Original Article

Effect of lesion level on the orthotic gait performance in individuals with complete paraplegia

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Study design: Cross-sectional, experimental research.

Objectives: To clarify the effect of lesion level on cardio-respiratory responses and biomechanical characteristics of walking with a reciprocating gait orthosis in complete paraplegia with spinal cord injury (SCI).

Setting: National Rehabilitation Center for Persons with Disabilities, Japan.

Methods: Ten SCI individuals (age: 20–34 years, injured level: Th5–12) who experienced orthotic gait training at least for 10 weeks participated in two experiments: (1) measurement of the cardiorespiratory responses during 20 min of orthotic gait exercise; and (2) three-dimensional motion analysis and ground reaction force measurement using the VICON system. We calculated the following parameters: pulmonary ventilation, oxygen consumption ($\dot{V}O_2$), heart rate (HR), gait speed, cadence, stride length, crutch force (CF), hip range of motion (ROM), and hip angular velocity (VEL). Further, energy consumption and energy cost were calculated using the steady-state value of $\dot{V}O_2$ and gait speed.

Results: The steady-state value of the $\dot{V}O_2$ (18.2 ± 3.80 ml/kg) and HR (133.0 ± 21.63 b/min) tended to be larger in higher thoracic SCI subjects. There were strong positive correlations between the lesion level and walking speed ($r=0.74$), energy cost ($r=0.85$), and hip ROM ($r=0.78$). On the other hand, negative correlation between the lesion level and peak CF ($r=-0.78$) was clarified.

Conclusions: The physiological intensity of the orthotic gait strongly depended on the level of lesion. It seems likely that a limited hip range of motion and excess upper limb load result in the low energy cost of orthotic gait for the higher thoracic level of paraplegic patients.

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Keywords: spinal cord injury; orthotic gait; energy consumption; motion analysis; cardio-respiratory response

Introduction

Orthotic gait exercise is usually prescribed for patients with spinal cord injury (SCI) in their therapeutic phase to promote their general health. Although the effectiveness of orthotic gait exercise is well recognized, there are several obstacles to achieve walking for complete paraplegic persons, in particular the high energy cost of the orthotic gait.^{1–5} SCI persons inevitably require larger energy expenditure for orthotic gait because they need to produce complementary upper limb and trunk motion in order to swing their paralyzed lower limb.^{6–9} Further, it can be pointed out that the neurological level

of paralysis considerably influences the achievement of orthotic gait motion and energy expenditure.

We have evaluated the energy expenditure during orthotic gait of thoracic level of SCI paraplegics, and suggest that, even with the higher level of lesion, the physiological intensity required was in a feasible range for cardiorespiratory function.¹⁰ We have also found that subjects who had higher levels of lesion demonstrated relatively slower gait speed and a relatively higher physiological intensity. These findings confirm the clinical impression that higher thoracic SCI subjects have some difficulties in performing orthotic walking. Although physicians and therapists already know this because of their clinical experience, it is not clear to what extent the motor paralysis influences orthotic gait performance, and what is the primary reason for limited

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gait performance for higher level SCI subjects. In the present study, we aimed to clarify the effect of injured level on the physiological intensity and biomechanical characteristics of orthotic gait on the complete paraplegic persons.

Methods

Subjects

Ten subjects with the thoracic level of SCI participated in this study. All subjects had complete motor paralysis in the lower limb muscles (ASIA classification; grade A or B¹¹) and no history of cardiorespiratory disease. Criteria for participation of this study were (1) judged to be better general health condition and have adequate exercise tolerance at the health check, (2) no cardiovascular disease, and (3) had past at least a half year after injury. The characteristics of the subjects in detail are summarized in Table 1. All subjects had participated in the basic rehabilitation process, and had undergone at least 10 weeks of orthotic gait training using the advanced reciprocating gait orthosis[®] (ARGO). Each

subject gave written informed consent for the experimental procedure, which was approved by the local biological ethics committee of the National Rehabilitation Center for Persons with Disabilities (NRCD).

