Gait energetic efficiency in older adults with and without knee pain: results from the Baltimore Longitudinal Study of Aging

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Abstract With aging, customary gait patterns change and energetic efficiency declines, but the relationship between these alterations is not well understood. If gait characteristics that develop with aging explain part of the decline in energetic efficiency that occur in most aging individuals, then efforts to modify these characteristics could delay or prevent mobility limitation. This study characterizes gait patterns in older persons with and without knee pain and tests the hypothesis that changes in gait characteristics due to knee pain are associated with increased energetic cost of walking in older adults. Study participants were 364 men and 170 women aged 60 to 96 years enrolled in the Baltimore Longitudinal Study of Aging (BLSA), of whom 86 had prevalent knee pain. Gait patterns were assessed at participant self-selected usual pace in the gait laboratory, and the energetic cost of walking was assessed by indirect calorimetry during self-selected usual pace walking over 2.5 min in a tiled corridor using a portable equipment. Participants with knee pain were less energetically efficient than those without pain (oxygen consumption 0.97 vs. 0.88 ml/(10 m·100 kg); $p=0.002$) and had slower gait speed and smaller range of motion (ROM) at the hip and knee joints ($p<0.05$, for all). Slower gait

speed and lower knee ROM in participants with knee pain and longer double support time and higher ankle ROM in participants without knee pain were associated with lower energetic efficiency ($p<0.05$, for all). Slower gait speed and lower knee ROM were correlates of knee pain and were found to mediate the association between age and oxygen consumption. Although knee pain is associated with a higher energetic cost of walking, gait characteristics associated with energetic efficiency differ by pain status which suggests that compensatory strategies both in the presence and absence of pain may impact gait efficiency.

Keywords Oxygen consumption · Knee pain · Energy efficiency in gait · Compensatory effort

Introduction

Previous studies suggest that metabolic energy demand during normal walking can be higher in older adults due to either increased mechanical work expenditure (Detrembleur et al. 2003) or decreased efficiency of mechanical work generation (Mian et al. 2006). Changes in gait characteristics that occur with aging and/or pathology have been intensively studied, but whether these changes account for impaired energetic efficiency, that is a higher energetic cost of walking, remains unknown (Inzitari et al. 2007; Kerrigan et al. 1998; Ko et al. 2011b). Prior studies have shown that older persons with slower habitual gait speed tend to consume more oxygen to walk the same distance than

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persons who walk faster, suggesting that at the same time as aerobic capacity declines with age, the energetic requirement needed for customary normal gait speed increases (Fiser et al. 2010). In addition, conceivably independent of changes in walking speed, physical impairments that tend to increase with age may contribute to the decline in energetic efficiency observed in late life. For example, knee pain in older adults may cause substantial limitation and disrupt complex motor strategies that minimize energetic requirement, making walking less energetically efficient. These changes may be particularly important in older persons because, given already limited energetic reserve, they may face high risk of mobility disability. On the other hand, if characteristic changes in gait induced by knee pain that reduce energetic efficiency in older persons could be identified, they could be targeted for intervention aimed at preventing disability progression.

In this study, oxygen consumption during normal pace walking and gait kinematics were examined in older adults with and without knee pain to elucidate the association between the energetic cost of walking and specific gait characteristics. For this aim, we explored the hypothesis that knee pain is responsible, at least in part, for the greater energetic cost of walking that occurs with aging (Schrack et al. 2012). To better understand the underlying mechanisms for this association, we examined specific gait parameters associated with knee pain (Ko et al. 2011a) and introduce those parameters as possible mediators of the relationship between age and energetic cost of walking.

Methods

Participants

Data are from 364 men and 170 women aged 60 to 96 years participating in the Baltimore Longitudinal Study of Aging (BLSA) who had a clinic visit between January 2008 and April 2012 and underwent evaluation in the gait laboratory and had measured oxygen consumption during a 2.5-min walk at usual pace in a tiled corridor. The BLSA is a continuous enrollment cohort study initiated in 1958 to study normative aging and currently supported by the Intramural Research Program of the National Institute on Aging, National Institutes of Health. Persons who had a hip or knee joint prosthesis, severe knee osteoarthritis, history of stroke or

Parkinson's disease, or unable to follow instructions and safely complete gait lab testing or the corridor walk task at their self-selected speed without using a walking aid were excluded. Knee pain was ascertained by highly trained nurse practitioners who used the following standard questions: "In the past 12 months, have you had knee pain lasting at least one month?" The BLSA protocol was approved by the Institutional Review Board of record at the time of data collection (MedStar Health Research Institute, Baltimore, MD or National Institute of Environmental Health Sciences, NC). Participants were given a detailed description of the study and consented to participate.

