Energy cost of walking of amputees: the influence of level of amputation

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Energy Cost of Walking of Amputees: The Influence of Level of Amputation

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ABSTRACT: **A comparison of selected gait parameters and the energy cost of prosthetic walking was made in seventy patients with unilateral traumatic and vascular amputations. Amputations above the knee, below the knee, and at the Syme's level were compared in both groups of amputees, and a control group of forty normal subjects also was studied. In both groups of amputees performance was significantly better the lower the level of the amputation. When preservation of function is the chief concern, amputation should be performed at the lowest possible level.**

It is a common clinical experience that below-the-knee amputees physically outperform above-the-knee amputees, and surgeons concerned primarily with maintaining maximum walking ability try to amputate at the lowest possible level. Other surgeons, concerned primarily with patient morbidity, select the level of amputation that will most likely assure prompt healing after one operation. These surgeons are more apt to amputate above the knee than below it.

Published data that might allow comparison of the energy cost of walking at different levels of amputation are inconclusive either because of small numbers of subjects or varied speed of walking, or because only one level of amputation was assessed [2,4,6,8,9,12]. It is well known that oxygen uptake depends on walking speed.

The purpose of this study was to measure the energy cost of walking by the same method at three levels of amputation: above the knee, below the knee, and at Syme's level. Testing was performed during unrestrained walking at the patient's chosen velocity. The findings are compared with those for a group of normal subjects tested by the same method.

Material and Methods

As controls, five normal persons of each sex in each decade from the third to the seventh were studied. The seventy unilateral amputees studied were selected using these criteria: None had stump pain, swelling, or pressure sores. All had worn a prosthesis for at least six months. All those with an above-the-knee amputation used a total-contact quadrilateral socket; all with a below-the-knee amputation used a patellar tendon-bearing socket; and all patients with a Syme's amputation used end-bearing sockets. Some of the amputees were older patients in whom amputation was performed for arterial insufficiency, while others, considerably younger, had their amputation because of trauma (Table I).

Each subject walked around a measured track 60.5 meters in circumference while expired air was collected in a modified Douglas bag for oxygen and carbon dioxide analyses. Heart rate, respiratory rate, and cadence were telemetered by transducers attached to the subject. All gas volumes were corrected to standard temperature, pressure, and humidity. Each test walk lasted approximately five minutes. The first three minutes served as a warm-up and data were collected during the following two minutes of steady state as indicated by a constant heart rate and respiratory rate. Two tests were performed: the first at the unrestrained speed and the second at the fastest possible speed. The values for oxygen consumption and heart rate obtained during the fast walk were used to predict [1] the subject's maximum aerobic capacity.

Results

The control data were similar to those previously reported by others [3,5].

Gait Velocity

The walking speed in the controls averaged eighty-two meters per minute (men, eighty-seven and women, seventy-four) and did not vary with age. This value progressively decreased in the amputee population the higher the level of amputation: for patients with traumatic below-the-knee amputation it was seventy-one meters per minute and for those with traumatic above-the-knee amputation, fifty-two meters per minute ($p < 0.05$) (Table II).

TABLE I

SUBJECTS

Level of Amputation	n	Age (*Yrs.*)	Height (*m*)	Weight (*kg*)	Duration of Prosthetic Use (*Yrs.*)
Vascular amputees					
Above the knee	13	60	1.76	70	1.2
Below the knee	13	63	1.71	71	1.4
Syme	15	57	1.69	79	1.1
Traumatic amputees					
Above the knee	15	31	1.72	72	10.0
Below the knee	14	29	1.77	80	9.5

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TABLE II

UNRESTRAINED WALKING IN AMPUTEES
(MEAN VALUES AND STANDARD DEVIATION)

