Effects of Powered Ankle Prostheses on Lower Limb Kinetics and Metabolics: A Literature Review

Brianna Buchanan[1], Nana Porter-Honicky[2], Hiva Razavi[1], Isaac Stein[1],
[1]School of Kinesiology, University of Michigan, Ann Arbor, MI 48109
[2]Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48105

Abstract

Background: Sloped walking is of particular difficulty for people with transtibial amputations. This can in part be attributed to their lack of plantar flexor power during push-off and lack of dorsiflexion to allow for toe clearance during swing (especially on inclines). Powered ankle-foot prostheses (PAFP) have been introduced as a possible solution to these issues. While these devices are designed to provide the kind of assistance that those with transtibial amputations seem to need at the ankle, it is unclear how beneficial these devices are when evaluated more wholistically.

Methods: A systemic literature review was performed using PUBMED, SCOPUS, WEB OF SCIENCE, IEEE Xplore, MEDLINE, EMBASE, and MANUAL SEARCH in September and October of 2024. The focus of our search was on people with unilateral transtibial amputations using a PAFP to walk on sloped surfaces. Outcome measures were narrowed down for commonality across the different papers following full text evaluation.

Results: This literature review garnered seven papers. Across these seven papers, four found reductions in metabolic expenditure in those using a PAFP, three found reductions in compensatory hip and knee kinetics of the contralateral leg, and four found improved ankle kinetics.

Significance: Given the small body of work that exists, it is difficult to make a wholistic assessment on PAFPs for use in sloped walking. The currently published works on the topic indicate multiple benefits, especially to those with pronounced compensatory hip and knee joint strategies. More work should be done to evaluate PAFPs for sloped walking using a wholistic slate of outcome measures such as balance metrics and temporal spacial parameters. There is also a need for work evaluating long term benefits or lack-there-off of PAFPs after ambulatory strategies have had time to full adjust to the device.

Keywords: powered-ankle, prosthesis, transtibial, sloped walking, joint kinetics, metabolics

1 Introduction

Walking on sloped surfaces poses significant biomechanical challenges for individuals with lower-limb amputations, including individuals with transtibial amputations (TTA) (1). Individuals with TTA must compensate for the loss of dynamic ankle functionality, often resulting in altered gait patterns and increased energy expenditure(2; 3; 4). Conventional passive prosthetic devices, while effective for level-ground walking, are limited in their ability to adapt to varying terrains, such as inclines and declines. These devices lack active control and energy return mechanisms, leading to reduced mobility and increased reliance on compensatory strategies at the knee and hip joints(5; 6). Powered ankle-foot prostheses (PAFPs) have emerged as an innovative solution to address these limitations by providing active propulsion and adaptable control during walking (7; 8). PAFPs are designed to mimic the biomechanical properties of the biological ankle, offering features such as powered plantarflexion, adjustable stiffness, and dynamic response to ground conditions (9). Unlike their passive counterparts, PAFPs can generate positive net work during walking, enabling smoother transitions and more symmetrical gait patterns (10). These characteristics are particularly important during sloped walking, where the demand for active ankle control is heightened. For instance, during uphill walking, powered prostheses can improve forward propulsion, while during downhill walking, they can aid in controlled deceleration and shock absorption (11). The effectiveness of PAFPs in addressing the unique demands of sloped walking can be evaluated through gait kinematics (12) and metabolic costs (13). Several studies have demonstrated that PAFPs can enhance these parameters, resulting in improved mobility and reduced compensatory efforts in individuals with unilateral transtibial amputations (14; 13; 12; 15). However, the variability in prosthetic designs, user populations, and experimental conditions necessitates a systematic approach to consolidate findings and identify trends. This systematic review aims to assess the effects of powered ankle-foot prostheses on gait kinematics and metabolic costs in individuals with unilateral transtibial amputations during sloped walking. By synthesizing the available evidence, the review seeks to provide a comprehensive understanding of the biomechanical benefits and limitations of PAFPs in slope-specific contexts. The findings of this review will contribute to the optimization of prosthetic designs and inform clinical practices, ultimately enhancing the mobility and quality of life for individuals with transtibial amputations.

2 Methods

2.1 Data Sources

Initial search terms were entered into multiple databases in September 2024. The search terms were "(transtibial OR trans-tibial OR tta OR below the knee OR below knee OR bka) AND (unilateral) AND (amputee OR amputees OR amputation OR prosth*) AND (slope* OR incline OR decline) AND (walking OR gait) AND (power*). These search terms yielded 65 papers. These included the databases PUBMED, SCOPUS, WEB OF SCIENCE, IEEE Xplore, MEDLINE, EMBASE, and MANUAL SEARCH 1. Forty papers were removed due to duplication done by Covidence. Papers were excluded if they were not deemed relevant during the screening of the title and abstract. Studies were not excluded due to publication date, even due to technological advancements. Papers were excluded if there was no mention of "powered" or "active" prosthetic ankle and "inclined" or "sloped" walking.

