Original Article

Energy expenditure during rest and treadmill gait training in quadriplegic subjects

DCL de Carvalho¹ and A Cliquet Jr^{*,1,2}

¹Orthopaedics Department, Faculty of Medical Sciences, State University of Campinas (UNICAMP), Campinas, Brazil; ²Department of Electrical Engineering, University of São Paulo (USP), São Carlos, Brazil

Study design: The analysis of oxygen uptake (VO_2) and energy consumption in quadriplegics after 6 months of treadmill gait with neuromuscular electrical stimulation (NMES).

Objectives: To compare metabolic responses in quadriplegics after 6 months of treadmill training, with NMES (30–50% body weight relief), with quadriplegics who did not perform gait.

Setting: Ambulatory of University Hospital, Brazil.

Methods: Quadriplegics were separated into gait and control groups (CGs). On inclusion, all subjects performed VO_2 test. In the gait group (GG) ($n = 11$), the protocol consisted of 8 min of rest, 10 min of treadmill walking using NMES and 10 min of recovery. In the CG ($n = 10$), testing consisted of 8 min rest, 15 min of quadriceps endurance exercise in sitting position with NMES and 10 min recovery. VO_2 , carbon dioxide production (VCO_2) and energy consumption were measured. The GG performed 6 months of treadmill training, using NMES, for 20 min, twice a week. The CG did not practice any activity with NMES, performing conventional physiotherapy only; the CG was stimulated only during the cardiorespiratory test.

Results: All parameters increased significantly for the GG: 36% for VO_2 (l/min), 43% for VCO_2 (l/min) and 32.5% for energy consumption (J/kg/s). For the CG, during knee extension exercise, VO_2 increased without changes in the energy consumption ($P < 0.05$); smaller values were obtained for all parameters when compared to those obtained during gait.

Conclusions: Quadriplegic gait was efficient towards increasing VO_2 and energy consumption, which can decrease the risk of cardiovascular diseases.

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Introduction

Oxygen uptake (VO_2) analysis allows determining the body capacity of delivering and consuming O_2 , and it is the best method to analyze the maximal aerobic power of the subject. Moreover, through VO_2 , it is possible to calculate the energy consumption of any physical activity.¹

VO_2 is influenced by some factors such as alterations in ventilation/perfusion; central cardiovascular system (related to heart rate and stroke volume) and peripheral oxygen consumed by skeletal muscles.^{2,3}

After a spinal cord injury, a decrease of physical capacity and, consequently, of energy consumption occurs due to the paralysis. Quadriplegic subjects with

complete lesions present a loss of motor and sensory functions below lesion level (which causes a diminution of rest VO_2), and also present an absence of sympathetic nervous system activity.^{4,5} The absence of sympathetic nervous system alters the cardiovascular responses during exercise, prejudicing the chronotropy (referring to heart rate increase) and inotropy responses (referring to myocardial performance).⁶

Thus, quadriplegic subjects present a lower physical performance, compared to paraplegic subjects, due to the extensive muscle mass paralysis, impairment of sympathetic cardiac regulation and small venous return, which decrease heart rate responses, cardiac output and VO_2 .^{7,8}

Neuromuscular electrical stimulation (NMES) produces muscular contraction of paralyzed muscles, which increases the venous return, cardiac preload and cardiac performance. Moreover, NMES increases muscular

*Correspondence: A Cliquet Jr, Departamento de Ortopedia e Traumatologia/F.C.M./UNICAMP, Rua Alexander Fleming 181, Cidade Universitária 'Zeferino Vaz' s/n, 13083-970 – Campinas, SP/Brasil

endurance and strength, increasing the oxygen extraction by muscle fibers.² These factors are responsible for the improvement of VO_2 and energy expenditure observed after physical training.

GOSS *et al.*⁹ observed an increase of VO_2 peak from 0.793 ± 0.23 to 1.013 ± 0.25 l/min after 6 months of electrically induced leg-cycle training, in paraplegic and quadriplegic subjects. Energy expenditure was within 3.26 at 5.16 kcal/min. Mohr *et al.*¹⁰ observed, after 12 months of cycle training provided by NMES, three times a week, for 30 min each session (in paraplegics and quadriplegics), an increase of VO_2 peak from 1.20 ± 0.08 to 1.41 ± 0.10 l/min after 6 months, achieving 1.43 ± 0.09 l/min after 12 months.

