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Energy flow analysis of the lower extremity during gait in persons with chronic stroke

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

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

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ABSTRACT

Background: A decline in walking capacity and high energy cost can limit mobility following stroke. Mechanical energy exchange between lower limb and trunk segments can reflect gait inefficiencies, but reveals little about active energy flow between adjacent segments through muscle actions. This study evaluated mechanical energy expenditures (MEEs) during walking in stroke and healthy groups to understand movement control and explore the impact of walking speed on mechanical energy exchanges.
Methods: Thirteen adults with hemiparesis and six healthy controls walked at self-selected speed. Power curves for each lower limb joint were segmented into concentric and eccentric sources of muscle power and transfer/no-transfer modes to calculate MEEs during stance.
Findings: MEEs were lower in the stroke group on the affected side compared to the less affected side and compared to controls. Specifically, the affected plantarflexors transferred less energy distally via concentric action in late stance compared to the less affected side. However, the stroke group generated greater energy at the ankle in the absence of transfer compared to controls. Less concentrically transferred energy through midstance and absorbed in late stance was evident by the knee extensors bilaterally in stroke. At the hip, the total energy (no transfer) was reduced on the affected side. Classifying stroke subjects by walking speed (<.6 m/s, >.6 m/s) revealed disruptions in harnessing energy through motion and transfer energy across segments in the slower group.
Interpretation: The limited ability of those with stroke to exploit intersegmental energy transfer to optimize efficiency may limit endurance and functional independence.

1. Introduction

A decline in walking capacity and high energy cost can limit endurance and independence [1]. Using a kinematic approach to quantify the energy costs of walking, Olney et al. [2] identified abnormalities in mechanical energy profiles and deficiencies in energy conserving exchanges between lower limb segments as indicative of gait inefficiencies in stroke. The approach however revealed little about muscle generated energy flow; that is, the mechanical energy transferred between adjoining segments via active muscle contraction. Kinetic studies describing the net joint powers and the energy absorbed and generated by muscles have demonstrated abnormal power profiles and contribute to our understanding of how altered walking patterns in stroke relate to the interaction of the work performed by different muscle groups [3–5]. The muscle generated energy transfer and exchange between segments however, remains unaddressed yet this interplay is critical to evaluating the efficiency of progression [6].

Healthy individuals demonstrate consistent patterns of energy exchange, likely optimizing metabolic energy consumption [7]. The amount of mechanical energy generated and absorbed at individual joints is associated with cadence [6]. Further, the relative energy contribution of the knee and hip increase, whereas that of the ankle decreases as cadence increases; a finding that the authors note is consistent with the influence of gait speed [6]. Following stroke, gait speed is abnormally slow which could impact intersegmental energy exchange via the muscles and, in combination with residual weakness, the ability to effectively

* Corresponding author at: Motor Performance Laboratory School of Rehabilitation Therapy, Queen's University, 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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exchange energy between limb segments may be further compromised. The extent to which this occurs is unknown and it is unclear whether joint specific deficits in energy flow can be compensated elsewhere.

Analyzing intersegmental energy flow in terms of the mechanical energy generated, absorbed or transferred via active muscles has served to identify compensatory patterns of movement in aging adults [8–10]. Similar analysis in stroke may provide insight into the mechanical efficiency of their gait whilst providing insight of the nature and origin of gait inefficiencies. The purpose of this study was to examine the mechanical energy expenditures (MEE) during walking in chronic stroke and healthy adults. A secondary objective was to explore if MEE patterns were reflective of walking speed.

2. Methods

2.1. Subjects

Thirteen subjects (10 males) with hemiparesis secondary to stroke an average of 44 months prior and ranging in age from 29 to 80 years (mean = 59.1 (18.3) years) participated (mean weight = 81.8 (14.4) kg; mean height = 158.3 (48.1) cm). All self-reported residual unilateral lower limb weakness. Four subjects were left side affected, nine subjects were right side affected. Six healthy subjects (four males) aged 50–73 years (mean = 60.2 (7.7) years) served as a comparison group (mean weight = 78.3 (15.3) kg; mean height = 176.3 (6.9) cm). Subjects were recruited from the community and formed a sample of convenience. The protocol was approved by the university's research ethics board and all participants provided their informed consent.

