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Energy Expenditure and Walking Speed in Lower Limb Amputees: a Cross Sectional Study

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SUMMARY

Background. Energy expenditure and walking speed are generally recommended for use as measures of status and outcome for walking. The objective of this study was to measure the physiological cost index (PCI) and comfort walking speed (CWS) at three levels of lower limb amputation: transfemoral, transtibial and Syme level, and the relationship of these physiological variables to prosthetic ambulation supported with walking aids and stump length.

Material and methods. This study was a prospective cross-sectional study.Eighty-nine individuals with lower limb amputation for reasons other than peripheral vascular disease (PVD) were recruited among patients at the Department of Prosthetics and Orthotics in University Clinical Center of Kosovo. PCI was assessed by five minutes of continuous indoor walking at CWS.

Results. Significant differences were found in PCI (F=29.87, $P < 0.001$) and CWS (F=19.33, $P < 0.001$) among the three amputation groups. Prosthetic ambulation supported with crutches showed an important impact on PCI (F=35.1, $P < 0.001$) and CWS (F=28.42, $P < 0.001$). Stump length was associated with significantly increased PCI (r=0.53, $P = 0.02$) and reduced CWS (r=0.58, $P = 0.004$) in transfemoral amputees.

Conclusions. 1. A higher level of amputation is associated with less energy-efficient walking and with lower walking speed. 2. Prosthetic ambulation supported with crutches has significant impact on increasing of energy expenditure and decreasing walking speed. 3. Stump length is shown to have a major impact on PCI and CWS in transfemoral amputees.

Key words: lower limb amputees, physiological cost index, comfort walking speed, crutches, stump length

BACKGROUND

Although many individuals with lower limb amputations learn to walk with a prosthesis, their walking is less energy efficient at a given walking speed [1]. The golden standard for the assessment of energy expenditure is to perform direct measurements of the volume of oxygen uptake (VO_2) and express the cost as VO_2 per unit of distance walked [1-3]. Although VO_2 measurements are a primary choice for assessing energy expenditure, they are cumbersome to conduct and require advanced equipment, a laboratory setting and trained personnel [4]. The more frequently used lower-technology approaches to energy measurement include the physiological cost index (PCI) as described by MacGregor [5], which gives a value of heart rate per meter walked.

The observed energy expenditure as well as the general ability to walk in patients who have undergone amputation of the lower limb are largely determined by the extent of amputation [2,6,7]. Sparing as much limb as possible may desirably influence both walking pace and energy utilized during walking [8]. A longer stump allows a better cantilever function in lifting the prosthesis, requiring less energy [9], and velocity increases linearly with increased length of the stump [10].

There is currently no clear consensus on how to define functional walking and to present the results due to lack of outcome measures that should be used. This issue has been explored and has been the subject of discussion in the field for some time. Reports in the literature present different periods of follow-up, groups with amputations from various causes, vascular combined with non-vascular causes, or analysis of only one level of amputation, such as transfemoral or mostly transtibial amputation [2,3,8,11-14]. As a result, it is often difficult to extrapolate findings that relate to the three amputation levels of the lower limb, particularly of Syme amputations, for reasons other than peripheral vascular disease (PVD).

After an analysis of the rehabilitation outcome in war-related transtibial amputees, for whom a rehabilitation program was applied for the first time in Kosovo, we reviewed the success of prosthetic ambulation in the amputees over more than ten years after completion of this program [15]. We followed up patients at three amputation levels and ascertained the validity of prosthetic ambulation as one of main goals of the rehabilitation program in terms of energy expenditure during walking, with or without external support.

We hypothesized that level of amputation, use of devices as support for walking, and stump length would have an impact on energy expenditure and walking speed in lower limb amputees. Therefore, the aim of this study was to measure PCI and comfort walking speed (CWS) at three levels of lower limb amputation: transfemoral, transtibial and the Syme level, walking with or without aids. We also examined the possible relationship between PCI and CWS and stump length.

MATERIAL AND METHODS

This was a prospective cross-sectional study. The research covered the period from the first of January to the first of July, 2012.

