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Effects of aging on mechanical efficiency and muscle activation during level and uphill walking

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ABSTRACT

Purpose: The metabolic cost of walking is greater in old compared to young adults. This study examines the relation between metabolic cost, muscular efficiency, and leg muscle co-activation during level and uphill walking in young and older adults. *Procedures:* Metabolic cost and leg muscle activation were measured in young (22.3 ± 3.6 years) and older adults (74.5 ± 2.9 years) walking on a treadmill at six different slopes (0.0–7.5% grade) and a speed of 1.3 m s^{-1}. Across the range of slopes, 'delta mechanical efficiency' of the muscular system and antagonist muscle co-activation were quantified. *Main findings:* Across all slopes, older adults walked with a 13–17% greater metabolic cost, 12% lower efficiency, and 25% more leg muscle co-activation than young adults. Among older adults, co-activation was weakly correlated to metabolic cost ($r = .233$) and not correlated to the lower delta efficiency. *Conclusion:* Lower muscular efficiency and increased leg muscle co-activation contribute to the greater metabolic cost of uphill slope walking among older adults but are unrelated to one another.

1. Introduction

Impaired mobility and reduced walking performance are closely associated with increased mortality among older adults (Studenski et al., 2011). A subtle yet important characteristic of impaired walking performance is an increase in metabolic energy consumption. This greater metabolic cost of walking likely increases muscle fatigue during walking and may contribute to less participation in walking exercise among older adults. During level and uphill walking, older adults consume ∼7–20% more metabolic energy to walk a given distance than young adults (Hortobagyi et al., 2011; Martin et al., 1992). Among several factors, the metabolic cost of performing mechanical work; i.e. muscular efficiency is a key determinant of the metabolic cost of walking (Cavagna and Kaneko, 1977; Donelan et al., 2002). Even though older adults perform a similar amount or even less external mechanical work during level and uphill walking than young adults (Franz et al., 2012; Mian et al., 2006; Ortega and Farley, 2007), whether they are performing that mechanical work as efficiently as young adults is uncertain. One factor that may contribute to lower mechanical efficiency of the muscular system during walking in older adults is increased co-activation of antagonist leg muscles (Mian et al., 2006).

In a variety of movements including walking, older adults use more co-activation of antagonist muscle pairs than young adults (Franz and Kram, 2012; Hortobagyi et al., 2011; Mian et al., 2006; Peterson and Martin, 2010). When walking on level ground and at a 6.0% uphill slope, co-activation of antagonist leg muscles has been shown to be 30–50% greater in older adults and to have a low to moderate association to metabolic cost (Hortobagyi et al., 2011; Mian et al., 2006; Peterson and Martin, 2010). Although these prior studies showed that metabolic cost and co-activation are greater in older walkers, they did not quantify the mechanical efficiency of the muscular system or its relation to co-activation of antagonist muscle. {Hortobagyi, 2011 #7312} Thus, it remains unclear how age-related changes in antagonist leg muscle co-activation during walking may be related to the mechanical efficiency and changes in metabolic energy consumption of the muscular system across a range of uphill slopes.

The purpose of the present study was to determine if the greater metabolic cost of level and uphill walking observed in older adults is related to reduced mechanical efficiently as a result of using greater co-activation of antagonist leg muscles than young adults. We hypothesized that across a range of slopes, older adults increase metabolic energy consumption more than young adults and thus perform mechanical work less efficiently during walking.

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We also hypothesized that antagonist leg muscle co-activation in older adults would be related to greater metabolic cost and reduced mechanical efficiency of walking. To test these hypotheses, we quantified metabolic cost, 'delta mechanical efficiency' of the muscular system (Gaesser and Brooks, 1975) and antagonist leg muscle co-activation as young and older adults walked at a constant speed up progressively steeper slopes. To our knowledge this is the first study to investigate muscular efficiency of steady-state level and uphill walking in older adults and its relation to leg muscle co-activation.

2. Methods

2.1. Participants

Thirteen healthy young adults (six male, seven female) and twelve healthy older adults (six male, six female) with no known orthopedic, neurological, or cardiovascular disease were recruited for this study. All subjects were physically active with no history falls in the year prior to participating in the study. Young and older subjects were similar in height, body mass, body mass index (BMI), and lean tissue mass (Table 1). Despite older subjects having greater body fat and a lower resting metabolic rate than young subjects, no subject characteristic other than age had a statistically significant influence on the dependent variables. All subjects gave their written informed consent before participating in the study. The University of Colorado Institutional Review Board approved this protocol.