2.2. Gait analysis

Kinematic and kinetic data were collected as individuals walked at their self-selected pace (no aids) on an 8-m long walkway with two force platforms (AMTI, Newton, MA, USA) embedded at the center. Two optoelectric cameras (Optotrak 3020, Northern Digital Inc., Waterloo, ON) were positioned on either side of the walkway for bilateral motion capture (for full details see [4,5]). Briefly, rigid clusters of four markers (infrared emitting diodes, IREDs) were secured bilaterally over the midfoot, midshank, and midthigh and a fin positioned over the sacrum projected outward to track the pelvis. Subjects were instructed to walk back and forth several times such that three successful trials were obtained. A successful trial was defined one in which the subject cleanly contacted the force plate and all markers were detected. Following the walking trials, subjects were asked to stand in a neutral posture while virtual landmarks approximating the distal and proximal ends of each segment were defined using a probe embedded with IREDs having a fixed orientation to the tip. This enabled the determination of joint centers, segment lengths and rotational axes. Segmental inertial properties were determined using Dempster's regression equations.

Data were resolved in the global coordinate system and kinetic variables were normalized to body mass. All data were analyzed for the stance phase of gait only.

2.3. Data analysis

Joint powers were calculated for the endpoints of adjoining segments. Using a mechanical energy approach [8–15] the power curves for each lower limb joint were segmented into regions of concentric and eccentric sources of muscle power and transfer/no-transfer conditions. This permitted calculation of MEEs for no transfer (MEE_N, adjoining segments rotate in opposite directions), and transfer conditions via active concentric muscle action (adjoining segments rotate in the same direction, concentric energy transfer (MEE_C), and via eccentric muscle action, eccentric energy transfer (MEE_E)). MEEs were determined at the ankle, knee and hip joints of the affected (Aff) and less affected (LAff) sides in stroke and the right side in healthy controls.

Descriptive statistics (means and standard deviations) were calculated for all outcome measures (SPSS version 17.0, San Rafael, CA, USA). Independent samples *t*-tests compared groups (stroke vs. control; Aff vs. control; LAff vs. control) and paired samples *t*-tests compared sides (Aff vs. LAff) for the stroke group (significance level of $p < .05$). Levene's test for equal variances was appropriately applied for all analyses. To explore whether those with stroke who walked more slowly demonstrate reduced efficiency compared to faster walkers, the MEEs associated with subgroups were compared. The cut-off speed of .6 m/s was based on previous literature [16]. Above this speed stroke subjects walked with substantial increases in generated power by the ankle and hip musculature compared to slower walkers.

3. Results

As expected, control subjects walked faster (mean (SD) = 1.2 (.1) m/s) than the stroke group (mean (SD) = .6 (.2) m/s) and showed little within group variation ($p < .001$).

Comparing groups, MEE magnitudes were generally lower in stroke on the affected side. The Aff side plantarflexors transferred less amount of energy distally via concentric action (MEE_C) in late stance (~80–100% of stance) compared to the LAff side ($p = .001$). Also a higher amount of energy was absorbed at the ankle during the no-transfer phase (MEE_N) compared to controls, who demonstrated little to no energy expended in the absence of transfer ($p < .042$). Less energy was transferred concentrically (MEE_C) via both the Aff and LAff knee extensor muscles through

Table 1
Mechanical energy expenditures (MEEs) (J/kg*100) of the ankle, knee and hip during the stance phase of gait (mean (SD)) for active concentric and eccentric transfer conditions.

	Affected side, stroke			Less affected side, stroke			
	All stroke (n = 13)	Slow group (<.6 m/s) (n = 6)	Fast group (>.6 m/s) (n = 7)	All stroke (n = 13)	Slow group (<.6 m/s) (n = 6)	Fast group (>.6 m/s) (n = 7)	Control (n = 6)
Ankle							
MEE_C	9.5 (7.3)[b]	5.8 (5.1)	12.6 (7.7)	23.1 (9.6)[b]	20.9 (9.8)	25.1 (9.7)	15.9 (7.4)
MEE_E	12.5 (7.1)	7.4 (6.5)	16.8 (4.2)	15.5 (6.5)	14.1 (8.5)	16.8 (4.4)	17.5 (7.5)
Knee							
MEE_C	4.9 (1.6)[a]	4.4 (1.7)	5.3 (1.4)	3.9 (2.6)[a]	3.3 (2.4)	4.4 (2.8)	7.9 (4.3)[a]
MEE_E	3.0 (1.4)	3.6 (1.3)	2.5 (1.4)	4.0 (4.6)	6.6 (6.1)	1.8 (1.0)	4.0 (1.9)
Hip							
MEE_C	5.3 (5.2)	3.9 (3.4)	6.5 (6.4)	5.1 (2.3)	5.6 (2.4)	4.7 (2.4)	7.7 (6.6)
MEE_E	1.4 (2.1)	1.4 (1.8)	1.4 (2.4)	.5 (.3)	.6 (.3)	.5 (.3)	2.8 (3.6)

MEE_C, concentric energy transfer condition; MEE_E, eccentric energy transfer condition.
[a] Indicates significant difference between groups (affected side stroke vs. control; less affected side stroke vs. control).
[b] Indicates significant difference between sides (affected vs. less affected).