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Energy expenditure of trans-tibial amputees during ambulation at self-selected pace

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Abstract

The purpose of this investigation was two-fold: 1) to compare the metabolic cost (VO_2), heart rate (HR), and self-selected speed of ambulation of trans-tibial amputees (TTAs) with those of non-amputee subjects; and 2) to determine whether a correlation exists between either stump length or prosthesis mass and the energy cost of ambulation at the self-selected ambulation pace of TTAs. Subjects were thirty-nine healthy male non-vascular TTAs between the ages of 22 and 75 years (mean ± sd = 47 ± 16). All had regularly used their prosthesis for longer than six months and were independent of assistive ambulation devices. Twenty-one healthy non-amputee males aged 27-47 years (31 ± 6) served as controls. Subjects ambulated at a self-selected pace over an indoor course, with steady-state VO_2, HR, and ambulation speed averaged across minutes seven, eight and nine of walking. Results showed that HR and VO_2 for TTAs were 16% greater, and the ambulation pace 11% slower than the non-amputee controls. Significant correlations were not observed between stump length or prosthesis mass and the energy cost of ambulation. However, when the TTA subject pool was stratified on the basis of long and short stump length, the former sustained significantly lower steady-state VO_2 and HR than the latter while walking at comparable pace. These data indicate that stump length may influence the metabolic cost of ambulation in TTAs.

Introduction

The surgical, rehabilitative, and prosthetic management of individuals sustaining amputation from all causes represents a significant challenge for contemporary health care professionals. In the United States alone, the National Centre for Health Statistics estimates that 105,000 to 115,000 amputations are performed annually, of which 25,000 to 30,000 involve loss of limb below the knee. Moreover, the National Health Interview Survey (1983-1985) reported that 268,000 survivors of amputation presently live in the United States. Based upon population growth, the total amputee population would now number nearly 311,000, of whom 77,750 will have undergone trans-tibial amputation (TTA).

The energy cost of ambulation following amputation has long been a topic of concern among physicians, prosthetists, and physical therapists. Related to this concern is the question of an optimal stump length following amputation, an aspect of surgical management which is highly influential in determining the success of post-amputation ambulation. Historically, opinions concerning the effect of stump on efficient prosthetic use date to Yale Medical Institute Professor Nathan Smith, whose lecture notes of 1825 contained the admonition that "as a general rule, you should save all the stump you can" (Sanders, 1986). More recently, investigations have directed their attention toward identifying a stump length for TTA which will optimize prosthetic fit, biomechanical conditions, and limb circulation (Levy, 1983) (Fig. 1).

The majority of studies examining metabolic

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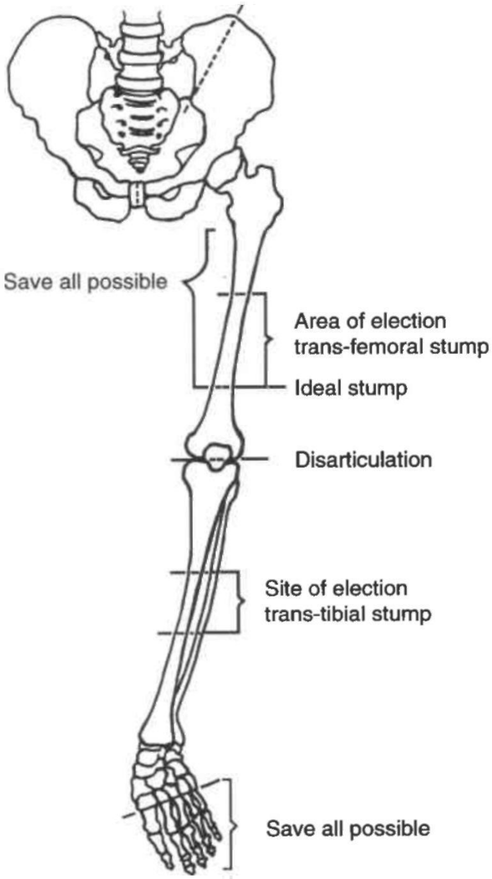

Fig. 1. Commonly accepted levels of amputation. (Adapted, with permission, from Levy, SW: Skin problems of the amputee. St. Louis, Warren H. Green Inc.).