Subject population

A convenience sample of individuals with amputations was recruited among patients at the Department of Prosthetics and Orthotics at the University Clinical Center of Kosovo.

The inclusion criteria were as follows: 1) above 18 years of age; 2) unilateral lower limb amputation, for reasons other than PVD; 3) Syme and higher level of amputation; 4) at least one year experience of using prosthesis; and 5) no cognitive disorders or other significant medical conditions. All participants provided informed consent.

All transfemoral amputees used modular (endoskeletal) prostheses with a quadrilateral socket, a 4-bar linkage knee with mechanical swing phase control, or a polycentric knee joint and a SACH-foot. Transtibial amputees used a modular patellar tendon bearing socket and the SACH-foot. Syme amputees used conventional prostheses: a constant bearing wall and the SACH-foot. The participants wore their prostheses almost all day for ordinary activities.

Measurements

PCI is calculated as the quotient of difference in working and resting heart rates divided by self-selected (comfort) walking speed (CWS).

PCI was calculated using the equation:

$$PCI = [\text{Mean } HR_{(W)} - \text{Mean } HR_{(R)}] / CWS$$

where $HR_{(W)}$=heart rate at walking, $HR_{(R)}$=heart rate at resting (both in beats/minute), and CWS was measured in meters/minute.

Mean PCI values for healthy adults are reported between 0.23 and 0.42 [5,16,17]. In healthy persons, CWS is reported between 60 and 100 m/min [18-20].

Testing procedure

PCI was assessed by 5 min of continuous indoor walking at CWS. The participant had an HR monitor (OXY-100 Handheld Pulse Oxymeter, 20060 Gessate (MI), Italy) attached around the chest and the receiver was attached on the second finger of their hand. Before registering HR at rest, the participant was seated in silence for approximately five minutes and then HR was recorded each minute for the following five minutes. Prior to the walking part of the test, the participant walked a short distance to warm up. The walking was conducted indoors, in a hallway with a regular floor surface. We chose a 76-m-long quadratic-shaped track with gently rounded corners (36 x 2 x 36 x 2), marked every meter. The patients were asked to walk at their self-selected comfortable speed, with the aid they normally use for support if walking continuously for a few hundred meters. Walking was performed for five minutes with the tester walking behind to read the HR at work every 30 seconds. A digital stopwatch was used to time the subjects as they walked over the track while the investigator recorded HR. All participants were instructed to avoid the intake of tobacco, coffee/tea or a large meal at least two hours prior to the test.

Residual limb measurements

The residual limb length for transfemoral amputation was measured from the ischial tuberosity to the fleshy end of the residual limb, while limb length for transtibial and Syme amputation was measured from the medial tibia plateau to the fleshy end of the residual limb [21].

Statistical methods

Statistical analysis was performed using the statistical package SPSS 17.0 at Sigma Stat 2.03. Descriptive statistics were calculated. To determine whether there were differences between the transfemoral, transtibial and Syme amputee groups in terms of distribution of gender, age and period of prosthetic use, the Chi-square test and one way analysis of variance (ANOVA) were used. In addition, for mean values of PCI and CWS in the three amputation groups, comparison of differences between groups and the impact of using crutches on these physiological determinants, one way ANOVA was used. The correlation between stump length and PCI or CWS by level of amputation was tested with linear regression analysis.

RESULTS

Eighty-nine lower limb amputees were recruited to participate in this study, including 22 transfemoral amputees, 61 transtibial amputees and 6 Syme amputees. The descriptive characteristics of all study participants are given in Table 1. There were no significant differences between the three amputee groups according to distribution of gender, age or period of prosthetic use. The most frequent cause of amputation was firearm injuries. Eleven of the transfemoral amputees and ten of the transtibial amputees used walking aids. The mean values of stump length are presented by level of amputation.

