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A comparison of energy expenditure by a high level trans-femoral amputee using the Intelligent Prosthesis and conventionally damped prosthetic limbs

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Abstract

Comparisons were made between the Intelligent Prosthesis (IP), Mauch and pneumatic swing phase control damping systems on the same prosthesis worn by a high level trans-femoral amputee. Speeds self selected by corridor walking (4.4 – 5.5 kmh^{-1}) proved not to be sustainable for treadmill walking. Comfortable speeds were attained when the subject walked on a treadmill at 2.0, 2.6 and 3.2 kmh^{-1} in two tests for each prosthesis type. Oxygen uptake ($\dot{V}O_2$), cadence and heart rate were measured over 5 minute walks interspersed with rest periods.

Spearman's correlation was used to test for differences between prosthesis types at each speed. At the two slower speeds no significant difference was found, but at the higher speed of 3.2 kmh^{-1}, the IP was associated with a significantly lower $\dot{V}O_2$ ($p<0.05$). A two way analysis of variance with replication (ANOVA) demonstrated a significant difference between $\dot{V}O_2$ for different limb types ($p=0.015$). A square law function was fitted to the mean $\dot{V}O_2$ for each prosthesis type by the method of least squares regression. ANOVA demonstrated a significant difference between velocity coefficients for the different prosthesis types ($p<0.05$). Cadence was almost constant during the period of each walk, varying by 1 step min^{-1} at most. However the test-retest differences in cadence were considerable.

It is concluded that there was little difference in energy expenditure between prosthesis types at slower speeds, but at higher speeds (=>3.2km h^{-1}) the IP gave a lower oxygen uptake by about 10%.

Introduction

Conventionally damped prosthetic limbs use a pneumatic or hydraulic damping cylinder which is adjusted by the prosthetist to provide optimum gait parameters at the subject's customary walking speed (CWS). If the amputee walks at a different speed, he or she must compensate for the pendulum action of the prosthesis in order to alter stride length or step rate by tilting the pelvis to delay extension or by " throwing the leg through", in order to ensure that the foot is in the right place for the next heel strike. This not only leads to an abnormal gait, but requires extra physical effort. In 1993, an "Intelligent Prosthesis" (IP) was introduced (Chas. A Blatchford & Sons Ltd) featuring a microprocessor controlled knee extension damper. The IP uses a proximity switch to detect the step time and automatically alters the level of knee extension damping to suit, using a motor driven needle valve on a pneumatic cylinder. Thus the knee should extend at a rate appropriate to the actual walking speed, removing the need to compensate and reducing effort.

Initial measurements and the results of a 100 subject survey of IP users were reported by Zahedi (1993). This early report suggested that the IP could reduce the physiological cost of walking by as much as 10%, that gait deviations are reduced and that optimum walking speed and range of speeds are increased. It is not clear

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whether optimum walking speed refers to CWS or to most metabolically efficient walking speed, not necessarily identical (Jaegers *et al.*, 1993). Amputees reported that the IP was not as tiring as conventionally damped prostheses, and that manoeuvring around obstacles was easier. Observers reported that the amputees walked more naturally and smoothly.

This study aimed to compare the relative energy expenditure necessary to walk at different speeds using the IP with conventional pneumatic and hydraulic prostheses. Energy expenditure was determined by measurement of rate of oxygen consumption ($\dot{V}O_2$) (Astrand and Rodahl, 1977) at three different speeds of treadmill walking. Early results were reported by Clark (1994).

Methods

Subject

The subject (one of the authors) was an active 33 year old male, an established amputee with a high level amputation (due to trauma) at the proximal quarter femur level.

The subject was taking antihypertensive drugs so heart rate could not be used as an indicator of energy expenditure. It was not expected that antihypertensive drugs would affect oxygen consumption.

Assessment of walking speeds

The manufacturer recommends that the IP is programmed for the subjects customary, fast and slow walking speeds. The IP parameters are programmed with the subject wearing the IP and walking in a straight line at self selected speed. It was planned to use these speeds for treadmill walking. These 3 self selected speeds were measured by timing the central 5 metres of 3 corridor walks of 10 metres at each speed. Slow, normal and fast walking speeds were 4.4, 5.1 and 5.5 kmh^{-1} respectively.

