PROSTHETICS/ORTHOTICS/DEVICES

Energy Cost of Walking: Comparison of ''Intelligent Prosthesis'' With Conventional Mechanism

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ABSTRACT. Buckley JG, Spence WD, Solomonidis SE. Energy cost of walking: comparison of ''intelligent prosthesis'' with conventional mechanism. Arch Phys Med Rehabil 1997;78:330-3.

Objective: To determine physiological energy cost with Blatchford's ''Intelligent Prosthesis'' (IP) compared to energy cost with a conventional pnuematic swing phase control (PSPC) mechanism.

Design: Before-After trial: subjects fitted with IP walked on programmable treadmill at speeds: 6min slow, 6min fast, 8min while speed changed, between slow, normal, and fast, every minute, and 6min normal. Breath-by-breath analysis of subject's expired air determined average V_{O_2} (L/min) within each period. Procedure repeated after 1-week interval using PSPC prosthesis. Testing sessions supervised by experienced prosthetist.

Setting: Rehabilitation centre.

Subjects: Volunteer sample. Three men, unilateral transfemoral traumatic amputee patients, ages 39 to 59 years. Normally used ischial containment socket, Blatchford Endolite Stabilised Stance Flex knee with PSPC and Multiflex foot and ankle.

Interventions: Fitting, programming, and alignment of IP (own socket) by Bioengineering Unit's resident prosthetist. IP's microprocessor programmed to facilitate five walking speeds.

Main Outcome Measure: Physiological energy cost (V_{O_2}), of using IP compared to using PSPC mechanism.

Results: Two subjects displayed reduced V_{O_2} of between 5.6% and 9.0% using IP compared to PSPC prosthesis at a pace either faster or slower than their normal pace. Third subject showed no significant change in oxygen consumption despite IP unit being heavier. All subjects displayed reduced V_{O_2} (averaging 4.1%) using IP for period of variable speed walking.

Conclusions: Although differences were small, they tend to indicate that use of the heavier IP unit lowered the energy cost of walking at speeds other than the amputee's normal pace.

THE ABILITY of the transtibial amputee patient to perform gait tasks better than a transfemoral amputee patient, in terms of energy cost, gait dynamics, and general mobility, reflects the importance of the knee in locomotion.[1] Efforts are continuously being made to develop artificial knee mechanisms that alleviate patient discomfort, increase stability, reduce loads transferred to the sound leg and vertebral column, and reduce the energy consumption during gait. Indeed, in an ideal situation the energy cost of using a particular device would be one of the most important considerations in the design and prescription of lower limb prostheses.

Biomechanical variables (such as knee flexion during support, center of mass oscillation and the amount of arm movement) account for a considerable portion of the variance in distance running economy (the rate of submaximal O_2 consumption) in able-bodied individuals.[2] In transfemoral amputee subjects, alterations in shank and foot inertia properties influence the metabolic energy expenditure during walking,[3] with such alterations also affecting the moment required at the hip.[4]

The incorporation of a pneumatic device into the artificial knee joint is an ideal method to control the swing time of the artificial shin during gait and has been well documented.[5] A nonlinear resistance is caused by two separate effects—the increase in pressure as air is reduced in volume, and the transfer of air from one side of a piston to another. Air compressed during knee flexion also provides an air spring to assist extension.

With a conventional pneumatic swing phase controlled (PSPC) mechanism, air flow is influenced by a fixed orifice, adjusted to suit the normal walking speed of the user. Faster pneumatic pumping, during faster gait, therefore tends to create a stiffer air spring, which causes a limitation to the knee flexion angle. Thus, significant variation in walking speed from the speed at which the swing phase control device was originally adjusted may result in abnormal gait deviations.[6]

The transfemoral microprocessor controlled prosthesis (fig 1),[a] is designed to allow the swing speed of the prosthetic shin to change automatically, according to the walking speed of the amputee patient. A sensing device, fitted at the artificial knee joint, detects the swing speed of the prosthetic shin, and a microprocessor, incorporated in the shin frame, sends a message to a stepper motor which automatically adjusts the valve orifice diameter of the pneumatic cylinder. This controls the level of heel rise and, in turn, the amount of air being compressed (extension assist). Thus, the shin-ankle-foot segment should swing optimally over a range of walking speeds. The principles of operation of the IP device are detailed in figure 2.

Although there has been much recent work comparing the biomechanical/mechanical function, metabolic cost, and impact-absorption and energy-returning properties of different prosthetic feet,[7-9] there has been little research that has compared the energy cost (mechanical or physiological) of amputee patients using different knee mechanisms. Such measurements are pertinent if an improved microprocessor-controlled transfemoral prosthesis is to be successfully developed that will significantly reduce the energy expenditure associated with ambulation.

