

RESPONSES OF OXYGEN CONSUMPTION, HEART RATE AND PERCEIVED EXERTION TO CRUTCH WALKING: A COMPARISON BETWEEN PARAPLEGIC AND ABLE-BODIED SUBJECTS

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ABSTRACT

In this study, 10 normal volunteers and 5 sports-trained paraplegics with lesions between T₆ and L₂ were studied whilst walking with axillary crutches and knee-ankle-foot orthoses. All subjects walked at their preferred speed on a figure-of-eight track. Normal subjects also walked at slower and faster speeds. Oxygen consumption, heart rate and rating of perceived exertion were measured.

In normal subjects, stable heart rates (± 2 beats/min) were rapidly reached within two minutes at all three speeds. In paraplegics, the heart rate responses were more variable. The heart rate response in lumbar level paraplegics resembled normal subjects. Thoracic level paraplegics rarely showed stable heart rates during walking and in some instances, the rate rose progressively up to values of about 180 beats/min.

In normal subjects walking in knee-ankle-foot orthoses, there was no significant difference of energy cost and physiological cost index between preferred and fast speeds. The preferred and fast speeds were also more efficient for crutch walking. There was a significant correlation ($p < 0.01$) between energy cost and physiological cost index ($r = 0.65$). Both energy cost and physiological cost index are standardized by dividing by speed; this has not been done for perceived exertion.

The results show a greater load on the cardio-respiratory system in paraplegics. This may be partly explained by decreased venous return due to impaired muscle function in the lower limb and relatively low frequency of stepping.

Keywords: Arm Crank Ergometry, Crutch Walking, Energy Cost, Energy Expenditure, Oxygen Consumption, Paraplegic, Perceived Exertion, Physiological Cost Index, Upper Body Exercise.

MJIRI, Vol. 11, No. 3, 209-217, 1997.

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INTRODUCTION

The physiological benefits gained from standing and crutch walking by paraplegics, i.e., the prevention of contractures, pressure sores and osteoporosis, and the improvement of kidney and bowel function, are known and documented.¹⁹ These factors partly prompted the establishment of orthoses for paraplegic locomotion. Nevertheless, most patients do not use their orthoses after leaving the hospital, probably partly due to the inefficiency of the available types of walking aids. Estimation of energy expenditure therefore becomes important for assessing the efficiency of walking aids in paraplegics.

Three indicators usually are used to assess energy expenditure in able-bodied subjects; oxygen consumption, heart rate and perceived exertion. The use of oxygen consumption for assessment of energy expenditure is inconvenient in paraplegics, because of their lack of proprioceptive sensation. The use of heart rate based methods (e.g., physiological cost index, i.e., increasing heart rate divided by walking speed)

therefore becomes more tempting, if it can be reliable. For using heart rate, two factors should be considered in paraplegics: the stabilization of heart rate and the period of time needed for steady heart rate to be achieved. It is well known that paraplegics are not able to walk for long periods of time due to their low exercise capacity. In addition, there is no study which compares the perceived exertion between paraplegic and able-bodied subjects during crutch walking.

On the other hand, regulation of cardiovascular adjustments is necessary to support muscular work effectively and previous studies investigating the cardiovascular responses to arm exercise in paraplegics reported that the redistribution of blood during arm exercise is disturbed.¹² It is suggested that the lack of sympathetic innervation below the level of the spinal cord lesion and the inability to activate the muscle pump in the legs result in lower venous return to the heart in paraplegics compared to able-bodied subjects.¹² In addition, this circulatory problem can be increased in the upright position due to the influence of gravity.

The aim of this study is therefore to investigate the responses of oxygen consumption, heart rate and perceived exertion to crutch walking in both paraplegic and able-bodied subjects.

Table I. Details of able-bodied subjects.

Able-bodied subjects	Age (years)	Mass (kg)	Height (cm)
1	27	62	172
2	22	73.8	182
3	21	65.3	176.3
4	24	84.4	186
5	31	82.4	184
6	29	90	188
7	35	84.8	186
8	27	66.7	174.2
9	27	93.5	191.9
10	24	70.7	177
Mean	26.7	77.4	181.7
SE	1.3	3.5	2.1

METHODS

Subjects

Ten able-bodied and 5 paraplegic subjects were studied. Their characteristics are summarized in Tables I and II. The hospital files of paraplegics were consulted for past medical history; their levels of lesions and causes of injuries are also indicated in Table II.