The subject was then introduced to treadmill walking and practised at increasing speeds in order to acclimatise to the unfamiliar walking technique. It became apparent that the subjects self selected speeds could not be sustained on the treadmill for periods long enough for energy expenditure to be reliably measured.

A second set of slow, comfortable and fast speeds was then determined by the subject for treadmill walking. These were measured at 2.0, 2.6 and 3.2 kmh^{-1} respectively.

The IP was reprogrammed for these new speeds which were felt by the subject to be more representative of, for example, walking in the street rather than his customary walk between rooms at his place of work. They are also close to the CWS for traumatic trans-femoral amputees (3.1 kmh^{-1}) found by Waters and Yakura (1989).

Prostheses tested

Four prosthesis types were tested:

- intelligent prosthesis (IP on)
- intelligent prosthesis programmed for constant damping (IP off)
- Mauch SNS hydraulic swing phase controller (MAUCH)
- Endolite pneumatic swing phase controller (PSPC).

All prostheses used had Endolite StanceFlex knees and the same quadrilateral socket, rigid pelvic belt and Seattle foot. Socket alignment was preserved by splitting the knee joint at the StanceFlex pivot pin leaving the alignment coupling attached to the socket.

The IP was programmed for the treadmill speeds 2 indicated previously (IP on). The case of constant damping (IP off) was included as it has been used to simulate the PSPC (Zahedi, 1993).

The conventionally damped prostheses were adjusted according to the manufacturers instructions and all prostheses included a foam cosmesis. In order to retain clinical validity, no attempt was made to equalise the weights of the prostheses. The subject had acquired at least 5 weeks experience with walking on each limb.

Oxygen uptake

$\dot{V}O_2$ and rate of carbon dioxide production ($\dot{V}CO_2$) (ml kg^{-1} min^{-1}) were measured using an Oxycon Gamma gas analyser fitted with a paramagnetic oxygen analyser and infra-red carbon dioxide analyser. The subject walked on the treadmill at the three identified walking speeds. It was expected that these speeds would represent exercise below the subjects anaerobic threshold (Waters and Yakura, 1989). Heart rate was continuously monitored.

Treadmill testing

The test limb was worn for at least 4 days before the treadmill walk to enable acclimatisation. Tests were carried out at 3pm on Fridays in order to minimise on confounding

Table 1. Oxygen uptake ($\dot{V}O_2$) for two trials of each limb type at the three test speeds

	Speed (kmh^{-1})	2	2.6	3.2
Oxygen Uptake $\dot{V}O_2$ ($ml\ kg^{-1}\ min^{-1}$)	PSPC	12.27	14.55	17.83
		13.82	16.16	19.18
	MAUCH	13.09	14.48	16.87
		12.70	14.45	16.84
	IP on	12.84	14.56	15.45
		12.58	13.66	16.40
	IP off	12.59	14.03	17.74
		11.64	13.31	17.17

factors due to variation in daily work patterns, eating, Circadian rhythms etc. Ambient temperatures were between 19.1 and 22.6° C. The subject's weight varied from 85.8 to 87.2 kg during the period of the tests.

Tests were carried out in order of increasing speed with 5 minutes walking with a 15 minute rest after the first test and a 30 minute rest after the second. $\dot{V}O_2$ and $\dot{V}CO_2$ were measured at rest and throughout the walk. Heart rate was recorded at rest and at 30 second intervals. Cadence was averaged over a 30 second interval at the beginning and end of each walk. Two separate test series were carried out on each prosthesis type, in the following sequence: PSPC, MAUCH, IP on, IP off, PSPC, MAUCH, IP on, IP off.

Results

$\dot{V}O_2$ and heart rate were calculated by averaging the measurements for the final 3 minutes of each 5 minute walk.

