ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

PENDULAR ENERGY TRANSDUCTION WITHIN STEP IN STROKE SUBJECTS IS DEPENDENT OF WALKING SPEED

[1,2]Gustavo Balbinot and [2,3]Clarissa Pedrini Schuch
[1]Department of Physical Education/ Federal University of Rio Grande do Sul, Brazil
[2]Department of Neuroscience/ Federal University of Rio Grande do Sul, Brazil
[3]Faculty of Medicine/ University of Ottawa, Canada
email: gustavo.balbinot@hotmail.com

SUMMARY
Results indicated that stroke group showed higher vertical Body Center Of Mass (BCM) oscillation and lesser BCM forward kinetic mechanical energy (E_{kf}) oscillation, as expected. Furthermore, stroke group showed ≈11% higher energy recovery within step (R_{int}) with the affected lower limb at slow speeds of walking (p=0,047) and ≈10% higher R_{int} with the unaffected lower limb at higher speeds of walking (p=0,045). These results provide insights to a better understanding of how mechanical energy and energy recovery affects gait in stroke patients and allows develop new therapeutic and physical interventions, such as, biofeedback instrumented treadmills for gait training.

INTRODUCTION
Ischemic stroke results from reduction in cerebral blood flow and triggers a cascade of biochemical events such as glutamatergic excitotoxicity, peri-infarct depolarizations, inflammation and programmed cell death [1]. This upper motor neuron injury remains the third leading cause of death in development countries [2]. After the ischemic episode around 80% of survivors live with some kind of sensory motor inability and generally a hemiparetic gait pattern appears. The main clinical features of stroke are motor impairments, such as, paresis, excessive muscle co-activation and spasticity, as well as changes in passive properties of muscles [3, 4]. Besides, abnormal kinematic patterns cause decreased range of motion and, consequently, reduction of walking speed [5, 6]. These neurological impairments lead to an increase in metabolic energy cost during walking. An essential question to the functionality in locomotion relates to total energy cost for this activity. Modifications in mechanics influence energy cost of locomotion. Minimization of energy expenditure has long been considered a fundamental characteristic of walking. This line of reasoning has led researchers to examine mechanism of energy conservation in persons with walking disabilities [7]. Human locomotion, when analyzed by BCM displacement, is influenced by two mechanical energies: gravitational potential energy (E_p) and kinetic energy (E_k) [8, 9]. The objective of this study was to compare mechanical energy and energy recovery between healthy and stroke subjects. This understanding has clinical implications for therapies aiming to improve walking economy in patients with gait disorders that affect center of mass displacement and metabolic cost [11].

METHODS
Study population
Six chronic hemiparetic post-stroke patients (5 men and 1 woman; mean age: 63±11 years; mean height: 168±8 cm; mean weight: 79±10 kg) were recruited from rehabilitation unities situated in Porto Alegre, Brazil between March and December 2010. Ten healthy age-matched subjects (six men and four women; mean age: 58±7 years; mean height: 168±7 cm; mean weight: 72±6 kg) were also evaluated and served as control group. Patients were able to walk independently and scored 100% for the Barthel Index [12]. Stroke patients were also evaluated by Ashworth scale and they scored 1. They were also able to walk on a treadmill for sufficient time to complete mechanical and metabolic analysis and had no other major medical disorders. International Physical Activity Questionnaire (IPAQ) was used to pair healthy subjects and patients about the level of physical activity [13]. This study was approved by the institutional ethics committee and all participants were made aware of potential risks before signing an informed consent form.

Experimental protocol
Measurements were made whilst participants walked on a motor-driven treadmill (BH fitness Explorer ProAction) at five different speeds: preferred walking speed (PWS); two speeds above PWS (1PWS and 2PWS) and two speeds bellow PWS (-1PWS and -2PWS), randomly. For control group the PWS was 3.0 $km.h^{-1}$ and for stroke group was 2.3 $km.h^{-1}$. Based on studies that assess pathological locomotion, hemiparetic subjects show limitation at the walking speed, which is between 1.69-3.6 $km.h^{-1}$ [5, 14]. So, PWS increment or decrement were encompassed in this range, thus the speed of walking ranged between 1.3-3.3 $km.h^{-1}$ for the stroke group and for the control group the speed ranged between 1-4.2.0 $km.h^{-1}$.