	Velocity (m/min)	Cadence (Steps/min)	Stride Length (m)	Rate of Oxygen Uptake (ml/kg-min)	Net Oxygen Cost (ml/kg-m)	Maximum Aerobic Capacity (ml/kg-min)	Relative Energy Cost (Per cent)	Heart Rate (Beats/min)	Respiratory Quotient
Vascular amputees									
Above the knee	36 ±15	72 ±18	1.00 ±0.20	12.6 ±2.9	0.35 ±0.06	20 ±7	63	126 ±17	0.96 ±0.13
Below the knee	45 ±9	87 ±7	1.02 ±0.13	11.7 ±1.6	0.26 ±0.05	28 ±5	42	105 ±17	0.82 ±0.06
Syme	54 ±10	98 ±13	1.10 ±0.16	11.5 ±1.5	0.21 ±0.06	27 ±8	43	108 ±13	0.85 ±0.08
Traumatic amputees									
Above the knee	52 ±14	87 ±13	1.20 ±0.18	12.9 ±3.4	0.25 ±0.05	35 ±6	37	111 ±12	0.90 ±0.07
Below the knee	71 ±10	99 ±9	1.44 ±0.16	15.5 ±2.9	0.20 ±0.05	45 ±9	35	106 ±11	0.83 ±0.08

The influence of level of amputation in vascular patients was also significant: the average velocity for patients with a Syme's amputation was fifty-four meters per minute; for below-the-knee amputees, forty-five; and for above-the-knee amputees, thirty-six. The decrease in velocity ranged from 13 to 66 per cent of normal.

At the two amputation levels available for comparison, the younger patients walked faster than the older ones: patients with traumatic above-the-knee amputation walked sixteen meters per minute faster than those with vascular above-the-knee amputation, and those with traumatic below-the-knee amputation walked twenty-six meters per minute faster than those with vascular below-the-knee amputation.

The results for cadence and stride length also showed that the amputees had a slower cadence and reduced stride length. The cadence for amputees was slower than that for the controls and also depended on the level of amputation. Cadence for normal subjects averaged 116 steps per minute and did not vary with age or sex. The vascular amputees' cadence differed significantly ($p < 0.05$) at the three amputation levels, averaging ninety-eight steps per minute for the Syme's amputation, eighty-seven steps per minute at the below-the-knee level, and seventy-two steps at the above-the-knee level. Similarly, among the patients with traumatic amputation, the cadence of ninety-nine steps per minute for patients with below-the-knee amputation was faster than the eighty-seven steps for patients with above-the-knee amputation.

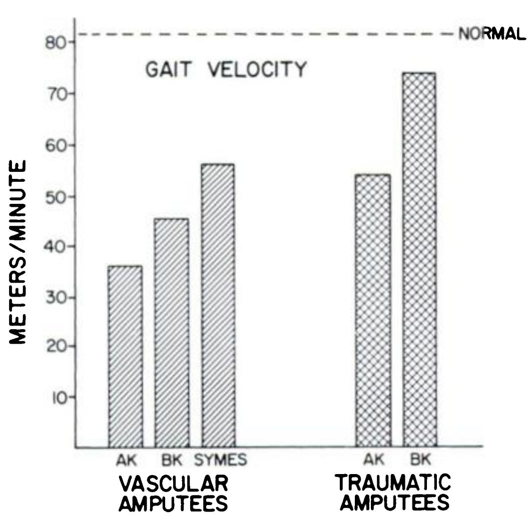

FIG. 1

The data recorded (Table II) are to be compared with the normal cadence of 116 steps per minute, not varying with age or sex, and with the normal stride length of 1.50 meters for men and 1.28 meters for women (average, 1.40).

Metabolic Cost

The energy cost was calculated in three ways: *rate of energy expenditure* (amount of oxygen consumed per minute), *energy cost per meter* (the amount of oxygen consumed per meter walked), and *relative energy cost* (rate of oxygen uptake divided by the individual's maximum ability to perform aerobic exercise, or maximum aerobic capacity).

Among the vascular amputees, the mean rate of *oxygen uptake per minute* at the below-the-knee and Syme's-amputation levels was 11.7 milliliters per kilogram-minute and 11.5 milliliters per kilogram-minute. The value for patients with above-the-knee amputation was greater (12.6 milliliters per kilogram-minute), but this difference was not statistically significant (Table II). The rate of oxygen uptake of patients with traumatic below-the-knee amputation was 15.5 milliliters per kilogram-minute, and the value for those with above-the-knee amputation was 12.9 milliliters per kilogram-minute. The mean rate of oxygen uptake for normal subjects was 13.0 ± 2.7 milliliters per kilogram-minute and did not vary with age or sex.

