Transfemoral Amputations: Is There an Effect of Residual Limb Length and Orientation on Energy Expenditure?

Johanna C. Bell MSE, Erik J. Wolf PhD,
Barri L. Schnall MPT, John E. Tis MD,
Benjamin K. Potter MD

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Abstract

Background Energy cost of ambulation has been evaluated using a variety of measures. With aberrant motions resulting from compensatory strategies, persons with transfemoral amputations generally exhibit a larger center of mass excursion and an increased energy cost. However, few studies have analyzed the effect of residual femur length and orientation on energy cost of ambulation.

Questions/purposes The purpose of this study was to compare residual limb length and orientation with energy

efficiency in patients with transfemoral amputation. We hypothesized that patients with shorter residual limbs and/or more abnormal residual femur alignment would have higher energy expenditure cost and greater center of mass movement than those with longer residual limbs resulting from lacking musculature, shorter and/or misoriented lever arms, and greater effort required to ambulate through use of compensatory movements.

Methods Twenty-six adults with acute, trauma-related unilateral transfemoral amputations underwent gait and metabolic analysis testing. Patients were separated into groups for analysis based on residual limb length and residual femoral angle.

Results Cohorts with longer residual limbs walked faster than those with shorter residual limbs (self-selected walking velocity 1.28 m/s versus 1.11 m/s, measured effect size = 1.08; 95% confidence interval = short 1.10–1.12, long 1.26–1.30; $p = 0.04$). However, there were no differences found with the numbers available between the compared cohorts regardless of limb length or orientation in regard to O_2 cost or other metabolic variables, including the center of mass motion.

Conclusions Those with longer residual limbs after transfemoral amputation chose a faster self-selected walking velocity, mirroring previous studies; however, metabolic energy and center of mass metrics did not demonstrate a difference in determining whether energy expenditure is affected by length or orientation of the residual limb after transfemoral amputation. These factors may therefore have less effect on transfemoral amputee gait efficiency and energy requirements than previously thought.

Level of Evidence Level II, prognostic study. See the Guidelines for Authors for a complete description of levels of evidence.

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J. C. Bell, E. J. Wolf, B. L. Schnall, B. K. Potter
Center for Performance & Clinical Research, Walter Reed
National Military Medical Center, Bethesda, MD, USA

J. E. Tis
Department of Orthopaedic Surgery, Johns Hopkins, Baltimore,
MD, USA

J. C. Bell (✉)
1400 Spring Garden Street, Apartment 807, Philadelphia, PA
19130, USA
e-mail: johannacbell@gmail.com

Introduction

Energy cost of ambulation has been evaluated using a variety of measures, including metabolic cost, mechanical work, and energy [8, 12, 14, 16, 32, 49–51]. In terms of mechanical energy, gait has been modeled as an inverted pendulum [9, 13, 39, 48] sometimes characterized as displacement of the body's center of mass [10, 13, 48, 49]. The center of mass progresses both vertically and laterally over the supporting leg in a smooth sinusoidal motion as a means of conserving energy during gait, continuously transferring potential and kinetic energy [9, 12, 13, 39, 46, 48]. Abnormal gait generally lacks a smooth, symmetric gait pattern, sometimes causing an increase in the vertical and lateral displacement of the center of mass resulting in increased energy demand [5, 19–21, 39, 43, 46]. With aberrant motions resulting from compensatory strategies, persons with transfemoral amputations generally exhibit a larger center of mass excursion and an increased energy cost [43].

Surgical treatment of the remaining musculature, resulting orientation of the femur, residual limb length, and eventual prosthesis fit all affect the muscular balance and resulting motor control capabilities in the residual limb of transfemoral amputation and, subsequently, gait [5, 19, 20, 26, 42]. These factors influence independent, functional mobility after amputation and have been investigated using energy expenditure, gait analysis, and other functional outcome measures to quantify functional mobility postamputation [2, 22, 27, 31]. Furthermore, they have been the focus of several studies in reference to the level of transection of the residual limb [2, 22, 27, 31]. Although these studies evaluated mobility in terms of gait, there is a paucity of literature related to the effect of residual femur length and orientation or energy cost of ambulation [22, 27].

Although the relationship between energy expenditure and the level of amputation has been explored previously, comparisons with regard to residual limb length or orientation within a single level are lacking [14, 17, 25, 37, 40, 44, 46, 47]. When compared with more distal amputations allowing for retention of vital musculature and joints such as in knee disarticulation or transtibial amputation, transfemoral amputation typically resulted in higher energy cost [14, 17, 37, 40, 46, 47].

