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Effect of replacing a wooden keel with a polymer keel in the sach foot on walking energy expenditure in transtibial prosthesis users: a pilot study in a resource-limited setting

A. S. Nugroho [1, 2], K. Sasaki [1], M. Nouman [1], R. Ismail [3]

[1] Sirindhorn School of Prosthetics and Orthotics, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand
[2] Departement Prosthetic and Orthotic, Politeknik Kesehatan Surakarta, Indonesia
[3] Department of Mechanical Engineering, Diponegoro University, Indonesia

Objective. This study aims to compare the energy expenditure of unilateral transtibial prosthesis users when using a prototype SACH foot with a polymer keel and a local SACH foot with a wood keel. Method: This study used a quasi-experimental pretest–posttest within-subject (paired) design involving 13 users of unilateral transtibial prosthesis. All participants underwent measurements using both types of prosthetic feet. Energy expenditure was measured using the Physiological Cost Index (PCI) derived from the 6-minute walk test, and heart rate was measured with the XOSS chest sensor. Normality was assessed using the Shapiro-Wilk test, and comparisons between conditions were analyzed using the Wilcoxon signed-rank test. Results. The average PCI for the local SACH foot was 0.461 ± 0.235, and for the prototype SACH foot, 0.458 ± 0.234. The Wilcoxon test showed no statistically significant difference between the two conditions ($p = 0.057$; $p > 0.05$). However, the effect size indicated a medium-to-large effect ($r\beta = -0.604$), with a tendency toward decreased PCI with the use of polymer SACH foot prototypes. Conclusion. This study shows that a prototype SACH foot with a polymer keel has the potential to increase walking energy efficiency compared to a local SACH foot with a wooden keel, although the difference was not statistically significant. These findings make an early contribution to the development of alternative, material-based prosthetic feet that are more efficient and better suited to rehabilitation services in developing countries. Follow-up research with larger sample sizes and more sensitive metabolic measurement methods is needed to confirm these findings.

Мета. Порівняти витрати енергії користувачами односторонніх протезів великогомілкової кістки під час використання прототипу стопи SACH із полімерним кілем і локальної стопи SACH із дерев'яним. Методи. Використано квазіекспериментальний внутрішньосуб'єктний (парний) дизайн перед-посттестового методу, що включав 13 користувачів одностороннього протеза великогомілкової кістки. Усі учасники пройшли вимірювання з використанням обох типів протезів. Витрати енергії вимірювали за допомогою фізіологічного індексу вартості (Physiological Cost Index, PCI), отриманого з 6-хвилинного тесту ходьби, а частоту серцевих скорочень вимірювали за допомогою нагрудного датчика XOSS. Нормальність оцінювали за допомогою тесту Шапіро-Уїлка, а порівняння між умовами аналізували за допомогою тесту знакових рангів Вілкоксона. Результати. Середній показник PCI для локальної стопи SACH становив 0,461 ± 0,235, а для прототипу стопи SACH — 0,458 ± 0,234. Тест Вілкоксона не показав статистично значущої різниці між двома умовами ($p = 0,057$; $p > 0,05$). Проте розмір ефекту вказував на середній або великий ефект ($r\beta = -0,604$) із тенденцією до зниження PCI під час використання полімерних прототипів стопи SACH. Висновок. Виявлено, що прототип стопи SACH із полімерним кілем має потенціал для підвищення енергоефективності ходьби порівняно з локальною стопою SACH із дерев'яним кілем. Ці результати роблять внесок у розробку альтернативних, матеріальних протезів стоп, які є більш ефективними. Для підтвердження цих висновків необхідні подальші дослідження з більшими вибірками та більш чутливими методами вимірювання метаболізму. Ключові слова. Транстибіальний протез, стопа SACH, полімерний кіль, витрати енергії, індекс фізіологічних витрат, протез стопи придатний для реабілітаційних послуг у країнах, що розвиваються.