The mean value of the *predicted maximum aerobic capacity* for all normal subjects was thirty-five milliliters per kilogram-minute. This did not vary significantly with

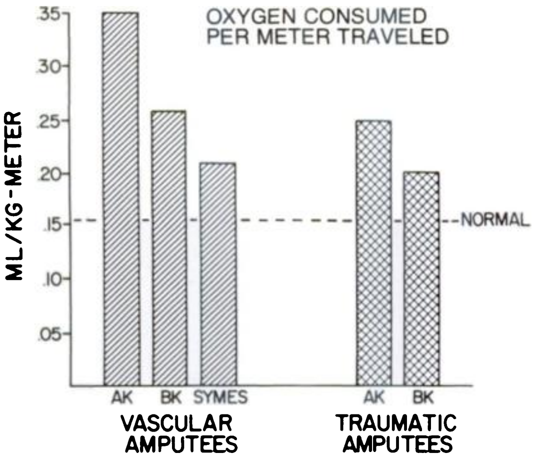

FIG. 2

sex but was influenced by age, a finding that is in agreement with the results of others [1,13]. For patients in the third decade of life, aerobic capacity averaged 41 ± 7 milliliters per kilogram-minute, but this dropped to 30 ± 8 for subjects in the sixth decade. These values are well within 10 per cent of directly measured values for aerobic capacity in untrained individuals of similar ages [1,13].

The maximum aerobic capacity showed the influence of both age and level of amputation (Table II). The maximum aerobic capacity for patients with vascular above-the-knee amputation was only twenty milliliters per kilogram-minute, while the below-the-knee amputees averaged twenty-eight milliliters per kilogram-minute and the patients with a Syme amputation, twenty-seven. The maximum aerobic capacities for younger (traumatic) amputees were much higher but they were also higher for patients with amputation below the knee than for those with amputation above the knee.

The mean value of the *relative energy cost* of unrestrained walking for the entire group of normal subjects was 38 per cent and increased with age because of the decline in the predicted maximum aerobic capacity. For patients with a vascular Syme or below-the-knee amputation the relative energy costs were 43 per cent and 42 per cent, values only slightly greater than the average obtained for normal persons fifty to fifty-nine years old (40 per cent). The value for patients with vascular above-the-knee amputation was markedly greater (63 per cent). The relative energy cost for patients with traumatic amputation below the knee and above the knee was 35 per cent, approximately the same as for controls in the third decade of life (34 per cent).

For the control group of normal subjects, the energy cost per meter averaged 0.16 milliliter per kilogram-meter. Females had a significantly greater value than males ($p < 0.05$). The mean oxygen cost was 0.15 milliliter per kilogram-meter for males and 0.17 milliliter per kilogram-meter for females. The cost for males was less because they walked faster yet consumed the same amount of oxygen per minute (13.0 milliliters per kilogram-minute). No differences occurred that were related to age. In both the vascular and traumatic amputation groups, the energy cost was dependent on the level of amputation (Table II). The differences were significant at the 0.05 level. The lower the level of amputation in both groups the lower was the energy cost per meter.

The mean value of the *respiratory quotient* in the control group was not affected by age or sex and averaged 0.85. With one exception, all amputee groups had essentially normal quotients. The exception was the group with vascular above-the-knee amputation which had an average respiratory quotient of 0.97, significantly greater than normal ($p < 0.05$).

The average *heart rate* for the normal controls (104 beats per minute) did not depend on age or sex and also did not significantly differ from that for the amputees except in the group with vascular above-the-knee amputation, in which it averaged 126 beats per minute ($p < 0.02$).

