A comparison of paraplegic gait performance using two types of reciprocating gait orthoses

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Abstract

This study examined the energy cost of ambulation using the reciprocating gait orthosis (RGO) and the modified Isocentric RGO in paraplegic spinal cord injured subjects. In 4 subjects, the rates of O_2 consumption per minute, O_2 cost per metre, heart rate (HR), respiratory exchange ratio, velocity, and physiologic cost index (PCI) were measured during ambulation with the two orthotic devices. PCI was calculated by dividing the difference between walking and resting HR by velocity. PCI was significantly lower during ambulation trials with the Isocentric RGO compared to the RGO, but was the only measurement that detected a significant difference beween the two orthotic devices. These results indicate that energy costs of ambulation at self-selected speeds were lower with the Isocentric RGO compared to the standard RGO. Furthermore, PCI could be used as a sensitive indicator of gait efficiency in spinal cord injury subjects.

Introduction

In the last decade, considerable attention has been directed towards the development of devices that would enable paralyzed people to achieve a reciprocal gait. The options available to the spinal cord injured individual include mechanical orthoses, functional electrical stimulation (FES), and a combination of these two systems. Current systems using FES are limited due to the low reliability and safety of these systems (Yamaguchi and Zajac, 1990). Therefore, at this time only the systems using mechanical orthoses are practical in a clinical and home setting (Stallard *et al.*, 1989).

The reciprocating gait orthosis (RGO) is one of the orthotic options available to spinal cord injured patients with paraplegia. The RGO consists of bilateral hip-knee-ankle-foot orthoses (HKAFO) connected by an extended pelvic band (Douglas *et al.*, 1983). This custom moulded pelvic band functions as a lever, so that ipsilateral hip extension is achieved when the individual extends his back. Two Bowden cables cross-connected to opposite sides of each hip joint, mechanically couple hip extension on one side to hip flexion on the contralateral side. Rhythmic activation of the cable system causes hip flexion on alternating sides, thus producing a reciprocal gait pattern.

Although crossed cables are a simple and reasonably effective way to produce reciprocal hip joint motion, they may not be the most efficient mechanical coupling available. Since the cables are secured only at each end, some of the energy associated with active hip extension is wasted in unwanted cable flexion. In addition, since a cable must be in tension to effectively transmit large amounts of force, only half of the system is being used at a time. For these reasons, any orthotic system that can achieve reciprocal hip joint motion without the need for a crossed cable coupling may theoretically be more efficient and subsequently require less effort on the part of the spinal cord injured patient.

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Recently, just such a modification of the original RGO has become available (Motloch, 1992). In this system (known as the Isocentric RGO), the crossed Bowden cables used to couple hip extension to contralateral hip flexion are replaced by a centrally pivoting bar and tie rod arrangement. Although apparently more efficient, no prior study has attempted to quantify the relative performance of the two systems on a group of trained subjects.

The extent to which walking with a particular orthosis will be a practical method of mobility is dependent on the engery cost to that individual. Energy expenditure can be estimated by measuring the oxygen consumption in the expired gas. Expired gases can be collected using a Douglas bag, spirometer, or mass spectrometer (Fisher and Gullickson, 1978). All of these methods require a mouthpiece, nose clip, and headgear that are cumbersome and may alter an individual's gait pattern. Measurements of the heart rate (HR) response and the velocity of walking are easily collected and can be used to provide an estimate of the energy cost of gait. MacGregor (1981) introduced the physiologic cost index (PCI) which is the ratio of the HR increase above resting HR to the velocity of ambulation. PCI has been used to demonstrate the difference in energy costs between normal and disabled children (Butler *et al.*, 1984) and in comparing energy costs of spastic diplegic children with and without ankle-foot orthoses (Mossberg *et al.*, 1990). PCI was used recently to assess the gait efficiency of a single spinal cord injured subject ambulating with the RGO and FES (Isakov *et al.*, 1992).

Estimating the energy expenditure of ambulation is essential for assessing the gait efficiency and the differences in orthotic systems in the spinal cord injured individual. Previous studies have demonstrated that the energy expenditure of walking with knee-ankle—foot orthoses (KAFO) (Huang *et al.*, 1979; Chantraine *et al.*, 1984; Miller *et al.*, 1984; Water *et al.*, 1989) and RGO (Hirokawa *et al.*, 1990) is above normal after a spinal cord injury. Hirokawa and colleagues (1990) reported that ambulation with the RGO is more efficient than ambulating with KAFO's. The energy expenditure of walking with the Isocentric RGO has not been determined.