The paraplegic subjects were members of the West-Scotland and Inverclyde Colts wheelchair basketball teams (in Scotland-UK). They were visited in the Bellahouston (in Glasgow) and Linwood sport centers (in Linwood) prior to the start of experiments. At this

Table II. Clinical details of paraplegic subjects.

Paraplegic subjects	Age (years)	Mass (kg)	Height (cm)	Age of lesion (years)	Cause of injury (years)	Level of lesion
1	45	83.5	172.5	8	Traumatic (traffic)	T ₆ , complete
2	23	59.6	186	3.5	Traumatic (sports)	T ₁₁ , complete
3	37	81.6	175	11	Traumatic (industry)	L ₁ , incomplete
4	37	80.5	161	37	Spina bifida	L ₂ , incomplete
5	47	58	157.7	45	Polio	L ₂ , incomplete
Mean	37.8	72.6	170.4	20.9		
SE	4.3	5.8	5.2	8.5		

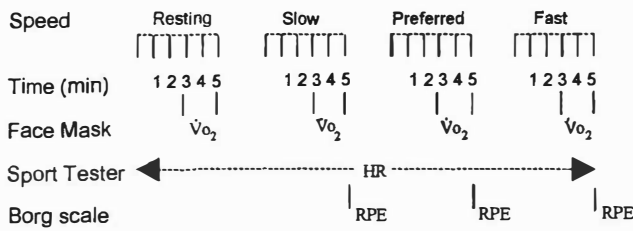


Fig. 1. The procedure of crutch walking experiments.

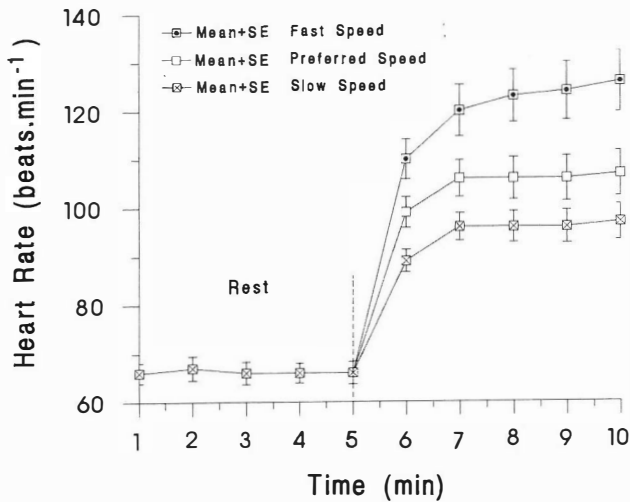


Fig. 2. Time course of heart rate during crutch walking at three speeds in able-bodied subjects. There are significant differences of heart rates at three speeds.

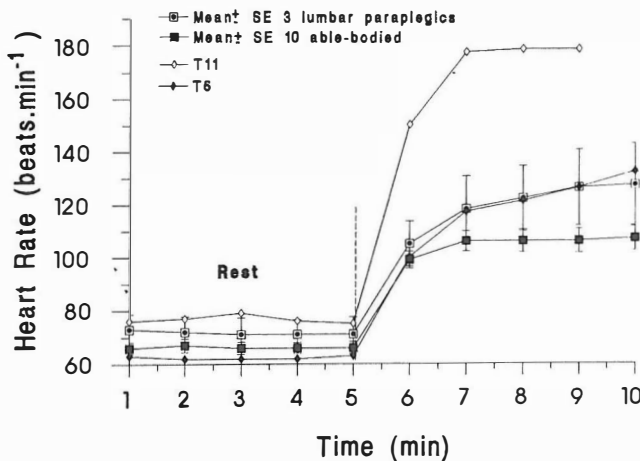


Fig. 3. Time course of heart rate during crutch walking at preferred speed in paraplegic and able-bodied subjects.

visit, the aims of experiments were described to them and they were familiarized with the equipment to be used in the physiological testing.