Crutch Walking without Prosthesis

The rate of oxygen consumption, heart rate, and respiratory quotient were significantly increased in all groups of amputees when walking with crutches and without a prosthesis. The increases ranged from 1.3 milliliters per kilogram-minute in the group with a vascular Syme amputation to 6.9 milliliters per kilogram-minute in the group with traumatic below-the-knee amputation (Table III). Of particular clinical significance, tachycardia was noted in all patients using crutches. All the amputee subgroups averaged between 120 and 125 heartbeats per minute. In contrast, when walking with a prosthesis without crutches, the mean heart rate was less than 111 beats per minute in all groups except the vascular above-the-knee amputees. Again with the exception of the vascular above-the-knee amputees, the mean respiratory quotient was less in all groups when using a prosthesis. The data on oxygen consumption, heart rate, and respiratory quotient clearly indicate that all amputee groups except patients with a vascular above-the-knee amputation walk with less effort with a prosthesis.

Discussion

Drillis, and later Finley and Cody, determined the average velocity, stride length, and cadence of pedestrians walking in selected urban areas who were unaware they were being observed. Over 2,000 people were included in these two studies. The close similarity between their data and the results from our control group of normal subjects indicates that our subjects undergoing experimental testing walked in an unrestrained manner and did not alter their gait pattern. Compared with these data the velocities selected by all our amputee subgroups were significantly lower, and the higher the level of amputation the lower was the velocity selected. Expressed as a percentage of the average value for the normal group of control subjects, the velocity for vascular amputees was 66 per cent at the Syme's-amputation level, 59 per cent at the below-the-knee level, and 44 per cent at the above-the-knee level. In

TABLE III

ENERGY COST OF WALKING WITHOUT A PROSTHESIS AND WITH CRUTCHES

	Velocity (m/min)	Rate of Oxygen Uptake (ml/kg-min)	Respiratory Quotient	Heart Rate (Beats/min)
Vascular amputees				
Above the knee	48 ± 11	15.0 ± 2.9	0.97 ± 0.09	130 ± 32
Below the knee	39 ± 13	14.6 ± 1.5	0.92 ± 0.14	124 ± 20
Syme	39 ± 14	12.8 ± 4.3	1.04 ± 0.09	129 ± 13
Traumatic amputees				
Above the knee	65 ± 16	15.9 ± 5.4	0.95 ± 0.08	129 ± 17
Below the knee	71 ± 10	22.4 ± 4.3	0.93 ± 0.07	135 ± 23

traumatic amputees it was 87 per cent at the below-the-knee level and 63 per cent at the above-the-knee level.

The traumatic amputees walked faster than patients with vascular amputation above or below the knee primarily because of differences in age. However, the duration of prosthetic use must also be taken into account when comparing the two groups. The average age of the vascular amputees was sixty years and their experience with the prosthesis was relatively short (mean, 1.2 years) because of their primary disease. The progression of vascular illness usually leads to death or another amputation in a few years. In contrast, the patients with traumatic amputation who were available for study were younger (average age, thirty years) and had worn a prosthesis longer (mean, 9.8 years). We could find no significant correlation in any group between duration of prosthetic use and gait velocity. It should be noted that recently fitted amputees whose walking speed would logically be expected to increase because of training were purposely excluded from this study and we included only subjects who had worn a prosthesis for a minimum of six months. We therefore believe that age is the major reason for the slower gait velocity in vascular amputees and the data on energy cost support this interpretation.

The rate of oxygen utilization per minute is the commonly accepted index of the energy cost of an activity. It might be expected that the amputees would have a higher than normal rate of oxygen uptake per minute in relation to their maximum aerobic capacity, but with the exception of the group with vascular above-the-knee amputation they did not. During unrestrained walking, the vascular amputees in the below-the-knee and Syme's amputation subgroups had a rate of oxygen uptake per minute of approximately the same percentage of their maximum aerobic capacity (42 per cent and 43 per cent) as the control subjects in the sixth decade of life (41 per cent). Similarly, the younger patients with traumatic above-the-knee and below-the-knee amputation adjusted their relative uptakes (37 and 35 per cent) to values close to that of the normal subjects in the third decade (34 per cent). Thus, with the exception of the group with vascular above-the-knee amputation, the amputees modified their walking speed to keep relative energy costs within normal limits. Also, the older amputees walked more slowly than the younger traumatic amputees, for the same reason. Reinforcing this interpretation is the fact that the heart rate and the respiratory quotient during unrestrained walking were approximately the same as the values for normal subjects, except for the patients with vascular above-the-knee amputation.