Oxygen uptake

Table 1 shows $\dot{V}O_2$ measured for each prosthesis type at the three test speeds. Spearman's correlation was used to test for differences between prosthesis types at each speed. At the two slower speeds no significant difference was found, but at the higher speed of 3.2 kmh^{-1} the IP was associated with a significantly lower $\dot{V}O_2$ ($p<0.05$). This result is similar to those of Molen (1973) and James (1973) who found no significant differences in $\dot{V}O_2$ between leg amputees and non-amputees until speeds of 3.6 kmh^{-1} (trans-tibial) and 3.9 kmh^{-1} (trans-femoral) were reached. A two way analysis of variance with replication (ANOVA) shows a significant difference between $\dot{V}O_2$ for different limb types ($p=0.015$).

Several workers have reported a linear correlation between the square of walking speed (v^2) and energy expenditure (Molen, 1973, James, 1973). The function $\dot{V}O_2 = l+kv^2$ (where l and k are constants) was fitted to the mean of the $\dot{V}O_2$ points for each limb and speed by the

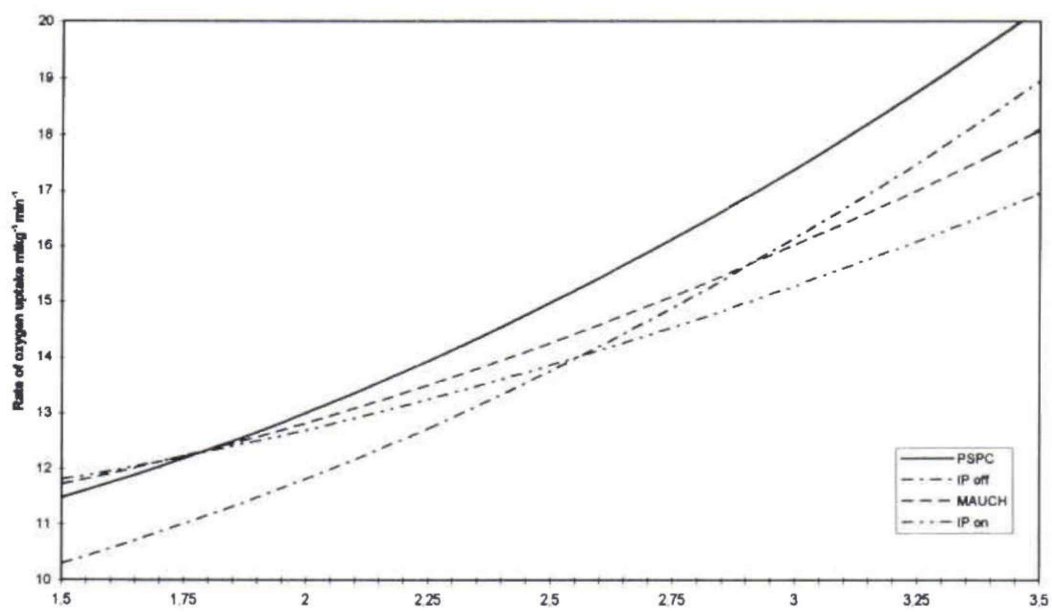

Fig. 1. Square law curves of the form $\dot{V}O_2 = l+ kv^2$ fitted to oxygen uptake measurements for the Intelligent Prosthesis and three conventionally damped prostheses.

method of least squares (shown graphically in Fig. 1). ANOVA on the coefficients produced demonstrates a significant difference between velocity coefficients (k) for the different limb types ($p<0.05$).

Respiratory quotient ($\dot{V}O_2$ / $\dot{V}CO_2$) did not rise above 1.0 indicating that aerobic work was being done.

No relationship was found between heart rate and prosthesis type.

Cadence

Table 2 shows the cadences adopted for the four prosthesis types in each trial. Cadence was almost constant during the period of each walk, varying by 1 step min^{-1} at most. However the test-retest differences were considerable, as illustrated in Figure 2.

Table 2. Cadence for two trials of each limb type at the three test speeds

	Speed (kmh^{-1})	2.0	2.6	3.2
Cadence (steps min^{-1})	PSPC	76	93	106
		71	100	114
	MAUCH	77	91	104
		80	94	101
	IP on	70	96	104
		85	96	108
	IP off	81	88	106
		80	93	108

Discussion

It is clearly dangerous to generalise from results obtained with only one subject. However this experience is illustrative of the clinical problems presented by a high level, active amputee who could be expected to exploit fully the capabilities of the IP.