The mean values for PCI and CWS as well as the differences between the three groups are shown in

Tab. 1. Characteristics of amputee study participants (n=89)

Characteristics	Transfemoral amputees (n=22)	Transtibial amputees (n=61)	Syme amputees (n=6)	*P*-value
Male/Female (n)	20/2	52/9	5/1	0.78*
Age, years (SD)	40.6 (12.5)	39.7 (13.1)	36.3 (6.2)	0.76**
Min-max	24–70	18–70	29–46	
Years of prosthetic use (SD)	17.1 (10.5)	14.5 (7.5)	11.3 (2.4)	0.26***
Cause of amputation (n)				
Firearm injuries	10	47	5	
Trauma (accidents)	9	11	1	
Anomalies	2	3		
Walking with aids (n)				
One crutch	8	5		
Two crutches	3	5		
Stump length, cm (SD)	26.9 (5.6)	16.9 (2.9)	41.1(2.6)	

Data are presented as means.
*Chi square=0.5 df=2 *P*=0,78
**One Way Analysis of Variance, F = 0.27 (*P*=0.76)
***One Way Analysis of Variance, F = 1.38 (*P*=0.26)

Tab. 2. Differences in physiological cost index (PCI) and comfortable walking speed (CWS) among transfemoral, transtibial and Syme amputees

	Transfemoral amputees (n=22)	Transtibial amputees (n=61)	Syme amputees n=6	Statistical analysis	*P*-value
PCI, Mean (SD)	0.57 (0.085)	0.43 (0.087)	0.35 (0.034)	One Way ANOVA F=29.87	<0.001
PCI min-max	0.378–0.75	0.29–0.72	0.29–0.39		
			-		
CWS, Mean (SD)	60.14 (6.8)	75.6 (12.9)	85.8 (5.7)	One Way ANOVA F=19.33	<0.001
CWS min-max	47–72	53–94	76–90		

Tab. 3. Differences in physiological cost index (PCI) and comfortable walking speed (CWS) among transfemoral and transtibial/Syme amputees in relation to using walking aids

Groups	PCI, mean±SD (min-max)	CWS, mean±SD (min-max)
Transfemoral, walking with aids (n=11)	0.62±0.05 (0.57–0.75)	54.64±3.67 (47–61)
Transfemoral, walking without aids (n=11)	0.53±0.09 (0.37–0.66)	65.64±4.18 (60–72)
Transtibial, walking with aids (n=10)	0.55±0.1 (0.35–0.72)	58.2±2.62 (53–62)
Transtibial, walking without aids (n=51)	0.40±0.06 (0.29–0.58)	79.02±11.26 (55–94)
Syme (n=6)	0.35±0.034 (0.29–0.39)	85.8±5.7 (76–90)
ANOVA one-way	F=35.1, *P*<0.001*	F=28.42, *P*<0.001*

*indicates statistical significance.

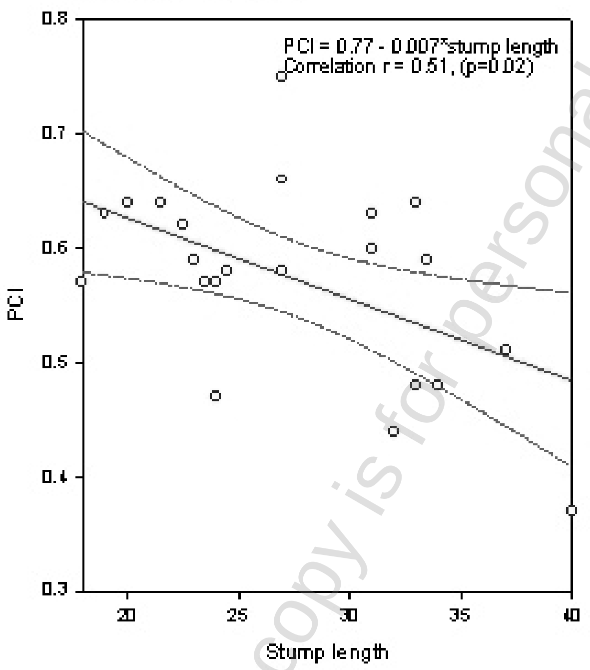

Fig. 1. Linear regression – transfemoral amputees. x variable: PCI, y variable: stump length

