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ORIGINAL RESEARCH

Assessment of Energy expenditure among different levels of Amputees using various Prosthetic components

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Abstract

Background: Lower-limb amputation significantly alters human gait and increases the physiological cost of ambulation, yet empirical evidence on energy expenditure among prosthetic users in Nigeria remains limited. This study assessed energy expenditure among amputees, with an emphasis on level of amputation, prosthesis components, and age.

Method: A cross-sectional comparative study. Sixty lower-limb amputees using prostheses participated in the study. Energy expenditure during ambulation was measured and analysed using independent-samples t-tests and Pearson product–moment correlation at the 0.05 significance level. Comparisons were made between above-knee and below-knee amputees, users of basic and advanced above-knee prostheses, and younger and older adult above-knee amputees.

Result: Above-knee amputees demonstrated substantially higher energy expenditure than below-knee amputees ($p = 0.05$). Users of advanced above-knee prosthetic devices expended significantly less energy than users of basic above-knee prosthetic devices. ($p < 0.05$). Age did not significantly influence energy expenditure among above-knee amputees ($p > 0.05$).

Conclusion: Energy expenditure among lower-limb amputees is primarily influenced by amputation level and prosthesis components. Age had no significant effect on the energy expenditure among lower-limb amputees. The importance of individualised prosthetic prescription, prolonged rehabilitation, and energy-focused gait training to optimise functional outcomes were highlighted. The study provides context-specific evidence to guide prosthetic rehabilitation practice and policy development in Nigeria and similar low-resource settings.

Keywords: Above-knee amputation, Energy expenditure, Lower-limb amputation, Prosthetic gait, Rehabilitation

Introduction

Individuals with lower limb amputations face significant challenges in their rehabilitation due to excessive energy consumption associated with prosthetic use, leading to reduced mobility, decreased functional independence, and compromised quality of life. Amputees are known to expend more energy during walking than able-bodied individuals. [1,2] Lower-limb prosthetic users (LLPUs), including those with trans-femoral or trans-tibial amputations, commonly experience reduced functional capacity in daily activities. [1,3] Their gait is characterised by altered spatiotemporal, kinematic, and kinetic movement patterns. Walking efficiency is compromised by a protective and unstable gait strategy, typically involving increased step width and prolonged stance time on the non-involved limb. Consequently, the metabolic cost of walking in lower-limb prosthetic users is greater than that of individuals without an amputation. [4,5]

Abnormal movement patterns characteristic of amputees' gait are thought to disrupt the smooth, pendulum-like motion of the body's centre of mass, thereby increasing the mechanical work required with each step. It has been widely assumed that more proximal levels of amputation are associated with greater energy expenditure during walking. However, this assumption remains contentious in the literature. [6]

Alterations in lower-limb mechanics, sensory feedback, and power generation resulting from limb loss substantially influence gait biomechanics and energetic demands in individuals with amputations. During unimpaired level walking, the ankle contributes considerable net positive power across the gait cycle, while other locomotor activities, such as uphill walking, require additional net positive power generation at the knee. [5,6]

Individuals with limb amputation generally expend more energy during walking because prosthetic limbs are mechanically less efficient and often result in an asymmetrical gait pattern. Waters and Mulroy reported that persons with unilateral trans-femoral amputation used approximately 60% more energy during ambulation than able-bodied individuals, whereas those with trans-tibial amputation demonstrated an increase in energy expenditure of about 20–30%. These

findings underscore the increased physical demands placed on prosthetic users.[3]

Similarly, Gailey et al.[5] observed that, at self-selected walking speeds, trans-tibial amputees exhibited a 16% higher metabolic cost (VO_2) and heart rate, alongside an 11% slower walking speed, compared to non-amputee controls. [5] Several studies have also investigated the influence of assistive devices on energy efficiency across different crutch gait patterns.