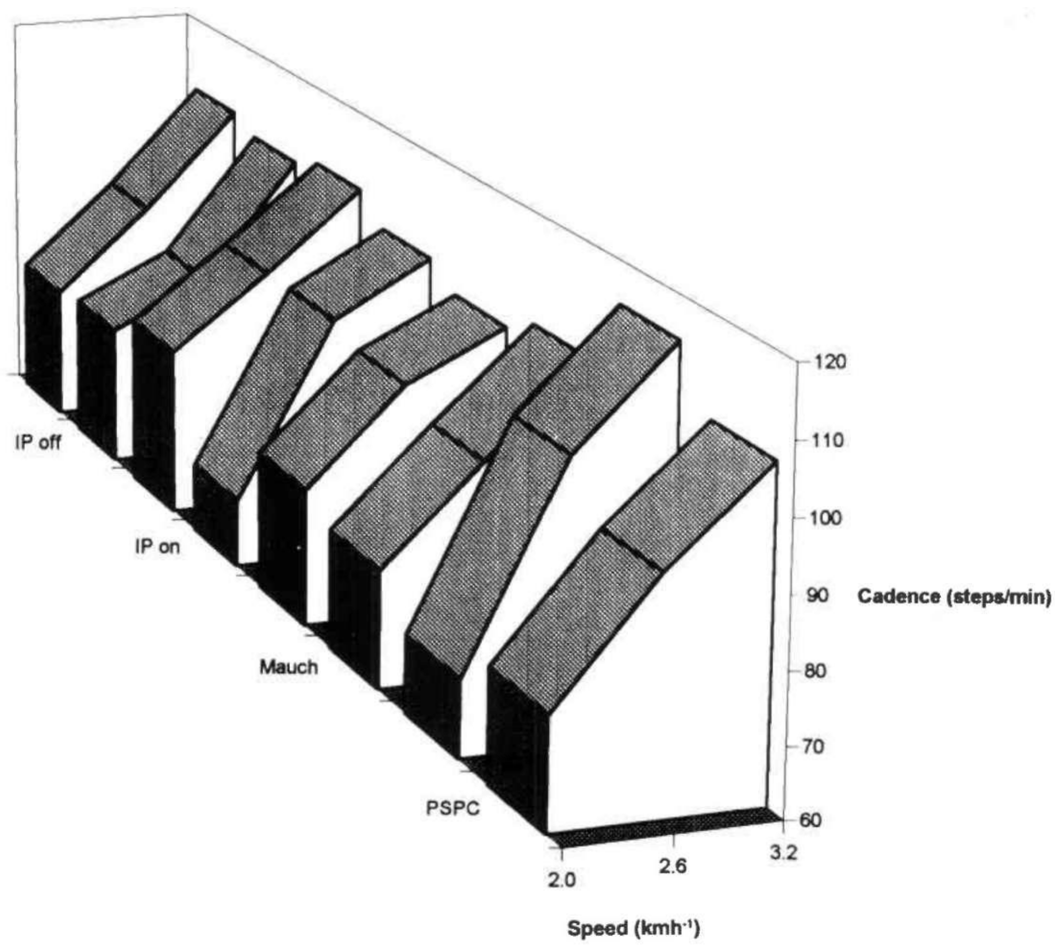

Fig. 2. Cadences adopted for two trials of each prosthesis type at the three test speeds.

The empirical, subjective method of assessing CWS as recommended by the manufacturer calls into question the validity of programming the IP for a range of speeds around this CWS, particularly in a device which it is claimed will alter the ease of walking at different speeds and even increase the CWS (Zahedi 1993). The manufacturer in fact recommends re-evaluation of CWS after a period of experience with the prosthesis. The authors were unable to evaluate changes in CWS as it had not been measured prior to IP use.