The purpose of this study was to compare residual limb length and orientation in patients with transfemoral amputation with energy efficiency. Based on the existing literature, we hypothesized that patients with shorter residual limbs and/or more abnormal residual alignment would have higher energy expenditure cost than those with longer residual limbs resulting from lacking musculature, shorter and/or misoriented lever arms, and effort to move

the limb through use of compensatory movements, which will increase inefficient movement of the center of mass of the body.

Patients and Methods

The study was approved by the Institutional Review Board at Walter Reed National Military Medical Center. Twenty-six military personnel, older than 18 years of age, with acute, trauma-related unilateral transfemoral amputations who were admitted to our facility from the beginning of Operation Enduring Freedom in October 2001 until September 2010 participated in this study. Patients with a severe contralateral lower extremity injury or amputation, major proximal ipsilateral injury, severe spinopelvic trauma, or traumatic brain injuries were excluded.

Informed consent was given by each subject before participation. Subjects underwent gait and metabolic analysis testing at a minimum of 24 months postoperatively in their current preferred prosthesis. Twenty-four months was selected as a reasonable time point by which these patients would have become medically stable, they had received their definitive socket, residual limb volume had stabilized, they had resumed daily activities, their intensive rehabilitation phase had ended, and major medical issues had been addressed or resolved. Twenty of 26 of the subjects wore the original microprocessor-controlled C-Leg (Otto Bock, Duderstadt, Germany) or the newer model of the C-Leg referred to as the Second Generation. The remainder of the subjects wore either a microprocessor knee similar to the C-Leg (fluid, hydraulic, Endolite Mercury; Endolite Miamisburg, OH, USA; Otto Bock Power Knee) or a hydraulic unit (fluid, mechanical, Otto Bock 3R80 or the Össur Total Knee; Össur, Foothill Ranch, CA, USA).

Demographic information was collected for all subjects, including age (32.0 ± 6.1 years), height (177 ± 7.8 cm), and weight (84.5 ± 13.6 kg). The subjects were separated into groups for analysis based on either their residual limb length or their residual femoral angle (residual femoral shaft axis angle). For the residual femoral length analysis, the subjects were separated into two groups based on residual limb ratio as defined by Baum et al. [2]: residual limb length divided by intact limb length. Based on established literature of optimal residual limb length postamputation [6, 19, 20, 33, 35], the separation of the subjects into groups was at two-thirds of the intact femoral length with a variability of 10%. Based on this range, the group with shorter residual limbs ($n = 10$) was 20% to 56% and the group with longer residual limbs ($n = 16$) was 57% to 86% of the intact limb length with all subjects except one with a residual limb ratio of 57%:77% (Table 1).

The residual femoral shaft axis angle defined the separation for femoral abduction angle groups with 0° as the separation point. A measured angle of less than zero resulting in a classification of abduction placed subjects in the femoral abduction cohort ($n = 16$) and if they were greater than zero (adduction), they were placed in the femoral adduction cohort ($n = 8$). The appearance of lateral femoral axis drift or an overt abduction contracture can infer that the adductor magnus was not adequately fixed [26] or, as is often the case after blast injuries and proximal transfemoral amputations, not present. The methods for measuring residual limb length and orientation as well as the gait analysis method are detailed in a previous publication [3].

All subjects were evaluated with both gait and metabolic analysis. The metabolic testing (COSMED[®] K4b² metabolic analysis system; COSMED, Rome, Italy) consisted of a 5-minute reclined rest followed by a 10-minute self-selected pace walk around a 65-m athletic track and completed with a 5-minute reclined rest, all while a heart rate monitor and metabolic collection mask were donned. Oxygen consumption ($\text{mL} \cdot \text{O}_2 \cdot \text{kg}^{-1}$) and heart rate (beats/minute) were collected. Velocity was calculated using the known distance of the athletic track used during the metabolic testing. Both the metabolic and gait collections were performed the same day. To derive the overall center of mass of the body in the lateral (CoMx) and vertical (COMz) directions, gait analysis was used to determine the mass center of each segment. Data were reduced and data points were exported using Visual 3D (C-Motion Inc, Germantown, MD, USA).