The purpose of this study was to quantify the physiological energy cost of using the so-called ''Intelligent Prosthesis'' (IP) compared to the cost of using a more conventional PSPC mechanism.

METHOD

Three transfemoral amputee men who had lost their limbs through trauma volunteered to participate in the study; all were

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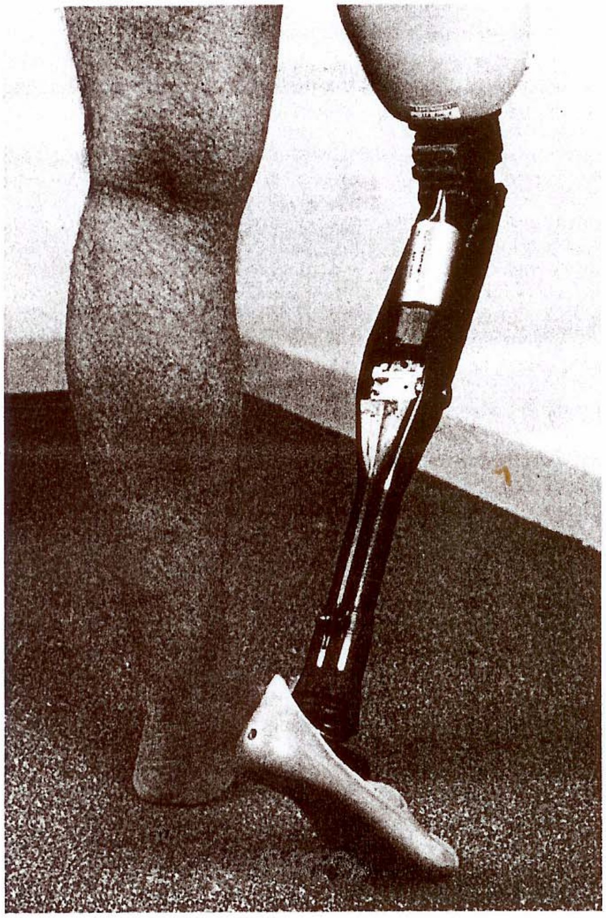

Fig 1. The "Intelligent Prosthesis" (IP).

fit and active and able to complete the protocol in full. Approval was obtained from the hospital's ethics board. All three subjects normally used a prosthesis consisting of an ischial containment (IC) socket, a Blatchford Endolite Stabilised Stance Flex knee with PSPC and a Multiflex foot and ankle.

Subjects were asked not to ingest alcohol or caffeine for the 24 hours prior to testing. A record of the subjects' diets, on the day of and prior to the initial testing session, was kept, and a similar diet was maintained for the subsequent testing session.

Individual age, body mass, height, and stump length data are listed in table 1.

The fitting, programming, and alignment of the IP to all three subjects, and the PSPC prosthesis to two subjects, was carried out by the Bioengineering Unit's resident prosthetist. The fitting and alignment of the remaining PSPC prosthesis had already been accomplished by the subject's "health service" prosthetist. The amputee's own socket was maintained for each prosthesis. Although it was not objectively quantified, alignment in each case was optimally set by a prosthetist. This was intended to simulate clinical practice. After the fitting and alignment of the IP, the microprocessor was programmed, in accordance with the manufacturer's instructions,[10] to facilitate a range of three walking speeds: normal (N), which was the subject's most comfortable walking speed, slow (S) and fast (F), which were the subjects' self-selected comfortable and sustainable slowest and fastest walking paces. Two further intermediate speeds, slow-normal (SN) and normal-fast (NF), were calculated, and all five speed boundaries for five different valve settings were programmed into the processor.

The subjects were allowed to practice walking on a motorized "Powerjog EG30"[b] programmable treadmill, with a 2.0m by 0.6m rubberized walking surface, until a "normal" gait pattern was observed by both subject and prosthetist. After a short rest, the subject was instructed to walk at his self-selected slow, normal, and fast speeds. Once the subject was comfortable and satisfied with each speed the treadmill speed was recorded (table 2).

After a 15- to 20-minute rest, the subject was exercised for a total of 26 consecutive minutes at the following sequential time intervals and self-selected walking speeds: (1) 6min slow walking; (2) 6min fast walking; (3) 1min slow-normal walking; (4) 1min normal-fast walking; (5) 1min slow-normal walking; (6) 1min slow walking; (7) 1min fast walking; (8) 1min slow walking; (9) 1min fast walking; (10) 1min slow walking; (11) 6min normal walking (manually adjusted).

Throughout this period, breath-by-breath analysis of the subject's expired air was carried out by means of a Oxycongamma Gas Analyser.[c] A printout giving the subject's average VO_2 (L/min) over consecutive 30-second intervals was processed by calculating the mean and standard deviation (table 2) during: (1) the 6min of slow walking, (2) the 6min of fast walking, (3) the 8min of walking when the treadmill speed changed every minute, and (4) the 6min of normal walking.

