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Original Article

Energy expenditure during walking with weight-bearing control (WBC) orthosis in thoracic level of paraplegic patients

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Study design: Comparative study of the effectiveness of walking exercise with a newly developed gait orthosis, the weight-bearing control (WBC) orthosis, for thoracic level of paraplegic patients.
Objectives: To test its feasibility as a rehabilitation alternative for paraplegic patients, the energy consumption and cost during walking with WBC were calculated and compared with the values of conventional orthoses given in previous reports.
Setting: National Rehabilitation Center for the Disabled, Japan.
Methods: Four paraplegic patients with traumatic spinal cord injuries ranging from T8 to T12 participated. Experiments were conducted after 3 months of the orthotic gait training with WBC. The cardiorespiratory parameters were continuously measured at rest and during walking with a telemetric device. The steady-state value of the oxygen uptake (V_{O_2}), heart rate (HR), the energy consumption (J/kg/s) and energy cost (J/kg/m) were calculated.
Results: The average walking speed was 19.0 ± 2.58 m/min. The steady-state value of the V_{O_2} and HR were 16.08 ± 1.93 ml/kg and 147.3 ± 10.94 b/min, respectively. The energy cost during orthotic walking tended to be better than the values of conventional orthoses, whereas the energy consumption was almost similar.
Conclusion: WBC enables thoracic level of paraplegic patients to walk at relatively higher speed than conventional orthoses under similar energy expenditure. The special devices equipped with WBC are therefore considered to lead to improvement of the energy cost of walking. The physical intensity presumed by cardiorespiratory responses during walking with WBC is suited to promote their aerobic capacity. Therefore, it is concluded that the WBC orthosis could be an effective alternative in rehabilitation for thoracic level of paraplegic patients.
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Keywords: spinal cord injury; orthotic gait; rehabilitation; energy consumption; energy cost; physical intensity

Introduction

Previous studies have pointed out that the high energy cost has been one of the major problems of the orthotic gait for paraplegic patients.[1–5] Although many devices have been developed to improve this problem to date, it is still difficult to satisfy the requirements of both paraplegic patients and therapists. The futile energy cost should lead to exhaustion in a few minutes of walking. As a consequence, orthotics are frequently abandoned after being used for only a short time in therapeutic phase.[6] Especially for thoracic level of paraplegic patients, a considerable effort of their upper limb and trunk above the paralysis is required during orthotic gait, and this is the main reason of the limitation of the orthotic use.[2,7]

One of the major purposes of the orthotic gait for paraplegic patients is the promotion of their health. Since previous studies have suggested the positive effects of walking exercise on secondary disorders, such as the urodynamics[8] and digestive functions,[9] paraplegic patients should make efforts to facilitate their own physical activities in daily life not only with a wheelchair, but also with walking exercise. To this end, the energy cost

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of orthotic gait should be lowered. Then, the users also need to make an appropriate level of physical intensity to promote their aerobic capacity with walking.

The weight-bearing control (WBC) orthosis was based on the concept to allow more dynamic reciprocal gait pattern for patients, especially those who could not swing their leg voluntarily.[10–12] This orthosis has a reciprocal guide assistance and movable foot plates, which facilitate leg swing and make a clearance between the foot's sole and the floor, respectively. We hypothesized that the special devices equipped with the WBC orthosis would enable thoracic level of paraplegic patients to walk easily with less effort. To ascertain this hypothesis, energy consumption and cost of walking with WBC orthosis were evaluated and compared with other types of orthoses in previous reports.

Methods

Subjects

Four traumatic spinal cord injury patients who satisfied the following criteria were selected: (1) age <30 years, (2) with a thoracic level injury and (3) postinjury time of >6 months. All of them were male, ages ranging from 21 to 28 years (mean 24.5 years). One subject had an incomplete spinal cord injury grade B according to the ASIA scale at a T12 level, other subjects had complete injuries grade A with lesion levels varying from T8 to T12 (details are listed in Table 1). None of the subjects had any symptoms related to cardiopulmonary function. Subjects gave their informed consent to the experimental procedure. Each subject had completed a standard rehabilitation program, which included muscle strengthening, taking the orthosis on and off, balancing in a standing position, after which, they had practiced the gait training with the WBC orthosis. After this training program, each subject could perform the orthotic gait smoothly and was able to walk continuously at least for 20 min.

WBC orthosis

This device was developed for thoracic level of paraplegic patients to walk independently with less effort. It aims to take appropriate physical intensity considering the following major needs: a rigid frame that supports the user's body weight, a special hip joint devise that reciprocally propels each leg forward, a gas-powered foot device that varies the sole thickness of the device for foot/floor clearance, and a control system of the orthosis.