cost of ambulation in TTAs have been cross-sectional in design, comparing subjects of varying stump length during ambulation at various speeds. In studies where correlation between metabolic cost and stump length has been analyzed, the interpretation has been hampered by small sample groups or by subject populations mixed with amputee subjects of traumatic and vascular etiologies. Gonzalez *et al.* (1974) studied 9 subjects with amputation resulting from peripheral vascular disease (n=4), trauma (n=4), and congenital malformation (n=1). The investigation found that a significant inverse relationship existed between stump length and energy expenditure measured during ambulation (r=0.74, p<0.05). When compared to non-amputee control subjects, amputees having a long stump used 10% more energy, while energy output of those with a short stump was 40% greater. By expressing limb length as a percentage of body height, the investigators then stratified the subjects into groups with short (n=3) and long stump length (n=6). While both groups ambulated at 2.4 mph (64.3m/min) – 22% slower than control subjects – correlational analysis showed no effect of stump length on comfortable walking pace.

Ganguli *et al.* (1974) reported that 20 TTA subjects found 50 m/min (1.86 mph) to be the average comfortable walking speed over a distance of 1 km. Their energy cost was higher when forced to walk at a pace which was slower than comfortable walking speed, and they expended the least amount of energy during walking at a self-selected pace. While ambulating at 50 m/min, non-amputees consumed 0.045 kcal/min/kg, while TTA subjects used 33% more energy (0.060 kcal/min/kg).

To date, Molen (1973) has studied the largest number of amputees from trauma alone. Fifty-four TTA subjects walked on a treadmill at a variety of imposed speeds ranging from 50-90 m/min. Comparison of energy costs of amputee and non-amputee control subjects at matched treadmill speeds showed the former to use 20% more energy. Water *et al.* (1976) studied 70 amputees who varied in level of amputation, cause of amputation, and age. When comparing 13 vascular and 14 traumatic trans-tibial amputees during walking on a 60.5 m track at either self-selected or fastest possible pace, vascular amputees walked 37% more slowly while utilizing 25% more energy than their traumatic TTA counterparts. A control group of 87 men and women was also tested, recording an average walking speed of 82 m/min (3.02 mph).

Collectively, these studies demonstrate general agreement that amputee subjects walk more slowly than non-amputee controls while using more energy. Unfortunately some have investigated small subject populations which challenges study validity as well as the ability to draw statistically significant conclusions; studies of amputee subject populations of mixed etiology may result in an overestimate of energy expenditure of ambulation in traumatic TTAs, as vascular amputees walk more slowly and use more energy than these individuals; the use of imposed ambulation pace may also overestimate energy expenditure, as walking at self-selected pace for TTAs has been shown to be most energy efficient. Moreover, few studies have attempted to establish a relationship between the metabolic cost of ambulation and specific variables that may directly influence energy expenditure, including stump length, baseline energy expenditure, age, and prosthesis mass. Thus, the purposes of this investigation were to: 1) compare the metabolic cost (VO_2), heart rate (HR), and self-selected speed of ambulation of trans-tibial amputees (TTAs) with those of non-amputee controls; and 2) determine whether a correlation exists between either stump length or prosthesis mass and the energy cost of ambulation at the self-selected ambulation pace of TTAs. It was hypothesized that pace of ambulation would be slower in the TTA subjects than non-amputee controls, that their energy expenditure would be greater during ambulation, and that a significant relationship would be observed between energy cost of ambulation, stump length, and mass of prosthesis.

Methods

Subjects

Subjects studied were thirty-nine healthy male non-vascular trans-tibial amputees between the ages of 22-75 years (47 ± 16). All subjects had used their prosthesis for more than six months and were independent of any assistive ambulation devices. Their stumps were free from skin irritation, swelling, or restrictive pain. Additionally, socket design and prosthetist for each subject varied, although all subjects were well-fitted regardless of socket design or components. Twenty-one healthy male non-disabled ambulators aged 24 to 47 years (31 ± 6) served as control subjects. All subjects consented to treatment in accordance with the guidelines of the Medical Sciences Subcommittee for the Protection of Human Subjects of the University of Miami School of Medicine.

