Prosthetics and Orthotics International, 1999, 23, 45–49

The efficacy of physiological cost index (PCI) measurement of a subject walking with an Intelligent Prosthesis

T. CHIN, S. SAWAMURA, H. FUJITA, S. NAKAJIMA, I. OJIMA, H. OYABU, Y. NAGAKURA, H. OTSUKA and A. NAKAGAWA

Hyogo Rehabilitation Centre, Kobe, Japan.

Abstract

The Intelligent Prosthesis may enable lower limb amputees to walk faster than with conventionally damped prostheses and as a result the physical burden involved in walking could be expected to be considerably higher. The aim of this study was to investigate whether or not physiological cost index (PCI) is applicable as an indicator for monitoring the amount of exercise load involved in walking with an Intelligent Prosthesis. The method used a treadmill and monitored gas exchange, ventilation and heart rate (HR) in 6 unilateral trans-femoral amputees, ages were between 17 and 34 with an average age of 23.1. The exercise protocol was as follows: for each person speeds at 0.8 times the subject's free level walking speed, 1.0 times, 1.2 times, 1.4 times and for some 1.6 times were applied. In each case the index of correlation between PCI and oxygen uptake in response to walking speed was calculated. A significant correlation was observed between PCI and oxygen uptake in each case, which indicated a close relationship between cardiopulmonary factor and energy consumption while walking. These results suggest that PCI is of use as an indicator for ascertaining the amount of exercise load in walking with an Intelligent Prosthesis.

Introduction

The, so called, Intelligent Prosthesis is electronically controlled to dynamically regulate the degree of opening of the needle valve of a pneumatic damping cylinder at the prosthetic knee joint in response to walking speed. A microcomputer is used for swing phase control. The Intelligent Prosthesis may allow lower limb amputees to walk faster than was possible with conventionally damped prostheses (Zahedi, 1993). The authors' centre offers an additional Intelligent Prosthesis walking training programme to teach amputees the techniques of walking rapidly. In this circumstance the exercise load involved in prosthetic walking can be expected to be considerably higher than normal. Consequently the exercise load while walking with the prosthesis must be appropriately monitored to make walking training safer. In many cases in clinical situations physical therapists are responsible for training and their work would be facilitated by a simple, convenient and real-time monitoring method.

PCI is one of the cardiopulmonary factors suggested by MacGregor as an indicator of energy cost. (MacGregor, 1979; MacGregor, 1981). This indicator is the value of the heart rate (HR) at rest subtracted from the HR under load and divided by the walking speed, which is comparatively simple to measure. The research reported here aims to investigate whether or not PCI is applicable as an indicator for monitoring the amount of exercise load involved in walking with an Intelligent Prosthesis.

Subjects

The subjects were 6 unilateral trans-femoral amputees (5 male, 1 female) aged between 17 and 34 with average age of 23.1 who had been hospitalised in the authors' centre and completed the Intelligent Prosthesis walking training programme. The amputees had been well trained

All correspondence to be addressed to Dr T. Chin, Hyogo Rehabilitation Centre, 1070, Akebono-Cho, Nishi-Ku, Kobe, 651-2181, Japan.

in the use of the Intelligent Prosthesis and were skilled in its use. The fit of prosthesis was clinically reviewed by certified prosthetists. Optimum adjustment of the Intelligent knee joint for each amputee was carried out by certified physical therapists. The physical characteristics of the subjects are shown in Table 1.

Method

Firstly most comfortable walking speed for each subject using an Intelligent Prosthesis, i.e. the free level walking speed (FWS), was measured prior to testing. HR at rest was recorded after the subject had been seated for 15 minutes. Laboratory environmental conditions were controlled at a temperature between 20°C and 23°C, and relative humidity at 60%. Informed written consent was obtained before entry into the study. In this research a treadmill was used. The exercise protocol was as follows: for each subject after 5 minutes of warm-up at 0.8 times the subject's FWS, the speed was increased continuously in steps every 5 minutes by 0.2 times the subject's FWS until the maximum speed was achieved. The treadmill was held level for the duration of testing. During exercise the respiratory gas was monitored with a respiromonitor (Minato RM-300 system, Osaka, Japan) on a breath by breath basis. At the same time the ECG and HR were monitored during exercise by Stress Test System (ML-5000, Fukuda Denshi, Tokyo, Japan), and cuff blood pressure was determined every minute with an autoelectrocardiometer (Colin STPB-780, Japan). Treadmill walking is used in the Intelligent Prosthesis walking training and it was judged that the subjects were skilled in its use. Consequently the measurements were taken only once. To guard against falling during measurement the subjects were allowed to lightly grip a support bar in both hands, but they were directed not to grip strongly (Fig. 1). The parameters during the last 2 minutes of the 5 minutes of each exercise stage were averaged. PCI was calculated as (HR while walking – HR at rest) / walking speed. The Pearson Product-Moment technique was used in all correlation analysis. Differences were considered significant at $p<0.05$.