Training, which increases the physical conditioning in spinal cord injured individuals and increases the energy expenditure, is beneficial towards diminishing the risk for cardiovascular disease, obesity, hypercholesterolemia and to increase the ability of performing daily activities.^{7,11,12}

Methods

In total, 21 complete subjects with quadriplegia, all male (mean age 31.95 ± 8.01 years), participated in this study. The lesion levels were within C4 and C8. Mean time postinjury was 66.42 ± 48.23 months (range 25–180 months). Mean body mass and height of subjects were 63.52 ± 9.41 kg and 176.28 ± 5.28 cm, respectively. Individuals were separated into two groups: gait group (GG) ($n=11$) with all individuals having a complete lesion (ASIA A) and control group (CG) ($n=10$) with all individuals having an incomplete lesion (ASIA Impairment Scale: B). All subjects belonged to the Spinal Cord Injuries' Rehabilitation Ambulatory of the University Hospital. The study was approved by the local ethical committee. Inclusion criteria included intact lower motor neurons, which are required for muscle contraction using surface electrical stimulation, and no history of cardiopulmonary disease. Body weight support (BWS) was provided by a harness suspended from an overhead support, and the support vest allowed for the free movement of the lower limbs.

All subjects of the GG had their quadriceps and tibialis anterior muscles being stimulated for at least 5 months before the beginning of gait training, in order to allow for the treadmill walking, with 30–50% of BWS during 20 min consecutively, with quadriceps extension supported by NMES. A 4-channel electrical stimulator delivered a signal of 25 Hz with monophasic rectangular pulses with 300 μ s duration and a maximum intensity of 200 V (1 k Ω load).

At the moment of inclusion, all subjects performed the VO_2 test, which was repeated three times to allow each subject to become accustomed to the system. In the GG, VO_2 test consisted of three different phases: 8 min of rest, 10 min of treadmill walking with NMES and 10 min of recovery. In the CG, the test consisted of 8 min of rest, 10 min total time of bilateral 2-channel stimulation for knee extension in the sitting position and 10 min

of recovery. Rest phases, for both control and gait groups, were performed in the sitting position. VO_2 and carbon dioxide production (VCO_2), were measured by open-circuit spirometry (SensorMedics, Vmax 29c Cardiopulmonary Exercise Testing Instrument). Calibration was performed prior to each test with reference gases. Values were averaged over the last five 30-s periods for each phase. All tests were done in the morning for all subjects: 2 h (previously to test) under fasting and 24 h before test they would only be allowed light meals; no caffeine or tobacco products were permitted.

VO_2 was obtained in order to analyze the energy consumption (J/kg/s) during rest and exercise (gait or knee extension exercise). Moreover, in the GG, energy cost was also calculated. Equations used to calculate energy consumption and energy cost are shown below:

$$\text{Energy consumption (J/kg/s)} = \frac{\text{VO}_2 \text{ ml/min} \times K}{\text{Body mass (kg)} \times 60}$$

$$\text{Energy cost (J/kg/m)}$$

$$= \frac{\text{VO}_2 \text{ ml/min} \times K}{\text{Speed (m/min)} \times \text{body mass (kg)}}$$

where $K=20.19$ J/ml. Since 1 ml $\text{O}_2=4.825$ cal and 1 cal = 4.184 J.

Individuals from the GG performed 6 months of chronic treadmill walking training, twice a week, during 20 min each session. All individuals started the treadmill gait training at 0.5 km/h speed, which was increased according to the capacity of each subject. The highest achieved speed was 1.3 km/h. Electrical stimulation was used to provide the stance gait phase through quadriceps muscle activation and the swing phase triggered by the withdrawn reflex (stimuli to the common peroneal nerve). Individuals from the CG only had stimulation at the actual time that the cardiorespiratory test was done in order to level the acute effect of electrical stimulation for both groups (10 min of NMES for both GG and CGs). During the 6 months, subjects of the CG were just allowed to perform conventional physiotherapy, twice a week. They did not practice any activity with NMES.

Data were statistically analyzed to determine the differences in metabolic responses after 6-months of treadmill gait training, compared to the responses of individuals from the CG. Statistical comparisons were done using paired *t*-tests. Results are presented as mean $\pm$ standard deviation (SD). Differences were considered significant at $P<0.05$.

Results

In the GG, before training, VO_2 tests were performed at 0.5 km/h speed. After 6 months, tests were performed at maximal achieved speed (within 1.0 to 1.3 km/h) and at 0.5 km/h.