The subjects initial corridor walk seemed typical of his usual speed of ambulation at work in the limb centre. This CWS of 5.1 kmh^{-1} is considerably higher than that found by Waters and Yakura (1989) and could not be sustained for 5 minutes of treadmill walking. The determination of CWS using treadmill walking was felt to yield speeds more representative of a middle distance walk — for example, when walking in the street. This CWS was closer to those found by Waters and Yakura (1989). Although it may be suspected that there are physiological differences between treadmill walking and free walking (Mattsson, 1989), several workers have used similar methods of CWS determination on a treadmill (Herbert *et al.*, 1994; Jaegers *et al.*, 1993). Waters and Yakura (1989) found no significant differences in the energy expenditure of non-amputees between free walking and treadmill walking.

Workers looking at normal walking speeds have generally compared different people walking in the same situation. For example Finley and Cody (1970) made covert measurements on people walking a 50 foot straight line in outdoor urban locations. Similar results were found by Waters *et al.* (1988) using an outdoor circular track with an instruction to walk at a comfortable pace. Various workers including Gailey *et al.* (1994) and Nene (1993) have used 'L' shaped or 'figure-of-eight' indoor tracks. Although intra-study CWS measurements will be valid, differences between studies would be important when selecting a 'typical' CWS for use in all walking situations, as in the case of IP set-up. For the full exploitation of the IP's adaptability further work should be done on the influence of environment on the range of amputee walking speeds.

$\dot{V}O_2$ measurements indicate that energy savings at low speeds are not significant. At speeds of 3.2 kmh^{-1} and above energy savings of from 5% (MAUCH) to 15% (PSPC) may be obtainable for treadmill walking. Extrapolating a square law equation to the subjects normal walking speed as initially assessed (5.1 kmh^{-1}) would again give greater savings.

Considerable test-retest variation is present in $\dot{V}O_2$ measurements. Little has been reported on test-retest variation of $\dot{V}O_2$ measurements on amputees, however Herbert *et al.* (1994) found a test-retest $\dot{V}O_2$ variation of the same order as the difference between amputee and non-amputee children walking at CWS. Changes in resting $\dot{V}O_2$ are unlikely to be attributable to changes in fitness of the subject over the period of the study.

There is considerable variation in the cadence patterns adopted between test pairs. This is in contrast to the unvarying nature of intra-test cadence and the results of Jaegers *et al.* (1993) who suggested that amputee cadence varies less than that of non-amputees. However variability in cadence will result in increased variability in $\dot{V}O_2$. Lukin *et al.* (1967) demonstrated that each step entails the raising of ones centre of gravity with its attendant work in acquiring potential energy. Thus ambulation at the same speed with increasing cadence will expend increasing amounts of energy. Empirical models of energy expenditure incorporating both cadence and stride length developed for non-amputees have not been validated for amputees (Zarrugh *et al.*, 1974). Cadence variation may result from the subject's attempts to cope with the unfamiliar technique of treadmill. It might be expected that the IP's method of measuring step time in order to adapt to different cadences might increase the range of cadences possible for a given speed. This was not evident. However, further work is needed to explore the relationship between speed, cadence and energy expenditure particularly in the use of IP.

Change in heart rate and physiological cost index are widely accepted as measures of energy expenditure. This study found no relationship between heart rate and walking speed. This finding was predicted because of the action of antihypertensive drugs on heart rate control mechanisms.

It is possible that measuring energy expenditure at constant speed is not the most sensitive measure of ease of ambulation when evaluating prosthetic lower limbs. Amputees walk more slowly than non-amputees and differences in energy expenditure are only evident at higher speeds. Also a large percentage of ambulation is spent manoeuvring around objects, walking on uneven terrain, changing speed, sitting down and standing up rather than steady level walking. Although some manoeuvres do not involve knee flexion it is possible that evaluation under more realistic conditions may be more revealing.

Conclusion

Oxygen uptake measured at slower speeds showed no demonstrable difference between limb types when used by this high level amputee. At higher speeds (=>3.2 kmh^{-1}) the IP gave a lower oxygen uptake of about 10%.

Relatively large variations in cadence were observed between tests on the same prosthesis type (although not within tests), contributing to variation in energy expenditure.

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