Keywords. Transtibial prosthesis, SACH foot, polymer keel, energy expenditure, Physiological Cost Index, prosthetic foot

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Introduction

Lower-limb amputation significantly affects mobility, independence, and quality of life worldwide. The primary causes of amputations include vehicular accidents, landmine injuries, and complications from medical conditions such as diabetes mellitus and peripheral vascular disease. According to the World Health Organization, over 40 million individuals worldwide require access to prosthetic and orthotic interventions; however, only 1 in 10 benefit from such services [1]. These statistics underscore critical disparities in access, especially in Low- and Middle-Income Countries (LMICs), where prosthetic services remain severely limited. The World Health Organization projects that only 5–15 % of individuals in low-income nations will likely obtain a prosthesis by 2025 [2]. A United Nations report indicates a marked increase in the prevalence of diabetes across Southeast Asia. Indonesia ranks fourth globally in the number of people affected by diabetes, with 10.7 million currently affected, a figure expected to rise to 13.7 million by 2030 [3]. This health condition increases the demand for lower-extremity prostheses. The prosthetic foot is a critical component of a lower-limb prosthesis. Consequently, prosthetic feet that replicate the functional attributes of a natural foot are essential to improving rehabilitation outcomes. However, in LMICs, procuring affordable prosthetic feet that emulate the functionality of a natural foot remains challenging, as cutting-edge prosthetic foot technologies are often prohibitively expensive and inaccessible. Thus, conventional prosthetic feet, such as the SACH foot, are widely used in LMICs due to their cost-effectiveness.

The keel is the central component of the SACH foot, an internal element that transmits load and influences deformation and energy-return characteristics during the heel strike, midstance, and terminal stance phases. Changes in the keel's mechanical properties will affect stress distribution, cyclic deformation, and the prosthetic's overall service life. Traditional keels are often made from wood in many local SACH foot productions because wood is readily available and inexpensive. However, wood is hygroscopic and absorbs moisture, which can cause dimensional swelling, reduce the modulus of elasticity, increase creep, and promote crack formation after repeated exposure to wet conditions. Replacing wood keels with polymer materials, such as thermoplastics or polymer-fiber composites, is a promising solution for LMICs. Modern polymer materials offer practical benefits, including resistance to moisture and decay, and can be reshaped through local manufacturing methods such as injection molding, thermoforming, and 3D printing. They also allow adjustment of mechanical properties to mimic the desired keel function. In addition, recent research highlights the potential of natural fiber-based composites or synthetic fibers as lower-cost alternatives that still meet mechanical and environmental standards. However, the impact of this material substitution on users' functional parameters, especially energy expenditure during walking, among users of lower-limb prosthetics, has not been thoroughly evaluated in LMIC populations. This knowledge gap is the focus of this research. In practical terms, if the polymer keel can offer greater durability without reducing or even improving metabolic walking efficiency, this would create an opportunity to produce a SACH foot better suited to LMIC conditions, resulting in fewer repairs, lower wear costs, and better functional outcomes for the user. Conversely, if material replacement significantly increases energy expenditure in a clinical setting, design recommendations and manufacturing processes should be adjusted to avoid sacrificing user performance in favor of durability [4].

Therefore, this study aims to evaluate how modifying the conventional SACH foot, particularly by replacing the wood keel with a polymer-based keel, affects walking energy expenditure in transtibial prosthesis users. Using the Physiological Cost Index (PCI) as a clinically practical indicator, the study adopted an in-subject design to detect subtle changes in energy efficiency. Importantly, beyond statistical significance, the study emphasizes the magnitude and clinical relevance of the effects, recognizing that moderate-to-large effect sizes can indicate meaningful functional improvements even in the absence of statistical significance. By providing preliminary evidence from the pilot study, the study seeks to bridge the gap between low-cost prosthetic accessibility and functional performance and to inform future large-scale studies aimed at optimizing the design of prosthetics widely used in resource-constrained settings.

