

Review

Gait Asymmetry and Metabolic Demand in Lower Limb Prosthesis Users: A Scoping Review

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Abstract

Background: Lower limb prosthesis users commonly exhibit gait asymmetry that may increase metabolic demand. Gait asymmetry, therefore, is frequently targeted in rehabilitation to improve walking efficiency. This review aimed to investigate whether interventions that improve gait asymmetry reduce metabolic demand in unilateral lower limb prosthesis users. **Methods:** A search of relevant English-language articles was conducted using PubMed and CINAHL, yielding a total of 1067 records. Following title, abstract, and full-text screening, 10 studies met eligibility requirements and were included in the qualitative synthesis. Data extraction focused on participant characteristics, gait asymmetry measures, metabolic outcomes, and intervention characteristics. **Results:** Four main intervention categories were identified: advanced prosthetic knees and ankles, prosthetic mass manipulation, feedback-based gait interventions, and exercise-based training. Across studies, changes in gait symmetry were not consistently associated with reductions in metabolic demand. Interventions targeting ankle function showed the most consistent reductions in metabolic demand, particularly during demanding walking tasks. In contrast, distal prosthetic mass addition consistently increased metabolic demand and worsened gait symmetry. **Conclusion:** Current evidence does not support a consistent or direct relationship between gait symmetry and metabolic demand in lower limb prosthesis users. Gait asymmetry may not be inherently metabolically disadvantageous and may represent an energetically optimal adaptation.

Keywords: prosthetics; amputation; metabolic cost; efficiency; symmetry



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1. Introduction

Lower limb prosthesis (LLP) users demonstrate pronounced walking asymmetries compared to the unimpaired population [1–3]. Patterns of walking asymmetry in LLP users typically include shorter intact step length [2,4,5] and swing time [3], shorter prosthetic stance time [3,6,7], lack of prosthetic knee flexion and hip extension during gait cycle [2], and reduction in the anterior propulsion force and prosthetic hip adduction moment [2]. Walking asymmetry appears to be a multifactorial postural pattern that can be exacerbated by residual limb pain [8], muscle weakness [9], higher level of amputation [1,3], and prosthetic factors (i.e., mass, components, alignment, or socket comfort) [10–12]. Although gait symmetry is frequently considered a desirable rehabilitation outcome, asymmetrical gait patterns may also represent functional compensatory strategies that help with fall recovery [13,14] and maintaining dynamic balance [5,6,15]. Furthermore, gait asymmetry encompasses a range of spatial, temporal, kinematic, and kinetic measures that capture

different aspects of gait and therefore should not be interpreted interchangeably. Gait asymmetry, therefore, should not be assumed to be inherently maladaptive, and its functional significance remains an area of ongoing investigation. Understanding the multifactorial nature and diverse presentation of walking asymmetry provides a necessary foundation for examining its potential functional and energetic consequences.

Several negative consequences of walking asymmetry have been documented, including decreased physical function and quality of life [16], and decreased movement efficiency (i.e., increased metabolic demand) [17–19]. Further, decreased movement efficiency has been found to contribute to reduced physical activity levels in LLP users [20,21] and increased risk of obesity and related comorbidities through sustained reductions in mobility and daily activity [8,22]. In a recent systematic review, increased metabolic demand was one of the main concerns and consequences of movement asymmetry [23]. Metabolic demand describes the physiological energy required to sustain walking and is commonly quantified by measures such as oxygen consumption, oxygen cost, energy expenditure, metabolic power, or metabolic cost of transport. As these measures reflect the energetic requirements of locomotion, they are frequently used to evaluate walking efficiency and the physiological consequences of altered gait patterns [24]. Human locomotion is designed to minimize mechanical and physiological energy expenditure. Disruption of normal gait mechanics may therefore increase the physiological energy required for walking (i.e., metabolic demand). Consequently, asymmetrical gait patterns may increase the energetic cost of walking by altering normal movement mechanics [17].

Previous studies have examined the relationship between walking asymmetry and efficiency in LLP users [25–27]; however, findings across these studies have been inconsistent. While several studies have reported reduction in metabolic demand in response to improved walking asymmetry [25,26,28], others have found little or no relationship [27,29]. This inconsistency may be attributable to heterogeneity in participant characteristics (e.g., etiology or level of amputation), interventions, gait asymmetry metrics, or method used to quantify metabolic demand. Collectively, these mixed results underscore the need to clarify whether walking asymmetry is a primary contributor to impaired walking efficiency or a compensatory strategy that arises in response to other underlying biomechanical or neuromuscular deficits. To our knowledge, no previous review has specifically synthesized the available evidence on the relationship between gait asymmetry and metabolic demand in lower limb prosthesis users. Such a review is needed to critically evaluate the current evidence, identify sources of heterogeneity, and guide future research and clinical decision-making.