Testing Procedures

Subjects were instructed to ambulate at their most comfortable pace around an open 36m L-shaped track covered with industrial carpeting. All turns were gently rounded and prompted no changes in the subjects' walking pace. Heart rates were monitored using a Vantage Performance Monitor[1]. Oxygen uptake (VO_2) was quantified by open-circuit spirometry using a calibrated Horizon System II Metabolic Measurements Analyzer[2] and a Hans-Rudolph non-rebreathing valve suspended from a stabilizing headset. Baseline VO_2 and HR measurements were obtained during one-minute of quiet standing before ambulation. Subjects then walked for nine minutes with data collected at minutes six and nine. Measurements were also taken while standing one minute after cessation of ambulation. Speed of ambulation was determined by dividing the distance travelled during the trial by the total time of ambulation (Fig. 2).

Fig. 2. Subject ambulating while being tested with MMC Horizon Metabolic Cart and Vantage Heart Rate Monitor.

Prosthesis mass and stump length

The prosthesis and shoe were weighed (kg) to determine the total mass suspended from the stump. The length of the stump (cm) was measured from the medial tibial plateau to the distal end of the tibia. The stump percentage length was expressed as the ratio of the amputated tibial length to the distance from the medial tibial plateau to the medial malleolus of the intact limb.

[1] Polar Electro Inc., P.O. Box 920, 300 Cottonwood Avenue, Hartland, WI 53029, USA.

[2] SensorMedics Corporation, 1630 South State College Boulevard, Anaheim, CA 92806, USA.

Data analysis

Descriptive characteristics were defined operationally as age, speed of ambulation, baseline HR and VO_2, prosthesis mass, and length and stump percentage length. Amputee and control subjects were compared for their descriptive characteristics (excluding prosthesis mass and stump length) using independent Student's t-tests. Pearson product moment correlation was used to explore association between descriptive characteristics and post-ambulation HR and VO_2. Differences in physiological responses of control and amputee subjects to ambulation were analyzed using a repeated measures ANOVA. Additionally, analysis of co-variance (ANCOV) was performed to control for the effects of observed differences of age and baseline VO_2 on ambulation VO_2. Multiple linear regression was performed to model the relationship between various descriptive characteristics and ambulation VO_2 in amputees.

Results

Amputee subjects were significantly older than the controls, and while there was no significant difference between the two groups in baseline VO_2, the amputee group had a significantly higher baseline heart rate (HR) than the control group (Table 1).

There was no significant difference between amputees and controls in the self-selected speed of ambulation during the trial (Table 2). However, there was a significant difference in both final HR and final VO_2. A two-group repeated measure ANOVA was calculated and the time-group interaction was statistically significant ($p<0.005$) indicating that the amputee and control groups differed in the change in mean VO_2 following ambulation (Table 3).

Table 1. Comparison of amputee and control group baseline characteristics

Characteristic	Amputee mean	Control mean	p-value[a]
Age (years)	47.05	31.19	0.0001
Baseline VO_2 (ml/kg.min)	4.9	4.5	0.2093
Baseline HR (bpm)	82.9	72.6	0.0008
Prosthetic mass (kg)	2.45 (5.37lb)		
Stump length (cm)	16.41 (6.46in)		

[a] Student's t-test
Amputee group N=39
Control group N=21

Table 2. Comparison of amputee and control group ambulation characteristics

Characteristic	Amputee mean	Control mean	p-value[a]
Walking speed (m/min)	69.7 (2.6mph)	75.0 (2.8mph)	0.1674
Final VO_2 (ml/kg.min)	12.9	10.9	0.0051
Final HR (bpm)	102.5	86.5	<0.0001

[a] Student's t-test
Amputee group N=39
Control group N=21

In order to understand factors which may contribute to the difference between amputees and controls in their VO_2, response to ambulation, correlation coefficients were calculated between the ambulation HR and ambulation VO_2 and various amputee and control characteristics. In both the amputee and control groups baseline VO_2 and baseline HR were significantly positively correlated with ambulation VO_2, and ambulation HR, respectively (Tables 4 and 5). In the amputee group, speed of ambulation was moderately negatively correlated with ambulation HR and moderately positively correlated with ambulation VO_2 (Table 4). Stump length was moderately negatively correlated with ambulation VO_2 but not with ambulation HR.