Procedure of crutch walking

1. Each able-bodied subject was asked to don an

adjusted knee-ankle-foot orthosis with locked knee and ankle; then to rest in the wheelchair. The paraplegic volunteers used their own callipers whenever possible. These were all knee-ankle-foot orthoses. The mass of the callipers was similar in all experiments (3.2 ± 0.6 kg [mean \pm SE] for paraplegics and 3.5 kg for able-bodied subjects).

2. Standard axillary crutches were used. Subjects were initially familiarized with the swing-to crutch walking. The crutches were adjusted to a height approximately 5 cm below the subject's axilla with the hand grip positioned to allow approximately 25° of elbow flexion.

3. Subjects wore a face mask system for the measurement of oxygen consumption (it was calibrated against the Douglas bag technique). The face mask was introduced to the subjects before sampling, for familiarization purposes. Oxygen consumption was measured during the last two minutes of each stage of crutch walking. Heart rate was continuously monitored throughout the experiment by PE 3000 Sport Tester with 15 seconds sampling rate. Rating of perceived exertion was evaluated at the end of each experiment (Fig. 1).

4. Each subject walked at his self-selected preferred speed on a figure-of-eight track. Able-bodied subjects also walked at slower and faster speeds than their preferred speed.

i) Preferred speed: the subject's own most convenient way of walking.

ii) Slow (relaxed) speed: a pattern of walking chosen while strolling in a park or passing leisure time.

iii) fast (hurried) speed: as when hurried for a train.

5. Before exercise, the resting value of heart rate was continuously monitored for 5 minutes and during the last two minutes, oxygen consumption was measured. Prior to the start of the experiment, the subject stood still until his heart rate stabilized.

6. Each subject moved continuously around a 13.5m figure-of-eight track. Each exercise period lasted 5 minutes.

7. Time and distance were recorded simultaneously to calculate velocity.

8. Between each of the 3 tests on able-bodied subjects, each person was allowed to sit down for resting, until their heart rate returned to pre-test level, before participating in the next test.

Statistical methods

Paired t-tests were used to investigate the significance of the effects of a change in speed (e.g., 18 to 41 m/min) on the energy cost and physiological cost index during crutch walking in able-bodied subjects.

Physiologic Responses in Crutch Walking

Table III. Heart rate (HR), oxygen consumption ($\dot{V}O_2$), energy cost, physiological cost index (PCI), speed and rating of perceived exertion (RPE) during crutch walking at preferred speed in thoracic and lumbar paraplegics. Mean \pm SE of these variables in lumbar paraplegics and able-bodied subjects are also indicated.

Volunteers	Level of lesion	HR (beats/min)	$\dot{V}O_2$ (mL/kg/min)	Energy cost (mL/kg/m)	PCI (beats/min)	Speed (m/min)	RPE
DT	T ₆	132	10.60	1.14	7.53	9.301	13
RO	T ₁₁	178	12.06	2.22	18.60	5.43	19
MG	L ₁	156	21.60	0.49	2.08	43.85	15
MM	L ₂	103	19.43	0.49	0.94	39.55	11
CD	L ₂	123	15.32	0.75	1.96	20.45	15
Lumbar paraplegics		127 \pm 15	18.78 \pm 1.87	0.58 \pm 0.09	1.66 \pm 0.37	34.62 \pm 7.33	13.7 \pm 1.4
Able-bodied subjects		107 \pm 5.0	14.58 \pm 0.84	0.52 \pm 0.03	1.46 \pm 0.11	28.05 \pm 1.463	13 \pm 0.6

RESULTS

Time course of heart rate changes

Figure 2 illustrates the mean \pm SE of heart rate obtained from the 10 able-bodied subjects for each of 5 consecutive minutes at rest and the 5 minutes at each of the 3 speeds of crutch walking. In these subjects, stable heart rates were reached within about 2 minutes at the 2 lower speeds: slow (18 \pm 1.6 m/min) and preferred (28 \pm 1.5m/min). However, at fast speed (41.1 \pm 2.2m/min) heart rates showed a continuing upward trend rising progressively one beat each minute from the 2nd to the 5th minute.