Rehabilitation is crucial in mitigating the increased energy demands associated with prosthetic gait. Physical therapy interventions are designed to strengthen residual limb musculature, enhance balance, and improve gait mechanics, all of which contribute to lowering the energy cost of walking. Evidence suggests that early and intensive rehabilitation facilitates adaptation to prosthetic use, leading to improved walking efficiency and reduced energy expenditure. [2,7,8] Technological advancements in prosthetic design have also contributed to improving energy efficiency during ambulation. Contemporary prostheses frequently incorporate energy-storing and -returning (ESAR) feet, which capture mechanical energy during the stance phase and release it during push-off, thereby reducing the metabolic cost of walking. Brian et al reported that ESAR feet enabled amputees to achieve faster walking speeds with lower energy expenditure than with conventional solid-ankle cushioned-heel (SACH) feet. [9] Similarly, microprocessor-controlled prosthetic knees, such as the C-Leg and Rheo Knee, have demonstrated substantial benefits in reducing energy demands. These devices dynamically adjust resistance and enhance stability during gait, promoting smoother phase transitions and minimising compensatory movements. Kenton's work indicates that users of microprocessor-controlled knees experience lower energy expenditure, particularly when navigating uneven surfaces or walking at varying speeds. [10] Despite these advancements, accurately assessing energy consumption among users of lower-limb prostheses remains challenging. Conventional approaches, including oxygen consumption testing, require specialised equipment and may not adequately represent functional performance in daily living environments. Moreover, energy expenditure is influenced by multiple factors, such as prosthetic alignment, individual physical

conditioning, and the nature of rehabilitation programmes.

Wearable technologies have recently emerged as valuable tools for monitoring energy consumption under real-life conditions. Devices such as accelerometers and inertial measurement units (IMUs) offer detailed information on prosthetic gait biomechanics and help identify opportunities to improve energy efficiency. [11] Nonetheless, additional research is necessary to refine these technologies and establish standardised assessment protocols for prosthetic users. [12]

The increased energy requirements of prosthetic ambulation may also lead to psychological and social consequences. Individuals who experience excessive fatigue during walking may become discouraged, which can reduce participation in rehabilitation and social engagement. [12,13] Furthermore, perceived difficulty in ambulation can undermine confidence and limit involvement in activities that demand sustained physical exertion.

Addressing psychological challenges is an essential component of comprehensive rehabilitation. Educating patients about realistic expectations regarding fatigue and energy demands, alongside teaching coping strategies, can enhance their engagement in rehabilitation. In addition, ongoing support from healthcare providers and peer support groups can help sustain motivation and encourage long-term adherence to rehabilitation objectives. [13]

The study focuses on understanding energy consumption in lower-limb prosthetic use, its relationship with rehabilitation outcomes, strategies and prosthetic innovations for reducing energy demands, and implications for clinical practice and future research. The objectives were to assess the energy expenditure among amputees and the influence of level of amputation, type and components of prosthesis, and age on energy expenditure.

Methods

Research Design: This study adopted a cross-sectional descriptive research design, enabling data to be collected at a single point in time. This design is suitable as it provides a clear snapshot of energy expenditure levels and related factors among lower limb prosthetic users in Enugu State. Both quantitative and qualitative approaches were employed to generate comprehensive insights into the energy expenditure patterns of prosthetic users.

Study Population: The study population comprised lower-limb prosthetic users residing in Enugu State, Nigeria, who were willing to participate in the study. Eligible participants included individuals with trans-femoral (above-knee) or trans-tibial (below-knee) amputations who had used a prosthetic limb for a minimum of six months. Participants must be able to ambulate independently, with or without assistive devices such as crutches or walking sticks, as the study focuses on energy expenditure during walking.

Inclusion Criteria: Adults aged 18 years and above with a trans-femoral or trans-tibial amputation were included. The amputee must have used a prosthetic limb for at least six months. Prosthetic users should have the ability to walk independently, with or without assistive devices. *Exclusion Criteria:* Amputees with congenital limb deficiencies, those with bilateral lower limb amputations (due to the added complexity of bilateral prosthetic use) and severe co-morbid conditions (like cardiovascular or neurological disorders) that could significantly affect mobility or energy expenditure were excluded.

Sample Size: A total of 60 lower limb prosthetic users were recruited for the study. This sample size was determined based on the estimated population of prosthetic users in Enugu State [7] and an acceptable margin of error of ±10%. Participants were proportionally allocated across categories such as level of amputation (trans-tibial or trans-femoral) and type of prosthetic device (basic or advanced).