Table 1. Physical characteristics of the subjects

Case no.	1	2	3	4	5	6
Sex	F	M	M	M	M	M
Age (yr)	19	23	20	26	34	17
Mass (kg)	47.8	66.0	57.0	64.0	70.0	58.5
Height (cm)	168	175	172	176	170	176
Amputation cause	T	T	T	T	T	T
Ambulatory aid	no	no	no	no	no	no
FWS (km/hr)	4.0	4.5	4.0	3.5	3.0	4.0

FWS: free level walking speed T: trauma

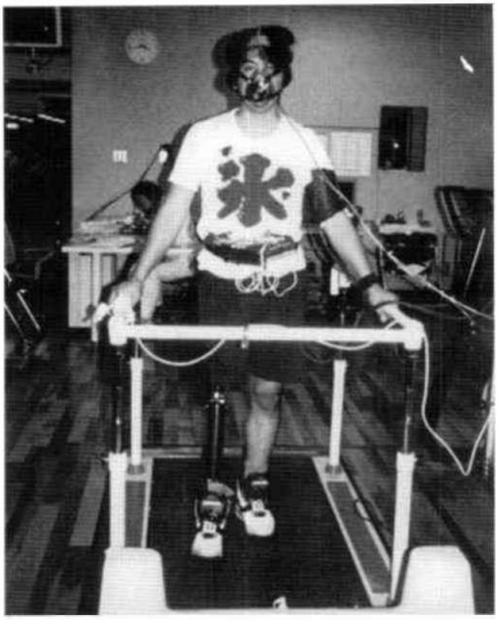

Fig. 1. Experimental subject undergoing respiratory gas analysis. Subject is instructed to hold the support bar lightly with both hands to avoid the danger of falling during measurement.

Results

The relationship between walking speed and oxygen uptake

In all cases oxygen uptake increased with increasing walking speed (Fig.2).

The relationship between walking speed and PCI

With the exception of case 5 PCI increased with increasing walking speed in each case. In case 5 PCI fell slightly at FWS and 1.2 times that speed, but there was a rising trend at 1.4 times and 1.6 times (Fig.3).

The relationship between PCI and oxygen uptake

In each case the index of correlation between PCI and oxygen uptake in response to walking

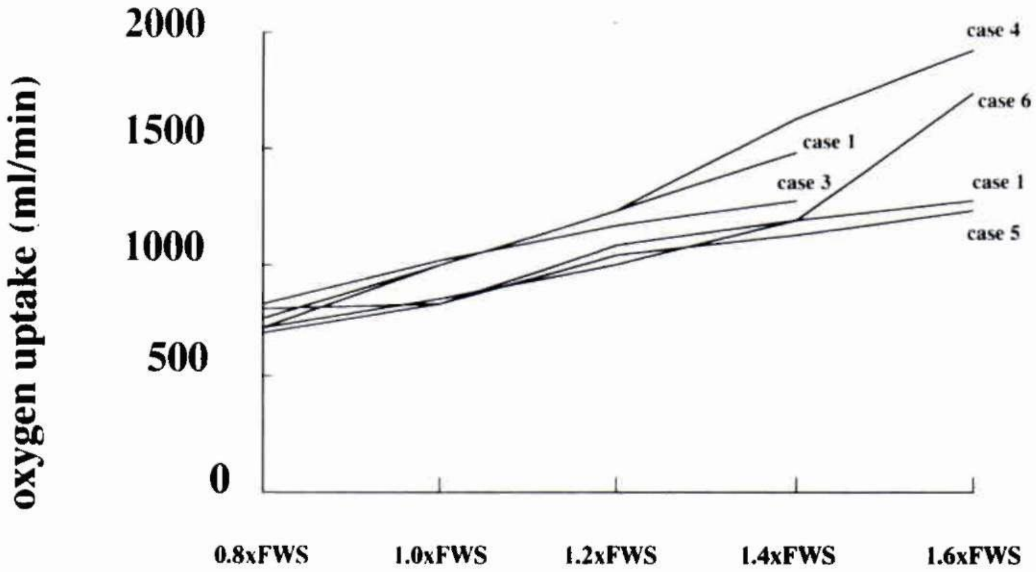

Fig. 2. The relationship between walking speed and oxygen uptake for each case.

speed was calculated. A significant correlation was observed between PCI and oxygen uptake in each case. In case 1 the correlation coefficient for the relationship between PCI and oxygen uptake was 0.926, indicating a significant correlation between the two ($p<0.05$). In case 2 the correlation coefficient was 0.972 ($p<0.001$). In case 3 the correlation coefficient was 0.751 ($p<0.001$). In case 4 the correlation coefficient was 0.997 ($p<0.01$). In case 5 the correlation coefficient was 0.907 ($p<0.05$). In case 6 the correlation coefficient was 0.903 ($p<0.05$). Figure 4 shows an example of the correlation for case 4.