Figure 3 shows the mean \pm SE of heart rate during crutch walking at preferred speed in paraplegics (with the data for able-bodied subjects repeated for comparison). Heart rates in the 3 lumbar paraplegics became stable during 5 minutes of exercise, as in able-bodied subjects. It should be recognized that the actual values of the heart rates cannot be directly compared between groups, because the speeds of crutch walking are not the same.

The two thoracic paraplegics responded differently from those with lower lesions. In the T₆ volunteer, whose speed was about 1/3 that of lumbar paraplegics and able-bodied subjects (Table III), heart rate rose progressively each minute until the end of 5 minutes of exercise and the difference in heart rate between the 4th and 5th minutes was 6 beats/min. In the T₁₁ subject, heart rate increased rapidly up to about 180 beats/min and it is to be noted that he was unable to complete the 5th minute of exercise, despite the fact that his speed was less than 1/5 that adopted preferentially by the lumbar paraplegics and able-bodied subjects.

Comparison of measured variables in able-bodied subjects

Table III and Figs. 4-6 show the mean \pm SE of oxygen consumption, heart rate and perceived exertion

Table IV. The correlation coefficients between variables during crutch walking at three speeds in 10 able-bodied subjects. Oxygen consumption and heart rate were measured at the last minute of each stage of crutch walking, and rating of perceived exertion was evaluated at the end of each experiment.

Variables	r-value (correlation coefficient)
Oxygen consumption/speed	0.736*
Heart rates/speed	0.684*
Rating of perceived exertion/speed	0.733*
Oxygen consumption/heart rate	0.633*
Energy cost/physiological cost index	0.649*

* $p < 0.01$

of the 10 able-bodied subjects under resting conditions and during crutch walking at 3 speeds with knee-ankle-foot orthoses. Table IV shows the correlations between all 3 variables and speed; all are significant.

Figs. 7 and 8 show the mean \pm SE of energy cost and physiological cost index of crutch walking at the 3 speeds in able-bodied subjects; and Table IV indicates that the two measures did correlate, though not particularly highly. The paired t-test did not show differences between preferred and fast speeds for either measure, but these speeds were more efficient for crutch walking than the slow speed.

Comparison of measured variables between paraplegic and able-bodied subjects

Table V indicates the energy cost, physiological cost index and perceived exertion, and mean \pm SE for able-bodied subjects and lumbar paraplegics.

As already noted, the preferred speed of crutch walking was lower in thoracic paraplegics than in lumbar and able-bodied subjects; nevertheless energy cost and physiological cost index, even at these speeds,

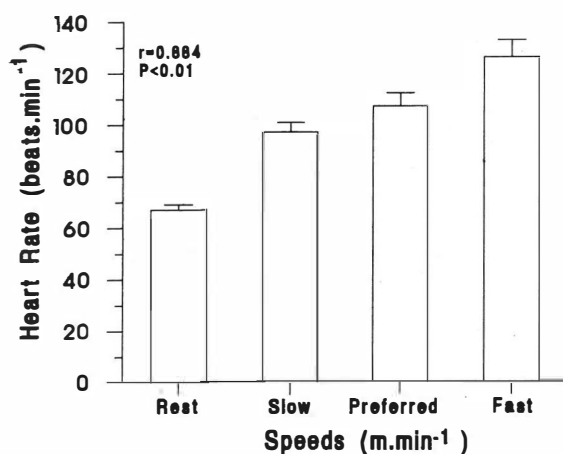


Fig. 4. The mean \pm SE of heart rate at rest and during crutch walking at three speeds in 10 able-bodied subjects. There is a significant correlation between heart rates and speeds of crutch walking.

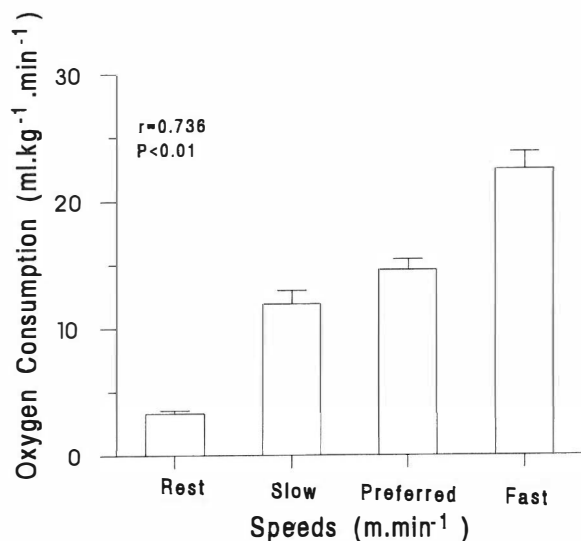


Fig. 5. The mean \pm SE of oxygen consumption at rest and during crutch walking at three speeds in 10 able-bodied subjects. There is a significant correlation between oxygen consumption and speed of crutch walking.

were higher. However, perceived exertion was higher in only one out of two thoracic-lesion patients.

