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Mechanical energy transfers across lower limb segments during stair ascent and descent in young and healthy older adults

Alison C. Novak [a], Qingguo Li [b], Shuozhi Yang [b], Brenda Brouwer [a,*]

[a] School of Rehabilitation Therapy, Queen's University, Kingston, ON, Canada
[b] Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON, Canada

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ABSTRACT

Older adults present with altered movement patterns during stair negotiation although the extent to which modifications in pattern and speed influence mechanical efficiency is unknown. This study evaluated mechanical energy transfers attributed to active force production during stair negotiation in young and older adults to provide insight into age-related changes in mechanical efficiency. Secondary analysis on data obtained from 23 young (23.7 ± 3.0 years) and 32 older adults (67.0 ± 8.2 years) during self-paced stair ascent and descent was conducted. Mechanical energy expenditures (MEE) during concentric transfer, eccentric transfer and no-transfer phases were determined for the ankle, knee and hip power profiles in the sagittal plane. Mechanical energy compensations (MEC) were also determined at each joint. During ascent, MEEs were similar for young and older adults although older adults compensated ankle muscles to a lesser extent during concentric muscle action. Controlling for cadence eliminated this difference. During descent, older adults demonstrated lower energy expenditures at the ankle and hip and similar expenditures at the knee compared to young adults. Changes in joint MEE in the older group resulted in reduced energy compensation at the ankle during concentric and eccentric activity and at the knee during eccentric activity. These age-related differences in mechanical energy transfers and related adjustments in MEC were not a function of the slower cadence in older adults and suggest a loss in mechanical efficiency. These results provide a benchmark against which physical impairments in older adults may be explored.

1. Introduction

Muscles generate or absorb mechanical energy (power) via concentric or eccentric contractions, respectively. Mechanical energy can also be transferred between adjoining segments via muscle activation (i.e. active energy transfer) if the two segments are rotating in the same direction [1,2]. For example, during walking, the foot and shank rotate in the same direction during push-off resulting in energy being transferred to the foot segment which partially compensates the work done by the plantarflexor muscles. In this case, inter-segmental energy transfer assists with propulsion thereby improving efficiency. One way to evaluate inter-segmental energy transfers and the efficiency of mobility is to consider mechanical energy expenditure, which is the net amount of energy produced by the muscles controlling the movements (the net result of agonist, synergist and antagonist activity at a joint), and the mechanical energy compensations. The latter reflects the proportion of active contractile muscle energy compensated by inter-segmental energy transfer [3]. By partitioning mechanical energy expenditure as a function of concentric/eccentric sources for each joint and transfer/no-transfer compensations, McGibbon and colleagues have quantified altered motor control strategies attributable to age and pathology [3–5]. Such insight into the efficiency of movement has provided valuable information about movement control and compensatory strategies associated with level ground walking [1,3–5] but other types of gait including stair negotiation remain unexplored.

Beyond 50 years of age measurable declines in joint mobility and strength result in altered or adapted movement patterns, particularly during higher demand physical activities [6–11]. Studies have reported a redistribution of the moments generated at lower limb joints during stair negotiation in older adults compared to young adults, reflecting an attempt to maintain muscle activity within safe, comfortable limits [10–12]. We have shown that older adults produce higher net support moments in late stance than their younger counterparts; possibly to enhance stability when transitioning from single to double support [12]. Further, older adults generally ascend and descend stairs more slowly [13] than young adults. It seems reasonable to speculate that such modifications in pattern and speed would influence mechanical efficiency by altering

* Corresponding author at: Motor Performance Laboratory, School of Rehabilitation Therapy, Queen's University, 31 George Street, Kingston, ON, K7L 3N6, Canada. Tel.: +1 613 533 6079; fax: +1 613 533 6015.
E-mail address: brouwerb@queensu.ca (B. Brouwer).

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the energy transferred across segments and/or the amount of muscle energy generated or absorbed when no inter-segmental transfer takes place. However, the extent to which this occurs or if localized deficits in energy flow can be compensated elsewhere is unknown. Determining mechanical energy expenditures and the proportion of muscle energy compensated by inter-segmental energy transfer is an important step toward understanding the energy costs associated with stair negotiation in older adults and is a key consideration for mobility independence.

The purpose of this study was to evaluate mechanical energy transfers attributed to the net effect of active muscular force production (active transfers) during stair negotiation in young and older adults. Based on the evidence cited above, we hypothesize that healthy older adults will demonstrate altered inter-segment energy transfer during stance compared to young adults.

2. Methodology

A secondary analysis of biomechanical data obtained from 23 young (23.7 ± 3.0 years) and 32 older adults (67.0 ± 8.2 years) was performed. Details about the subjects and study protocol are described elsewhere [12]. Briefly, self-reported healthy subjects were recruited from the university and local communities and all were able to ascend and descend a flight of stairs independently without the use of a handrail. The protocol was approved by the university's research ethics board and all subjects provided informed consent. Subjects completed three ascent and three descent self-paced trials without a handrail on a specially constructed four-step staircase of standard dimensions (rise = 15 cm; run = 26 cm) with a forceplate forming the centre of the second step. Optoelectric cameras tracked clusters of infrared emitted diodes (Optotrak 3020, Northern Digital Inc., Waterloo, ON) secured to the subjects' lower limbs to provide the three dimensional spatial coordinates of lower limb joints and segments. The data were synchronized with the force plate data using commercial software (Visual 3D, C-Motion, Inc., Germantown, MD), and segment kinematics and joint moments were computed using an inverse dynamics approach based on a seven segment model. All data were resolved in the global coordinate system and kinetic variables were normalized to body mass. Data are reported for the dominant limb only (18 young and 31 older adults were right leg dominant) and normalized to 100% of the stance phase.