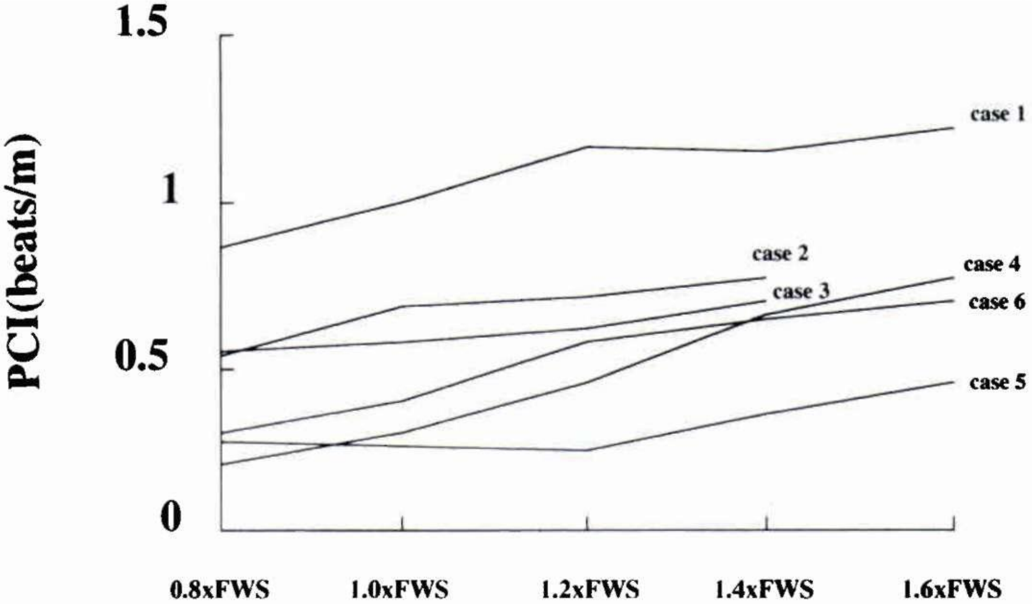

Fig. 3. The relationship between walking speed and PCI for each case.

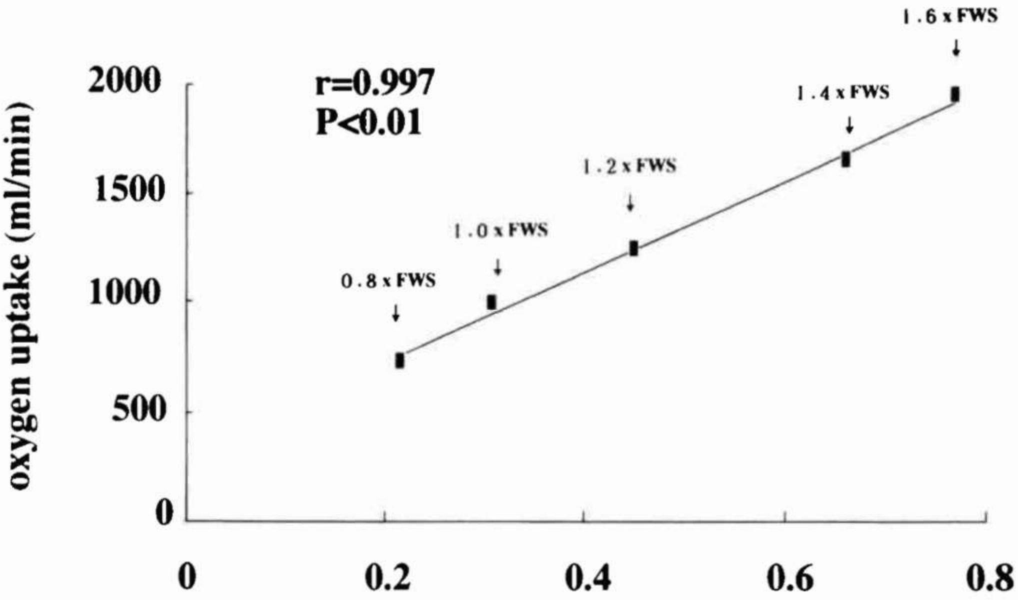

Fig. 4. Single correlation chart for case 4. Examination of relationship between PCI and oxygen uptake in response to walking speed gives a significant correlation between the two ($r=0.997$, $p<0.01$).