Energetic cost of walking/energetic efficiency

Energy expenditure was measured by indirect calorimetry using a Cosmed K4b2 portable metabolic analyzer (Cosmed, Rome, Italy) and calculated from the volume of oxygen consumed while walking at a self-selected usual pace for 2.5 min. The Cosmed unit uses a rubberized face mask and turbine for gas collection. Sustained walking energy expenditure was assessed during the warm-up component of the long-distance corridor walk, a validated measure of cardiorespiratory fitness in older adults (Simonsick et al. 2006). The participant was instructed to walk at his or her usual pace back and forth along a 20-m-long corridor marked by orange traffic cones. Readings from the first 1.5 min were discarded to account for adjustment to the workload, and the remaining readings were averaged to arrive at a single measure of the mean energy expended in milliliters of oxygen per kilogram of body weight per distance of 10 m. Thus, higher expenditure of oxygen can be interpreted as higher energetic cost of walking and lower energetic efficiency in gait (Richardson et al. 2014; Schrack et al. 2012).

Gait measurements

The procedure for the gait analysis performed in the BLSA gait laboratory has been described previously (Ko et al. 2011b). Briefly, participants were instrumented with 20 reflective markers placed at anatomical landmarks: anterior and posterior superior iliac spines, medial and lateral knees, medial and lateral ankles, toe (second metatarsal head), heel, and lateral malleoli over the mid-femur and mid-tibia. To avoid errors in hip joint calculation due to excessive adipose tissue of

overweight and obese participants, a tie band was used in the pelvic area, and the distance between left and right anterior superior iliac spines (ASIS) was measured manually. A Vicon 3D motion capture system with 10 digital cameras (Vicon 612 system, Oxford Metrics Ltd., Oxford, UK) measured the 3D locations of all markers on the landmarks of lower extremity segments (60-Hz sampling frequency).

After all markers were positioned on the skin and non-reflective, form-fitting spandex pants, participants were asked to walk across a 10-m-long gait laboratory walkway at self-selected speed (“like walking in the street”). The raw coordinate data of marker positions were digitally filtered with fourth-order zero-lag Butterworth filter with a cutoff at 6 Hz. For the present study, fundamental gait parameters included gait speed, double support time, and range of motion (ROM) for lower extremity joints (hip, knee, and ankle) in the sagittal plane (kinematics).

Statistical analysis

Characteristics of the study population and oxygen consumption were compared using general linear regression analysis and were reported as mean values and standard errors separately according to knee pain status (Table 1). Associations between energetic cost and gait parameters stratified by knee pain were explored by general linear regression models. All models were adjusted for age, gait speed (except when gait speed was the parameter of interest), sex, weight, and height (Table 2). Also, mediation analyses between age and oxygen consumption were considered to verify certain gait parameters as mediators (MacKinnon et al. 2007). Statistical significance was defined using a *p* value less than 0.05. Statistical analyses were performed with SAS 9.2 Statistical Package (SAS Institute, Inc., Cary, NC, USA).

Results

Participants with knee pain were older ($p<0.001$) and less energetically efficient (consumed more oxygen for the same distance walked) than those without pain (oxygen consumption 0.97 vs. 0.88 ml/(10 m·100 kg); $p=0.002$, Table 1). Compared to participants with no pain, those with knee pain had slower gait speed ($p=0.014$) and smaller range of motion (ROM) at the hip ($p=0.037$) and knee joints ($p=0.004$). In participants with knee pain, gait speed ($\beta=-0.165$, $p=0.018$) and knee ROM ($\beta=-3.944$, $p=0.035$) were negatively associated with oxygen consumption (Fig. 1); whereas in participants without knee pain, double support time ($p=0.009$) and ankle ROM ($p=0.005$, Table 2) were positively associated with oxygen consumption.