The procedure was repeated, after at least a 1-week interval, with the subjects now using their own PSPC prosthesis. Clothing, footwear, and time of day were kept constant. During this session each subject was asked to walk at treadmill velocities identical to those determined when using the IP.

Differences in VO_2 when using the IP compared to PSPC

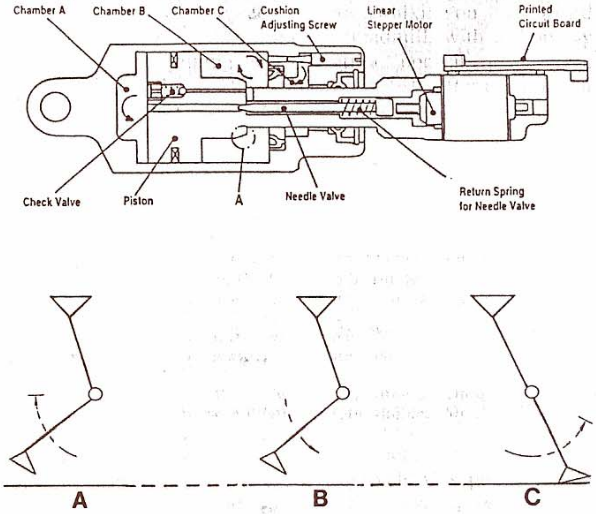

Fig 2. The IP in operation. (A) Air compressed in chamber A during knee flexion flows to chamber B, the flow rate being determined by the position of the needle valve. The air compressed in chamber-A determines the level of heel rise. (B) Air compressed in chamber A during knee flexion initiates extension. During extension air now being compressed in chamber B flows to chamber A via the check valve. (C) As knee becomes fully extended part "A" is forced into the cushion seal. Compressed air from chamber B now flows to chamber C through the passage provided with the cushion adjusting screw, the setting of which determines the terminal impact.

Table 1: Subject Data

Subject	Age (yr)	Mass (kg)	Height (m)	Leg Amputated	Stump Length (m)
1	39	62	1.65	Left	.255
2	59	78	1.75	Left	.210
3	47	76	1.73	Right	.235

prosthesis were determined for each consecutive walking period as follows:

$$\text{diff} = \frac{\text{Vo}_2 \text{ with IP} - \text{Vo}_2 \text{ with PSPC}}{\text{Vo}_2 \text{ with PSPC}} \times 100$$

A negative percentage difference would thus indicate an energy saving, and a positive an energy increase, when using the IP.

RESULTS

The mean Vo_2 for each subject, when using the IP and PSPC device, is compared in table 2. Any differences of less than 5% (normal variation in Vo_2 for submaximal exercise[11]) were considered nonsignificant (ie, clinically not important). There was no notable difference in the Vo_2 when using the IP or PSPC prostheses for walking at the subject's normal pace. For walking at a pace that was either slower or faster than their normal pace, results showed that subjects 2 and 3 demonstrated a reduced Vo_2 (of between 5.6% and 9.0%) using the IP, and subject 1 showed no significant difference. For the period of walking in which the treadmill speed was changed every minute, all three subjects had a reduced Vo_2 when using the IP. Because differences were between 2.2% and 7.0% (average = 4.1%), they only indicate a trend.

DISCUSSION

Given that a PSPC device, adjusted to ensure the swing time of the artificial shin, is optimal for the subject's self-selected normal walking speed, a comparison of the physiological energy cost of using IP and PSPC prostheses for walking at an amputee subject's normal pace would be expected to show little or no difference. The results of the present study support this, with the average difference for all three subjects being 0.2% for normal walking speed.

For walking at a pace that was either slower or faster than the subjects' normal speed and using the IP, there was a notable reduction in oxygen consumption for two subjects, with no significant difference observed from the third. In addition, for the period of walking in which the treadmill speed was changed every minute, all three subjects consumed less oxygen using the IP (average difference of 4.1%).

It has been shown that in able-bodied subjects, submaximal Vo_2 increases with the addition of mass to the lower limb. Martin[12] reported an increase of 3.5% and 7.0%, respectively, for every 0.5kg added to a runner's thigh or foot. Catlin and Dressendorfer[13] found that the addition of 0.2kg of shoe mass (0.1kg per shoe) resulted in a 1.9% increase in running submaximal Vo_2. In addition, Holewijn[14] reported that Vo_2, expressed as a percentage of the subject's Vo_2max, increased from 42% to 53% when walking at 6.5km/h wearing combat boots compared to walking barefoot. Considering that the mass of the IP was 0.2kg more than the PSPC device, the trend found in the present study showing a reduced Vo_2 using the IP would seem to indicate that the expected effect of increased weight has been largely negated by the functional benefit of the IP unit. In other words, these findings may suggest that if the weight of the IP was the same as the pneumatic device, then a larger reduction in Vo_2 would be found. Further investigation would be necessary to test this hypothesis. It is possible that having the use of a transfemoral prosthesis that functions optimally over a range of walking speeds is of more importance in decreasing the energy cost of ambulation than merely reducing the weight of the prosthesis.