Table 1 presents the metabolic results during rest and treadmill gait, before and after 6 months of gait training.

Table 1 Metabolic parameters obtained before and after 6 months of treadmill gait training in GG

Metabolic parameters	Before gait training		After 6 months of gait training		
	Rest	Gait (0.5 km/h)	Rest	Gait (0.5 km/h)	Gait (within 1.0–1.3 km/h)
VO ₂ (l/min)	0.183 ± 0.06	0.430 ± 0.09	0.158 ± 0.03	0.438 ± 0.07	0.586 ± 0.14
VO ₂ (ml/kg/min)	2.94 ± 1.19	6.96 ± 1.79	2.62 ± 0.63	7.05 ± 1.49	9.57 ± 2.54
VCO ₂ (l/min)	0.127 ± 0.04	0.356 ± 0.08	0.115 ± 0.02	0.366 ± 0.06	0.509 ± 0.13
RER	0.71 ± 0.09	0.81 ± 0.06	0.72 ± 0.07	0.82 ± 0.04	0.85 ± 0.04
Energy consumption (J/kg/s)	1.01 ± 0.40	2.37 ± 0.65	0.83 ± 0.25	2.40 ± 0.48	3.14 ± 0.90
Energy cost (J/kg/m)	—	17.1 ± 4.65	—	17.32 ± 3.46	8.83 ± 2.32

Table 2 Metabolic parameters obtained at the moment of inclusion and after 6 months in CG

Metabolic parameters	At the moment of inclusion		After 6 months	
	Rest	Knee extension exercise	Rest	Knee extension exercise
VO ₂ (l/min)	0.159 ± 0.05	0.232 ± 0.05	0.208 ± 0.06	0.293 ± 0.09
VO ₂ (ml/kg/min)	2.33 ± 0.74	3.45 ± 0.66	3.24 ± 1.09	4.62 ± 1.30
VCO ₂ (l/min)	0.122 ± 0.04	0.190 ± 0.04	0.143 ± 0.05	0.223 ± 0.07
RER	0.77 ± 0.09	0.82 ± 0.03	0.70 ± 0.05	0.76 ± 0.07
Energy consumption (J/kg/s)	0.81 ± 0.25	1.17 ± 0.31	1.09 ± 0.37	1.44 ± 0.51

Before training, individuals from the GG presented during gait, the mean peak VO₂ was 0.430 ± 0.09 l/min, VCO₂ was 0.356 ± 0.08 l/min and energy consumption was 2.37 ± 0.65 J/kg/s. After 6 months training, during gait, at maximal achieved speed, the mean peak VO₂ was 0.586 ± 0.14 l/min, VCO₂ was 0.509 ± 0.13 l/min and energy consumption was 3.14 ± 0.90 J/kg/s. All parameters increased significantly during the gait phase ($P < 0.05$) when compared to rest. After training, during gait at 0.5 km/h speed (the same speed as before training), the mean peak VO₂ was 0.438 ± 0.07 l/min, VCO₂ was 0.366 ± 0.06 l/min and energy consumption was 2.40 ± 0.48 J/kg/s, values that were not significantly distinct from those obtained before training, at the same speed.

Energy cost during gait was 17.1 ± 4.65 J/kg/m and after 6 months of treadmill gait training (at maximal achieved speed), energy cost obtained decreased significantly to 8.83 ± 2.32 J/kg/m. After training, during gait at 0.5 km/h speed (the same speed as before training), energy cost (17.32 ± 3.46 J/kg/m) did not change.

Before training, for the GG, the mean energy consumption was 2.34 times higher than at rest. After 6 months of gait training (at maximal achieved speed), the mean energy consumption was 3.78 times higher than at rest. During gait phase, a significant increase of energy consumption was observed after gait training ($P = 0.0004$). During rest, energy consumption did not change significantly ($P = 0.25$).