DISCUSSION

Oxygen consumption, heart rate and perceived exertion responses to crutch walking in able-bodied subjects

The purpose of assessment of energy expenditure in

able-bodied subjects during crutch walking is to compare their data as a control group with paraplegics. The same conditions, as far as possible, have then been applied for both groups of subjects. Because the paraplegics use the callipers to stabilize their paralyzed legs during crutch walking, the same type of calliper was also used for able-bodied subjects.

Patterson and Fisher²² reported a slow rising of heart rate during crutch walking at speeds of 30 to 70 m/min in able-bodied subjects. By contrast, Annesley et al.¹ in the same type of experiment at the speed of about 40 m/min showed steady heart rates. In the present project the difference in heart rates between the two last minutes of exercise was only about 2 beats per minute, and these virtually stable heart rates were achieved in less than 2 minutes at all three speeds. It may be concluded that no significant recruitment of further motor units or muscle groups occurred during these observations.

The results of this study showed that significant correlations between the different variables investigated during crutch walking were in agreement with able-bodied subjects (Table IV). The significant correlation between heart rate and oxygen consumption during axillary crutch walking agrees with the previous study of Ghosh et al.¹⁰

The energy costs in the present study (0.523 mL/kg/m at preferred speed) are higher than those of previous studies (0.344 to 0.439 mL/kg/m is the range of energy cost from 4 studies,^{2,11,15,22} all of which used axillary crutches without callipers). This could be explained by the use of callipers, as it has been reported that crutch walking with a cast has a higher energy cost than without a cast.¹³ In addition, it should be considered that the small figure-of-eight track can play a role in diminishing the speed of crutch walking and increasing its energy cost. However, MacGregor¹⁶ stated that, "I believe the tightness of our track gives a more realistic view of walking than the usual unencumbered circumstances of the very large laboratory. Fairly sharp turns are also typical of most homes and workplaces."

Heart rate and walking speed measurements are found to provide possible means for assessment of energy expenditure.²³ The method embodying these two variables (i.e., physiological cost index) was primarily established by MacGregor¹⁶ for assessment of energy expenditure during walking. However, crutch walking is upper body activity and cardiovascular responses to lower and upper body exercise are different.

In accord with these generalizations, Bhambani and Clarkson² compared the physiological responses during three modes of exercise, i.e., axillary crutch walking, normal walking and running. Their results led them to conclude that "axillary crutch walking was the most stressful activity".

Some workers described unstable heart rates during crutch walking in able-bodied subjects.^{2,22} This made the assessment of energy expenditure from heart rate measurement during crutch walking difficult.

The present study has however shown steady heart rate in able-bodied subjects (at slow and preferred speeds, if not at high). Mean physiological cost index in this study at preferred speed was 1.46 beats/m. However, there are to our knowledge no published data which used physiological cost index during crutch walking with or without callipers in able-bodied subjects, for comparing with these results.

The perceived exertion quantified subjective feelings of effort during physical activity.² However, despite the studies about the physiological responses to crutch walking in able-bodied subjects, no researchers have published experiments examining the perceptual responses during crutch walking. Rating of perceived exertion, recorded during crutch walking, supports the physiological evidence in our experiments and at the same oxygen consumption and heart rate, it has shown a significant correlation with walking speeds.

The preferred speed of crutch walking with callipers in this study (28m/min) was slower than in previous studies^{3,11} which dealt with crutch walking without callipers (39 and 43 m/min). The lower speed can be explained by the use of orthoses and the small size of the walkway available in our laboratory.