As the Vo_2 of ambulation has been shown to be as much as 65% higher for unilateral transfemoral amputee subjects walking at half the velocity of able-bodied controls,[15,16] even a modest percentage reduction in Vo_2 would be important. Thus, although the differences were small, the trend of reduced Vo_2 for walking at speeds other than normal pace support the notion that an IP would lower the energy cost of ambulation in the physically active transfemoral amputee patient who desires, and can achieve, a range of walking speeds.

The increased Vo_2 when using the PSPC device for walking at a pace other than the subject's normal speed may have been because the amputee subject had to employ compensatory biomechanical actions which resulted in unwanted gait deviations such as vaulting, circumduction, and excessive lateral sway.

Individuals who have had transfemoral amputation because of advanced peripheral vascular disease (PVD) (the main cause for amputation performed in the western world[17]), in the age group 50 to 90,[18] are inclined to live a sedentary life, perhaps only using their prosthesis for relatively short distances. The potential benefits to these individuals of a prosthesis that is able to automatically change its swing speed will need to be investigated. For patients with vascular-indicated leg amputation, it has been demonstrated that the security of a locked knee enables a higher walking velocity and a lower increase in heart rate than when using an unlocked knee.[19] In such cases reducing the weight of the prothesis is perhaps the predominant consideration in decreasing the energy cost of ambulation.

Table 2: Mean Vo_2 When Using the IP Compared to PSPC Prosthesis for the Consecutive Walking Periods of: 6min Slow Speed, 6min Fast Speed, 8min With Speed Changing, and 6min Normal Speed

	Slow		Fast		Changing		Normal	
	IP	PSPC	IP	PSPC	IP	PSPC	IP	PSPC
Subject 1								
Speed (km/h)	2.0		4.2		—		3.3	
Vo_2 (L/min)	.662 (±.077)	.651 (±.047)	1.116 (±.084)	1.097 (±.072)	.635 (±.111)	.683 (±.097)	.839 (±.096)	.841 (±.115)
Diff	+1.7%		+1.7%		−7.0%		−0.2%	
Subject 2								
Speed (km/h)	1.0		2.0		—		1.5	
Vo_2 (L/min)	.727 (±.064)	.799 (±.045)	.917 (±.060)	.971 (±.072)	.898 (±.057)	.918 (±.093)	.836 (±.076)	.850 (±.083)
Diff	−9.0%		−5.6%		−2.2%		−1.7%	
Subject 3								
Speed (km/h)	2.0		3.6		—		2.8	
Vo_2 (L/min)	.921 (±.095)	.979 (±.128)	1.366 (±.132)	1.453 (±.098)	1.170 (±.104)	1.209 (±.131)	1.111 (±.101)	1.097 (±.167)
Diff	−5.9%		−6.0%		−3.2%		+1.3%	

In contrast, in young congenital or traumatic amputee patients who are not normally impaired in other ways, the level of physical activity observed is much higher.[19] For these individuals a prosthesis that allows optimum range of mobility with minimal energy expenditure should be the goal of the rehabilitation programme. The results of the present study suggest an IP could help fulfill this goal.

CONCLUSIONS

Results showed that two of the three subjects displayed a reduced V_{O_2} of between 5.6% and 9.0% when using the IP compared to PSPC prosthesis for treadmill walking at a pace either faster or slower than their normal pace, and all subjects displayed a reduced V_{O_2} (averaging 4.1%) using the IP for the period of variable speed walking. Although the differences were small, they tend to indicate that the IP reduced the energy cost of walking at speeds other than the subjects' normal pace.

The trend found justifies the need for further detailed analysis of gait in amputee subjects using the IP. In future studies emphasis should be given to comparisons in biomechanical characteristics, as well as to charting the impact such a device has on the rehabilitation of different transfemoral amputee groups, eg, individuals who have peripheral vascular disease or who have bilateral amputations.

Since this study was completed, an updated IP (the IP plus) that incorporates a slightly modified microprocessor has been introduced. Programming is much easier with the new model, which is approximately 50 grams lighter. It would be interesting to evaluate whether the reduction in weight alone has any effect on energy expenditure.

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Suppliers

a. Chas A. Blatchford and Sons, Ltd., Basingstoke, Hampshire, UK.
b. Sports Engineering Ltd., Birmingham, UK.
c. Cranlea, Birmingham, UK.