The objective of this review was to evaluate the existing literature that reported the relationship between gait asymmetry and walking efficiency (i.e., metabolic demand) in unilateral LLP users. Addressing this uncertainty requires an evaluation of the existing evidence to determine when, and under what conditions, changes in walking asymmetry are associated with meaningful changes in metabolic demand. Although walking efficiency is influenced by multiple factors, including prosthetic design, residual limb characteristics, walking speed, and individual adaptations, understanding the contribution of gait asymmetry may provide insight into one potential determinant of walking efficiency. Such knowledge may help guide the selection of existing rehabilitation strategies and inform the development of future interventions aimed at improving walking efficiency.

2. Methods

2.1. Literature Search

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) extension for the Scoping Reviews checklist was followed (See Supplementary Materials,

File S1). In order to collect all studies related to gait asymmetry and metabolic demand in LLP users, searches in PubMed and the Cumulative Index to Nursing and Allied Health Literature Expanded Index (CINAHL) were performed on 13 May 2025. Three main keywords were used: amputation, asymmetry, and metabolic demand. The following search string was used in both PubMed and CINAHL: (energ* OR metaboli* OR expen*) AND (symmet* OR asymmet*) AND (amput* OR prosth* OR limb loss OR below-knee OR transtibial OR trans-tibial OR above-knee OR transfemoral OR trans-femoral OR leg OR lower-limb OR lower limb OR above knee OR below knee).

2.2. Inclusion and Exclusion Criteria

Original research articles were included if they: (1) were written in English, (2) were published in a peer-reviewed journal, (3) were conducted on people with unilateral lower limb amputation, and (4) evaluated the relationship between at least one measure of gait asymmetry (e.g., spatial, temporal, kinematic, or kinetic asymmetry) and at least one measure of metabolic demand (e.g., oxygen consumption, metabolic power, energy expenditure, or metabolic cost of transport). Articles were excluded if they: (1) were not original research studies (e.g., literature reviews), (2) were pilot studies or case reports, defined as studies with less than five participants, or (3) used computer modeling in place of participant testing.

2.3. Screening and Review of Publications

A total of 1067 studies were found in both databases (PubMed 903, and CINAHL 164). Data extracted from each included study comprised: (1) study characteristics (author and year); (2) participant characteristics, including sample size, age, sex, amputation level, time since amputation, etiology, and prosthetic components; (3) study objective; (4) walking condition and intervention/training protocol, where applicable; (5) gait asymmetry assessment, including the symmetry domain, asymmetry variable(s), and calculation method; (6) metabolic demand assessment, including the metabolic outcome measure and method used to calculate metabolic demand or walking efficiency; and (7) the principal findings describing the relationship between gait asymmetry and metabolic demand. Two authors were responsible for scanning the papers and applying the inclusion and exclusion criteria (MT and MGF). All these articles were scanned at first by reading the titles and those that did not include lower limb prosthesis users or were not original research studies (e.g., literature reviews) were excluded. The abstracts of the chosen papers were reviewed to exclude those that were pilot studies or case reports or were not peer-reviewed. Full-text articles were excluded if they were not available in English, used computer modeling in place of participant testing, or did not report both walking asymmetry and efficiency data. Author MGF performed the searches and exported the search data. Author MT manually performed title, abstract, and full-text screening. MGF and MT reviewed all articles that passed full-text screening to ensure inclusion of appropriate articles. MT manually performed all data extraction.

3. Results

3.1. Included Manuscripts

After removing duplicates and applying the inclusion and exclusion criteria, 10 articles remained for full-text review (Figure 1). Four studies [26,27,30,31] assessed the symmetry–efficiency relationship by manipulating gait asymmetry while six studies [25,28,29,32–34] induced interventions to assess the impact on both gait symmetry and walking energetics.