Orthotic gait

Sequential pictures of walking with the ARGO are shown in Figure 1a. The ARGO has a single cable which connects both sides of the leg frame. With this device, a torque exerted by the right (left) hip joint is mechanically transmitted to the left (right) hip joint, resulting in the torque to the opposite direction exerted by the left (right) hip joint. Although there is individual variation, in many cases, paraplegic patients with injury to a lower thoracic level could walk after 10 weeks of gait training independently, while patients with injury at a higher thoracic level needed additional practice. After the training period, each subject could perform the orthotic gait (subjects F, H, and J still required light support to avoid falling) independently, and were able to walk continuously for at least 20 min.

All subjects participated in two experiments on the separate day; one was the measurement of cardiorespiratory responses during 20 min of orthotic gait exercise, and another was the three-dimensional motion analysis with the use of the VICON system.

Measurement of the cardiorespiratory responses

Subjects were asked to abstain from alcohol and caffeine for at least 12 h before the experiment. The temperature and humidity during the experiment were $23.5 \pm 4.2^\circ\text{C}$ and $58.3 \pm 3.3\%$, respectively. The experimental procedure was as follows: 3 min of rest in the standing position followed by 20 min of continuous walking at the most comfortable speed. The cardiorespiratory responses at rest and during walking were measured continuously with a telemetric device (K4-RQ Cosmed

Table 1 Characteristics of the SCI subjects

	Sex	Age (years)	Weight (kg)	Lesion level	Grade of ASIA	Duration of paraplegia (months)
A	M	30	67	Th12	A	32
B	M	25	79	Th12	A	28
C	M	26	80	Th12	A	16
D	M	29	72	Th11	B	12
E	F	27	45	Th10	A	18
F	M	32	74	Th10	A	10
G	M	30	74	Th8	A	22
H	M	22	65	Th7	A	30
I	M	34	54	Th6	A	36
J	M	20	53	Th5	B	28

Figure 1 (a) Sequential picture of walking with the ARGO in a SCI subject (injured at Th12). (b) Time series data of the GRF (body and stick) and joint angle motion (Hip, Knee, and Ankle) obtained by the VICON system. (c) Typical example of the changes in the cardiorespiratory parameters during orthotic gait exercise

s.r.l., Rome, Italy) and were analyzed in real time. The telemetric device consisted of a transmitting unit, a facemask for sampling the expired gas, a heart rate (HR) chest strap, a battery, and a receiving unit. The following cardiorespiratory parameters were obtained: pulmonary ventilation (VE), oxygen uptake ($\dot{V}O_2$), and HR. Typical example of the changes in the cardiorespiratory parameters during orthotic gait exercise was shown in the Figure 1b. The amount of time required to walk 10 m was recorded during the exercise period, and gait speed was calculated after the experiment. After the experiments, the energy consumption and energy cost were calculated. The terms adopted were those of Nene and Patrick,¹² and calculations were performed according to their protocol:

$$\begin{aligned} \text{Energy consumption (J/kg/s)} \\ = \frac{\text{Ambulatory min } \dot{V}O_2 \text{ (ml/min)}}{\text{Weight (kg)} \times 60} \times K \end{aligned}$$

$$\begin{aligned} \text{Energy cost (J/kg/m)} \\ = \frac{\text{Ambulatory min } \dot{V}O_2 \text{ (ml/min)}}{\text{Speed (m/min)} \times 60} \times K \end{aligned}$$

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

Motion analysis

Subjects performed orthotic walking along a 10-m walkway in the laboratory at least five times at a comfortable (self-determined) speed. In order to obtain the kinematics and kinetics variables of the orthotic gait, the gait motion was measured with a three-dimensional motion-analysis system (VICON 370, Vicon Motion Systems Ltd, Oxford, UK). The motion-analysis system consisted of a conventional video-analysis system with seven cameras and force plates (Kistler, Switzerland). The force plates, $160 \times 450 \text{ cm}$ in size, consisted of two $80 \times 200 \text{ cm}$ plates and four $40 \times 250 \text{ cm}$ plates. These separate force plates enabled us to measure ground reaction forces (GRF) under the feet and canes on both sides, separately. A total of 17 markers were attached to the orthosis and to the body of the subject on the skin overlying the following marks: the vertex, both sides of the acromium (SHO), the lateral aspects of the hip (HIP), knee (KNE), and ankle (AKL) joints of the orthosis, the top of the great toe (TOE), the protrusion of the ulna at the elbow and wrist joint, and the tip of the crutch. We defined the hip angle as the angle formed by the SHO, HIP, and KNE, and the ankle angle as that formed by the KNE, AKL, and TOE, respectively. Typical time series data of the GRF (body and stick) and joint angle motion (Hip, Knee, and Ankle) obtained by the VICON system was shown in the Figure 1c.