For oxygen consumption and heart rate, 2 minutes of data were averaged once they had achieved steady state; the data collected were body weight-normalized. Metabolic energy was calculated three ways. From oxygen consumption, the power requirement for walking (O_2 rate, $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) was determined as a result of normalizing by body weight, which included the weight of their prosthetic limb. Physiological work of walking (O_2 cost, $\text{mL} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) was calculated from oxygen consumed (normalized to body weight) per unit of distance walked.

Statistical analysis was performed on the results using SPSS 15.0 (SPSS Inc, Chicago, IL, USA). An independent samples t-test with significance set at a two-tailed $\alpha < 0.05$ was used. A bivariate Pearson correlation was then conducted to determine if there were any linear correlations of the gait variables in response to the residual femoral length, the femoral shaft axis angle, or knee component. The strength of the Pearson correlation was graded as defined by Portney and Watkins as: $r < 0.25$ has little to no relationship, $0.25 < r < 0.5$ indicates fair correlation, $0.5 < r < 0.75$ suggests a moderate to good correlation, and values of $r > 0.75$ are good to excellent [38].

Table 1. Femoral length and residual limb ratio

Patient number	RL group	Femoral length (cm)		RL ratio	FA group	FA angle (degrees)*	
		Residual limb	Intact limb			Residual	Intact
1	L	32.5	46.3	0.70	AD	3.50	6.43
2	L	35.9	46.7	0.77	AD	4.67	11.96
3	L	40.4	47.3	0.85	AB	-3.40	3.60
4	L	34	46.5	0.73	AB	-7.08	7.06
5	L	30.3	52.1	0.58	AB	-1.21	9.41
6	L	29.5	44.8	0.66	AB	-4.33	6.37
7	S	16.8	46.4	0.36	AB	-18.11	6.38
8	S	20.7	45.6	0.45	AB	-2.23	5.92
9	S	9.6	46.6	0.21	AB	-19.43	1.67
10	S	18.1	47.1	0.38	AB	-24.04	7.39
11	S	16.4	45.5	0.36	AB	-9.69	9.03
12	L	27.3	46.9	0.58	AD	1.17	6.31
13	L	34.7	52.8	0.66	AD	9.39	8.08
14	L	34.1	47.2	0.72	AD	4.38	1.50
15	S	27.4	49.1	0.56	AD	1.23	6.42
16	L	31.3	47	0.67	AB	-3.76	3.31
17	S	14.6	42.5	0.34	-	-	-
18	L	39	53	0.74	-	-	-
19	S	26	49.3	0.53	AD	6.60	7.85
20	L	36.9	51.8	0.71	AD	5.29	1.75
21	S	14.9	51	0.29	AB	-10.94	4.84
22	L	30.9	43.1	0.72	AB	-7.02	6.05
23	L	30.4	48.1	0.63	AB	-4.49	4.04
24	L	28.7	49	0.59	AB	-4.65	4.06
25	S	24.2	48.2	0.50	AB	-6.00	2.71
26	L	30.2	44.8	0.67	AB	-3.22	7.22
All	S, L	27.49 (8.3)	47.64 (2.8)	0.58 (0.17)	AB, AD	-3.89 (8.3)	5.81 (2.6)
Group	S	18.87 (5.6)	47.13 (2.4)	0.40 (0.11)	AB	-8.1 (6.8)	5.56 (2.2)
Group	L	32.88 (3.8)	47.96 (3.0)	0.69 (0.07)	AD	4.53 (2.7)	6.29 (3.4)

Last three rows are averages (SDs) of corresponding measurements; * a negative number signifies abduction; - indicates missing data; RL = residual limb; FA = femoral abduction; L = long; S = short; AD = adduction; AB = abduction.

Results

The cohort with longer residual limbs walked 0.17 m/s faster (effect size = 1.08 with an achieved power of .83, short limb 95% confidence interval [CI] 1.10–1.12, long limb 95% CI 1.26–1.30; $p = 0.037$) in terms of self-selected walking velocity between the residual limb ratio groups. With the numbers available, we detected no other differences in the other metabolic cost parameters between the short and long residual limb length cohorts (Table 2) or the femoral abduction angle cohorts (Table 3). There was a fair correlation between speed and the excursion of the