Table 2 presents the metabolic results during rest and knee extension exercise, at the moment of inclusion and after 6 months (period that individuals did not perform

Figure 1 Energy consumption at the initial and after 6 months of treadmill gait training. (a) During rest; (b) during gait (at the final test, gait was performed at maximal achieved speed). Values are presented as mean ± SD

Figure 2 Energy consumption at the initial and after 6 months. (a) During rest; (b) during knee extension exercise. Values are presented as mean $\pm$ SD

any activity with NMES). Before training, individuals from the CG presented, during knee extension exercise, the mean peak of VO_2 of $0.232 \pm 0.051/\text{min}$, VCO_2 of $0.190 \pm 0.041/\text{min}$ and energy consumption was $1.17 \pm 0.31 \text{ J/kg/s}$. After 6 months, during exercise, the mean VO_2 peak was $0.293 \pm 0.091/\text{min}$, mean VCO_2 peak was $0.223 \pm 0.071/\text{min}$ and energy consumption was $1.44 \pm 0.51 \text{ J/kg/s}$. Before training, in the CG, the mean energy consumption was 1.42 times higher than at rest. After 6 months, the mean energy consumption was 1.32 times higher than at rest. After 6 months, the results have shown a significant increase of VO_2 during rest and knee extension exercise ($P < 0.05$) and an increase of energy consumption during rest.

However, higher values were observed for gait rather than for knee extension exercise in all parameters analyzed.

Figure 1 illustrates the mean values of energy consumption obtained in the GG, during rest and gait, at initial and after 6 months of gait training. The final test was performed at maximal achieved speed.

Figure 2 illustrates the mean values of energy consumption obtained in the CG, during rest and knee extension exercise, at beginning and after 6 months.

Figures 3 and 4 illustrate a preliminary study, on a single quadriplegic subject (lesion level C6), in order to

Figure 3 Relation between oxygen uptake (VO_2) and different speeds (km/h), during a quadriplegic gait

Figure 4 Energy cost obtained during different speeds (km/h)

observe the relationship between oxygen consumption and gait speed; and between energy cost and gait speed, respectively.

Discussion

Results obtained have shown that even incomplete subjects are overtaken by complete individuals who have undergone gait, in term of clinical improvements. In general, incompletes might present changes not related to an eventual intervention, while completes would not show any changes but those triggered or related to intervention. Therefore, complete subjects can also benefit, in terms of cardio-respiratory parameters, from physical activities,^{4,13,14} since they also have risks of cardiovascular diseases.

Based upon Buchholz and Pencharz,¹⁵ quadriplegic subjects present low values compared to paraplegics for total daily energy expenditure (25% lower) and for physical activity level (18% lower), due to extensive muscle mass paralysis.

Janseen *et al*¹⁶ analyzed the physical capacity in 59 quadriplegics, lesion level within C4–C8, and classified as poor level for $\text{VO}_2 < 0.51 \text{ l/min}$ and for $\text{VO}_2 < 7.6 \text{ ml/kg/min}$. Fair level was achieved for VO_2 within $0.52\text{--}0.79 \text{ l/min}$ and for VO_2 within $7.61\text{--}10.0 \text{ ml/kg/min}$. Average level for VO_2 was within $0.80\text{--}0.96 \text{ l/min}$ and for VO_2 within $10.01\text{--}13.39 \text{ ml/kg/min}$. Good level for VO_2 was within $0.97\text{--}1.19 \text{ l/min}$ and for VO_2 within $13.40\text{--}16.94 \text{ ml/kg/min}$. Excellent level was for $\text{VO}_2 > 1.19 \text{ l/min}$ and for $\text{VO}_2 > 16.94 \text{ ml/kg/min}$.

Before training, individuals from the GG, during gait, achieved values classified as poor physical activity ($\text{VO}_2 = 0.430 \pm 0.091/\text{min}$), with energy consumption of

2.37 ± 0.65 J/kg/s. After 6 months of training, physical activity was classified as fair ($\text{VO}_2 = 0.586 \pm 0.141/\text{min}$), with energy consumption (per unit of time) of 3.14 ± 0.90 J/kg/s. Energy consumption increased significantly ($P = 0.0004$) after training.

Results have shown that after 6 months of training, at maximal achieved speed, mean VO_2 value obtained from the GG increased significantly. However, at 0.5 km/h, no differences were observed. Faghri *et al.*,² did not observe any difference when values were compared to those obtained during submaximal activity. This fact can be related to the increase of muscular mechanical efficiency.

Individuals from the CG, during knee extension exercise, in the beginning and after 6 months, presented metabolic values related to poor physical activity ($\text{VO}_2 = 0.32 \pm 0.5$ and $0.293 \pm 0.091/\text{min}$, respectively). Energy consumptions at the beginning and at the end were 1.17 ± 0.31 and 1.44 ± 0.51 J/kg/s, respectively.