We sampled 10-step cycles for the analysis. The following kinematic and kinetic variables were evaluated on the basis of the motion analysis: cadence, stride length, hip joint range of motion (ROM), hip angular

velocity (VEL), and crutch force (CF) (peak crutch force (PCF) and mean crutch force (MCF)). Cadence was calculated as the time required between heel contacts detected by the body GRF. Stride length was calculated as the distance of the toe marker between two consecutive gait cycles.

Statistics

Values were given as means $\pm$ SEM. Pearson's product moment correlation coefficient was used to examine the relationship between the level of lesion and the kinematic and kinetic variables. Moreover, since the injured level is not strictly regarded as a parametric variable, we also examined this relationship using the Spearman rank-correlation coefficient. For this analysis, the parameters used were the average value for each subject. Significance was accepted at $P < 0.01$ and $P < 0.05$.

Results

Figure 1a shows a sequential picture of walking with the ARGO, the typical waveform of the GRF of each body and of the opposite side of the crutch, joint motion (Hip, Knee, and Ankle) (Figure 1b), and the typical data of the cardiorespiratory responses (Figure 1c). As shown in this figure, dynamic hip joint motion and periodic load application appeared during orthotic gait. In the orthotic gait, in contrast with normal walking, the knee joint was held in an extended position throughout the locomotion cycle. Although the ankle was held by the plastic socket, angle changes were observed to some extent in the stance phase.

Gait speed

The average walking speeds calculated during field walking (during cardiorespiratory measurement) and laboratory walking (during motion analysis) were 19.8 ± 6.16 and $21.3 \pm 5.82 \text{ m/min}$, respectively. There was a strong relationship between these variables ($r = 0.87$, $P < 0.01$). Therefore, in this study, the former value was used as the gait speed. Eight of 10 subjects were able to walk continuously for 20 min without a long break. Subjects H and J, who had relatively higher levels of injury, required rest intervals due to arm fatigue and a pressure on the heels of hands.

Cardiorespiratory responses during orthotic gait

Table 2 shows the cardiorespiratory responses at rest and the steady-state value during orthotic walking. In the subjects H and J, the resting value of the HR was much higher than in other subjects. This is presumably caused by a disorder of the autonomic nervous functions. As clearly shown in Figure 1c, cardiorespiratory parameters rapidly increased after the beginning of the walking exercise. HR reached a plateau level in the first few minutes, whereas some subjects with a higher level of lesion (subjects I and H) showed further

increases of HR during prolongation of the exercise. The steady-state value of HR ranged from 99.2 to 166.4 b/min (average value: 130.0 ± 21.63 b/min). As with HR, $\dot{V}O_2$ reached a plateau level about 3–4 min after the beginning of exercise. The steady-state value of $\dot{V}O_2$ ranged from 14.91 to 24.83 ml/kg (18.17 ± 3.80 ml/kg), and this value is approximately 3–4 times the resting level.

The energy consumption and energy cost during walking were 6.11 ± 1.28 J/kg/s and 20.12 ± 7.35 J/kg/m, respectively (Table 3). Figure 2a shows the relationship between energy consumption (y-axis) and energy cost (x-axis) in each subject. As the walking speed was determined by dividing the energy consumption by the energy cost, the slope of the line from zero to each point plotted reflects the walking speed of each subject. It was found that the plots of persons with higher level injuries tended to shift to the right side, which signifies a relatively slower gait speed and a higher energy cost.