Figs. 7 and 8 show that energy cost and physiological cost index at preferred and fast speeds were significantly lower ($p < 0.01$) than at slow speed. This agrees with the previous studies.^{9,10} Ganguli et al. stated that the energy cost of walking is higher at slow speed because of the "uncomfortable speed".⁹ What this means physiologically is less clear, but in the present study it was observed that during crutch walking at lower speeds, the crutch users faced difficulties in maintaining balance and rhythm.

Oxygen consumption, heart rate and perceived exertion responses to crutch walking in paraplegics and their comparisons with findings from able-bodied subjects

A-Time course of heart rate changes

The stabilization of heart rate is necessary if an indicator based on heart rate is to be used for assessment of energy expenditure. In addition, paraplegics are not able to continue crutch walking for a long period of time, due to their low exercise capacity.⁸ Then, the period of time needed for the stable heart rate to be achieved, should be considered. Some previous researchers^{4,17,18,20} state that stable heart rate was achieved during crutch walking in their experiments,

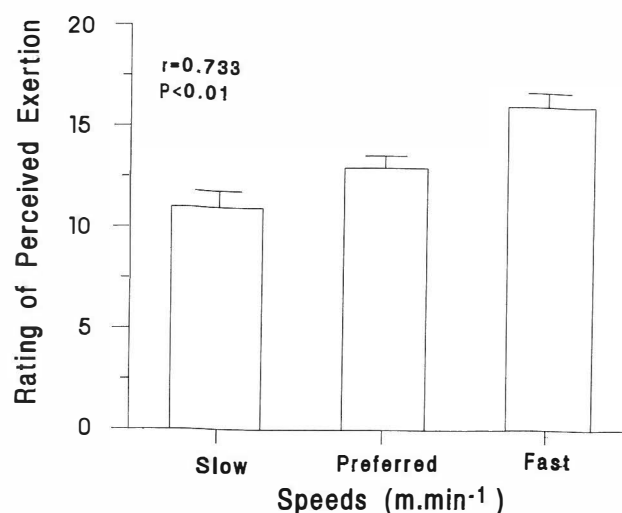


Fig. 6 The mean \pm SE of rating of perceived exertion during crutch walking at three speeds in 10 able-bodied subjects. There is a significant correlation between rating of perceived exertions and speeds of crutch walking.

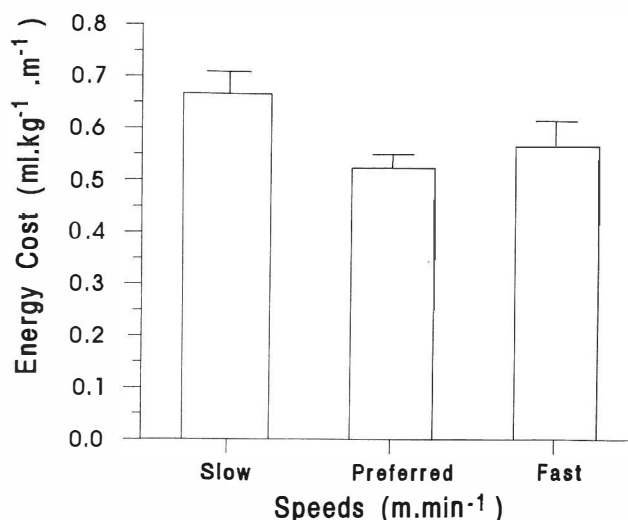


Fig. 7. The mean \pm SE of energy cost during crutch walking at three speeds in 10 able-bodied subjects. Energy cost at preferred and fast speeds are significantly lower ($p < 0.01$) than at slow speed.

but do not say how long this took.

However, the results of lumbar paraplegics confirm that stable rates are achieved (normally within 2 minutes), but in the two thoracic paraplegics (Fig. 3), the heart rate responses were different.