Individuals included in the CG, after 6 months, presented a significant increase for VO_2 during rest and knee extension exercise. Based on Janseen *et al.*,¹⁶ quadriplegic subjects increase their physical capacity within 48 months after lesion, which is the required time to adapt to their new condition. In the CG, 6 individuals had lesion time less than 48 months and two individuals had 50 months of lesion. Thus, the increase of oxygen consumption and energy consumption during rest can be related to the adaptation phase associated to physiotherapy benefits.

The mean value of energy consumption, in the CG during exercise (after 6 months) was significantly lower ($P = 0.0015$) than the mean value obtained during gait in the GG, even before training.

The low energy consumption can be the reason for low VO_2 achieved during physical activity. The low VO_2 is associated with muscular paralysis and impairment of the sympathetic nervous system. Despite the fact that training using NMES can be efficient to increase strength and muscular endurance^{17–19} and, consequently, increase the oxygen extraction by muscles, it is limited by the incapacity of the cardiovascular system (in quadriplegics with complete lesions), to increase functional efficiency towards delivering oxygen in higher amounts to muscles being activated.

Results of energy cost (per unit of distance) after 6 months of training (for the GG), with gait performed at maximal speed (within 1.0–1.3 km/h), have shown that a significant decrease of obtained values occurred.

If very low speeds are increased, this might even decrease energy cost, which means more efficient gait with less consumption. It has been the aim of spinal cord injured restored gait to increase their speed so that they can reduce their energy consumption.^{20,21} For quadriplegic gait, in particular, not much is known about their oxygen consumption, energy expenditure, etc.

The possibility of recovering gait ability, through medical and/or technological advances,^{22,23} yields the necessity to study which speed is more efficient towards gait of spinal cord-injured subjects. Figure 3 shows that

VO_2 was lower when gait was performed at 0.9 km/h, without considering gait at 0.3 km/h (no functional gait speed). However, when the energy cost was analyzed (Figure 4), gait performed at 1.1 km/h was more efficient than that at other speeds. Moreover, these figures allow noticing that 0.7 and 1.3 km/h gait speeds, for this subject, provided higher values of VO_2 , probably due to the higher metabolic stress. Despite the higher VO_2 obtained at 1.3 km/h, the energy cost was not so high.

Individuals from the GG were able to achieve the maximal speed of 1.3 km/h, keeping a satisfactory gait pattern. As Figures 3 and 4 have shown that at 0.7 and 1.3 km/h the oxygen consumption values were similar, they probably indicate that, towards improving the metabolic stress, it is not really necessary to perform gait at maximal speed, since there was an equivalent response at a lower speed. However, during 1.3 km/h, the energy cost was lower than at 0.7 km/h. This study shall be performed using a larger group of subjects.

Lapointe *et al.*²⁴ 2001 observed that spinal cord injured subjects, during gait at maximal velocity, were 30% slower than healthy subjects, but presented an energy cost 300% higher. Cunha-Filho *et al.*²⁵ also observed that spinal cord injured subjects during gait (ASIA C and D) presented higher energy cost (0.57 ± 0.38 ml/kg/m) and lower speed (0.55 ± 0.31 m/s) when compared to the healthy group (0.18 ± 0.02 and 0.90 ± 0.11 m/s, respectively).

Thus, results have shown that gait training provided by NMES is capable of increasing the VO_2 and energy consumption, which demonstrate the positive effect on physical fitness in quadriplegic subjects. However, the preliminary results demonstrate that higher speeds decreased the energy cost during gait, which are associated to a more efficient gait.

In healthy adult subjects, physical activity shall be performed during 30 min, with moderate intensity, all days of the week (preferably) in order to decrease the risk of cardiovascular diseases.²⁶ For spinal cord-injured subjects, there are no established protocols yet towards health benefits. However, persons with a spinal cord injury must increase their physical activity level, since they present an increase of fat mass, associated with a decrease of lean mass, when compared to normal subjects.²⁷ The increase of physical activities allows spinal cord injured subjects to achieve total daily energy expenditure approaching that of able-bodied persons.¹⁵

Conclusions

In summary, results have shown that treadmill gait provided by NMES was efficient to increase VO_2 and energy consumption, even in quadriplegic subjects, who present extensive muscle paralysis and impairment of the sympathetic nervous system. Such increase probably decreases the risk of cardiovascular disease, hypercholesterolemia and improves life quality.

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