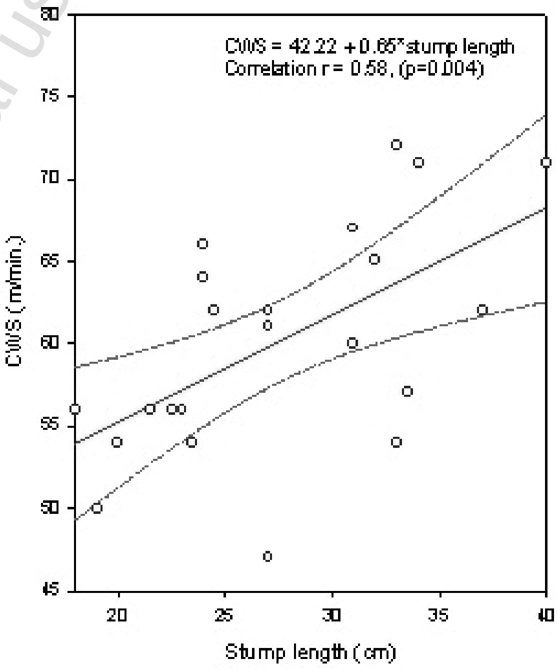

Fig. 2. Linear regression – transfemoral amputees. x variable: CWS, y variable: stump length

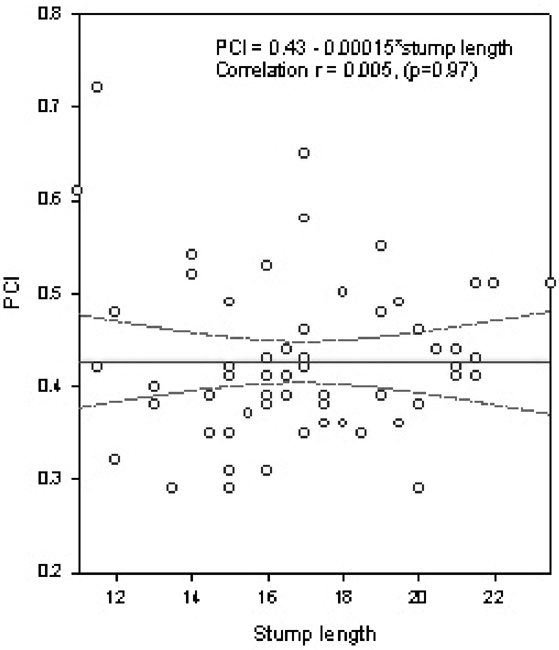

Fig. 3. Linear regression – transtibial amputees. x variable: PCI, y variable: stump length

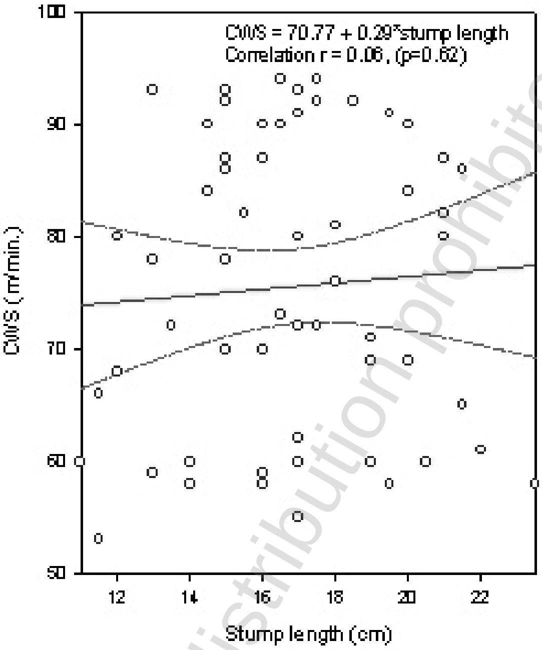

Fig. 4. Linear regression – transtibial amputees. x variable: CWS, y variable: stump length

Tab. 4. Linear regression – impact of stump length on physiological cost index (PCI) and comfortable walking speed (CWS) by level of amputation