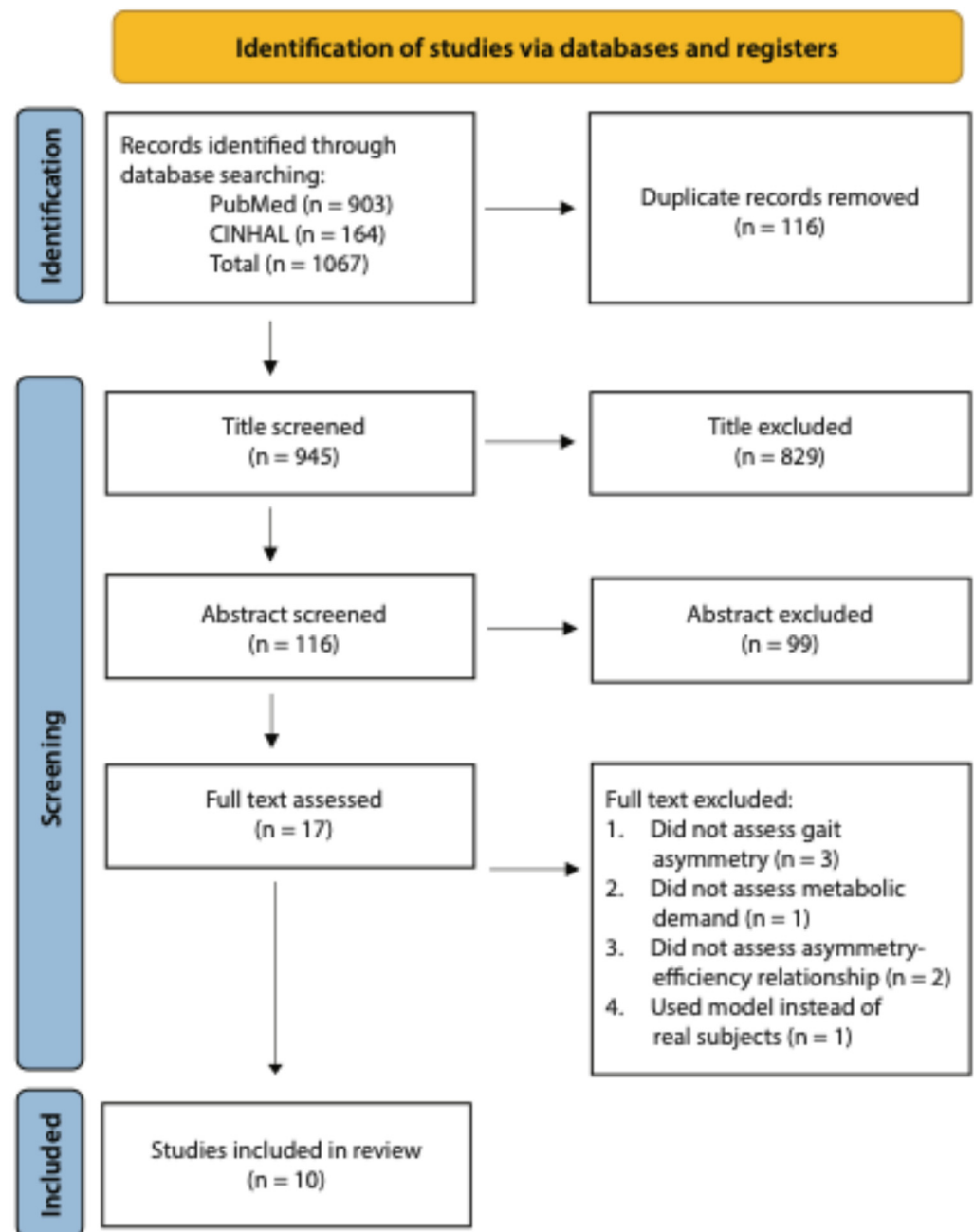


Figure 1. Flow diagram of the inclusion criteria.

3.2. Participants

Table 1 presents the characteristics of participants included in each study. Most studies included small sample sizes, ranging from 6 to 18 participants. Specifically, articles included less than 10 participants ($n = 6$, where n represents the number of studies), and between 10 and 18 participants ($n = 4$). One article did not report sex, and the remaining articles primarily included male participants ($n = 9$; $n = 1$ only included male participants; 72 participants in total) compared to female participants ($n = 8$; 17 participants in total). Mean participant age ranged from 31 years to 49 years across all 10 studies. Eight studies reported time since amputation, with means ranging between 7 and 40 years. Five studies only included unilateral transtibial prosthesis users, while four studies included only transfemoral prosthesis users, and one study included both transtibial and transfemoral prosthesis users. Of the 9 studies that reported etiology, traumatic amputation was most

commonly reported ($n = 9$) and the most predominant etiology across all studies. Several studies also included dysvascular ($n = 2$), congenital ($n = 4$), and cancer ($n = 4$) etiologies.