The objective of this study was to determine the energy cost of paraplegic persons walking with the RGO and with the Isocentric RGO. In addition, the PCI was calculated to determine if PCI alone can be used in future studies as a replacement for direct oxygen measurements.

Methods

Subjects

Four male subjects with paraplegia participated in this study. Criteria for participation were a diagnosis of thoracic paraplegia, at least 2 years post injury, absence of lower limb contractures, and no pressure sores. All subjects were given a physical examination to assess their general health and an orthopedic examination to determine the condition of bones in the lower limb and spine. All subjects read and signed the informed consent form approved by the Institutional Review Board at the University of Texas Southwestern Medical Center at Dallas.

Gait training

All subjects were fitted with a custom RGO fabricated by a certified orthotist who had prior experience with this device. The RGO was fabricated and fitted according to the Louisiana State University (LSU) guidelines (Douglas *et al.*, 1983), and was aligned so that each of the subjects could stand without upper limb support for approximately one minute. Care was taken to align the uprights so that excessive abduction or adduction was avoided during

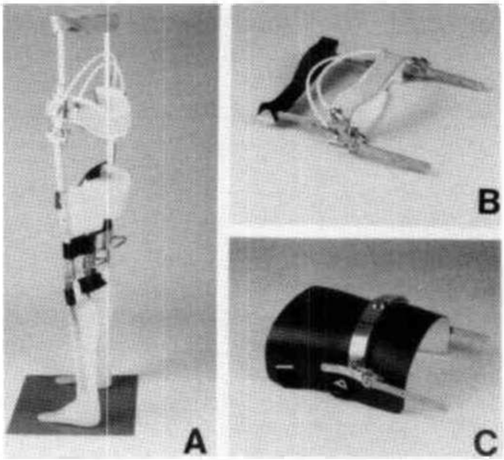

Figure 1. The reciprocating gait orthosis (RGO) is shown in (A). An enlarged view of the hip joint and the associated cable assembly of the RGO and the hip joint of the Isocentric RGO is shown in (B) and (C.).

swing. Each subject also received an Isocentric RGO hip joint that was made to be interchangeable with the KAFO. Figure 1A illustrates the RGO with the standard reciprocating cable assembly and a close-up view of the standard RGO hip joint (Fig. 1B) and Isocentric RGO hip joint (Fig. 1C).

After being fitted with the orthoses, each subject was scheduled for gait training with a licensed physical therapist. These sessions were scheduled for 2 hours, 2–3 times weekly. Training included donning and doffing the RGO, coming to standing and sitting, and walking on level surfaces. The average time of gait training was 35±7.5 hours. The majority of the gait training was done with the standard reciprocating cable assembly (RGO=23 hours versus Isocentric RGO=12 hours).

Testing procedures

When the subjects could ambulate independently with a rolling walker for a minimum of 25 metres they were scheduled for two testing sessions with one week. Velocity, cadence, HR VO_2, VCO_2, and respiratory rate were measured during ambulation with the sandard RGO and the Isocentric RGO. The order of testing for the orthotic device was randomized.

HR was monitored continuously with a wireless telemetry device. Two EKG electrodes were placed on the left midclavicular line and on the midsternal line. The transmitter was attached to the electrodes and taped securely to the trunk of the subject. Each subject was fitted with a nose clip, headgear, and a mouthpiece from which a flexible tube was connected to a rolling metabolic cart pushed behind them while they walked. Time was allotted for the subject to get used to the apparatus. HR and respiratory rate were monitored continuously. VO_2 and VCO_2 were monitored breath-by-breath.