2.2. Protocol

Subjects participated in two testing sessions. In the first session, we measured each subject's height, leg length, and body composition. Subjects were then familiarized to level and uphill treadmill walking (0–7.5% grade) at the moderate speed of 1.3 m s^{-1} for a minimum of 30 min (Wall and Charteris, 1981). In the second session, each subject performed one resting trial and six walking trials in order for us to calculate delta efficiency and lower limb co-activation during walking across a range of slopes. In this session, we first measured resting metabolic rate as subjects stood quietly for seven minutes. Each subject then walked at 1.3 m s^{-1} on a motorized treadmill (Model 18–60, Quinton Instruments, Seattle, WA, USA) at six different slopes (0.0%, 1.5%, 3.0%, 4.5%, 6.0%, 7.5% grade) in randomized order as we collected metabolic, electromyography (EMG), and stride frequency data. The order of slopes was also counterbalanced across subjects.

For the walking trials, each subject performed one seven-minute trial per slope with a 3–5 min rest period between trials. During the last three minutes of each seven-minute trial, we collected the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using indirect calorimetry, leg muscle activation using EMG, and stride frequency. Average stride frequency was calculated from the time required to take 30 strides and was determined during the last 2 min of each trial.

Table 1
Participant characteristics with statistics for comparison of young versus older adults. Values are mean ± SD.

	Young (n = 13)	Old (n = 12)
Age (years)	22.3 ± 3.7	74.7 ± 3.1
Height (m)	1.76 ± 0.10	1.69 ± 0.09
Leg length (m)	0.90 ± 0.07	0.89 ± 0.05
Body mass (kg)	65.9 ± 9.3	66.8 ± 14.3
Lean tissue mass (kg)	50.8 ± 11.5	45.5 ± 10.2
Body fat (% body mass)	20.1 ± 6.8	28.0 ± 4.5*
Body mass index (kg/m^2)	21.2 ± 1.8	23.1 ± 2.9
Standing metabolic rate (W kg^{-1})	1.64 ± 0.28	1.39 ± 0.15*

* Indicates a significant age difference ($p < .05$).

2.3. Metabolic energy consumption

We measured sub-maximal steady-state $\dot{V}O_2$ (mlO$_2$ min^{-1}) and $\dot{V}CO_2$ (mlCO$_2$ min^{-1}) using open-circuit indirect calorimetry (Physio-Dyne Instruments CO., Quogue, NY, USA) to calculate metabolic power consumption. We calculated average metabolic power per kilogram body mass (W kg^{-1}) (Brockway, 1987) using the average $\dot{V}O_2$ and $\dot{V}CO_2$ for the last two minutes of each trial when the $\dot{V}O_2$ indicated that metabolic steady-state had been achieved. For each walking trial, we calculated net metabolic power consumption (W kg^{-1}) by subtracting the standing metabolic rate from gross metabolic rate during walking.

2.4. Delta efficiency

We determined delta efficiency for each subject from the increase in net mechanical power output and the increase in net metabolic power consumption across the range of uphill slopes (Gaesser and Brooks, 1975). Net mechanical power output represents the minimum power required to lift the body during uphill walking at a given speed and was calculated from the slope and speed of the treadmill using a standard equation (Brooks et al., 1996). Thus, the six slopes (0.0%, 1.5%, 3.0%, 4.5%, 6.0%, 7.5% grade) corresponded to six net mechanical power levels including 0.0, 0.19, 0.38, 0.57, 0.76, and 0.95 W kg^{-1}. We calculated each subject's delta efficiency from the inverse slope of the regression line representing the relationship of mechanical power output to net metabolic power consumption across the range of slopes (Gaesser and Brooks, 1975). Delta efficiency represents the mechanical power output achieved for each watt of metabolic power consumption expressed as a percent.

2.5. Electromyography (EMG)

To quantify the effects of age and uphill slope on muscle activity, we measured surface EMG signals (Noraxon, Scottsdale, AZ) using International Society for Electrophysiology and Kinesiology standard procedures (Merletti et al., 1999). The skin over the lateral gastrocnemius (LG), soleus (SOL), tibialis anterior (TA), vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF) muscles and lateral malleolus (ground electrode) of the right leg were shaved and abraded with electrode preparation gel prior to placing bipolar Ag/AgCl surface electrodes (10 mm diameter discs by Noraxon USA, Inc., Scottsdale, AZ) over each muscle belly. Two electrodes were place at the center of each muscle in parallel with muscle fiber orientation and at an inter-electrode distance of 20 mm. The EMG signals were collected at a rate of 1000 Hz and pre-amplified with a gain of 1700 (input impedance >100 MΩ, common mode rejection ratio >110 dB at 60 Hz). Using standard methods (Criswell and Cram, 2011), we verified that electrode impedance was less than 5000 Ω and that the cross talk between muscles was negligible. After data collection, raw EMG data was band-pass filtered (6th order Butterworth) to retain frequencies between 10 and 500 Hz.

For each trial, we processed ten consecutive strides of EMG data in two stages using a custom Matlab program (MATLAB, R2012b, MathWorks, Inc., Natick, MA). First, a temporal analysis was performed to determine when muscles were active in the stride cycle and, second, an amplitude analysis was performed to quantify the magnitudes of muscle activation and antagonist muscle co-activation.