In a mediation analysis of the positive association between oxygen consumption and age ($p=0.003$), gait speed and knee ROM were found to be full mediators between age and oxygen consumption (because “age” was no longer significantly associated with oxygen consumption when speed and knee ROM were controlled for in step 4), while double support time was a partial mediator in the same model (because “age” was still significantly associated with oxygen consumption as was double support time in step 4, Table 3).

Discussion

Oxygen consumption normalized for weight and distance walked at usual normal pace was examined in older adults with and without knee pain to elucidate the association between specific gait characteristics and energetic efficiency; that is, the cost of walking in older adults. It is notable that participants with knee pain consumed more oxygen and therefore had lower energetic efficiency than participants without knee pain even

Table 1 Participant characteristics

	Participant characteristics	Without knee pain (<i>N</i> =278) Mean (SE)	With knee pain (<i>N</i> =86) Mean (SE)	<i>p</i> value
	Age, year	71.46 (0.51)	75.38 (0.92)	<0.001
	Sex, women/men	130/148	40/46	
Bold parameters indicate significance at $p<0.05$	Height, m	1.69 (0.54)	1.68 (0.98)	0.235
	Weight, kg	77.03 (0.91)	76.42 (1.64)	0.745
^a Adjusted for age, sex, height, weight, and gait speed	Oxygen, ml/(10 m·100 kg) ^a	0.88 (0.01)	0.97 (0.03)	0.002

Table 2 Gait parameter comparisons between participants with and without knee pain and associations between gait parameters and oxygen consumption

		Means and comparison		Association with O ₂ /kg/10 m	
		Mean (SE)	<i>p</i> value	β	<i>p</i> value
Gait speed, m/s	No pain	1.13 (0.01)	0.014	0.060	0.931
	Pain	1.07 (0.02)		−0.165	0.018
Double support time, s	No pain	0.21 (0.00)	0.423	0.034	0.009
	Pain	0.22 (0.00)		0.019	0.186
Range of motion (ROM)					
Hip, degree	No pain	38.96 (0.27)	0.037	2.331	0.115
	Pain	37.72 (0.52)		−2.653	0.105
Knee, degree	No pain	54.70 (0.31)	0.004	−2.401	0.157
	Pain	52.74 (0.59)		−3.944	0.035
Ankle, degree	No pain	24.15 (0.25)	0.438	3.954	0.005
	Pain	24.59 (0.50)		−1.613	0.296

Bold parameters indicate significance at $p < 0.05$

Gait speed model was adjusted for age, sex, height, and weight, while other models were adjusted for age, sex, height, weight, and gait speed

Fig. 1 Gait speed (a) and Knee ROM (b) in participants with and without knee pain as a function of oxygen consumption during normal walking (ml oxygen/10 m · 100 kg)

after adjusting for gait speed. As the prevalence of knee pain increases substantially with age, it is reasonable to hypothesize that knee pain might be responsible, at least in part, for the increase in energetic cost (i.e., decline in energetic efficiency) of walking that occurs with aging. To better understand the underlying mechanisms for this association, we examined specific gait parameters associated with knee pain and introduced those parameters as possible mediators of the relationship between age and energetic cost.

Interestingly, gait speed and knee ROM, which were slower and smaller, respectively, in participants with knee pain compared to participants without knee pain, were negatively associated with the energetic cost of walking only for participants with knee pain (Fig. 1). Previously reported negative associations between gait speed and oxygen consumption can be more specifically interpreted through the pain-related model in this study (Fiser et al. 2010). Higher oxygen consumption to regain required gait speed and knee rotation in older adults can be due to pain related pathology rather than just normal aging. These findings indicate the presence of energetic inefficiency in older adults who have pain.

Longer double support time and augmented ankle ROM were associated with higher oxygen consumption in participants without knee pain. Increased stability can be achieved with longer double support time, and knee strength can be supported through augmented ankle ROM (Ko et al. 2012). Thus, the increased energetic

Table 3 Mediation analysis between age and oxygen consumption with each gait parameter as a possible mediator