Objective. This study aimed to evaluate and compare walking energy expenditure among transtibial prosthesis users using a locally produced SACH foot with wooden keels and a prototype SACH foot with polymer keels. Specifically, it sought to determine whether the prototype design could improve walking efficiency, as measured by the Physiological Cost Index (PCI), and to estimate the magnitude of its clinical effect in a resource-limited setting.

Methodology

This study used a within-subject (paired) quasi-experimental pretest-posttest design to compare

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energy expenditure during walking between a locally produced SACH foot with a wooden keel, which is manually produced with traditional equipment, and a prototype SACH foot with a polymer keel made of Acrylonitrile-Butadiene-Styrene (ABS), which is produced using the 3D printing method, as shown in Figure 1. Thirteen individuals with transtibial amputation participated in this study. Ethical approval was obtained from the Health Research Ethics Committee of Politeknik Kesehatan Surakarta (No. DP.04.04/F.XXV/2959/2024). Participants met the inclusion criteria, including unilateral transtibial amputation, functional level K2-K3, age 17–65 years, sufficient residual limb length, and at least 6–12 months of prosthesis use. Those with conditions affecting gait or cognition were excluded. Before participating in the research, all participants signed an informed consent form and an ethical agreement, in accordance with the protocol approved by the institution's ethics committee. All participants used the same type of transtibial prosthesis, which was replaced with a prototype SACH foot only during the required data collection period. Before each test, participants rested in a seated position for five minutes to obtain resting heart rate (HRrest). Heart rate was continuously recorded using the XOSS chest-strap heart rate monitor, which sampled heart rate every five seconds throughout the assessment (HRwalking). Participants completed a standardized six-minute walk test (6MWT) on a flat rectangular walkway. Walking speed was calculated by dividing the total walking distance by six minutes. Each participant's walking energy was measured using the Physiological Cost Index (PCI) formula: PCI = (heart rate during walking – resting heart rate) / walking speed. Participants followed the energy expenditure measurement protocol, which included equipment such as a flat track at least 20 meters long, a stopwatch, and a time recorder. The XOSS chest-strap heart-rate sensor is worn on the chest and paired with the device as specified in the manufacturer's manual, as shown in Figure 2. Initially, each participant underwent PCI measurements with the local SACH foot. After collecting PCI data, the local SACH foot was replaced with the Prototype SACH foot, which was worn for 1 month to allow acclimatization to the prototype. PCI data were subsequently collected using the prototype SACH foot after one month of the adaptation phase. The fixed testing sequence may have introduced adaptation-related bias. Statistical analysis was performed in SPSS and included descriptive statistics, Shapiro-Wilk normality testing, and paired comparisons using t-tests or Wilcoxon signed-rank tests, depending on the data distribution. Significance was set at $p < 0.05$, and effect sizes were reported to assess the magnitude of the differences.

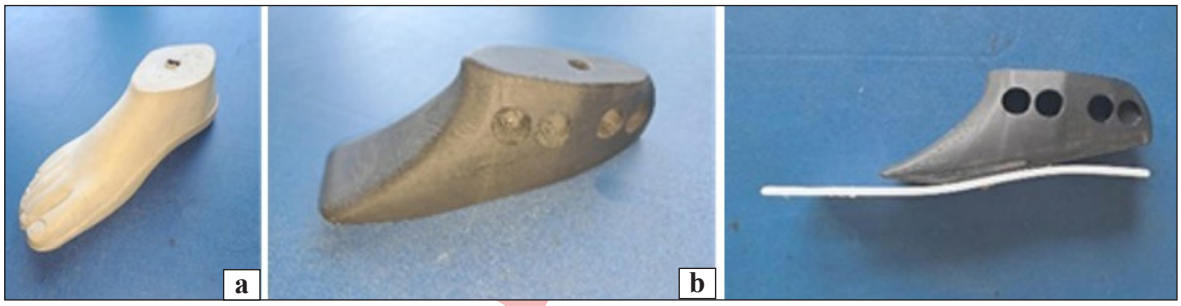


Fig. 1. (a) SACH Foot With Polymer keel; (b) 3D Printed polymer keel



Fig. 2. Illustration 6 Minutes Walking Test of PCI data capture

Results

A total of 13 transtibial prosthesis users were included in this study. The sample consisted of 9 males (69.2 %) and 4 females (30.8 %), aged 26 to 64 years. The causes of amputation were heterogeneous, including trauma, diabetes mellitus, and congenital conditions. All participants were classified as K-level 3 ambulators. All participants had at least one year of prosthetic experience, and no comorbidities affected gait performance. This ensured a relatively homogeneous functional level among participants. As shown in Table 1 below.

