intercept (β_0)	1.373	0.281	<0.001 *

Cost Ratio = Ratio of the energetic cost of slow walking to peak energy expenditure

* p is significant at the 0.05 level

Model r-squared: 24.6%

Table 3a

Participant Characteristics – Stratified Analysis

Mean	(n = 216)	(n=189)	p for difference
	<18.3 ml/kg/min	18.3 ml/kg/min	
Sex, % male	47.95	59.68	0.02 *
Age, yrs	70.99	64.68	<0.001 *
BMI, kg/m ²	27.52	25.96	<0.001 *
Ratio of fat-to-lean mass	0.62	0.52	<0.001 *
UGS, m/s	1.07	1.25	<0.001 *
Cost Ratio	0.61	0.41	<0.001 *

Values are means; *n*, no. of subjects; BMI, body mass index; UGS, usual gait speed.

* p is significant at the 0.05 level

Table 3b

Parameter Estimates for Stratified General Linear Models

Variable	(n = 216)			(n=189)		
	< 18.3 ml/kg/min Coefficient (β_1)	Std. Err.	p-value	18.3 ml/kg/min Coefficient (β_1)	Std. Err.	p-value
Cost Ratio	-0.210	0.097	0.038 *	-0.111	0.194	0.568
Age	-0.008	0.001	<0.001 *	-0.003	0.001	0.070
Male sex	-0.055	0.044	0.213	-0.068	0.045	0.133
Height	0.004	0.002	0.046 *	0.002	0.002	0.464
Ratio of fat-to-lean mass	-0.088	0.068	0.198	-0.127	0.079	0.105
Intercept (β_0)	1.153	0.380	0.002	1.287	0.406	0.002

* p is significant at the 0.05 level

Model r-squared < 18.3 ml/kg/min: 25.4

Model r-squared 18.3 ml/kg/min: 6.0