Table 1 Characteristics of the patients

Subject	*Age (years)*	*Weight (kg)*	*Lesion level*	*Grade of ASIA*	*Duration of paraplegia (months)*
1	21	46	T12	B	32
2	27	60	T10	A	10
3	22	68	T12	A	8
4	28	63	T8	A	12

Experiment procedure

The cardiorespiratory parameter at rest and during walking was measured continuously with a telemetric device (K4 Cosmed, Italy). This device consists of a transmitting unit, a face mask to sample expired gas, a heart rate (HR) chest strip, a battery and a receiving unit. The experimental procedure was: 5 min at rest in the sitting position, 20 min of continuous walking at the most comfortable speed on a field. During walking, data were continuously acquired and analyzed in real time. The following cardiorespiratory parameters were acquired: oxygen uptake (V_{O_2}) and HR. Walking speed in the steady state during walking was also recorded. The measurements were conducted at 3 months after the onset of training. After the experiments, the energy consumption and walking energy cost were calculated. The terms adopted were those of Nane and Patrick[3] and calculations performed according to their protocol:

$$\text{Energy consumption (J/kg/s)} = \frac{\text{Ambulatory min } V_{O_2}\text{(ml/min)}}{\text{Weight (kg)} \times 60} \times K$$

$$\text{Energy cost (J/kg/m)} = \frac{\text{Ambulatory min } V_{O_2}\text{(ml/min)}}{\text{Speed (m/min)} \times 60} \times K$$

where $K = 20.19$ J/ml, since 1 ml $O_2 = 4.825$ cal and 1 cal $= 4.184$ J.

Results

All subjects could walk continuously without exhaustion and stumbling throughout the walking session for 20 min. They did not take a break except for the time of direction converting. The total distance traveled in 20 min was 269 ± 32 m. The average walking speed with WBC was 19 ± 2.58 m/min.

Table 2 shows the cardiorespiratory responses at rest and during orthotic gait. During walking, cardiorespiratory parameters clearly showed a significant increase compared with resting rate. The steady-state value of the

Table 2 Cardiorespiratory response (V_{O_2} and HR) at rest and in steady state during exercise

Subject	*V_{O_2} (ml/kg)* Rest	*V_{O_2} (ml/kg)* Exercise	*HR (beat/min)* Rest	*HR (beat/min)* Exercise
1	4.57	18.05	96.0	145.1
2	6.11	14.20	93.4	157.3
3	6.76	14.67	104.4	132.9
4	8.84	17.39	84.6	154.0
Mean	6.57	16.08	97.9	147.3
SD	1.77	1.93	5.7	10.94

V_{O_2} was ranged from 14.20 to 18.05 ml/kg (average value = 16.08 ± 1.93 ml/kg), and HR was 132.9–157.3 b/min (average value = 147.3 ± 10.94 b/min).

Table 3 shows the energy consumption and energy cost. The energy consumption during walking was about three times greater than during rest (rest versus exercise: 1.99 ± 0.40 versus 5.41 ± 0.65 J/kg/s). The average value of the energy cost during walking was 17.12 ± 0.72 J/kg/m.

Table 4 summarized the value of the energy consumption, energy cost and walking speed in previous reports using reciprocating gait orthosis, that is, HGO, RGO and ARGO. While the energy consumption during walking with WBC was slightly larger than that in previous report (median value = 4.37 J/kg/s), the energy cost tended to be better than the value of previous reports (present versus previous: 17.12 versus 21.16 J/kg/m).

Discussion

The present results show that the energy cost during walking with WBC was better than the values given in previous reports of conventional orthoses, such as HGO, RGO and ARGO for thoracic level of paraplegic patients (Table 4). In the following discussion, our results of energy consumption and cost will be compared with previous reports. Then, the feasibility of the walking with WBC as the rehabilitation alternatives for thoracic level of paraplegic patients will be discussed.

Table 3 Energy consumption, energy cost and speed during walking

Subject	*Energy consmption (J/kg/s)* Rest	Exercise	*Energy cost (J/kg/m)*	*Gait speed (m/min)*
1	1.54	6.07	16.56	22
2	2.16	4.78	17.91	16
3	2.27	4.94	16.45	18
4	2.83	5.85	17.55	20
Mean	1.99	5.41	17.12	19
SD	0.40	0.65	0.72	2.58

Since the pioneering study by Gordon and Vanderwalde,[1] many researchers have reported extremely higher energy requirements of orthotic gait.[2–7] Although paraplegic patients with high thoracic level lesions found it difficult to achieve orthotic gait in the early stages of researches,[13] later improvement enabled them to walk independently and reciprocally.[4,5,14] However, the high energy cost is still the major reason for the limitation of the orthotic use.[4,5] As Waters *et al*[15] pointed out, there was a high correlation between the lower extremity muscle scores and the energy cost of the orthotic walking. Actually, considerable effort of their upper limb and trunk above the paralysis is required to accomplish walking for thoracic level of paraplegic patients.[3,7] This loss of the energy expenditure prevents the achievement of aerobic condition during orthotic gait. To promote general health for paraplegic patients, it is necessary to facilitate aerobic condition. In this vein, the decrement of the energy cost is the primary problem.