Table 2 presents the results of the normality test for the Physiological Cost Index (PCI) data, assessed using the Shapiro-Wilk test. PCI values from both prosthetic conditions were normally distributed (local SACH: W = 0.913, p = 0.199; SACH prototype: W = 0.908, p = 0.170). However, the distribution of paired differences (prototype – local) deviated significantly from normality (W = 0.840, p = 0.022), indicating a violation of the assumptions for parametric tests. Therefore, a Wilcoxon signed-rank test was used as a nonparametric alternative for paired comparisons.

Table 3 presents results on energy expenditure during walking, assessed using the Physiological Cost Index (PCI), with lower values indicating greater walking efficiency. Descriptive statistics showed that the mean PCI for the local SACH foot was 0.461 ± 0.235 (95 % CI: 0.319–0.603), whereas the prototype SACH foot had a slightly lower mean PCI of 0.458 ± 0.234 (95 % CI: 0.317–0.599). The mean pairwise difference was −0.0036 ± 0.0065 (95 % CI: –0.0076 to 0.0003), indicating a consistent reduction in PCI with the SACH foot prototype.

Table 1

Data characteristics of 13 participants with a transtibial prosthesis

No	Gender	Age	Cause of amputation	Year of amputation	Amputee side	K-Level Activity
1	Male	43	Accident	2008	Left	K-3
2	Male	46	Diabetes	2022	Right	K-3
3	Male	55	Accident	2011	Right	K-3
4	Male	36	Accident	2021	Right	K-3
5	Male	26	Accident	2020	Right	K-3
6	Male	28	Accident	2021	Right	K-3
7	Male	60	Accident	2019	Left	K-3
8	Male	28	Accident	2015	Right	K-3
9	Male	64	Diabetes	2023	Right	K-3
10	Female	51	Diabetes	2023	Right	K-3
11	Female	31	Accident	2020	Left	K-3
12	Female	41	Congenital	1984	Left	K-3
13	Female	31	Accident	2020	Left	K-3

Table 2

PCI Normality tests Local SACH foot Vs Prototype SACH foot

Variable	Test	Statistics W	p-value	Distribution
PCI SACH Local	Shapiro-Wilk	0.913	0.199 (> 0.05)	Normal
PCI SACH Prototype	Shapiro-Wilk	0.908	0.170 (> 0.05)	Normal
Differences PCI (Prototype – Local)	Shapiro-Wilk	0.840	0.022 (< 0.05)	Abnormal

Table 3

Wilcoxon signed-rank test: PCI local SACH foot vs prototype SACH foot

Variable	Mean ±SD	95 % CI	Statistic test	Statistic value	p-value	Effect Size
PCI Local SACH foot	0.461 ± 0.235	0.319–0.603	—	—	—	—
PCI Prototype SACH foot	0.458 ± 0.234	0.317–0.599	—	—	—	—
Difference PCI (Prototype – Local)	−0.0036 ± 0.0065	−0.0076–0.0003	Wilcoxon signed-rank	W = 18,0	0.057 (> 0.05)	$r_{rβ}$ = −0.604 (Medium–Large)

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The Wilcoxon signed-rank test showed that this difference was not statistically significant (W = 18.0, p = 0.057). Nevertheless, the calculated biserial correlation ($r_{r\beta}$ = –0.604) indicated a moderate-to-large effect size, suggesting a significant change in energy expenditure. Although the difference did not reach statistical significance, the consistent direction of change across participants and the observed moderate-to-large effect size suggest a potentially meaningful clinical trend that warrants further investigation.