			Regression model for each model		Beta coefficient and <i>p</i> value	
Common			Step1	$O2 = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = 0.005$	($p = 0.003$)
For each mediator						
Gait speed, m/s			Step 2	$\text{Speed} = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = -0.011$	($p < 0.001$)
			Step 3	$O2 = \beta_0 + \beta_1 \text{ speed} + e$	$\beta_1 = -0.183$	($p = 0.003$)
			Step 4	$O2 = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ speed} + e$	$\beta_1 = 0.003$	($p = 0.067$), $\beta_2 = -0.123$ ($p = 0.077$)
Double support time, s			Step 2	$\text{Double Support} = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = 0.001$	($p < 0.001$)
			Step 3	$O2 = \beta_0 + \beta_1 \text{ DoubleSupport} + e$	$\beta_1 = 1.063$	($p < 0.001$)
			Step 4	$O2 = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ DoubleSupport} + e$	$\beta_1 = 0.003$	($p = 0.034$), $\beta_2 = 0.904$ ($p = 0.002$)
Hip ROM, degree			Step 2	$\text{Hip ROM} = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = -0.236$	($p < 0.001$)
			Step 3	$O2 = \beta_0 + \beta_1 \text{ HipROM} + e$	$\beta_1 = -0.005$	($p = 0.031$)
			Step 4	$O2 = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ HipROM} + e$	$\beta_1 = 0.004$	($p = 0.018$), $\beta_2 = -0.003$ ($p = 0.266$)
Knee ROM, degree			Step 2	$\text{Knee ROM} = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = -0.274$	($p < 0.001$)
			Step 3	$O2 = \beta_0 + \beta_1 \text{ KneeROM} + e$	$\beta_1 = -0.009$	($p < 0.001$)
			Step 4	$O2 = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ KneeROM} + e$	$\beta_1 = 0.002$	($p = 0.132$), $\beta_2 = -0.008$ ($p = 0.002$)
Ankle ROM, degree			Step 2	$\text{Ankle ROM} = \beta_0 + \beta_1 \text{ age} + e$	$\beta_1 = -0.151$	($p < 0.001$)
			Step 3	$O2 = \beta_0 + \beta_1 \text{ AnkleROM} + e$	$\beta_1 = 0.001$	($p = 0.739$)
			Step 4	$O2 = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ AnkleROM} + e$	$\beta_1 = 0.005$	($p = 0.001$), $\beta_2 = 0.004$ ($p = 0.183$)

Bold parameters indicate significance at $p < 0.05$

O2 oxygen consumption in 10 m walking normalized by weight ml/(10 m · 100 kg)

cost associated with gait parameters of temporal and ankle activity in participants without knee pain can be considered as possible compensatory factors.

Consistent with prior studies, energetic cost was higher with older age (Cunningham et al. 1982; Detrembleur et al. 2003; Mian et al. 2006). To identify specific gait parameters associated with energetic inefficiency in older adults, mediation analyses were performed in the regression model of age and oxygen consumption with each gait parameter considered as a possible mediator. By showing significant associations in the sequential regression models, between age and gait parameter (step 2) and gait parameter and oxygen consumption (step 3), gait speed and knee ROM were found to be full mediators, which may account for increasing energetic inefficiency with older age (Table 3).

This study has limitations. Gait lab variables in this study were limited to measures in the sagittal plane and excluded kinetics. Thus, medial-lateral rotations of lower extremities, which are not dominant in normal walking but still worthy to consider, were not included.

Kinetic gait variables, if considered in the future study, will provide the opportunity to compare mechanical energy and metabolic energy during walking. To evaluate the presence of a causal relationship between gait patterns and the energetic cost of walking will require longitudinal data which is not yet available of sufficient numbers of participants.

In conclusion, findings from the present study confirm existing evidence of greater energetic inefficiency in older adults and extend the findings to persons with and without knee pain and identify specific gait mechanisms associated with knee pain. In older adults with knee pain, energetic inefficiency was associated with slower gait speed and smaller knee ROM, whereas energetic inefficiency was associated with longer double support time and greater ankle ROM in older adults without knee pain. Thus, from a biomechanical point of view, greater energetic cost of walking in older adults can stem from pain-related declines in gait speed and knee ROM or due to compensatory efforts in double support time and ankle kinematics. Evaluation of oxygen consumption during normal pace walking over a

standardized distance may facilitate detection of subtle and specific gait abnormalities and modifications in older adults with different pathological conditions. This approach may aid the identification of condition-specific targets for walking habilitation in older adults at risk of mobility decline.

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Conflict of interest All the authors declare that no financial or personal relationships were conducted with other people or organizations that could inappropriately influence or bias this work.

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