Table 1. Participant characteristics of the included manuscripts.

Articles	No.	Age (yrs) Mean $\pm$ SD	Sex	Amputation Level	Time Since Amputation	Etiology	Prosthetic Knee	Prosthetic Foot
[29]	6	37 $\pm$ 6	M: 5 F: 1	TF	17 $\pm$ 14	Trauma & congenital	Endolite Stance Flex & Endolite Uniaxial Knee	ESAR
[30]	6	35 $\pm$ 12	--	TT	7 $\pm$ 5	Trauma: 3 Cancer: 1 Congenital: 1 Dysvascular: 1	Not Applicable	ESAR
[26]	11	46 $\pm$ 8	M: 10 F: 1	TT: 8 TF: 3	Not reported	Trauma: 8 Dysvascular: 3	Mauch hydraulic & Blackmax	ESAR and SACH
[28]	8	41 $\pm$ 12	M: 5 F: 3	TF	15 $\pm$ 11	Trauma & cancer	C-leg	ESAR
[33]	6	47 $\pm$ 16	M: 5 F: 1	TT	14 $\pm$ 14	Trauma: 5 Congenital: 1	Not Applicable	ESAR
[32]	10	42 $\pm$ 11	M: 6 F: 4	TT	Not reported	Not reported	Not Applicable	ESAR
[25]	9	41 $\pm$ 14	M	TT	13 $\pm$ 14	Trauma	Not Applicable	ESAR
[27]	18	31 $\pm$ 5	M: 17 F: 1	TF	40 $\pm$ 14	Trauma	Microprocessor & hydraulic knees	ESAR
[34]	14	49 $\pm$ 16	M: 10 F: 4	TF	26 $\pm$ 20	Trauma: 9 Cancer: 5	Microprocessor & non- microprocessor knees	Not reported
[31]	7	37 $\pm$ 13	M: 5 F: 2	TT	17 $\pm$ 12	Trauma: 4 congenital: 2 Cancer: 1	Not Applicable	ESAR

ESAR: Energy-storage and return; F: Female; M: Male; SACH: Solid ankle cushion heel; SD: Standard deviation TT: Transtibial; TF: Transfemoral; --: Not provided.

3.3. Gait Symmetry

Regarding walking environment and task, all ten studies assessed treadmill walking, while approximately half of the studies also incorporated overground walking for specific assessments ($n = 5$). Eight studies included level-ground walking, whereas two additionally examined inclined or declined walking conditions. Walking symmetry was assessed using kinematic or spatiotemporal parameters in the majority of studies ($n = 8$), with two studies employing mechanical or kinetic measures of inter-limb symmetry based on ground reaction forces or center-of-mass work. Stance time ($n = 5$) and step length ($n = 5$) were the most frequently reported symmetry variables, followed by step time ($n = 3$). Across all studies, walking symmetry was quantified using normalized differences or ratios between prosthetic and intact limb parameters ($n = 10$). These metrics were commonly expressed as percentages or unitless ratios, with values approaching zero or unity indicating greater symmetry, depending on the formulation used (Table 2).

Table 2. Summary of walking symmetry measures and metabolic demand calculations in the included manuscripts.

Article	Symmetry Domain	Symmetry Variables	Symmetry Calculation	Metabolic Outcomes	Efficiency Calculation
[29]	Spatiotemporal	Step length	$(\text{prosthetic} - \text{intact}) / [0.5(\text{prosthetic} + \text{intact})] \times 100\%$	Oxygen consumption	VO ₂
[30]	Spatiotemporal	Step length and stance & swing time	$(\text{prosthetic} - \text{intact}) / [0.5(\text{prosthetic} + \text{intact})] \times 100\%$	Metabolic demand	VO ₂ & VCO ₂ → energy rate
[26]	Temporal	Step time	$(X_{\text{right}} - X_{\text{left}}) / (X_{\text{right}} + X_{\text{left}}) \times 100\%$	Oxygen consumption	VO ₂
[28]	Spatiotemporal	Step length, stance time	Stance phase ratio = prosthetic/intact; Step length ratio = longer/shorter	Metabolic demand, Walking economy	EE (W/kg) EC = EE/speed
[33]	Temporal	Step & stance time	$(\text{intact} - \text{prosthetic}) / (\text{intact} + \text{prosthetic}) \times 100\%$	Net metabolic cost	Walking – resting metabolic energy
[32]	Mechanical	Positive work symmetry	prosthetic limb/intact limb	Net metabolic power	Walking – standing metabolic power
[25]	Mechanical/CoM	CoM displacement symmetry	Dynamic Symmetry Indices computed from coefficients of a 10-harmonic Fourier series	Walking economy, Mechanical efficiency	Cmet = (steady state -standing)/speed η _{loco} = WTOT/Cmet
[27]	Spatiotemporal	Step length & time	$(S_{\text{long}} - S_{\text{short}}) / (S_{\text{long}} + S_{\text{short}}) \times 100\%$	Gross metabolic power, Metabolic economy	VO ₂ & VCO ₂ → gross metabolic power, Metabolic economy = gross metabolic power/SSWV
[34]	Spatiotemporal	Step length, stance time	$(\text{intact} - \text{prosthetic}) / \text{mean}(\text{intact} + \text{prosthetic}) \times 100\%$	Oxygen consumption, Metabolic power, Cost of transport	Net VO ₂ , Power via Brockway, CoT = power/(mass × speed)
[31]	Temporal	Stance time	$(\text{intact} - \text{prosthetic}) / (\text{intact} + \text{prosthetic}) \times 100\%$	Cost of transport (CoT)	Net CoT