A regression analysis was conducted to examine the contribution of various factors to the ambulation VO_2 in amputees. Baseline VO_2 alone explained 40% of the variance in ambulation VO_2. Age, speed of ambulation, and stump length each individually explained between 10 and 18% of the variance. Age was

Table 3. Change in VO_2 during ambulation by group

Group	Baseline VO_2	Final VO_2
Amputee (ml/kg.min)	4.92	12.87
Control (ml/kg.min)	4.47	10.88
Source of variance	**F[a]**	**p-value**
Group effect	6.50	0.0100
Time effect	886.98	0.0001
Time* Group effect	8.66	0.0047

[a] Two group repeated measures ANOVA

Table 4. Association between descriptive characteristics and ambulation outcomes in amputee group

	Ambulation heart rate	Ambulation VO_2
Baseline heart rate	0.7138[a]	0.0978
	0.0001[b]	0.5535
Baseline VO_2	0.1711	0.6351
	0.2978	0.0001
Age	-0.0367	-0.3575
	0.8243	0.0255
Speed	-0.4750	0.4354
	0.0022	0.0056
Prosthesis mass	-0.1285	0.0978
	0.4355	0.5538
Stump length	-0.0548	-0.3223
	0.7404	0.0454

[a] Pearson product moment correlation
[b] p-value

not a significant factor when added to a model containing baseline VO_2 and speed of ambulation. The final model which contained baseline VO_2, speed of ambulation and stump length, explained 63% of the variance in ambulation VO_2 (Table 6).

The effect of prosthetic mass on ambulation VO_2 was examined by dividing the amputee group into those who have had heavy prostheses – operationally defined as of mass greater than 2.27kg (5 pounds) (N=23) and those who had light prostheses, defined as of mass 2.27kg (5 pounds) or less (N=16). Significant effects testing the stratified heavy and light prosthetic groups were limited to the mean prosthetic mass. Differences in mean stump length approached statistical significance (Table 7). An analysis of co-variance was performed to test for the difference between the heavy and light prostheses groups in ambulation VO_2 adjusting for possible confounding factors. Even after controlling for stump length, age, speed of ambulation and baseline VO_2, there was no significant difference in ambulation VO_2 between the heavy and light prosthetic groups (Table 8).

Table 5. Association between descriptive characteristics and ambulation outcomes in control group

	Ambulation heart rate	Ambulation VO_2
Baseline heart rate	0.7693[a]	0.1231
	0.0001[b]	0.5949
Baseline VO_2	0.0829	0.7144
	0.7210	0.0003
Age	0.0800	0.1909
	0.7302	0.4070
Speed	0.0815	0.3941
	0.7254	0.0771

[a] Pearson product moment correlation
[b] p-value

Table 6. Factors predicting ambulation VO_2 in amputees

Model	R-square	F	p-value
1. Baseline VO_2	0.4034	25.017	0.0001
2. Age	0.1278	5.421	0.0255
3. Speed	0.1895	8.654	0.0056
4. Stump length	0.1038	4.288	0.0454
5. Baseline VO_2 Speed	0.5465	21.691	0.0001
6. Baseline VO_2 Speed Age	0.5671	15.284	0.0001
7. Baseline VO_2 Speed Stump length	0.6277	19.667	0.0001

Discussion

The stump lengths of subjects presently under study were representative of common practice for persons undergoing TTA, and similar to those observed in TTA subjects previously studied. The subjects in this study had an

Table 7. A comparison of heavy versus light prostheses

Factor	Light[a] prosthesis	Heavy[b] prosthesis	p-value
Prosthesis mass (kg)	2.0 (4.5lb)	2.7 (5.9lb)	0.0001
Stump length (cm)	15.2 (5.98in)	17.3 (6.80in)	0.0884
Age (yrs)	50.6	44.6	0.2660
Baseline HR (bpm)	85.9	80.8	0.1220
Ambulation HR (bpm)	103.8	101.6	0.5061
Baseline VO_2 (ml/kg.min)	4.8	5.0	0.6997
Ambulation VO_2	12.4	13.1	0.3411
Speed (m/min)	67.0 (2.5mph)	72.4 (2.7mph)	0.2561