Table 2 VE, $\dot{V}O_2$, and HR at rest and during orthotic gait exercise

	VE (ml/kg)		$\dot{V}O_2$ (ml/kg)		HR (beat/min)	
	Rest	Exercise	Rest	Exercise	Rest	Exercise
A	194.0	437.3	6.70	16.01	60.1	99.2
B	171.5	525.1	4.48	17.63	70.4	114.3
C	139.2	574.2	4.29	14.91	87.6	140.2
D	172.9	664.9	4.66	15.62	92.1	129.5
E	185.8	624.2	6.78	24.20	62.1	132.5
F	175.3	592.9	6.62	15.41	78.3	131.5
G	155.0	634.4	4.43	16.75	77.9	110.1
H	221.8	560.6	5.80	15.19	107.8	163.0
I	277.9	660.5	9.75	24.83	81.0	143.7
J	265.1	687.7	8.29	21.14	144.1	166.4
Mean	195.8	596.2	6.18	18.17	86.13	133.0
SD	45.61	75.67	1.83	3.80	24.78	21.63

In order to confirm the data reproducibility, we compared the energy consumption and energy cost evaluated at 2 and 3 months after the beginning of the training in six of 10 subjects (Figure 2b). Although these data include the training effect (improvement of the energy cost), data reproducibility can be well recognized from this figure.

Kinematics and kinetics

The parameters obtained from motion analysis are summarized in Table 3. Cadence and stride length were 44.0 ± 6.27 step/min and 97.4 ± 16.36 cm, respectively. Hip ROM was 44.1 ± 5.20 deg. The angular velocities of the flexion and extension phases were 124.3 ± 11.56 and 21.7 ± 7.12 deg/s, respectively. Figure 3 shows the stick picture (top) and ensemble averaged waveform of the hip angle and GRF for both body and crutch during orthotic gait obtained from subjects A (injured at Th12) and J (Th5). As clearly shown in this figure, there are remarkable differences in the gait motion between the SCI subjects injured at a lower and higher level. This figure also shows good reproducibility of both hip motion and GRF during orthotic gait.

Relationship between injury level and each parameter

Table 4 summarizes the Pearson's product moment correlation coefficient (r_p) and the Spearman rank-correlation coefficient (r_s) between the injured level and each parameter obtained in this study. Figure 4 also shows the correlation diagram between the level of injury and with gait speed, energy consumption, energy cost, hip ROM, and mean GRF of the body and crutch. The parameters that showed strong relevance to the injury level were gait speed ($r_p = 0.74$; $P < 0.01$, $r_s = 0.89$; $P < 0.01$), energy cost ($r_p = -0.88$; $P < 0.01$, $r_s = -0.92$; $P < 0.01$), stride length ($r_p = 0.79$; $P < 0.01$, $r_s = 0.78$; $P < 0.01$), peak CF ($r_p = -0.78$; $P < 0.01$, $r_s = 0.80$; $P < 0.01$), and hip ROM ($r_p = 0.78$; $P < 0.01$, $r_s = 0.77$; $P < 0.01$). By evaluating the Spearman rank-correlation

Table 3 All parameters calculated in this study

	Gait speed (m/min)	E consmp. (J/kg/s)	E cost (J/kg/m)	Cadence (step/min)	Stride length (cm)	Peak CF (N/kg)	Mean CF (N/kg/s)	Hip ROM (deg)	Hip fVEL (deg/s)	Hip eVEL (deg/s)
A	20.06	5.39	16.12	40.86	106.6	1.81	0.32	45.44	110.2	24.35
B	32.58	5.93	10.93	56.92	122.5	2.81	0.34	51.04	142.6	38.90
C	27.22	5.02	11.06	47.62	107.7	2.62	0.33	47.95	126.0	23.91
D	21.55	5.26	14.63	40.59	118.8	3.93	0.46	49.52	127.6	24.17
E	19.99	8.14	24.44	36.34	79.9	3.73	0.49	40.91	119.0	13.36
F	18.35	5.19	16.95	47.10	102.9	3.37	0.60	46.35	131.0	22.20
G	11.64	5.64	29.05	36.81	83.8	4.31	0.47	43.08	110.0	15.78
H	15.58	5.11	19.67	42.25	89.8	4.39	0.50	42.23	132.9	18.00
I	17.09	8.35	29.33	48.98	77.5	5.02	0.45	38.83	133.9	18.75
J	14.69	7.11	29.06	42.01	84.8	3.92	0.55	41.92	109.7	17.79
Mean	19.88	6.11	20.12	43.95	97.4	3.59	0.45	44.73	124.3	21.72
SD	6.16	1.28	7.35	6.27	16.36	0.96	0.09	3.98	11.56	7.12