CoM: Center of mass; CoT: Cost of transport ($\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$); Cmet: Net metabolic cost of locomotion; EC: Energy cost ($\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$); EE: Energy expenditure ($\text{W} \cdot \text{kg}^{-1}$); η_{loco}: Locomotor efficiency; Slong: longer step length; Sshort: shorter step length; SSWV: Self-selected walking velocity; VCO₂: Rate of carbon dioxide production; VO₂: Rate of oxygen consumption; WTOT: Total mechanical work during walking.

3.4. Walking Efficiency

All included studies assessed walking energetics using indirect measures of metabolic demand derived from oxygen consumption, rather than direct measures of mechanical efficiency. Metabolic outcomes included oxygen consumption or oxygen cost (VO₂-based measures expressed in $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; $n = 6$), metabolic power or energy expenditure derived from VO₂ and VCO₂ ($\text{W} \cdot \text{kg}^{-1}$; $n = 6$), and cost of transport expressed as metabolic energy expenditure per unit distance ($\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ or dimensionless cost of transport; $n = 5$). Reported outcomes included gross or net oxygen consumption ($n = 6$), gross or net metabolic power calculated using established equations (e.g., Brockway or Weir; $n = 6$), and cost of transport normalized to walking speed and body mass ($n = 5$). Only one study additionally reported a locomotor efficiency ratio, defined as the ratio of mechanical work to metabolic cost ($n = 1$). Baseline subtraction procedures were inconsistent across studies, with some reporting net metabolic measures following subtraction of resting or standing values, while others reported gross values only (Table 2).

3.5. Interventions

Table 3 summarizes study findings by intervention. Four main types of intervention were identified: advanced prosthetic knees or ankles ($n = 3$ total; knees $n = 1$, ankles $n = 2$) [25,29,32], added mass or matched limb inertia ($n = 3$) [30,33,34], visual or

real-time gait feedback ($n = 3$) [26,27,31], and home-based treadmill or exercise training ($n = 1$) [28].

Table 3. Intervention-specific effects on walking symmetry and metabolic demand in the included manuscripts.

Intervention	Articles	Walking Condition	Training	Findings
Advanced prosthesis	[29]	Treadmill walking at slow, normal & fast speeds	Several months of prior use of microprocessor knee (≈ 4 –7 months)	↓ step-length asymmetry ($\sim 1\%$) during slow and fast walking, No change in VO_2
	[32]	Treadmill walking at 1.25 m/s on 0° , $+3^\circ$, $+6^\circ$, and $+9^\circ$ inclined angles	6 h adaptation to power ankle	↓ leg net-work asymmetry at $+6^\circ$, ↓ net metabolic power ($\sim 5\%$) during uphill walking ($+6^\circ$)
	[25]	Treadmill walking at 0.8–1.6 m/s speed, and 5 – 10° decline angles	Short accommodation period prior to testing	↓ inter-limb asymmetry during 10° decline, ↓ net metabolic cost of locomotion (~ 12 – 20%)
Added mass	[30]	Treadmill walking combined with overground trials at $1.34 \text{ m}\cdot\text{s}^{-1}$	~ 30 min treadmill accommodation prior to data collection	↑ stance-time and step-length asymmetry, ↑ VO_2 (~ 6 – 7%)
	[33]	Treadmill (metabolic) and overground (kinematic) at self-selected speed	Short accommodation period	↑ temporal asymmetry, ↑ net metabolic cost ($\sim 12\%$)
	[34]	Overground & treadmill walking at self-selected speed	~ 2 min per condition for treadmill trials	↑ stance-time asymmetry (47%), ↑ VO_2 (~ 5.3 – 6.1%)
Feedback	[26]	Self-paced treadmill walking	~ 4 min practice with feedback prior to data collection	↓ asymmetry ($\sim 7\%$), ↓ VO_2 ($\sim 6\%$)
	[27]	Overground at self-selected speed and split-belt treadmill at 0.5 – 1.5 m/s	4 min acclimation; 15 min split-belt adaptation (case analysis)	Cohort: no symmetry-efficiency correlation, Case: ↓ asymmetry and ↓ metabolic power
	[31]	Treadmill walking at preferred overground speed	Brief familiarization session	↓ asymmetry, ↑ net CoT by $\sim 13.6\%$
Training	[28]	Overground & treadmill walking at self-selected and maximum speeds	8-week progressive home treadmill training program	↓ asymmetry ↓ energy expenditure and cost