[a] Light defined as prosthesis weighing 2.27kg (5lb) or less. N=16.
[b] Heavy defined as prosthesis weighing more than 2.27kg (5lb). N=23

Table 8. Comparison of ambulation VO_2 between heavy and light prostheses controlling for possible confounding

Model	Adjusted VO_2 (light)	Adjusted VO_2 (heavy)	R-square	p-value for means equal
1. Mass group	12.44	13.15	0.0245	0.3411
2. Mass group stump length	12.15	13.36	0.1692	0.1010
3. Mass group Stump length age	12.32	13.20	0.2769	0.1894
4. Mass group Stump length Age Speed	12.44	13.15	0.3497	0.3010
5. Mass group Stump length Age Speed Baseline VO_2	12.51	13.11	0.6695	0.2279

average stump length equal to 40% of their unaffected limb, with a mean stump length of 16.41cm (6.46 in). This is within the range commonly recommended by surgeons when the amputation site is not dictated by trauma, tumour or vascular considerations. For example, Levy (1983) has advised that a site 12.7 to 17.8cm (5 to 7in) below the knee joint is ideal for TTA, as it represents a length that allows for the muscular padding of the gastrocnemius and soleus muscles used in the posterior flap technique. While this length might be optimal for surgical construction of the amputation stump, the question as to whether a longer stump might result in improved gait, increased ambulation speed, or might minimize energy cost of ambulation for persons with traumatic amputation has received limited attention.

The subject-selected comfortable walking speed (CWS) and energy expenditure of TTA in this study were similar to those reported in two other studies. Gonzalez *et al.* (1974) described an ambulation speed of 64 m/min at an oxygen consumption of 13.06 ml/kg.min in a mixed population including TTAs of peripheral vascular etiology. Pagliarulo *et al.* (1979) reported that 15 traumatic TTAs walked at 71 m/min with an energy expenditure of 15.5 ml/kg.min. The 39 non-vascular TTAs in the present study walked at an average pace of 67.1 m/min and an energy cost of 12.9 ml/kg.min, 5% slower using 2% less energy than subjects studied by Gonzalez *et al.*, and 5% slower with 17% lower metabolic expenditure than those reported by Pagliarulo *et al.*

The length of the stump following amputation has long been considered an important factor in determining the energy cost and speed of walking. This difference has best been demonstrated when comparing energy cost of ambulation between trans-femoral and trans-tibial amputees, in which the metabolic cost of walking in the former is higher, and the speed of ambulation slower. To date, however, Gonzalez *et al.* (1974) have performed the only study specifically addressing the relationship between stump length and ambulation energy cost in TTAs, in which a significant negative correlation was observed between stump length and energy cost. These findings differ from those reported herein when subjects were not segregated by long and short stump length. This observation suggests that small differences in stump length might have minimal impact on metabolic consequences of ambulation in these subjects. In contrast, stratification of subjects on the basis of long and short stump length suggests that sparing as much limb as possible may desirably influence both walking pace and energy utilized during walking.

In order to understand factors contributing to differences in metabolic response between amputees and non-amputee controls, correlation coefficients were calculated between the ambulation HR and ambulation VO_2 as well as various amputee and control characteristics. In both the amputee and control groups, baseline VO_2 and baseline HR were significantly positvely correlated with ambulation VO_2 and ambulation HR, respectively (Tables 4 and 5). Interestingly, in the amputee speed of ambulation was moderately negatively correlated with ambulation HR and moderately positively correlated with ambulation VO_2 (Table 4). Stump length was moderately negatively correlated with ambulation VO_2 but not with ambulation HR. Thus, a paradox exists in which HR and VO_2, which normally respond in parallel fashion during submaximal work, do not respond this way in trans-tibial amputee subjects. The basis for this paradox is not immediately clear, but may represent a loss of the feedback from joint, tendon and muscle movement sensors, as well as muscle chemical receptors, which normally regulates the heart response to work in the intact lower limb. While HR and VO_2 responses to work throughout the submaximal exertional range are normally positively correlated in persons without amputation, the HR response is also influenced by peripheral neurogenic input which may be lost or diminished in a limb without a distal leg, ankle joint, and foot.