Figure 2 (a) The relationship between energy consumption and cost in each investigation. The slope of each line from zero to each plot reflects the walking speed. The subjects represented by points plotted on the upper and left side of the figure can be considered to have adequate aerobic conditioning. (b) Differences of the energy consumption and cost between 2 and 3 months after the beginning of the orthotic gait training. Gray and black markers indicate each subject's data and averaged data, respectively. Error bar indicates standard deviation

coefficient, mean CF ($r_s = -0.67$; $P < 0.05$) and hip extension VEL ($r_s = 0.74$; $P < 0.05$) also showed a strong relevance to the injury level.

Discussion

The present results clearly show the significant relationship between the level of neurological lesion and orthotic gait performance (Figure 4 and Table 4). The injured segment of the spinal cord in our subjects ranged from Th5 to 12. This included the anatomical levels of those innervating muscles that move the trunk, for example, the volitional control of the abdominal and iliopsoas muscle. This was intact in those injured at Th12, but not in those injured at Th5. It is therefore likely that these results are attributable to the degree of residual motor function around the trunk.

Physiological intensity of orthotic gait exercise

In the present study, the steady-state values of the $\dot{V}O_2$ and HR during orthotic gait were 18.2 ± 3.80 ml/kg and

Figure 3 Differences in the gait motion between SCI subjects injured at a lower (left; Th12) and higher level (right; Th5). The stick pictures represented were standardized by the marker on the GTR

Table 4 Pearson's product moment correlation coefficient and Spearman rank-correlation coefficient between injured level and each parameter

Level versus	Gait speed	E consmp.	E cost	Cadence	Stride length	Peak CF	Mean CF	Hip ROM	Hip fVEL	Hip eVEL
Pearson	0.74**	-0.54	-0.88**	0.22	0.79**	-0.78**	-0.60	0.78**	0.23	0.60
Spearman	0.89**	-0.44	-0.92**	0.14	0.78**	-0.80**	-0.67*	0.77**	0.20	0.74*

* $P < 0.05$, ** $P < 0.01$

Figure 4 Effects of the level of injury on gait speed, cadence, stride length, energy consumption, energy cost, and hip range of motion. The lines indicate the linear regression lines of the level of injury against each parameter

Table 5 Energy consumption, cost and gait speed with different orthoses in previous studies and our present study

Series	Number of subjects	E. consump (J/kg/s)	E. cost (J/kg/m)	Gait speed (m/min)	Level and aid
Hirokawa <i>et al</i> ⁵	6	4.18	21	12.48	T1–T10 RGO
Winchester <i>et al</i> ¹³	4	4.37	19.44	13.5	T5–T10 RGO
Bernardi <i>et al</i> ⁴	10	4.3	20	12.78	T4–12 RGO
Felici <i>et al</i> ¹⁴	6	8.26	32.3	15.34	T5–L1 RGO, ARGO
Massucci <i>et al</i> ¹⁵	6	4.64	29	9.6	T3–T12 ARGO
Ijzerman <i>et al</i> ⁸	10	5.92	28.20	12.6	T4–12 ARGO
Merati <i>et al</i> ¹⁶	6	4.64	24.87	11.2	T3–T11 RGO
Present study	10	6.11	20.12	19.88	T5–12 ARGO
<i>Normal subject</i>					
Blessey ¹⁷		4.35	3.25	82.2	
Bernardi <i>et al</i> ¹⁸	18	4.52	3.53	76.8	

All values are expressed as averages

133.0 ± 21.63 b/min, respectively (Table 2), approximately a three-fold increase over the respective resting values. We note that the physiological intensity presumed by these values tended to be larger in the higher thoracic SCI subjects. This is clearly shown in Figure 2, where we show that the energy consumption in the higher thoracic SCI subjects is relatively larger, while that in the lower thoracic SCI subjects remained at the same level as that of normal walking. As the subjects were asked to walk at their preferred speed, this result suggests that higher level SCI persons cannot walk comfortably because of their larger area of motor paralysis.