CoT: Cost of transport ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$); VO_2 : Oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$); ↓: Decrease; ↑: Increase.

4. Discussion

The objective of this review was to evaluate the evidence regarding the relationship between gait asymmetry and metabolic demand in unilateral lower-limb prosthesis (LLP) users. Four main categories of interventions were identified among the included studies. Advanced powered and hydraulic ankle-foot prostheses demonstrated some of the strongest concurrent improvements in gait symmetry and metabolic outcomes, with reductions in metabolic demand accompanied by improvements in mechanical or center-of-mass-based symmetry measures during inclined and declined walking. In contrast, microprocessor prosthetic knees improved spatiotemporal gait symmetry without corresponding reductions in metabolic demand. Real-time visual gait feedback produced encouraging but variable results, with modest improvements in temporal symmetry and reductions in oxygen consumption; however, these effects were not consistent across all symmetry measures or participant cohorts. Home-based treadmill training also demonstrated concurrent improvements in spatiotemporal symmetry and metabolic demand,

although these findings were limited to a single study. Conversely, interventions involving added prosthetic mass consistently resulted in greater gait asymmetry and increased metabolic demand. Overall, the findings indicate that the relationship between gait asymmetry and metabolic demand is highly dependent on the type of intervention and walking task, and improvements in gait symmetry do not consistently translate into reductions in the metabolic demands of walking.

Gait asymmetry measures may contribute to the inconsistency in the reported symmetry–efficiency relationships across the included studies. Gait asymmetry was assessed using a wide range of metrics, including step-length asymmetry [29,30,34], step- or stance-time asymmetry [26,31,33], combined spatiotemporal measures [27,28], and mechanical or kinetic symmetry indices [25,32]. These measures capture distinct domains of gait control. Previous reviews have shown that spatial, temporal, and kinetic asymmetries reflect different underlying mechanisms and may respond differently to interventions [35,36]. Experimental work further demonstrates that the energetic consequences of asymmetry depend on the specific parameter examined. For example, step-time asymmetry has been shown to be more strongly related to metabolic cost than step-length asymmetry [17]. Furthermore, preferred asymmetry patterns may represent energetically optimal solutions rather than inefficiencies, as enforcing perfect symmetry can increase metabolic cost [37]. In LLP users, gait asymmetry has also been linked to functional outcomes such as walking speed and endurance, independent of metabolic measures [38]. Together, these findings may suggest that improvements in one asymmetry metric do not necessarily correspond to improvements in others or reliably predict changes in metabolic cost. The lack of standardized asymmetry outcomes therefore limits direct comparison across studies and complicates interpretation of symmetry–efficiency relationships.