Mechanical energy and pendular energy transduction within step
Gait was assessed by three-dimensional (3D) analysis. Segmental kinematics were measured with a four-camera system (JVC GR-DVL 9800 – JVC Company of America, Wayne, New Jersey, USA; sampling rate of 50 Hz for 60s). Eighteen reflective markers (15 mm diameter) were attached bilaterally to landmarks which defined segment extremities: immediately anterior to tragus of ear, shoulder, elbow, wrist, greater trochanter, lateral epicondyle of femur, lateral maleolus, calcaneous, and 5th metatarsal head [15, 16]. Data were filtered with low-pass, fourth-order Butterworth filter and the cutoff frequency was determined by residual analysis of Winter [17]. Anthropometric data of 11 rigid segments (head-trunk, upper arms, lower arms, thighs, shanks, feet) were used to compute position of the segments and BCM [18, 19]. Linear and angular velocity of each segment and linear velocity of BCM was determined by mathematical derivative. Computational algorithms were constructed to calculate the mechanical energy and R_{int} using Labview® (version 8.5, National Instruments, Austin, USA), as follows:

$$E_{ext}(t) = \frac{1}{2}Mv(t)_f^2 + \frac{1}{2}Mv(t)_v^2 + Mgy(t) \qquad (1)\ [20]$$

Where M is body mass in kg, v_f is the forward velocity of BCM in ms^{-1}, v_v is vertical velocity of BCM in ms^{-1}, g is acceleration due to gravity (9.81ms^{-2}) and y is vertical position of BCM. The first term of the equation is the forward kinetic mechanical energy (E_{kf}), second term is the vertical kinetic mechanical energy (E_{kv}) and the third part is the potential mechanical energy (E_p); which in sum is the external mechanical energy (E_{ext}) [20]

$$r(t) = 1 - \left[\frac{|E_{ext}(t)|}{|E_p(t)| + |E_k(t)|} \right] \qquad (2)\ [20]$$

Where $E_{ext}(t)$ is the external mechanical energy (i.e., E_p + E_k) at instant of time t in Joules; $E_p(t)$ is the potential mechanical energy at instant of time t *in Joules; $E_k(t)$ is the kinetic mechanical energy at instant of time t in Joules. The term r(t) is the pendular transduction (AU).* [20]

$$R_{\text{int}}(t) = \{(\int_0^T r(u)du)/T\}x100 \quad (3)\ [20]$$

Where R_{int} is the pendular transduction within step in %; r(u) is the energy recovery at instant of time u (AU), or pendular transduction; T is the period of time at which energy recovery occurs (i.e., gait cycle). [20]

Statistical Analysis

Mean and standard error were determined for each group at each speed. Significance was accepted when α=0.05 and p<0.05. Data were tested with the Shapiro-Wilk test and were normally distributed. Significant differences between subjects were tested with ANOVA for repeated measures followed by Tukey's post-hoc analysis. Statistical analysis was carried out using SPSS software (version 15.0).

RESULTS AND DISCUSSION

E_p oscillation was higher in stroke group by an average of ≈45% (Fig. 1a and 1b). Stoke gait shows higher vertical displacements of BCM [14] and a flattened patter of the E_{kf} [5, 14]. In addiction there was a significant higher R_{int} for stroke group at 50% of gait cycle (p=0,047) at -2PWS and a higher R_{int} at 100% of gait cycle (p=0,045) at 2PWS.

At -1PWS, PWS and 1PWS control group had higher R_{int} at all comparisons (data not shown). This study is the first to calculate R_{int} for stroke subjects. This method is important because it is possible to understand at which % of gait cycle stroke subjects have more or less mechanical energy recovery. In the past, stroke gait energy recovery was analyzed [5], as a result these authors found less energy recovery for stroke subjects when compared to control group, but only the PWS and usual energy recovery calculation were employed. In this study we analyzed 5 different speeds and with a new method of calculation [20]. Thus, it was possible to notice differences which could not been in the past. The results of this study showed a higher R_{int} at 50% of gait cycle (-2PWS; Figure 1c), so at slow speeds stroke subjects are using the affected lower limb to optimize pendular transduction [20]. Furthermore, at 2PWS stroke group had higher R_{int} at 100% of gait cycle, with an optimization for energy recovery with unaffected side.

CONCLUSIONS

Considerable differences were found in R_{int} between control group and stroke group by means of this method proposed by Cavagna *et al.* (2002) [20]. These differences which once were not detectable appeared. Besides lesser R_{int} at intermediate speeds (-1PWS, PWS and 1PWS; data not shown) stroke subjects performed (i) ≈11% higher R_{int} with the affected lower limb at slow speeds of walking (p=0,047) and (ii) ≈10% higher R_{int} with the unaffected lower limb at higher speeds of walking (p=0,045). In the first case, it is possible that the stroke group had developed a neuromuscular strategy to overcome the functional deficits due to hemiparesis, using the affected limb optimized for pendular transduction, overcoming the functional deficits due to partial loss of muscle strength. By this means stroke group could be more efficient, even without the muscle power to do it. And, in the second case, our research group verified increased gait symmetry for the stroke group at higher speeds, and this could explain the higher energy recovery at such speed (data not published). These results allows verifying the efficacy of and to develop new therapeutic interventions for stroke treatment.