Discussion

The present pilot study investigated whether replacing the conventional wooden keel of a Solod Ankle Cushion Heel (SACH) foot with a polymer–based keel could influence walking energy expenditure in individuals with unilateral transtibial amputation. The principal finding was a consistent reduction in the Physiological Cost Index (PCI) when participants walked using the prototype polymer keel SACH foot compared with the locally manufactured wooden – keel SACH foot, Although the difference did not reach the conventional threshold for stastistical significance (p = 0.057), the observed rank-biseral correlation (r = –0.604) indicated a moderate – to – large effect size, suggesting that the intervention may have produced a clinically relevant reduction in walking energy expenditure. Importantly, the absence of statistical significance should not be interpreted as evidence that the polymer keel had no physiological effect. Rather, it indicates that the present pilot study did not provide sufficient statistical evidence to reject the null hypothesis in testing because pilot studies are primarily designed to evaluate feasibility, estimate variability, and generate effect-size estimates for subsequent adequately powered clinical trials. Consequently, the present findings should be interpreted as demonstrating a promising trend toward improved walking efficiency rather than definitive evidence that the polymer–keel design is superior to the conventional wooden-keel SACH foot. This interpretation is consistent with recent systematic evidence showing that differences in metabolic energy expenditure among passive prosthetic feet are generally modest and are influenced by numerous interacting factors, including prosthetic stiffness, walking speed, user adaptation, and individual gait compensation strategies. Hafner et al. reported that although different prosthetic feet may alter metabolic demand, improvements are frequently small and often become clinically meaningful only after considering participant adaptation and effect size rather than statistical significance alone[5]. From a biomechanical perspective, the keel functions as the primary load-bearing structure within the SACH foot, governing deformation behavior during heel strike, mid-stance, and terminal stance. Consequently, even relatively small changes in keel stiffness or deformation characteristics may influence the progression of the center pressure, ankle rollover behavior, and the temporal distribution of loading throughout stance. Finite element investigations have demonstrated that material properties substantially influence stress distribution, rollover geometry, ankle moment arm, and deformation characteristics of passive prosthetic feet. These biomechanical parameters are closely associated with the mechanical behavior of the prosthetic foot during walking and therefore may indirectly influence physiological energy expenditure [5, 6]. Nevertheless, it is important to emphasize that these proposed mechanisms remain hypothetical within the context of the present investigation. The current study did not directly evaluate gait biomechanics through three-dimensional motion analysis, force-platform measurements, plantar pressure assessment, or inverse dynamics. Consequently, the observed reduction in PCI cannot be interpreted as direct evidence that the polymer keel improved shock absorption, rollover characteristics, or overall gait biomechanics. Instead, these biomechanical explanations should be regarded as plausible hypotheses generated from existing biomechanical literature that require confirmation in future studies integrating kinetic, kinematic, and musculoskeletal analyses. Such cautious interpretations directly address the limitations of the present experimental design while remaining consistent with current evidence regarding passive prosthetic foot mechanics [6]. The results of this study are consistent with several previous studies reporting that design and material modifications to passive prosthetic feet, including the SACH foot, generally yield small but still functionally meaningful metabolic changes among users with transtibial amputations [7].The absence of statistically significant differences in this study is likely influenced by the basic biomechanical characteristics of the SACH foot, which is passive and not designed as an energy-storing-and-return (ESAR) system. In the SACH design, propulsion during the push-off phase is relatively minimal, so changing the keel material alone is unlikely to produce large metabolic changes during walking [5, 8]. In addition, the efficiency of walking in users with transtibial amputations is affected not only by the characteristics of the prosthetic foot but also by compensation strategies in the proximal joints, especially the knee and pelvis, which

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often dominate energy expenditure during gait [6]. Recent research has also shown that changes in stiffness of passive foot prosthetics generally have only a small effect on biomechanical parameters and walking energy expenditure, especially at self-selected walking speed [9]. On the other hand, the use of polymer materials such as ABS still has important potential in the development of prostheses in developing countries because it offers resistance to moisture, better dimensional stability, and compatibility with 3D printing-based manufacturing technology compared with conventional wood materials [10].