2.1. Mechanical energy calculations

For rotational motion, that is, motion about a joint axis, the power of the proximal (P_p) and distal (P_d) ends of the distal and proximal articulating segments, respectively was calculated as the product of the muscle moment (M_j, where $M_j^p = -M_j^d$) and the segment's angular velocity (ω). At a given joint (j), the net muscle power (P_j, W/kg) is the summation of the power at the endpoints of adjoining segments:

$$P_j = P_p + P_d = M_{jp}w_p + M_{jd}w_d$$

where P = muscle power, W/kg; M = muscle moment, N m/kg; ω = angular velocity, rads/s.

The sign and relative magnitudes of the power terms indicate whether the muscles generate or absorb energy and whether the energy is transferred across segments [1,3–5]. When segments on either side of the joint rotate in opposite directions, muscles either generate or absorb power entirely. If the adjoining segments rotate in the same direction, energy transfers can be directed proximally ($P_d < 0$ and $P_p > 0$) or distally ($P_d > 0$ and $P_p < 0$) to facilitate muscular effort [1,3–5]. Table 1 summarizes all possible energy transfers and their directions that can occur across segments linked at a joint.

To determine the net amount of energy produced by the system, the mechanical energy expenditure (MEE) was calculated using the method described by McGibbon and colleagues [3–5]. The net joint MEE was calculated separately for concentric transfer conditions ($MEE_C = MEE_{condition3} + MEE_{condition5}$), eccentric transfer conditions ($MEE_E = MEE_{condition4} + MEE_{condition6}$) and no transfer conditions ($MEE_N = -MEE_{condition1} + MEE_{condition2}$); where conditions are those described in Table 1 and MEE is the integral of the net joint power curve segmented by power condition. In addition to the net joint MEE, mechanical energy compensation (MEC), defined as the proportion of muscle energy compensated by inter-segmental energy transfer [3], was determined for the periods of concentric and eccentric activity at each joint. The MEC is the ratio of the net joint MEE for each contraction type (concentric, eccentric) and the total absolute MEE. MEC is always zero when no segmental transfer occurs and therefore is not reported for those conditions.

2.2. Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for all outcome measures (SPSS version 17.0, San Rafael, CA). Independent samples *t*-tests comparing groups were conducted for the MEE and MEC measures at each joint (ankle, knee and hip) and for stair ascent and descent. A significance level of $p < 0.05$ was adopted for all analyses.

3. Results

Cadence differed significantly by group ($p < .031$) during stair ascent (young adults: 102.50 ± 8.86 steps/min; older adults: 94.76 ± 13.03 steps/min) and descent (young adults: 110.64 ± 10.24 steps/min; older adults: 103.68 ± 15.64 steps/min).

Table 1
Summary of the power flow conditions that determine the energy transfer between adjoining segments (modified from McGibbon et al. [3], Robertson and Winter [1]). The relative velocities of the segments, power flow conditions and net joint power determine transfer of energy, direction and the type of muscle contraction, respectively.

	Condition	Muscle moment	Angular velocity: Proximal	Angular velocity: Distal	Power flow	Type of contraction	Description
Segments rotating in opposite directions	1	$M_j^p > 0$	$\omega^p > 0$	$\omega^d < 0$	$P_p > 0$, $P_d > 0$, $P_j > 0$	Concentric	All power is generated by the muscles; no transfer occurs
		$M_j^p < 0$	$\omega^p < 0$	$\omega^d > 0$			
	2	$M_j^p > 0$	$\omega^p < 0$	$\omega^d > 0$	$P_p < 0$, $P_d < 0$, $P_j < 0$	Eccentric	All power is absorbed by the muscles; no transfer occurs
		$M_j^p < 0$	$\omega^p > 0$	$\omega^d < 0$			
Segments rotating in same direction	3	$M_j^p > 0$ $M_j^p < 0$	$\omega^p > 0$ $\omega^p < 0$	$\omega^d > 0$ $\omega^d < 0$	$P_p > 0$, $P_d < 0$, $P_j > 0$	Concentric	Power generated (concentric) or absorbed (eccentric) and proximally directed (transferred from distal to proximal)
	4	$M_j^p > 0$ $M_j^p < 0$	$\omega^p > 0$ $\omega^p < 0$	$\omega^d > 0$ $\omega^d < 0$	$P_p > 0$, $P_d < 0$, $P_j < 0$	Eccentric	
	5	$M_j^p > 0$ $M_j^p < 0$	$\omega^p < 0$ $\omega^p > 0$	$\omega^d < 0$ $\omega^d > 0$	$P_p < 0$, $P_d > 0$, $P_j > 0$	Concentric	Power generated (concentric) or absorbed (eccentric) and distally directed (transferred from proximal to distal)
	6	$M_j^p > 0$ $M_j^p < 0$	$\omega^p < 0$ $\omega^p > 0$	$\omega^d < 0$ $\omega^d > 0$	$P_p < 0$, $P_d > 0$, $P_j < 0$	Eccentric	

M, muscle moment; ω, angular velocity; P, power; j, joint; p, proximal segment; d, distal segment.