Sampling Technique: A stratified random sampling method was used to ensure adequate representation of both trans-femoral and trans-tibial amputees. Stratification was based on the level of amputation and the type of prosthetic device used. Participants within each stratum were randomly selected to ensure that the sample reflects the distribution of lower limb prosthetic users in Enugu State.

Data Collection Methods

Energy expenditure measurement: Energy expenditure was assessed using indirect calorimetry with a portable metabolic system, such as the K4b2 Metabolic System. This device measures oxygen consumption (VO_2) and carbon dioxide production (VCO_2) during physical activity. The measurements provided data on resting metabolic rate (RMR) and net energy expenditure during walking.

Procedure: Participants walked at a self-selected pace on a treadmill or in an open walking space if a treadmill was unavailable,

for 10–15 minutes. VO_2 and VCO_2 were recorded continuously throughout the walking session. Energy expenditure (EE) was calculated using the formula:

$EE = VO_2 \times 5$ kcal/min

*Gait Analysis***:** Gait analysis was performed using motion capture systems such as Qualisys or Vicon to evaluate walking patterns and their influence on energy expenditure. Parameters assessed include: Stride length, Cadence (steps per minute), Gait speed and joint kinematics (hip, knee, and ankle angles during walking). These data helped to determine walking efficiency and its relationship with energy expenditure, as well as allow comparisons between users of basic and advanced prosthetic devices.

Questionnaire and Interview: A structured questionnaire was administered to obtain demographic and clinical information, including: Age, sex, level of amputation, and duration of prosthesis use, Type of prosthetic device (basic or advanced), Physical activity level, assessed using the International Physical Activity Questionnaire (IPAQ), General health status and presence of co-morbid conditions such as diabetes or hypertension. Additionally, semi-structured interviews were conducted to collect qualitative data on participants' lived experiences with prosthetic use, perceived challenges, and subjective perceptions of energy expenditure during ambulation.

*Ethical Considerations***:** Ethical approval was obtained from the Ethics Committee of School Health Technology, Federal University of Technology, Owerri, Imo State, with the approval number "SOHT/POT/2025/009," and the study followed established ethical standards. Participants provided written informed consent after receiving full information about the study; their confidentiality was ensured through anonymised and securely stored data; participation was voluntary with the right to withdraw at any time; and procedures were designed to minimise harm and discomfort

Data Analysis

*Quantitative data analysis***:** The study used descriptive statistics (means, standard deviations, and ranges) to summarise energy expenditure data. Independent t-tests or analysis of variance (ANOVA) were applied to compare energy expenditure across groups (e.g., basic vs. advanced prostheses; trans-femoral vs trans-tibial amputees), and multiple regression analysis was conducted to identify factors influencing energy expenditure,

including prosthesis type, level of amputation, and physical fitness.

Qualitative Data Analysis: Interview transcripts were analysed using thematic analysis to identify recurring themes related to mobility, energy expenditure, and prosthetic use. NVivo software was utilised to facilitate systematic organisation and analysis of qualitative data.

Results

Males (60%) constituted a larger proportion of amputees than females (40%); 51.7% of respondents had below-knee (BK) amputations, while 48.3% had above-knee (AK) amputations. Figure 1 presents the distribution of prosthetic types used by respondents. The majority of the amputees used basic prosthetic devices; 89% of above-knee amputees and 76% of below-knee amputees used basic prosthetic devices, respectively