Table 2. Variable means (SDs) for RL ratio groups

Parameter	Group		p value	Correlation with RL ratio R [†]
	RL _S	RL _L		
Velocity (m/s)*	1.11 (0.1)	1.28 (0.2)	0.04	0.30
Heart rate at rest (beats/min)	73.0 (13.9)	75.0 (10.0)	0.70	0.28
Heart rate during exercise (beats/min)	127.0 (17.6)	123.6 (22.5)	0.70	-0.05
VO ₂ at rest (mL/VO ₂ /kg/min)	3.0 (0.4)	3.3 (0.7)	0.35	0.25
O ₂ at rate (mL/VO ₂ /kg/min)	17.3 (5.0)	17.3 (2.7)	0.97	0.02
O ₂ cost (mL/VO ₂ /kg/m)	0.25 (0.07)	0.23 (0.04)	0.38	-0.08
Functional energy	5.7 (1.29)	5.41 (1.07)	0.57	-0.18
COM _x excursion (cm)	4.82 (0.9)	4.11 (1.5)	0.20	-0.13
COM _z excursion (cm)	5.58 (1.2)	5.03 (1.5)	0.35	-0.09

* Significance $p < 0.05$ between group means; [†]Pearson correlation with RL ratio; RL = residual limb; _S = short; _L = long; VO₂ = oxygen consumption; COM = center of mass; _x = lateral direction; _z = vertical direction.

body center of mass in the mediolateral direction ($r = -0.471$, $p = 0.02$). There were no differences found with the numbers available when comparing types of prosthetic knee component.

Discussion

It is well known that lower limb amputation will have an impact on energy and gait. As formerly discussed, many factors influence independent, functional mobility after amputation and have been previously investigated using a variety of measures. However, the exploration of the relationship between energy expenditure and the level of transfemoral amputation or orientation is lacking. Our hypothesis that metabolic parameters and overall energy expenditure among transfemoral amputees would differ based on residual femoral length and orientation resulting from lack of musculature and subsequent stabilization in the shorter residual limbs was not supported by the data in the present study.

The present study has several limitations and is subject to potential confounding factors. One limitation of this study is the small cohort of subjects within each group. A

Table 3. Variable means (SDs) for FA angle groups

Parameter	Group		p value	Correlation with FA angle R [†]
	AB (1)	AD (2)		
Velocity (m/s)*	1.19 (0.2)	1.29 (0.2)	0.29	0.23
Heart rate at rest (beats/min)	72.9 (10.6)	77.0 (14.3)	0.46	0.17
Heart rate during exercise (beats/min)	127.1 (19.0)	120.4 (25.4)	0.50	-0.15
VO ₂ at rest (mL/VO ₂ /kg/min)	3.4 (0.6)	2.9 (0.4)	0.08	-0.40
O ₂ rate (mL/VO ₂ /kg/min)	17.4 (4.2)	17.3 (2.4)	0.95	-0.01
O ₂ cost (mL/VO ₂ /kg/m)	0.24 (0.06)	0.23 (0.04)	0.72	-0.15
Functional energy	5.2 (1.18)	6.04 (0.94)	0.12	0.13
COM _x excursion (cm)	4.37 (1.4)	4.39 (1.4)	0.98	0.01
COM _z excursion (cm)	5.06 (1.5)	5.28 (1.0)	0.72	0.08

* Significance $p < 0.05$ between group means; [†]Pearson correlation with residual limb ratio; FA = femoral abduction; AB = abduction; AD = adduction; VO₂ = oxygen consumption; COM = center of mass; _x = lateral direction; _z = vertical direction.

post hoc power analysis revealed that for 26 participants, the required effect size for detecting differences between groups would be 1 and for requirement for a significant Pearson correlation would be 0.47. Although most of our reported findings do not meet these criteria, these data are still clinically relevant because almost no differences were seen between groups. Beyond the need for more subjects to be tested, there may also be some relationships within the existing data that could increase our power. For example, the relationship between residual limb length and some of the metabolic variables may not be linear as assumed. Additionally, the cutoff selected for separating the groups could be altered. These are both areas that could be explored further with additional research.

Although the knee component was not controlled for, no differences were found with the numbers available between the different knee components. A review of the literature found mixed results in metabolic cost between different knee components; however, the variety of components, comfort/confidence in each knee unit, and health of the individuals tested could explain some of the observed differences. Several studies failed to find differences in energy cost between the different prostheses; however, there was no consensus about whether the energy reduction from one knee component to another was clinically important or whether energy cost is an appropriate measure

to determine a difference [4, 29, 41]. Additionally, the weight, knee center, and weight distribution of the prosthesis were not factored into the energy cost of the individuals; the weight of the prosthesis may or may not have had an impact on the metabolic efficiency at a self-selected pace [7, 11, 15, 24, 30]. In this study, the mass of the subjects included the mass of the prosthesis, which may not have accurately represented the work being performed. Although these are factors to consider in reviewing the results of this study, the components worn by the subjects were not substantially different from one another in either weight or functional capabilities.