Characteristics		Transfemoral amputees (n=22)			Transtibial amputees (n=61)			Syme amputees (n=6)		
		Coeff.	Beta	*P*	Coeff.	Beta	*P*	Coeff.	Beta	*P*
PCI	Constant	0.77			0.43			0.09		
	Stump length	-0.007	0.51	0.02*	-0.00015	0.005	0.97	0.006	0.50	0.31
CWS	Constant	42.22			70.77			103.75		
	Stump length	0.65	0.58	0.004*	0.29	0.06	0.62	-0.44	0.19	0.71

* indicates statistical significance

Table 2. Significant differences were found between groups (ANOVA F=29.87, $P < 0.001$), showing that energy expenditure increased with each higher level of amputation. The significant differences in CWS (ANOVA F=19.33, $P < 0.001$) indicated that the transfemoral group walked significantly more slowly than the transtibial and Syme groups, and significant differences were also observed in the transtibial group compared to the Syme group.

The average PCI values were also significantly different among the five groups, categorized by level of amputation and use of crutches (ANOVA F= 39.5 $P < 0.001$) (Table 3)

Walking speed also significantly differed among the five groups (ANOVA F=28.42, $P< 0.001$) (Tab. 3).

Pearson-Conn's coefficient showed significant correlations in transfemoral amputees between stump length and PCI (r=0.51, P=0.02) and CWS (r=0.58, P=0.004) (Fig. 1 and 2), while no significant correlation was observed in transtibial amputees (Fig. 3 and 4). Linear regression analysis failed to reveal a major impact of stump length on PCI and CWS in transtibial and Syme amputees (Tab. 4)

DISCUSSION

The energy cost of ambulation following amputation has long been a topic of concern among physicians, prosthetists, and physical therapists, and it has been well documented in the clinical population. Nevertheless, this issue still remains unclear as measurement protocols for assessing energy expenditure differ between studies in terms of the measuring equipment used and the surface walked by the subjects.

Currently, the PCI is commonly used as it is more suitable for clinical research. PCI was introduced by MacGregor to estimate the energy cost of walking in healthy people, and it has been used to analyze patients with different locomotion disorders as well as individuals walking with a prosthesis [8,12, 22-27].

The walking surface also differs between studies in terms of length and design of the track, the duration of walking effort, or walking on a treadmill instead of a floor track [17,24,25-30]. Based on previous studies, we selected a floor with a long oval shape track as more appropriate for individuals with lower limb amputation, particularly for older amputees and for those who supported prosthetic ambulation with crutches [17,28,29].

Waters at al. examined amputees in three levels, including Syme amputees, though only in a vascular group. Additionally, the measurements were different from the approach used in this study and performed by measuring oxygen consumption. The authors concluded that the lower the level of amputation, the lower the energy expenditure and higher the self-selected walking speed [2]. In another study, children with Syme and transtibial amputation or knee disarticulation walked with essentially the same speed and oxygen cost as normal children in the same age group, while children with transfemoral amputation and hip disarticulation showed higher oxygen consumption and lower walking speed compared with the control group [31].

To the best of our knowledge, ours is the first study comparing energy expenditure in adult patients post lower limb amputation at three levels (transfemoral, transtibial and Syme) due to reasons other than PVD. Our findings indicate that the level of amputation had a great impact on energy expenditure and walking speed.

In our study, the mean PCI value for the transfemoral group (0.57, SD=0.085) was comparable with values in studies with testing procedures similar to our procedure. In a study of twelve transfemoral cases for comparisons of two different socket designs, the mean PCI values were 0.48 and 0.55, and a study of transfemoral amputees reported a mean PCI value of 0.55 [13,32].

The mean value of PCI in transtibial amputees (0.43, SD=0.087) was also comparable with the mean PCI values for long residual limb (0.33) and short residual limb (0.53) presented in a study with four walking speeds in children with below-knee amputation where the mean value between the short and long residual limb was 0.43 [14]. To the best of our knowledge, no study has examined PCI in Syme amputees.