Differences between advanced prosthetic knee and ankle–foot interventions may help explain how joint-specific function and task demands influence the relationship between gait symmetry and metabolic demand. The ankle is a major contributor to positive mechanical work during late stance and plays a critical role in forward propulsion and step-to-step transitions, both of which are closely related to the metabolic demands of walking. Accordingly, prosthetic ankle–foot devices that restore or augment push-off power may be more likely to reduce metabolic demand, particularly during energetically demanding tasks such as uphill or controlled downhill walking, as demonstrated in the studies included in this review [25,32]. In contrast, the knee contributes relatively little net positive mechanical work to center-of-mass progression during level walking and primarily functions to regulate limb loading, stability, and swing-phase clearance [39,40]. Consequently, advanced or microprocessor-controlled knees may improve spatiotemporal gait symmetry without producing measurable reductions in metabolic demand, as observed by Kirker et al. [29]. Task conditions may further influence these outcomes, as uphill walking increases the requirement for positive mechanical work and may amplify the energetic benefits of ankle assistance, whereas level walking may limit the potential metabolic effects of knee-focused interventions [41]. Furthermore, lower-limb joint mechanics are highly interdependent; therefore, restoring ankle push-off may reduce compensatory demands at more proximal joints, whereas improvements in knee function alone may not consistently alter whole-body energetics [39]. These biomechanical differences may partially explain why advanced ankle–foot prostheses demonstrated concurrent improvements in gait symmetry and metabolic demand, while microprocessor knee interventions primarily improved symmetry outcomes.

Across feedback-based studies, differences in participant characteristics and walking protocols may have contributed to the variability in findings. Davis et al. and Mahon et al. included individuals with transfemoral (TF) amputation [26,27], whereas Wedge

et al. studied only individuals with transtibial (TT) amputation [31]. Individuals with TF amputation generally exhibit greater gait asymmetry and higher metabolic demands during walking due to the loss of both knee and ankle function and a greater reliance on proximal compensatory strategies [42–44]. Consequently, intervention-related changes in gait symmetry among TF users may be more likely to coincide with detectable changes in metabolic demand. This may partly explain why Davis et al. reported reductions in oxygen consumption following real-time visual feedback [26] and why Mahon et al. observed reductions in metabolic power at the individual level during split-belt adaptation [27], despite finding no significant relationship between gait symmetry and metabolic demand at the group level. In contrast, interventions that explicitly enforce symmetrical gait patterns may disrupt preferred compensatory strategies rather than improve walking economy [15]. Consistent with this interpretation, Wedge et al. demonstrated that enforcing stance-time symmetry increased the cost of transport relative to a mild, self-selected asymmetry [31]. Walking speed and testing environment may have further influenced these outcomes. For example, Wedge et al. fixed treadmill speed to each participant's preferred overground walking speed, which may have imposed greater physiological demands than self-paced treadmill walking [45]. Collectively, these findings suggest that the effects of feedback-based interventions on gait symmetry and metabolic demand are influenced by a combination of amputation level, walking conditions, and the nature of the feedback provided. As such, differences across studies likely reflect context-specific responses to feedback interventions rather than conflicting evidence regarding the relationship between gait symmetry and metabolic demand.

Evidence from home-based treadmill training provides insight into how exercise may influence both walking asymmetry and metabolic demand through physiological and neuromotor adaptations rather than direct mechanical manipulation. The observed improvements in the symmetry–efficiency relationship following exercise may be attributed to overall enhancements in gait performance. Previous studies have shown that structured exercise and gait training programs can improve gait performance and functional mobility in lower-limb prosthesis (LLP) users [46,47] while also reducing the relative metabolic demand of walking through improvements in aerobic capacity and neuromuscular efficiency [24]. Importantly, these adaptations do not necessarily require direct targeting of gait symmetry and may occur independently of specific asymmetry measures, with improvements in symmetry emerging as a secondary consequence of enhanced motor control. Although the findings from the home-based treadmill training intervention are promising, demonstrating concurrent improvements in walking symmetry and metabolic demand, they are derived from a single study. Therefore, additional studies employing standardized metabolic outcome measures and longer training durations are needed to clarify the role of exercise-based interventions in improving both gait mechanics and walking energetics in LLP users.

Prosthetic mass distribution, in contrast to other interventions, demonstrated relatively consistent effects across studies. Adding distal mass to the prosthesis was associated with worsening gait symmetry and increased metabolic demand in all three mass-addition studies. This consistency was observed despite differences in methodological approaches, including walking speed, testing environment, prosthesis type, and accommodation duration. The observed effects may be explained by the disproportionate increase in limb moment of inertia resulting from distal mass addition, which increases the muscular effort required to accelerate and decelerate the prosthetic limb during walking and, consequently, elevates overall metabolic demand [40,48]. Unlike interventions designed to modify gait coordination or provide mechanical assistance, added prosthetic mass imposes a direct mechanical burden that is difficult to compensate for through gait adaptations. As a result,

increases in both gait asymmetry and metabolic demand were consistently observed. Collectively, these findings suggest that prosthetic mass distribution has a reliably detrimental effect on gait symmetry and walking energetics, reinforcing the importance of minimizing distal mass in prosthetic design.