From a broader rehabilitation perspective, the importance of the present findings extends beyond the observed reduction in PCI. The principal advantage of replacing conventional wooden keels with polymer materials may lie in improving the overall sustainability of prosthetic service delivery in low–and middle–income countries (LMICs), where affordability, manufacturing capacity, maintenance requirements, and environmental durability remain major challenges. Wooden keels have traditionally been selected because of their low cost and widespread availability. Nevertheless, wood is a hygroscopic material that absorbs moisture, resulting in dimensional instability, biological degradation, and progressive deterioration under prolonged exposure to humid tropical environments. Such environmental conditions are common throughout Southeast Asia and frequently contribute to reduced prosthetic lifespan and increased maintenance requirements. In contrast, thermoplastic polymers such as ABS offer greater resistance to moisture, more consistent mechanical properties, and improved compatibility with digital manufacturing techniques including computer-aided design (CAD), additive manufacturing, and fused filament fabrication. These manufacturing approaches enable standardized production, improved quality control, and greater reproducibility while simultaneously reducing fabrication time and production cost. Consequently, polymer–based SACH feet represent a potentially attractive solution for expanding access to affordable prosthetic technologies and have similarly emphasized that improving affordability should not compromise biomechanical performance but instead optimize the balance between cost, durability, and functional outcomes [11]. Modern polymer and composite-based materials are known to have better resistance to moisture, biological corrosion, and deformation caused by the tropical environment than conventional wood materials [10]. In addition, the development of additive manufacturing and 3D printing technology allows prostheses to be fabricated faster, lighter, and more economically without reducing the mechanical characteristics required during gait [12, 13]. Some recent studies have also shown that polymer-based design optimization can improve stress distribution, structural stability, and comfort for transtibial prosthesis users [6]. In the context of low- and middle-income countries (LMICs), this approach is particularly relevant because it can support the development of prostheses that are more affordable, easier to produce locally, and more durable under environmental conditions with limited resources [14]. Therefore, although the metabolic improvement observed in this study was relatively small, combining acceptable walking performance with improved material durability may provide meaningful long-term clinical advantages for prosthetic users living in LMICs.

The Physiological Cost Index (PCI) was used in this study because it is a simple, practical, and easily applied method in clinical settings with limited resources. PCI has been widely used as an indicator of walking efficiency among users of lower-extremity prostheses because it requires only measurements of heart rate and walking speed, without the need for complex metabolic equipment [15]. However, some recent studies have shown that the sensitivity of PCI in detecting small changes in energy expenditure remains lower than that of direct measurement of oxygen consumption (VO_2) or metabolic analysis based on portable gas analysis [16, 5]. This condition may also contribute to the lack of statistical significance in this study, although there was a tendency for the PCI value to decrease, with a medium-to-large effect size. In addition, the relatively small sample size in this pilot study may limit the statistical power to detect subtle metabolic changes in transtibial prosthesis users [17]. Therefore, further studies are recommended to use a randomized crossover trial design with a larger sample size and to combine PCI measurements with more comprehensive biomechanical and metabolic evaluations to obtain a more accurate picture of the performance of polymer prosthetic feet [17].

Clinically, the results of this study indicate that a polymer-material-based SACH foot has the potential to be a more suitable prosthetic alternative for rehabilitation services in developing countries. A locally sourced material approach and simple fabrication technologies, such as 3D printing, can support the production of more affordable, lightweight, and easily replicated prostheses in rehab facilities with limited resources [18]In addition to cost, the use of modern polymer materials also has the potential to increase the durability and structural stability of

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prostheses in tropical environments with high humidity, which is often a challenge with conventional wooden keels. Therefore, the future development of prosthetic feet will need to focus not only on improving biomechanical performance but also on addressing accessibility, material sustainability, user comfort, and suitability for rehabilitation contexts in low- and middle-income countries (LMICs).