Previous studies have shown that amputees walk more slowly than normal subjects [33]. Thus the first research question concerned the physical possibilities of locomotion with the prosthesis after one year or more of using the prosthesis as expressed by walking speed. CWS is considered to be a reliable measure that is highly correlated to other aspects of walking [34].

In our study, the mean CWS value for transfemoral amputees (60.14 m/min, SD=6.8) was in line with previous results and close to the speed of 57 m/min that was reported in a study of healthy males walking with transfemoral prostheses on a treadmill [2,13, 19,35].

The mean value of CWS for transtibial amputees (76.5 m/min, SD= 12.8) was similar to other studies particularly with CWS (71 m/min.), reported in Pagliarulo at al. and Waters at al.2 with traumatic transtibial amputees [3,6,8]. The CWS in the Syme amputees in our study was within the reference values of able-bodied persons, which was consistent with findings in a study of children with Syme amputation [31].

Our study also included cases in which prosthetic ambulation in daily life was assisted with crutches, so we tested crutches while participants walked with assistive devices. Energy cost significantly increased and walking speed significantly decreased both in transfemoral and transtibial amputees in whom prosthetic walking was supported by aids. All Syme amputees walked without crutches. No study has previously analyzed walking with a prosthesis and with crutches, but two previous studies have analyzed the difference between prosthetic walking and walking with crutches without prosthesis. Walters at al. found that the rate of oxygen consumption, heart rate, and respiratory quotient were significantly increased in all groups of amputees with regard to the level of lower limb amputation [2]. One study analyzed unilateral transtibial traumatic amputees and found that crutch walking requires more exertion than walking with a prosthesis without crutches [36]. However, the authors suggested that patients with transtibial amputations should be prescribed prosthetic walking supported with crutches compared to walking with crutches alone, which is consistent with our findings.

The stump length following amputation has long been considered an important factor in determining the energy cost and walking speed. We also analyzed the impact of stump length on PCI and CWS in relation with level of amputation. In our cases, we found no relevant impact of stump length on these physiological determinants, except in transfemoral amputees. In the present study, the subjects were not grouped according to short or long stump length, so the small differences in stump length might have had minimal impact on energy cost and ambulation speed. This observation might provide an explanation for a previous study, in which the authors found an important effect of stump length on energy cost and walking speed only when transtibial amputees were stratified by long and short stump length, indicating that the longer the stump length, the less the energy cost and the higher the CWS [8]. Majumdar at al. grouped transtibial amputees by stump length and concluded that the amputees with a longer stump length performed more efficient gait in terms of less energy consumption and more velocity [10]. However, another study found no differences between two groups of children with below-knee amputation grouped by stump length with respect to the PCI and CWS [14]. Another report demonstrated that PCI showed an inverse relation with the below-knee stump length only in the status of walking at a fast speed, but not with slower speeds [27].

This study has several limitations. Although the number of subjects included in our paper was considerable, the number of cases with Syme amputation was relatively small. We investigated the PCI in individuals with a lower-limb amputation due to reasons other than vascular disease. However, currently the most common reason for lower-limb amputation is severe vascular disease, and this group of patients is generally older. For this reason, the results presented in the current study should not be generalized and applied to the larger group of geriatric amputees. It is possible that measuring energy expenditure at self-selected walking speed while combining all amputees to form a group according to stump length by level of amputation is not the most sensitive measure.

Also, it would have been desirable to retest subjects with lower limb amputations. Such re-testing, however, was not possible due to the time frame of the investigation and the proximity of the amputees to the Department of Prosthetics and Orthotics at the University Clinical Center of Kosovo.

CONCLUSIONS

1. A higher level of amputation is associated with less energy-efficient walking and with lower walking speed. Even though prosthetic ambulation supported with crutches has a significant impact on increasing energy expenditure and decreasing walking speed, prescribing crutches seems to be better for the purpose of extra stability or security if needed by some amputees due to various pathological conditions.
2. These findings suggest that proper gait training with both assistive devices and a prosthesis should have been provided to amputees to quantify the exact energy expenditure, as different gait patterns may alter energy expenditures. Further research to investigate the relationships among prosthetic walking speed, energy cost, use of walking aids and specific training would be of major interest.

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