WBC was designed on the concept of allowing more dynamic reciprocal gait pattern for patients, especially those who could not swing their leg voluntarily.[10–12] Figure 1 shows the relation between the energy consumption and energy cost in each previous investigation.[3–5,7,14,16–18] Since the walking speed was delivered to divide the energy consumption by the energy cost, the slope of line from zero to each plot reflects the walking speed of each orthosis. This figure clearly shows that the WBC enables paraplegic patients to walk at relatively higher speed than other reports under almost relatively lower energy cost. It is considered that the special devices equipped with WBC would lead to the improvement of energy cost. As mentioned above, it needs both of lower energy cost and adequate energy consumption to acquire an aerobic conditioning. To this end, those on the upper and left side of the figure can be

Table 4 Energy consumption and energy cost with different orthoses in previous studies and our present study. All values are expressed as an average

Series	*Number of subjects*	*Energy consumption (J/kg/s)*	*Energy cost (J/ks/m)*	*Walking speed (m/min)*	*Level and aid*
Nene (1989)	10	3.10	14.48	12.84	T4–T9 Parawaker
Nene (1990)	5	2.59	11.22	13.8	T4–T7 Parawaker
Hirokawa (1990)	6	4.18	21.00	12.48	T1–T10 RGO
Winchester (1993)	4	4.37	19.44	13.5	T5–T10 RGO
Bernardi (1995)	10	4.30	20.00	12.78	T4–12 RGO
Felici (1997)	6	8.26	32.30	15.34	T5–L1 RGO, ARGO
Massucci (1997)	6	4.64	29.00	9.6	T3–T12 ARGO
Merati (2000)	6	4.64	24.87	11.2	T3–T11 RGO
Present study	4	5.41	17.12	19	T8–12 WBC

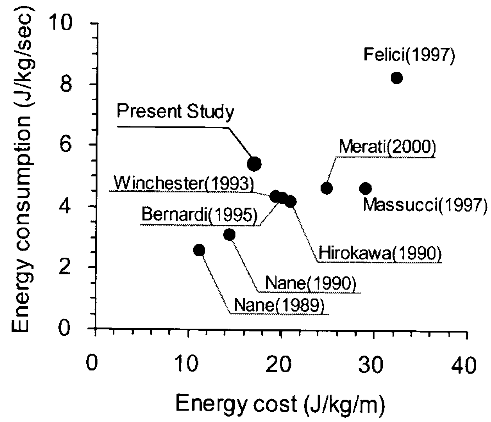

Figure 1 The relation between the energy consumption and cost in each investigations

considered as having suitable physical intensity for patients.

It is well known that paraplegic patients have significantly reduced V_{O_2} peak values as a consequence of the reduction in the daily activity levels.[19] In addition, the isolation of the upright standing and walking should lead to various secondary disorders, for example, the decrement of the bone mineral density[20,21] and malfunction of the peripheral circulation in paralyzed areas.[22] Although there is little agreement of the effect on the above point, there is no doubt that some purposeful effects should be offered by orthotic gait. Previous studies have demonstrated that orthotic gait provides some benefits to the physical functions for paraplegic patients, such as the improvement of the urodynamics[8] and digestive functions.[9] Therefore, paraplegic patients should make efforts to facilitate their own physical activities in daily life, not only with wheelchair but also walking. Today, the benefits of walking exercise for paraplegic patients are well recognized. However, there are several obstacles in achieving locomotion for paraplegic patients. As we have mentioned, conventional gait orthoses require a very high energy expenditure that usually leads to exhaustion in a few minutes of walking.

In this study, we investigated the energy expenditure and energy cost during orthotic walking with WBC, and showed that paraplegic patients could walk at relatively higher speed and lower energy cost compared with the conventional orthoses. Using WBC, all of our subjects could walk more than 20 min without exhaustion at the end of their training period. Further, the physical intensity presumed by the cardiorespiratory responses was considered to be suited to promote their general health. It is therefore concluded that the WBC orthosis could be an effective alternative in rehabilitation for thoracic level of paraplegic patients to promote their health conditions. In further investigation, a more direct approach, such as the clinical or physiological evaluation, will be needed to clarify the effectiveness of the orthotic gait for paraplegic patients.

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