Conclusion

This study investigated how replacing the wooden keel of a conventional SACH foot with a polymer-based keel affected walking energy expenditure in transtibial prosthesis users. The results showed a consistent reduction in the Physiological Cost Index (PCI) with the SACH foot prototype, indicating a tendency toward improved walking efficiency compared to the local SACH foot. Although statistical significance was not achieved, the prototype demonstrated a consistent reduction in PCI with a moderate-to-large effect size, indicating a potential clinically meaningful trend rather than definitive evidence of superiority.

These findings support the hypothesis that material properties play an important role in prosthetic foot performance. One possible explanation is that the polymer keel may provide more favorable deformation characteristics during the stance phase, resulting in improved walking efficiency. However, this hypothesis should be verified through future gait biomechanics studies. Importantly, this improvement was observed within the same prosthetic foot category, highlighting that even simple modifications to conventional designs can yield functional benefits.

As a pilot study, these findings provide preliminary evidence on the magnitude and direction of the effects of material-based modifications. However, the relatively small sample size limits statistical power and the generalizability of the findings. Further studies with larger sample sizes, randomized designs, and additional outcome measures, such as metabolic energy consumption, gait kinematics, and patient-reported outcomes, are needed to confirm and expand on these findings. These findings are particularly relevant to prosthetic service delivery in LMICs, where cost-effective innovations are critical to scaling access to rehabilitation.

Clinical Implications

The results of this study have several important implications for clinical practice and prosthetic development, particularly in resource-constrained settings. First, the findings suggest that low-cost material modifications can improve walking efficiency without requiring complex or expensive prosthetic technology. This is especially relevant in low- and middle-income countries, where access to advanced prosthetic components is limited. Using polymer materials as an alternative to traditional wooden keels can provide a practical, scalable way to improve prosthetic performance. Second, even modest reductions in energy expenditure can yield meaningful functional improvements for prosthetic wearers, including reduced fatigue, greater walking endurance, and greater participation in daily activities. Therefore, doctors and prosthetists should consider not only structural design but also material selection when optimizing prosthetic components. Third, the study underscores the importance of incorporating clinically accessible outcome measures, such as the Physiological Cost Index (PCI), into routine prosthetic evaluations. These measures can provide valuable insights into functional performance and guide evidence-based decision-making in clinical settings.

Finally, these findings support a broader shift toward context-appropriate innovation, in which affordability, accessibility, and functional performance are addressed simultaneously. This approach is critical to improving rehabilitation outcomes at the population level, especially in settings with limited health resources.

Conflict of interest. The authors declare no conflict of interest.

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EFFECT OF REPLACING A WOODEN KEEL WITH A POLYMER KEEL IN THE SACH FOOT ON WALKING ENERGY EXPENDITURE IN TRANSTIBIAL PROSTHESIS USERS: A PILOT STUDY IN A RESOURCE-LIMITED SETTING

A. S. Nugroho [1, 2], K. Sasaki [1], M. Nouman [1], R. Ismail [3]

[1] Sirindhorn School of Prosthetics and Orthotics, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand
[2] Departement Prosthetic and Orthotic, Politeknik Kesehatan Surakarta, Indonesia
[3] Department of Mechanical Engineering, Diponegoro University, Indonesia

✉ Agus Setyo Nugroho, Ph.D Student Prosthetic and Orthotic: agussetyo.nug@gmail.com; https://orcid.org/0009-0004-9313-8216
✉ Kazuhiko Sasaki, PhD, Engineering in Electronic and Information Engineering: kazuhiko.sas@mahidol.edu; https://orcid.org/0000-0002-1778-6308
✉ Muhammad Nouman, PhD, Biomedical Engineering: muhammad.nou@mahidol.ac.th; https://orcid.org/0000-0001-5747-6518
✉ Rifky Ismail, PhD, Engineering: rifky_ismail@ft.undip.ac.id; https://orcid.org/0000-0003-0445-3405

PREVIEW