Discussion

The aim of the study was to investigate whether or not PCI is applicable as an indicator for monitoring the amount of exercise load involved in walking with an Intelligent Prosthesis. PCI is one of the cardiopulmonary factors, which combine the elements of HR and walking speed, suggested by MacGregor (MacGregor, 1979; MacGregor, 1981). Steven *et al.* (1983) have reported that PCI is effective in judging the efficacy of medication on patients with rheumatoid arthritis. Butler *et al.* (1984) demonstrated that in a comparison of PCI between children with impaired walking and children with normal walking, the PCI is a useful indicator for the diagnosis of walking. Nene and Jennings (1992) measured the PCI of patients with spinal cord injury walking with the aid of the ORLAU ParaWalker and found it useful in comparison with other movement measurement methods. In Japan, Wada *et al.* (1993) have observed a significant correlation between PCI and walking energy consumption in patients suffering from osteoarthritis of the coxa. Thus PCI is known as an indicator for evaluation of walking efficiency.

It is well known that for lower limb amputees, particularly trans-femoral amputees, the energy consumption required for walking with a prosthesis is high (Gonzalez *et al.*, 1974; Waters *et al.*, 1976). The characteristics of an Intelligent Prosthesis may allow a higher walking speed than with conventionally damped prostheses (Zahedi, 1993). In this circumstance the energy consumed in walking would be higher and the burden on the cardiopulmonary function greater. It is therefore important to ascertain accurately the exercise load involved in walking with an Intelligent Prosthesis to provide safety in its use. The best means of accurately ascertaining the exercise load is to directly measure oxygen uptake. However, it is not easy to measure this directly due to the complexity and awkwardness of the equipment and measurement technique. Furthermore, it is not possible to make direct measurement during prosthetic walking training in the ordinary place of rehabilitation. Therefore in place of oxygen uptake a simple objective indicator which will allow the estimation of exercise load is required.

In this research the energy consumption of walking with an intelligent prosthesis was measured by oxygen uptake at a wide range of walking speeds and the relationship with PCI was investigated. In each case it was observed that an increase in walking speed was accompanied by a tendency toward increased PCI and oxygen uptake. Furthermore, in each case there was a significant correlation between PCI and oxygen uptake as they varied with walking speed, which indicates a close relationship between cardiopulmonary factor and energy consumption factor while walking. PCI can be measured easily in a clinical environment while it makes it potentially useful as an indicator for ascertaining the amount of exercise load involved in walking with an Intelligent Prosthesis and monitoring the cardiopulmonary function under exercise load.

Conclusion

The applicability of PCI measurement as an indicator for monitoring the amount of exercise load involved in walking with an Intelligent Prosthesis has been established. This study indicated the feasibility of the clinical application of PCI in Intelligent Prosthesis walking training for amputees.

REFERENCES

Butler P, Engelbrecht M, Major RE, Tait JH, Stallard J, Patrick JH (1984). Physiological cost index of walking for normal children and its use as an indicator of physical handicap. *Dev Med Child Neurol* **26**, 607-612.

Gonzalez EG, Corcoran PJ, Peters RL (1974). Energy expenditure in below-knee amputees: correlation with stump length. *Arch Phys Med Rehabil* **55**, 111-119.

Wada I, Ikeda T, Hayashi N, Matsui N, Horiba M (1993). The energy consumption and cadiac tasks during free level walking in preoperative patients with osteoarthritic hip. *Jap J Rehabil Med* **35**, 49-53.

MacGregor J (1979). The objective measurement of physical performance with long term ambulatory physiological surveillance equipment (LAPSE). Proceedings of 3rd International Symposium on Ambulatory Monitoring./edited by Stott FD, Raftery EB, Goulding L, London: *Academic Press* p29-39.

MacGregor J (1981). The evaluation of patient performance using long term ambulatory monitoring technique in the domiciliary environment. *Physiotherapy* **67**, 30-33.

Nene AV, Jennings SJ (1992). Physiological cost index of paraplegic locomotion using the ORLAU ParaWalker. *Paralegia* **30**, 246-252.

Steven MM, Capell HA, Sturrock RD, MacGregor J (1983). The physiological cost of gait (PCG): a new technique for evaluating nonsteroidal anti-inflammatory drugs in rheumatoid arthritis. *Br J Rheumatol* **22**, 141-145.

Waters RL, Perry J, Antonelli D, Hislop HJ (1976) Energy cost of walking of amputees: influence of level of amputation. *J Bone Joint Surg* **58A**, 42-46

Zahedi S (1993). The results of the field trial of the endolite Intelligent Prosthesis. In: Proceedings of the XII International Congress of INTERBOR, September, 1993.