These values are important because at low relative work rates the adenosine triphosphate for muscle contraction is principally supplied via aerobic pathways and an individual can sustain prolonged exercise for many hours with no easily definable point of exhaustion. When oxygen demand exceeds 50 per cent of the maximum aerobic capacity, anaerobic mechanisms are called on to assist muscle metabolism. Only one-nineteenth as much adenosine triphosphate is produced by this method and endurance decreases rapidly above 50 per cent.

The energy cost for unrestrained walking for patients with vascular above-the-knee amputation was high (63 per cent of the maximum aerobic capacity). The average heart rate and respiratory quotient also were significantly elevated and were approximately the same as when these patients walked with crutches (without a prosthesis). The high energy cost of crutch walking is well known [11]. All amputee subgroups with the exception of the patients with vascular above-the-knee amputations had significantly lower oxygen uptake, heart rate, and respiratory quotient when walking with a prosthesis. Because we have not found it possible to fit even 10 per cent of patients with vascular above-the-knee amputations initially with a prosthesis at our hospital, and fewer than one-half of those fitted met our criteria for inclusion in the study, we must conclude that amputation below the knee is essential for the older amputee with vascular disease.

The amputees (with the single exception of the group with vascular above-the-knee amputation) adjusted their gait velocity to keep the rate of energy expenditure within normal limits. It is of interest to see how efficiently a well fitted prosthesis allows the patient to walk as compared with normal. The slower walking speed of amputees in all subgroups is a measure of the loss in efficiency. The oxygen uptake per meter walked is the true net energy cost and is the best way to compare the gait efficiency at different amputation levels. The added energy cost of amputation at higher levels is apparent when these values are considered.

The maximum aerobic capacity in the groups with vascular or traumatic amputation above the knee was significantly lower than in the below-the-knee amputees or in normal subjects. In a study of thirty-seven patients with traumatic above-the-knee amputation, James reported the same average maximum aerobic capacity as was determined in this study [9].

Reasons for the reduced aerobic capacity were further investigated in studies of one-legged and two-legged exercise in normal persons and above-the-knee amputees [9,10]. These data suggested that above-the-knee amputees adapt their life style to a less active one that results in reduced physical conditioning of the muscles of the remaining lower extremity.

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The Upper-Extremity Amputee

Early and Immediate Post-Surgical Prosthetic Fitting

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Abstract: **The results of immediate and early post-surgical prosthetic fitting in eighty-seven upper-extremity amputees as well as the results in nine patients with shoulder dislocation who were fitted with temporary devices were reviewed. No local wound complications occurred and the rate of prosthetic acceptance was high. A practice prosthesis, with a filler insert formed from liquid Silastic foam allowed to set between the walls of the practice prosthesis and the amputation stump, was used extensively in this series. With the Silastic insert and practice prosthesis, prosthetic training could be instituted during healing of the amputation wounds, proximal wounds, or fractures.**

The use of a rigid dressing and early or immediate prosthetic fitting has been well documented for the lower extremity [2,3,4,8,11,13]. The advantages of the method, which include protection of the wound, control of edema, and immobilization of injured tissues, have made this a widely used technique after below-the-knee amputation. However, fitting of a metal shank with a prosthetic foot and shoe on the rigid dressing has met with variable success, and several authors have abandoned this procedure because of wound breakdown in the presence of vascular insufficiency [8,9,13].

Immediate or early fitting of upper-extremity prostheses offers the same advantages and, in addition, use of a temporary prosthesis does not jeopardize wound healing as it does in the lower extremity. Most upper-extremity amputees have traumatic amputations and the vessels are generally much less involved by degenerative disease in their upper than in their lower extremities. An additional advantage is that with early fitting of a temporary prosthesis, teaching a two-handed pattern of activity utilizing one normal hand and one prosthetic hook can be instituted within a few days after amputation [1,7,10,12], so that one-handed patterns of activity do not develop.

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