A regression analysis was conducted to examine the contribution of various factors to the ambulation VO_2 in amputees. Interestingly, baseline VO_2 alone explained 40% of the variance in ambulation VO_2, a finding which implicates level of fitness as a major factor influencing the metabolic cost of ambulation. Otherwise, subject age, speed of ambulation, and stump length each individually explained between 10% and 18% of the variance. Age did not significantly influence ambulation. VO_2 when added to a model containing baseline VO_2 and speed of ambulation. The final model which contained baseline VO_2, speed of ambulation and stump length, explained 63% of the variance in ambulation VO_2 (Table 6).

Prosthetic manufacturers and prosthetists have long been concerned with minimizing the mass of the amputee's prosthesis. During the past two decades, use of lightweight materials including titanium and carbon graphite composites have decreased overall prosthesis mass, in some cases, by half. Prosthetic limb mass in this study (which included the shoe) ranged from 1.59 to 3.4 kg (3.5 to 7.5 lb) (mean ± sd = 2.45 ± 0.4 kg). It was interesting to observe however, that prosthesis mass did not explain a significant percentage of the variance observed in ambulation VO_2. Moreover, when controlling for stump length, age, speed of ambulation, and baseline VO_2, there was no significant difference in ambulation VO_2 between groups that were segregated on the basis of heavy and light prostheses. One might normally expect that additional mass of the prosthetic limb would penalize the heavy prosthesis user through higher energy cost. While significant effects of mass on energy cost might be unmasked by testing during longer ambulation periods, heavier prosthetic limbs might also stimulate musculoskeletal and cardiopulmonary adaptations favouring greater tolerance of the additional mass. This finding is important, especially as considerable emphasis is placed during prosthesis design and fabrication on minimizing its mass, emphasis possibly at the exclusion of componentry or materials which might favour improved function and decreased energy expenditure. Moreover, the small advantage provided by a lightweight prosthesis might eventually be buffered by user characteristics including age, gait mechanics, level of fitness, or training effects imposed by the mass of the prosthesis itself. However, as not all trans-tibial prosthesis users are young and fit, these results may not be generally applicable to those with deteriorating vascular conditions, sensory loss in the amputated limb, muscle dysfunction, or cardiac impairment. Nonetheless, and within the boundaries of successful amputation procedure and proper prosthetic fitting, an optimal "window of mass" might exist in which a device provides optimal function without excluding the use of selected componentry on the basis of excessive mass. For example, if a rotation device or locking mechanism, once thought to be contraindicated due to mass considerations, could be incorporated into the prosthesis, function might be improved without increasing the energy cost of walking.

Moreover, physicians and prosthetists have generally credited longer stump lengths with specific advantages, including: 1. longer lever arm; 2. greater muscle capacity; and 3. greater load bearing capability.

Conclusion

It was concluded that:

1. Non-vascular TTAs in the present study walked at an average pace of 67.1 m/min and an energy cost of 12.9 ml/kg.min which is comparable to that reported by other investigators.
2. A significant effect of stump length on metabolic cost and speed of ambulation was observed when TTA subjects were stratified by long and short stump length. This indicates that while small differences in amputation level might have minimal impact on metabolic consequences of ambulation in these subjects, sparing as much limb as possible may desirably influence both walking pace and energy utilized during walking.

3. Resting VO_2 explained 40% of the variance observed in ambulation VO_2, a finding which implicates level of fitness as a major factor influencing the metabolic cost of ambulation. To a lesser extent, age, speed of ambulation, and stump length each represent meaningful factors in predicating energy cost of walking.
4. Prosthesis mass did not significantly alter ambulation VO_2, and when controlling for stump length, age, speed of ambulation, and baseline VO_2, no significant difference in ambulation VO_2 was observed between groups that were segregated by heavy and light prostheses.
5. Absence of a significant effect of prosthesis mass on VO_2 may be explained by musculoskeletal adaptation to heavier prostheses. As the mass of the prosthesis does not apparently affect the amount of energy expended during walking this might suggest greater use of accessories such as rotators and multi-axial feet and other componentry that might improve ambulation gait and efficiency.

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