Patients with longer residual limbs self-selected faster walking speeds, whereas the remainder of the metabolic variables failed to show differences for either the residual limb length or femoral abduction angle analyses. Some prior work has suggested that loss of the knee and subsequent muscular imbalance resulting in abduction of the femur results in greater energy cost [5, 19–21]; however, in our study, there was no difference within this subject population of transfemoral amputations. With shorter residual limbs there is thought to be a loss of anatomy that allows for muscular balance [28], but in the case of these subjects, treatment of the musculature (ie, myodesis) may have impacted the outcome. Although all subjects with transfemoral amputations in this study exhibited a higher metabolic cost when compared with asymptomatic populations (speed = 1.36–1.45 m/s, O_2 rate = 12–13 mL $\cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, O_2 cost = 0.15 mL $\cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) [45, 47], their O_2 cost was similar to other traumatic transfemoral amputation populations and there was no difference found between the compared cohorts regardless of limb length or orientation. Comparatively, another study chose to examine the cost of energy expenditure in relation to transection level (in all levels of lower limb amputation) determining that those with shorter residual limbs did exhibit a slower self-selected walk, but the measures of heart rate and oxygen consumption did not show a difference at a comfortable walking speed [46]. Based on this and our own results, one may conclude that energy expenditure for persons with transfemoral amputations is not dependent on the residual limb length regardless of pace, possibly as a result of the choice of self-selected walking velocity, which has been shown in the literature to be the most energy-efficient walking velocity [12, 34, 46, 47]. Most often the literature did not directly compare varying transfemoral amputation levels, but instead included transtibial amputations as well as hip and knee disarticulations. Although knee disarticulations still require a prosthetic knee, they were not included in our study. The literature displayed more favorable results for knee disarticulation in a variety of measures, including better surgical outcomes, increased walking speed, and either similar or reduced energy cost [5,

23, 36, 37, 46, 47]. Some of these results were potentially influenced by age and cardiovascular fitness of dysvascular subjects in these studies [5, 23, 36, 37, 46, 47]. Although metabolic expenditure may capture some energy exchange, the mechanical energy of the system may not be accounted for. While walking, the human form experiences both internal and external work in a variety of exchanges making capture of energy expenditure challenging [10, 13, 49]. Internal work has been defined as movement of the individual body segments and musculature within the system in relation to the center of mass of the entire body [48]. The energy expended in displacement of the center of mass has been used as a determinant in many methods of energy expenditure derivation representing external work [1, 48]. Some authors strenuously oppose this methodology stating that the center of mass displacement underrepresents the kinetic energy changes resulting from reciprocal, symmetrical movements of the limbs found in gait [18, 49]. However, if this method is compared both with the external and internal work being performed, the reciprocal work will be included in this system [48].

Center of mass displacement is not a measure of the entire machine of energy expenditure; however, the comparison of center of mass motion can still lend insight into a difference in energy cost. The methods used in this study summed the center of mass of each segment to determine a gross center of mass for the entire body and the displacement of that gross center of mass was described here. Because vertical center of mass movement has been shown to be dependent on speed [12], the slower speed of the cohorts with short residual limbs could indicate higher energy consumption; however, the optimum gait speed will result in a minimum energy cost [12], which may explain the lack of difference in center of mass excursion revealed between the different residual limb and femoral adduction cohorts, respectively.

In determining whether energy expenditure is affected by length or orientation of the residual limb after transfemoral amputation, the metabolic energy, speed, and center of mass metrics did not demonstrate a difference between the abduction and adduction angle groups; however, self-selected walking velocity was slower in short than in longer residual limb groups, mirroring previous studies [23, 37, 46, 47]. Because self-selected walking velocity is determined by the walker and is the most energy-efficient, perhaps a longer residual limb should not necessarily be the end goal clinically. Further exploration should include a larger population of those with transfemoral amputations exhibiting varying lengths of residual limbs to include knee disarticulations. This would allow for more detailed analysis of energy measures as well as a more detailed look into whether the knee center has any impact on these measures.

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