The T₁₁ patient stabilized at so high a rate that his maximal work capacity and endurance must both have been seriously diminished. Heart rates in the T₆ patient did not stabilize during the 5 minutes test, though they remained lower than the T₁₁ patient's figures. This

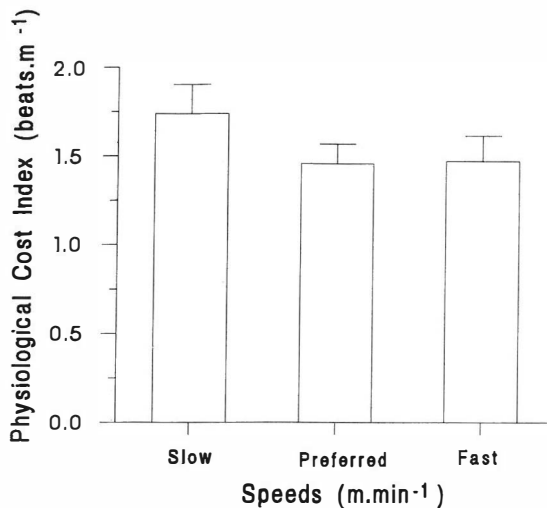


Fig. 8. The mean \pm SE of physiological cost index during crutch walking at three speeds in 10 able-bodied subjects. Physiological cost index at preferred and fast speeds are significantly lower ($p < 0.01$) than at slow speed.

seemingly paradoxical difference between the lower and higher thoracic patients could have an unrecognized physical explanation, but the possibility of an essentially psychological one should perhaps not be ruled out. In this connection, it should be pointed out that the person with the T₆ injury had several years of experience of walking with callipers and crutches but his T₁₁ counterpart did not.

In addition, Chantraine et al.⁶ have already reported that paraplegics accustomed to crutch walking averaged speeds five times greater than unaccustomed patients, yet their cardiorespiratory responses were clearly lower. Therefore, the different response of heart rate between lumbar (accustomed to crutch walking) and thoracic paraplegics in this study could be partly explained by less frequent use of crutches. The thoracic paraplegics presumably also suffer from reduced venous return. Thus, the duration of crutch walking in thoracic paraplegics is limited by their low exercise capacity (in agreement with Eriksson et al.⁸) and, heart rate is an unsatisfactory indicator of energy expenditure in some, if not all, thoracic paraplegics.

B-Energy cost

The aerobic capacity of paraplegics during exercise was measured by several researchers.⁵⁻⁷

In the results of the present project, energy cost of crutch walking was lower in lumbar than thoracic paraplegics. The results in lumbar paraplegics, who were accustomed to using the long leg brace, were comparable with those of Chantraine's (0.61 mL/kg/m), who tested seven accustomed paraplegics (T₉-L₁) with

long leg braces during crutch walking. Energy cost of crutch walking was also close between lumbar paraplegics (0.557 mL/kg/m) and able-bodied subjects (0.523 mL/kg/m) in this project. This is not surprising, indeed Chantraine et al.⁶ reported that accustomed paraplegics had an oxygen consumption which was actually lower than that of able-bodied subjects during the same crutch walking exercise. Therefore, they concluded that the energy cost of crutch walking is inversely related to the regular use of long leg braces. As to the thoracic paraplegics, the energy costs of crutch walking found in the present study (i.e., 2.222 and 1.139 mL/kg/min T₁₁ and T₆, respectively) lie within the range of literature values for simple orthoses. Clearly, crutch walking is a high energy cost activity in thoracic paraplegics. Their walking energy costs were between two and five times those of able-bodied subjects, crutch walking with the long leg brace, in spite of the fact that the physiological stress associated with axillary crutch walking is already high in able-bodied subjects.²

The extra energy cost or inefficiency of crutch walking in the thoracic paraplegics using the long leg brace can probably be explained by the lack of muscular support for their lower limbs and trunks. It has been shown that the much more expensive reciprocal gait orthoses, which provide paraplegics with more lower limb and trunk support, increase the efficiency of upright movements.

C-Physiological cost index

The use of physiological cost index has recently become popular for assessment of energy expenditure in paraplegic locomotion.^{4,14,20,24} Some of the above workers report having found stable heart rates during crutch walking, in apparent conflict with the results of the present experiments, in that stable work-related heart rates were not achieved in thoracic paraplegics with long leg braces. The probable explanation is that the findings of stable rates have involved more sophisticated support systems (reciprocal gait orthosis or parawalker), which both (though to a different degree) probably assist venous return from the legs. The ranges of physiological cost index in the above reports were extremely wide between 1 and 5 beats/m.