This review highlights several important implications for clinical practice and research in prosthetic rehabilitation. The inconsistent relationship between gait symmetry and metabolic demand suggests that caution is warranted when targeting one outcome with the expectation of improving the other. Although several interventions improved gait symmetry, these improvements did not consistently translate into reductions in metabolic demand. In contrast, the consistent findings observed in studies investigating prosthetic mass distribution provide strong evidence supporting the reduction in distal prosthetic mass to minimize the metabolic demands of walking. Advanced ankle–foot prostheses and home-based gait training interventions also demonstrated promising outcomes, suggesting that restoring natural joint function and enhancing neuromuscular capacity may be more effective strategies than mechanically enforcing symmetrical gait patterns. Furthermore, the variability in individual responses across studies highlights the need for personalized rehabilitation approaches that consider factors such as amputation level, prosthetic components, walking environment, and patient-specific goals. Collectively, these findings support a shift toward function- and energetics-focused clinical decision-making, in which gait symmetry is considered alongside metabolic demand, walking performance, and patient preference rather than being treated as an isolated indicator of rehabilitation success.

Several limitations of this review should be acknowledged. First, only full-text articles published in English were included, which may have resulted in the exclusion of relevant studies published in other languages or available only as conference proceedings. Second, most included studies were characterized by small sample sizes, frequently involving ten or fewer participants, limiting statistical power and reducing the generalizability of the findings. In addition, the majority of participants had traumatic etiologies, whereas individuals with dysvascular amputation represent a substantial proportion of lower-limb prosthesis users [49,50]. Given the distinct clinical characteristics, comorbidities, and functional limitations associated with dysvascular amputation, the applicability of the current findings to this population remains uncertain. Additionally, while two databases are generally considered appropriate for a scoping review, there is a risk that two databases may not have encompassed all available articles on this topic. We also chose to exclude articles with five or fewer participants to characterize trends across cohorts, which may have excluded some potentially informative studies. The authors also did not perform duplicate screening or data extraction, which may have introduced screening and data extraction errors. Furthermore, considerable methodological heterogeneity existed across studies, including differences in intervention type, outcome measures, walking conditions, prosthetic components, and participant characteristics. This heterogeneity limited direct comparisons between studies and precluded quantitative synthesis of the findings. Future research should include larger and more diverse cohorts, particularly individuals with dysvascular amputation, and adopt standardized measures of gait asymmetry and metabolic demand. Additional studies are also needed to examine how intervention dosage, adaptation duration, and walking context influence the relationship between gait asymmetry and metabolic demand, and whether intervention-related changes translate into meaningful improvements in functional performance and patient-reported outcomes over time.

5. Conclusions

This review evaluated the evidence regarding the relationship between gait asymmetry and metabolic demand in lower-limb prosthesis (LLP) users. Overall, the included

studies did not consistently support the assumption that improvements in gait symmetry lead to reductions in the metabolic demands of walking. Although some interventions, such as home-based treadmill training and advanced ankle–foot prostheses, produced concurrent improvements in gait symmetry and metabolic outcomes, substantial methodological heterogeneity existed across studies, including differences in intervention type, outcome measures, and participant characteristics. Collectively, the available evidence suggests that gait asymmetry may not be inherently metabolically disadvantageous and, in some circumstances, may represent an adaptive walking strategy rather than a deficit requiring correction. However, these findings should be interpreted with caution because of the limited number of studies and the substantial methodological heterogeneity in study designs, interventions, gait asymmetry measures, and metabolic outcome measures. Consequently, definitive conclusions regarding the relationship between gait asymmetry and metabolic demand cannot yet be drawn. Future research should adopt a more holistic and individualized approach to prosthetic rehabilitation by considering gait symmetry alongside metabolic demand, walking performance, and patient-centered outcomes. Greater emphasis should also be placed on the use of standardized outcome measures and the investigation of the mechanisms through which interventions influence both gait mechanics and walking energetics.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/sym18081299/s1>, File S1. Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist. Reference [51] is cited in the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

CoM	Center of mass
CoT	Cost of transport
Cmet	Net metabolic cost of locomotion
EC	Energy cost
EE	Energy expenditure
LLP	Lower Limb Prosthesis
η_{loco}	Locomotor efficiency

SSWV	Self-selected walking velocity
VCO ₂	Rate of carbon dioxide production
VO ₂	Rate of oxygen consumption
WTOT	Total mechanical work during walking

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