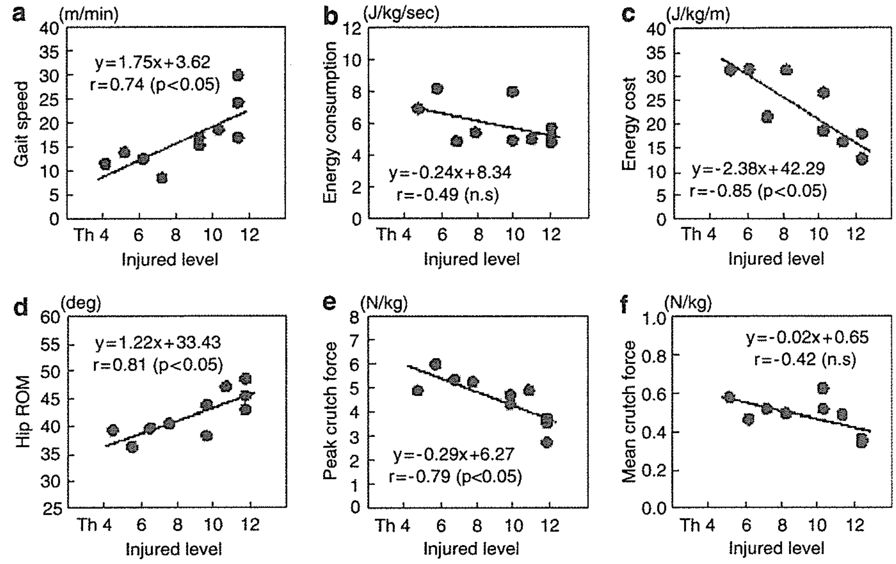

Figure 4 Effects of the level of injury on gait speed, cadence, stride length, energy consumption, energy cost, and hip range of motion. The lines indicate the linear regression lines of the level of injury against each parameter

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 *et al*[5]	6	4.18	21	12.48	T1–T10 RGO
Winchester *et al*[13]	4	4.37	19.44	13.5	T5–T10 RGO
Bernardi *et al*[4]	10	4.3	20	12.78	T4–12 RGO
Felici *et al*[14]	6	8.26	32.3	15.34	T5–L1 RGO, ARGO
Massucci *et al*[15]	6	4.64	29	9.6	T3–T12 ARGO
Ijzerman *et al*[8]	10	5.92	28.20	12.6	T4–12 ARGO
Merati *et al*[16]	6	4.64	24.87	11.2	T3–T11 RGO
Present study	10	6.11	20.12	19.88	T5–12 ARGO
Normal subject					
Blessey[17]		4.35	3.25	82.2	
Bernardi *et al*[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 valuables 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.

References

1 Gordon EE, Vanderwalde H. Energy requirements in paraplegic ambulation. *Arch Phys Med Rehabil* 1956; **37:** 276–285.

2 Chantraine A, Crielaard JM, Onkelinx A, Pirnay F. Energy expenditure of ambulation in paraplegics: effects of long term use of bracing. *Paraplegia* 1984; **22:** 173–181.

3 Nene AV, Patrick JH. Energy cost of paraplegic locomotion with the ORLAU parawalker. *Spinal Cord* 1989; **27:** 5–18.

4 Bernardi M, Canale I, Castellano V, Di Filippo L, Felici F, Marchetti M. The efficiency of walking of paraplegic patients using a reciprocating gait orthosis. *Paraplegia* 1995; **33:** 409–415.

5 Hirokawa S, Grimm M, Le T, Solomonow M, Baratta RV, D'Ambrosia RD. Energy consumption in paraplegic ambulation using the reciprocating gait orthosis and electric stimulation on the thigh muscles. *Arch Phys Med Rehabil* 1990; **71:** 687–694.

6 Butler PB, Major RE, Patrick JH. The technique of reciprocal walking using the hip guidance orthosis (hgo) with crutches. *Prosthet Orthot Int* 1984; **8:** 33–38.

7 Jefferson RJ, Whittle MW. Performance of three walking orthoses for the paralysed: a case study using gait analysis. *Prosthet Orthot Int* 1990; **14:** 103–110.

8 IJzerman MJ, Baardman G, van 't Hof MA, Boom HB, Hermens HJ, Veltink PH. Validity and reproducibility of crutch force and heart rate measurements to assess energy expenditure of paraplegic gait. *Arch Phys Med Rehabil* 1999; **80:** 1017–1023.

9 Solomonow M, Baratta RV, D'Ambrosia R. Standing and walking after spinal cord injury: experience with the reciprocating gait orthosis powered by electrical muscle stimulation. *Top Spinal Cord Injury Rehabil* 2000; **5:** 29–53.

10 Kawashima N, Nakazawa K, Ishii N, Akai M, Yano H. Potential impact of orthotic gait on natural killer cell activities in thoracic level of spinal cord injured patients. *Spinal Cord* 2004; **42:** 420–424.

11 Maynard Jr FM *et al.* International standards for neurological and functional classification of spinal cord injury. *Spinal Cord* 1997; **35:** 266–274.

12 Nene AV, Patrick JH. Energy cost of paraplegic locomotion using the parawalker-electrical stimulation 'hybrid' orthosis. *Arch Phys Med Rehabil* 1990; **71:** 116–120.

13 Winchester PK *et al*. A comparison of paraplegic gait performance using two types of reciprocating gait orthoses. *Prosthet Orthot Int* 1993; **17:** 101–106.
14 Felici F, Bernardi M, Radio A, Marchettoni P, Castellano V, Macaluso A. Rehabilitation of walking for paraplegic patients by means of a treadmill. *Spinal cord* 1997; **35:** 383–385.
15 Massucci M, Brunetti G, Piperno R, Betti L, Franceschini M. Walking with the advanced reciprocating gait orthosis (ARGO) in thoracic paraplegic patients: energy expenditure and cardiorespiratory performance. *Spinal cord* 1998; **36:** 223–227.
16 Merati G, Sarchi P, Ferrarin M, Pedotti A, Veicsteinas A. Paraplegic adaptation to assisted-walking: energy expenditure during wheelchair *versus* orthosis use. *Spinal Cord* 2000; **38:** 37–44.
17 Blessey R. Energy cost of normal walking. *Orthop Clin North Am* 1978; **9:** 356–358.
18 Bernardi M *et al*. Cost of walking and locomotor impairment. *J Electromyogr Kinesiol* 1999; **9:** 149–157.