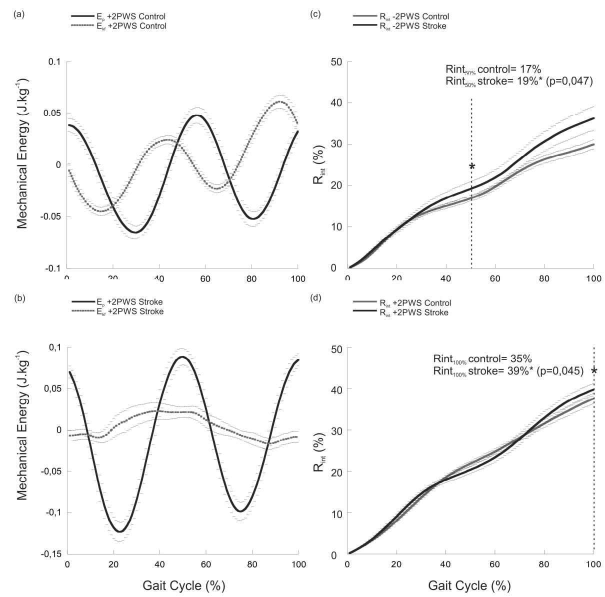

Figure 1: Mean and SE for mechanical energy and energy transduction (R_{int}) for control (n=10) and stroke (n=6) groups. (a) Control group E_p and E_{kf}; black line is E_p and gray dashed line is E_{kf}. (b) Stroke group E_p and E_{kf}; black line is E_p and gray dashed line is E_{kf}. (c) R_{int} for -2PWS; black line is stroke group and gray line is control group. (d) R_{int} for 2PWS; black line is stroke group and gray line is control group. The gait cycle was considered from right leg touch down (affected side for stroke group) to the next right leg touch down.

REFERENCES

1. Dirnagl, U., et al. Pathobiology of ischaemic stroke:an integrated view. *Trends Neurosci*. **22**: p. 391–397, 1999.
2. Thom, T., et al. Heart disease and stroke statistics. *Journal of the American Heart Association.* **6(113):** p. 86-151, 2006.
3. Lamontagne, M., et al. Contribution of passive stiffness to ankle plantarflexor moment during gait after stroke. *Arch Phys Med Rehabil*. **81(3):** p. 351-358, 2000.
4. Stoquart, G., et al. Efficiency of work production by spastic muscles. *Gait & Posture*. **22:** p. 331-337, 2005.
5. Detrembleur, C., et al. Energy cost, mechanical work, and efficiency of hemiparetic walking. *Gait Posture*. **18(2):** p. 47-55, 2003
6. Harris-Love, M., et al. Hemiparetic gait parameters in overground versus treadmill walking. *Neurorehabilitation and Neural Repair*. **15(2)**: p. 105-112, 2001.
7. Bennett, B., et al., Center of mass movement and energy transfer during walking in children with cerebral palsy. *Arch Phys Med Rehabil*. **86(11):** p. 2189-2194, 2005
8. Saibene, F. and A.E. Minetti, Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol*. **88(4-5):** p. 297-316, 2003
9. Cavagna, G.A., H. Thys, and A. Zamboni, The sources of external work in level walking and running. *J Physiol*. **262(3):** p. 639-57, 1976
10. Willems P. A., et al., External, internal and total work in human locomotion. J *Exp Biol,* **198:** p. 379-393, 1995.
11. Ortega, J.D. and C.T. Farley, Minimizing center of mass vertical movement increases metabolic cost in walking. *J Appl Physiol*. **99(6):** p. 2099-107, 2005.
12. Mahoney, F. and D. Barthel, Functional evaluation: The Barthel Index. *Maryland State Medical Journal.* **14:** p. 56-61, 1965.
13. Marshall, A. and A. Baumann, The internacional physical activity questionnaire summary report of the reliability and validity studies. Document of IPAQ Excecutive Commite, 2001.
14. Olney, S. and C. Richards, Hemiparetic gait following stroke. Part I: Characteristics. *Gait & Posture*. **4:** p. 136-148, 1996.
15. Kadaba, M., H. Ramakrishnan, and M. Wootten, Measurement of Lower Extremity Kinematics During Level Walking *Journal of Orthopaedic Research*. **8:** p. 383-392, 1990.
16. Minetti, A.E., L.P. Ardigo, and F. Saibene, Mechanical determinants of gradient walking energetics in man. *J Physiol*. **472:** p. 725-35, 1993.
17. Winter, D.A., Biomechanics and motor control of human movement. New Jersey: John Wiley & Sons Ltda. 325, 2005.
18. Pavol, M.J., T.M. Owings, and M.D. Grabiner, Body segment inertial parameter estimation for the general population of older adults. *Journal of Biomechanics*. **35:** p. 707–712, 2002.
19. Dempster, W.T., W.C. Gabel, and F. W.J.L., The anthropometry of manual workspace for the seated subject. *American Journal Physiological Anthropometry*. **17:** p. 289-317, 1959.
20. Cavagna G. A., Willems P. A., Legramandi M. A. Heglund C. Pendular energy transduction within the step in human walking. *The Journal of Experimental Biology* **205:** p. 3413–3422, 2002.