VO_2, VCO_2, respiratory rate, and heart rate were collected for 5 minutes while the subject sat quietly. These metabolic measures were collected for 3 minutes once the subject stood to establish basal HR and energy expenditure during quiet standing. The subject was then instructed to walk along a 12 metre gait lane at a self-selected velocity. Care was taken to keep the metabolic cart and flexible tube slack so that it did not interfere with the subject's

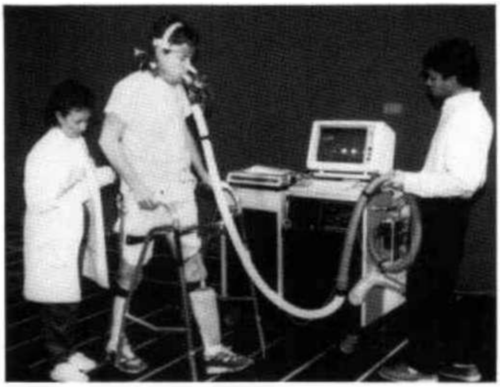

Figure 2. A subject being measured during a testing session showing the mouthpiece, noseclip, and headgear with the metabolic cart.

locomotion pattern (Fig. 2). At the end of the gait lane, the subject turned immediately and stood at the starting line for 3 minutes. This procedure was repeated for a total of four complete passes. After the final pass, the subject sat down and data were recorded for 3–5 minutes, depending on when measurements returned to the basal resting rate.

Data analysis

Velocity, cadence, and peak respiratory exchange ratio (RER) for each subject were calculated for each pass. The values for HR, VO_2, VCO_2, and respiratory rate were also determined. Although metabolic gases were collected for the entire time the patient was walking, only peak VO_2, VCO_2 measurements achieved during steady state were used for analysis. Energy expenditure during walking was expressed in two manners; the rate of O_2 per minute normalized to body weight (ml/kg min) and the O_2 cost per metre normalized to body weight (ml/kg m). PCI was calculated as follows:

$$\text{PCI (beats/metre)} = \frac{(HR_W - HR_R)}{V}$$

where: HR_W=peak HR during walking (beats/min)
HR_R=peak HR at rest (beats/min)
V =velocity (m/min)

Descriptive statistics included means ±SD were calculated. A one-way multivariate analysis of variance (MANOVA) was used to analyze O_2 rate per minute, O_2 cost per metre, RER, HR, PCI, velocity, and cadence with respect to type of orthoses. Post hoc testing was

Table 1. Subject information

Subject	Age (yrs)	Height (m)	Weight (kg)	Level of Injury	Time since Injury (months)
1	36	1.83	70.31	T5	27
2	24	1.68	70.31	T8	25
3	25	1.89	83.92	T8	58
4	34	1.93	88.00	T10	33

conducted to determine which variable demonstrated a significant difference between walking performance in the RGO and Isocentric RGO. Significance was accepted at an alpha level of 0.05.

Results

Subject profiles are summarized in Table 1. The subjects were between the age of 24 and 36 with a mean age of 29.8±6.1 years. The average height was 1.8±0.1 m and weight was 78.1±9.2 kg. The patients selected represented injury levels ranging from T5 to T10 and the average time since the onset of spinal cord injury was 35.7±15.2 months. Two subjects were complete paraplegics and the other two subjects were motor incomplete paraparetics.

The mean ±SD for measurements of gait performance are given in Table 2. The mean PCI for ambulation with the RGO was 3.61±0.66 beats/metre compared to 2.56± 0.47 beats/metre with the Isocentric RGO. This difference in PCI during ambulation was significantly different between orthotic types (P=0.04). PCI decreased 28.01±13.49% during ambulation with the Isocentric RGO compared to ambulation with the standard RGO. All other parameters of gait performance except for RER were consistently better with the Isocentric RGO, but the differences were not statistically significant at the alpha level of 0.05.

Table 2. Measurements of gait performance with the RGO and Isocentric RGO

	RGO	Isocentric RGO
O_2 rate (ml/kg min)	14.2±1.8	13.0±1.4
O_2 cost (ml/kg m)	1.1±0.3	1.0±0.1
RER	1.1±0.1	1.2±0.2
HR (beats/min)	145±23	144±20
PCI (beats/m)	3.6±0.7	2.6±0.5*
velocity (m/min)	12.7±1.9	13.5±2.1
cadence (steps/min)	30.3±6.2	31.3±7.9

Values are mean±SD*
indicates significant difference (p=0.04) between the RGO and isocentric RGO.