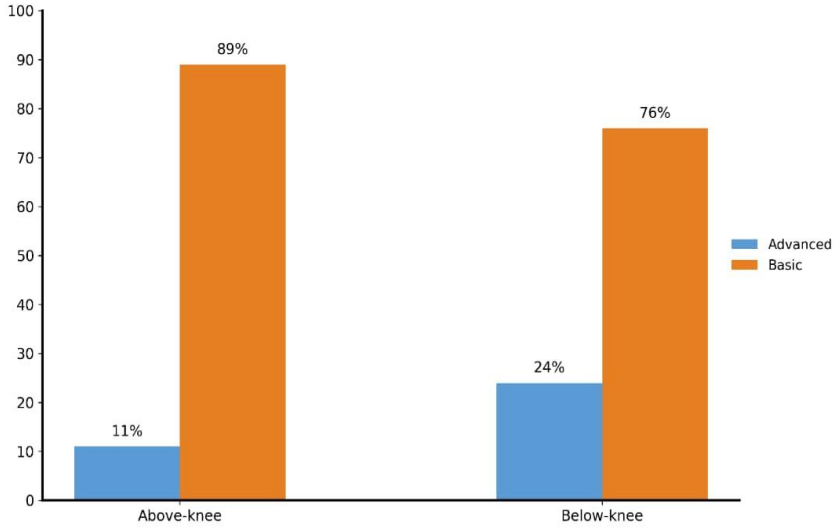

Figure 1. Types of prostheses used by the amputees

In Table I; from Ia, the independent-samples t-test showed a statistically significant difference in energy consumption between amputees with above-knee (AK) and those with below-knee (BK) prostheses, t(45.47) = 4.02, p =0.000. The mean energy expenditure for AK amputees (M = 32.85 kcal, SD = 3.34) was higher than that of BK amputees (M = 29.78 kcal, SD = 2.34).

Ib shows the descriptive statistics, which indicate that users of advanced prostheses (N = 6) recorded a mean energy consumption of 26.33 with a standard deviation of 3.20. Users of basic prostheses (N = 22) recorded a higher

mean energy consumption of 34.73 with a standard deviation of 3.07. The Levene's test for equality of variances produced a significance value of 0.914, which is greater than the 0.05 threshold, utilizing the t-test results.

Table I: Energy expenditure of different categories of amputees

Component	Group	N	M	SD	SE	T	df	p	Mean diff.	SE diff.	95% CL
Ia	AK	27	32.85	3.34	0.64	4.02	46.47	0.000	3.07	0.76	1.533
	BK	32	29.78	2.34	0.41						
Ib	AK	6	26.33	3.20	1.31	5.88	26	0.000	8.39	1.44	5.46
	BK	22	34.73	3.07	0.66						
Ic	AK	23	33.39	3.14	0.65	0.49	26	0.62	0.79	1.60	4.10
	BK	5	32.60	3.85							
Id	AK	16	34.50	1.33	0.46	1.02	18	0.320	1.00	0.98	3.05
	BK	4	33.50	1.29	0.65						

Ia: Difference in energy consumption between above-knee and below-knee prosthesis users

Ib: Difference in energy consumption between advanced and basic above-knee prosthesis users.

Ic: Difference in energy Consumption among Above-Knee (AK) prosthesis users – Older vs younger adults (Advanced Prostheses)

Id: Difference in energy consumption between younger and older amputees with AK prostheses (basic)

The t-test result showed a statistically significant difference in energy consumption between the two groups (above-knee and below-knee amputees), $t(26) = 5.737$, $p < 0.001$. The mean difference between the two groups was 8.39, with a standard error of 1.46. The 95% confidence interval of the difference ranged from 4.99 to 11.79.

Ic shows that the result of the independent-samples t-test, which tested whether there is any difference in energy consumption between younger (≤ 37 years) and older adults (≥ 38 years) with AK prostheses, revealed no significant difference in energy consumption between older and younger amputees using AK prostheses ($t_{26} = 5.23$, $p > 0.05$).

Discussion

The predominance of younger adults (71.7%) aged (18- 37 years) among the amputees may be attributed to their greater exposure to occupational risks associated with the nature of their jobs. This finding suggests that amputation disproportionately affects individuals within the economically active population. Similarly, Osuji et al. [14] reported that younger adults may be particularly vulnerable to amputation due to occupational hazards and road-traffic accidents, especially in developing regions. Regarding amputation level, 51.7% of respondents had below-knee (BK) amputations, while 48.3% had above-knee (AK) amputations. This relatively balanced distribution is consistent with Gailey et al.[5], who reported that below-knee amputations are generally slightly more prevalent, particularly when knee joint preservation is possible. Preservation of the knee joint is clinically advantageous because it facilitates more efficient gait and is associated with lower metabolic energy expenditure compared with above-knee amputation [2,3].