Although the physiological intensity of orthotic gait is in a feasible range to allow safe walking because these

patients have sufficient aerobic capacity even in the higher thoracic SCI subjects, the excess energy expenditure and burden on their upper limbs make it impossible to achieve suitable exercise intensity for promoting general health. Therefore, it is important to discover ways to reduce this excess physiological load. In the following section, we will discuss the reason for limited orthotic gait performance in higher thoracic level of SCI patients based on our results of motion analysis.

Relevance between residual motor function and orthotic gait mechanics

During orthotic gait with the ARGO, in order to swing the paralyzed lower limb, the user first puts his or her

weight onto one foot, and rises up the upper body by coincidentally pushing the ground throughout the crutch. By inducing this upper body motion, the reciprocating device mounted on the hip joint functions to swing opposite side of the leg.^{7,8} Therefore, the trunk muscle contraction and compensatory upper limb motion are important for creating the hip swing motion. The mechanics of orthotic gait are the key to explaining our results. As clearly shown in Figures 3 and 4d, subjects with higher thoracic injuries showed a remarkably small hip ROM as compared to that in lower thoracic SCI subjects. This result might imply that the upper body motion was insufficient to produce the leg swing in higher level SCI subjects because of their trunk and hip muscle paralysis. Concerning the CF, as is clearly shown in Figure 4e, PCF shows an inverse relationship to the injury level. This result indicates an additional upper limb burden in the compensation for the trunk paralysis in the higher thoracic SCI subjects. It is therefore considered that the slower gait speed and higher energy cost of higher thoracic SCI subjects may be attributed to the limited hip motion and excess upper limb load.

Comparison with previous results

As compared to the other reports^{4,5,13–16} where the energy expenditure of orthotic gait was measured in reciprocating gait orthosis (RGO and ARGO), our data shows a faster gait speed with similar energy expenditures (Tables 4 and 5). The gait speed reported by Massucci *et al*¹⁵ and Ijzerman *et al*⁸ both of which used ARGO, was remarkably slower than that shown in our data. Taken together with the similarity in the injured level of the subjects between these two studies, this result may indicate that our degree of training especially in time spent practicing, may have influenced the gait speed. Our subjects initially showed a slower gait speed, and reached exhaustion in only a few minutes. However, throughout the training period, they had acquired gait skills and thus improved their energy cost when performing the orthotic gait.

When the present results for energy expenditure during orthotic gait are compared to those for energy expenditure during walking in neurologically normal persons,^{17,18} although the levels of energy consumption are within a similar range, the levels of energy cost are considerably worse (approximately six times) during orthotic gait.

Implication for rehabilitation

Owing to the physiological need of gait training for SCI patients, it is important to find a way to reduce the excess physiological load during orthotic gait movement. Many researchers have paid attention to this issue, and in some studies they have attempted to accomplish effective orthotic gait performance with the use of functional electrical stimulation (FES). Although

some studies suggested the effectiveness of FES based on the additional muscle contraction of the paralyzed area in, for instance, the reduced energy cost (Hirokawa *et al*⁵), it is obvious that the FES technique is insufficient as a solution to the above problem.

In addition to the higher energy cost of orthotic gait movement, the present results clearly show the relationship between orthotic gait performance and the thoracic level of lesion in SCI patients. Further, the results of the motion analysis have revealed that the slower gait speed and higher energy cost of higher thoracic SCI subjects can be attributed to their limited hip motion and presumed excess upper limb load. Our results indicate that higher thoracic SCI patients need some way of reducing the excess physiological load to acquire the suitable exercise intensity.

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