The physiological cost index in the lumbar paraplegics of the present study was near to that of the able-bodied subjects. The physiological cost index, as best it could be calculated, was 18.60 beats/m in the T₁₁ and 7.527 beats/m in the T₆ subject. These higher physiological cost indices in thoracic paraplegics compared with the above studies could be explained by the following points:

- i. The effect of the type of orthosis: Edwards and

Marsolais⁷ showed that in spite of a lower speed of crutch walking with the long leg brace than with other orthoses (e.g., reciprocal gait orthosis, parawalker), the energy cost during crutch walking was higher with the long leg brace in their thoracic paraplegic.

ii. The speed of crutch walking: the speeds of crutch walking in our T₁₁ and T₆ subjects were 5.43 and 9.301 m/min, respectively. They were lower than the range of speeds of the above authors (13-25 m/min). In addition to the type of orthosis, the small figure-of-eight track could be a further explanation for this.

iii. The regular use of crutches: the regular use of crutches is one of the main factors for decreasing the energy cost of crutch walking.⁶ Some workers used a training program before collecting the data, e.g., Edwards and Marsolais⁷ trained their subject three times per week for one month with the reciprocal gait orthosis. In addition, their subjects had walked with a long leg brace for five years previously. It will be recalled that the T₆ subject in this study used crutches at home; and his physiological cost index was less than 40% of that found for the other thoracic paraplegic, even though the latter's lesion was lower.

iv. Finally, the resting heart rate can also play an important role in changing the physiological cost index. In our experiment for all subjects (i.e., thoracic and lumbar paraplegics as well as able-bodied subjects), resting heart rates were between 60 and 77 beats/min; the above studies reported 80 to 90 beats/min.

The high physiological cost indices of the thoracic paraplegics in the present project can be explained by contributions from each of the above factors. Nevertheless, the problems associated with this measure, in high-lesion patients, must be continually borne in mind.

D-Rating of perceived exertion

In any ambulatory study (with or without assistive devices), walking speed must be taken into consideration, because there is a linear relationship between energy expenditure and velocity.¹¹ Both energy cost (mL/kg/m) and physiological cost index (beats/m) are standardized, by dividing by speed; then they are used as indicators for comparison among different individuals during crutch walking. This has not been done for perceived exertion. In spite of clearly higher energy cost and physiological cost index and also lower preferred speed of crutch walking in T₆ compared with the mean of those in able-bodied subjects and lumbar paraplegics, perceived exertion showed only slight differences between the groups. Though more high lesion patients should obviously be studied, the occurrence of even this one case strongly suggests that perceived exertion is not a suitable indicator for

comparison among subjects whose preferred walking speeds are different. For comparison between individuals, crutch walking at a given speed on the treadmill could have value.

CONCLUSION

The energy cost of crutch walking in able-bodied subjects observed in this study, including the high cost of the slow speed⁹ is comparable with that found in previous studies,^{2,11,15,22} if allowance is made for the use of callipers (knee-ankle-foot orthoses). Because these orthoses were used in the present study, the information obtained permits direct comparison of the cardiorespiratory responses to crutch walking between paraplegic and able-bodied subjects. Such a comparison does not seem to have been made before. Having talked about "able-bodied", it seems very asymmetrical not to talk directly about paraplegics, before comparing the two. This study has shown that crutch walking with knee-ankle-foot orthoses has a high energy cost in thoracic paraplegics. This may contribute to their reluctance to use orthoses.

In addition, the unstable heart rate during crutch walking with the long leg brace, conflicted with the use of physiological cost index for assessment of energy expenditure in the thoracic paraplegics. If its use is restricted to those subjects who show stabilized heart rates, varying monotonically with work rate or walking speed, it will undoubtedly be more reliable than perceived exertion; but oxygen consumption (supplemented, where necessary, by oxygen debt), must remain the "gold standard" of energy-expenditure assessment, despite the practical limitations on its widespread use.

ACKNOWLEDGEMENTS

The first author much appreciates the contribution of Mr J. Wilson of Sports Science and Mr. J. Sinclair in the electronic laboratories in the Institute of Biomedical Research in Glasgow University for their technical assistance and thanks Mr. T. Aitchison in the Department of Statistics in the University of Glasgow for statistical assistance.

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