The independent-samples t-test showed a statistically significant difference in energy consumption between amputees with above-knee (AK) and those with below-knee (BK) prostheses, $t(45.47) = 4.02$, $p < .05$. The mean energy expenditure for AK amputees ($M = 32.85$ kcal, $SD = 3.34$) was higher than that of BK amputees ($M = 29.78$ kcal, $SD = 2.34$). The mean difference of 3.07 kcal suggests that ambulation with an AK prosthesis requires substantially greater metabolic effort than ambulation with a BK prosthesis. This outcome confirms that amputation level significantly affects the physiological cost of walking. The higher energy demand among AK amputees is primarily due to the loss of the knee joint, which plays a key role in gait propulsion and stability. Without an anatomical knee, prosthetic users rely heavily on hip extensors and flexors to advance the limb and stabilise the body during stance and swing phases [5]. This compensatory mechanism increases oxygen consumption, heart rate, and muscular workload, thereby raising total energy expenditure.

Several studies corroborate this finding. Water et al. [3] reported that AK amputees expend about 25–35% more energy than BK users at comparable walking speeds [3]. Gailey et al. [5] further explained that the absence of the knee joint disrupts biomechanical symmetry,

forcing the intact limb to bear more weight, which elevates the metabolic cost of gait [5]. Sanders & Fatone [1]–also observed that BK prostheses generally facilitate more natural limb mechanics, leading to smoother gait transitions and reduced oxygen uptake. In addition, the energy difference observed in this study (3.07 kcal) corresponds with previous experimental estimates of approximately 10–15% greater energy cost for AK users reported by Morgenroth et al. [18] This implies that even minor anatomical losses above the knee substantially influence locomotor efficiency. The findings thus validate the second hypothesis, which proposed that AK amputees would exhibit significantly higher energy expenditure than BK amputees.

A larger proportion of amputees use basic prostheses, while fewer have access to advanced devices due to cost and availability constraints in developing settings. Basic prostheses are affordable but less efficient, lacking features that enhance energy transfer during walking. In contrast, advanced prostheses improve gait symmetry, stability, and safety. The findings indicate that above-knee amputees using advanced devices expend less metabolic energy during walking, likely due to better biomechanical efficiency and improved joint function. This supports previous research showing that less sophisticated prostheses are associated with higher energy expenditure.[16,17]

However, while the basic prosthetic devices enhance mobility, they often provide less efficient energy transfer and poorer shock absorption, which increases the metabolic cost of walking [1]. Advanced prostheses, in contrast, integrate microprocessor knees or energy-storing feet that improve symmetry and gait smoothness, though they initially demand higher muscular effort and user adaptation [18]. The relatively low uptake of such advanced devices in this study highlights the need for improved funding and local fabrication technologies to make high-performance prostheses more accessible in Nigeria.

This finding reinforces the general pattern that age alone is not a determining factor in energy cost once the amputee has mastered gait training. Water et al. [3] argue that prosthetic efficiency depends more on socket comfort, suspension system, and user balance than chronological age. [3] Thus, any slight numerical difference observed may result from gait speed preferences or conditioning levels rather than inherent physiological disparities.

In essence, this supports the assertion that rehabilitation interventions should focus on training and prosthetic optimisation rather than

age-based differentiation. Both younger and older adults can achieve comparable gait efficiency through proper rehabilitation.

Limitations: The study has some limitations. The unwillingness of all the respondents to participate in the study affected the sample size, which restricts the generalisability of the findings. Energy expenditure was measured using indirect methods rather than direct oxygen consumption, which may reduce precision. The cross-sectional design also prevents tracking changes in energy use over time as prosthetic users adapt. Furthermore, environmental factors like walking surface and speed were not controlled and could have affected the results.

Conclusion

In Conclusion, lower-limb amputation predominantly affects younger, economically active adults. Above-knee amputees have significantly higher energy expenditure than below-knee amputees, largely due to reduced gait efficiency, increased compensatory muscle activity, and greater demands on the intact limb. Advanced prosthetic technologies may improve gait efficiency and reduce energy expenditure, although their cost and limited availability remain challenges in Nigeria. Overall, individualised rehabilitation, gait training, prosthetic optimisation, and improved access to energy-efficient prostheses are essential for enhancing mobility and reducing the energy demands of walking among lower-limb amputees.

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