Discussion

The extent to which walking will be a practical method of mobility after spinal cord injury is dependent on the energy costs involved in ambulation. Several researchers have measured the energy cost of walking by spinal cord injured subjects in bilateral KAFOs (Huang *et al.*, 1979; Chantraine *et al.*, 1984; Miller *et al.*, 1984; Water *et al.*, 1989) but only one study has measured oxygen consumption during ambulation with RGO (Hirokawa *et al.*, 1990). Hirokawa *et al.* (1990) measured the total VO_2 during cadence controlled walks in 6 subjects ambulating with RGO. The energy expenditures per minute and per metre were then calculated. Correlating the energy expenditure to velocity, Hirokawa *et al.* (1990) ranked the orthotic systems and concluded that at slow speeds the energy cost of ambulating with the RGO was less than the costs of ambulating with a KAFO or with the Hip Guidance Orthosis (Parawalker). No analysis beside the ranking was performed that demonstrated if the energy expenditure between orthoses was significantly different. Furthermore, the type of walking assistive device the subjects used was not a controlled factor.

Hirokawa *et al.* (1990) reported a preferred walking speed of 0.208 m/sec (12.48 m/min.) for 6 paraplegic persons ambulating with the RGO. This is very similar to the velocity reported in this study; 12.71 and 13.54 m/min. for the RGO and Isocentric RGO, respectively. Using the HR and velocity data presented in the Hirokawa *et al.* (1990) study, the authors of this paper calculated the PCI of 3.61 beats/metre for their group of subjects. This is the same value found for the subjects in this study ambulating with the RGO. Isakov *et al.* (1992) recently used PCI to evaluate performance of walking in a T4 spinal cord injured individual. They reported a PCI of 2.55 beats/metre in their subject ambulating with an RGO. This value is considerably lower than the mean value reported in this study. This difference could be due to the length of training with the RGO. Their subject had been ambulating with the RGO for two years and averaged 8 hours/week of gait training.

A significant reduction in the PCI was found in the group of subjects in this study when the standard RGO hip joint was replaced by the Isocentric RGO hip joint. Caution must be exercised when a conclusion is based on a small sample size, however, subjective reports from the subjects included that they felt less fatigued when walking with the Isocentric RGO.

Although a decrease in the O_2 rate per minute and the O_2 cost per metre was observed, these two methods of expressing energy expenditure were not statistically different between orthotic devices. One reason for this may be the small sample size. However, an O_2 recording system that requires a face mask, nose clip, and tethered cart may be so disruptive to the subject that the oxygen consumption measurements may not be representative of the true energy requirements of walking. It has been observed that face masks can block a test subject's vision. This is not a problem for normal subjects, but in certain disabilities where proprioception and kinesthesia are absent or impaired, subjects may have to rely upon visual feedback for foot placement during gait. In the earlier stages of this study an attempt was made to use a face mask that covered both the nose and mouth but the collection apparatus had to be modified to allow the subjects a better visual field. The advantages of using measurements of HR and velocity to estimate energy expenditure in paraplegic individuals is that it eliminates the use of mouthpieces and nose clips that the patients may find cumbersome or functionally interfering. Furthermore, it does not require the use of expensive gas collection apparatus.

This study demonstrated that PCI can be used as a tool in the assessment of gait efficiency in spinal cord injured subjects. Combining a physiological measurement (HR) with a functional measurement (velocity) may make PCI a more sensitive measure for detecting small but significant differences in energy expenditure. Previous investigators have used PCI as an assessment tool in normal (MacGregor, 1981), disabled children (Butler *et al.*, 1984; Mossberg *et al.*, 1990), and paraplegic subjects (Bowker *et al.*, 1992; Isakov *et al.*, 1992). Isakov *et al.* (1992) reported a dramatic reduction of PCI values in a spinal cord injured subject ambulating with RGO and FES compared to ambulating with just the RGO. Only minimal changes were observed in other parameters of gait performance such as cadence, velocity, and step length. A slight improvement is reported here in velocity and cadence with the Isocentric RGO, however, these measurements do not reflect changes in the energy demand of walking.

In this study, it is reported that modifying the standard RGO by exchanging the cables for an isocentric bar resulted in a significant reduction in the PCI of spinal cord injured individuals. Future studies incorporating kinematic analyses of gait with the RGO and the Isocentric RGO may provide insight that will continue to improve the design and function of this orthotic device.

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