2.2 Eligibility Criteria

A paper was deemed eligible for inclusion due to the established criteria. The inclusion criteria were: 1) Populations of individuals with unilateral below-the-knee/transtibial amputation, 2) Participants walking on a sloped or inclined surface, and 3) Use of an active or powered ankle prosthetic device. Studies were excluded if having the following conditions from this literature review: individuals with above-the-knee or transfemoral amputation or prosthesis, individuals with bilateral amputations, level or even ground, rocky or uneven surfaces, passive ankle prosthesis, and powered knee prosthesis. The selection protocol is displayed in Figure 1. Each author read all the papers with a majority rules agreement to determine whether eligibility criteria were accurate before including them in the final list.

2.3 Data Extraction and Data Synthesis

The included papers were screened in full text, and population, intervention, outcomes, and results were put into an Excel sheet. The intervention was categorized by surface type (sloped treadmill or ramp) and prosthetic design. The outcome measures of interest were ankle, knee, and hip kinematics and kinetics, metabolic cost, and muscle activation.

3 Results

The search resulted in a total of 65 articles. After removing duplicates and filtering titles and abstracts for relevance there were a total of 14 articles. The 14 articles were read in full text and assessed based on the exclusion criteria resulting in a total of 7 articles included in this literature review.

3.1 Demographics

The journal articles in this literature review included individuals with unilateral transtibial amputations. Four of the included studies had a sample size of 10, with the remaining three including 8, 6, and 5 participants. Three studies had populations with a mean age of 29.7 years and the remaining four studies had an average age between 40-50 years (M=44.1). The 7 included articles had a total participant population of 44 males and 15 females. Of the 7 studies included, 4 had a control group matched by height and weight.

3.2 Hip Kinetics

Powered prostheses improved hip power dynamics in several contexts. They reduced compensatory increases in hip power absorption (12) and decreased hip power generation required for large inclines and declines, though hip power demands increased for level walking (Pickle, 2016). In early stance, powered prostheses resulted in reduced power generation and midstance power absorption compared to energy-storing prostheses. However, power generation and absorption were higher during normalized-speed walking, possibly to account for leg length differences (16).

Hip moments also varied across conditions. The prosthetic limb showed reduced hip extensor moments during loading response and reduced flexion moments during terminal stance. Intact limb hip extensor moments and power generation peaks were 36%–78% higher than able-bodied levels during early stance, with PWR prostheses increasing peak moments in loading response compared to ESR prostheses (16).

3.3 Knee Kinetics

The knee extensors in the prosthetic limb exhibited reduced power generation and range of motion compared to the intact limb and able-bodied individuals across various slopes (16; 12). Knee flexion during loading response was significantly lower in the prosthetic limb for both powered (PWR) and energy-storing-and-returning (ESR) prostheses. ESR prostheses increased knee extensor demands on the intact limb at midstance, requiring 47%–78% more effort than able-bodied levels. In contrast, PWR normalized these demands closer to able-bodied levels, reducing the burden on the intact limb (16).

The PWR prosthesis decreased intact limb knee extensor power generation relative to ESR and reduced prosthetic limb knee power generation peaks during midstance (Rábago et al., 2016). Peak knee power absorption was also lower during decline walking (12). Additionally, reductions in knee extensor moments were observed in both limbs, particularly at midstance, with prosthetic limb moments lower than able-bodied levels (16).

3.4 Ankle Kinetics

The PWR prosthesis significantly improved ankle performance compared to the ESR. Positive ankle work increased by 89% at +6° and 55% at +9°, with net ankle work increasing by up to 10 times on steep slopes (11). Peak angles and power were also greater with the PWR prosthesis compared to the ESR (13). These benefits improved propulsion and reduced compensatory demands on the intact limb.

Torque production was enhanced with the addition of parallel springs, which increased peak torque by 13.81% and reduced motor torque demand (17). Parallel springs also optimized energy use, reducing energy consumption by 19.97% (17)). However, peak push-off force with the PWR prosthesis remained 35% lower than the intact limb, suggesting some residual limitations (16).

3.5 Metabolic Cost

Powered prostheses provided significant metabolic advantages over ESR devices, particularly during incline walking. The PWR prosthesis reduced metabolic cost by 5%–26%, with the largest improvements at +6° and +9° inclines (18). Adjusted spring mechanisms further reduced metabolic cost by an average of 26.37% across slopes (17).

Improvements in symmetry also contributed to energy efficiency. Powered ankles increased net work of the affected leg by 146% at +6° and 82% at +9° compared to passive devices (11). These benefits supported greater work symmetry and reduced fatigue, enhancing mobility and quality of life for users.

4 Discussion

The positive impacts the of PAFPs on hip and knee mechanics became more pronounced on larger inclines and declines indicating that this class of devices may be particularly well suited to address the needs of people with transtibial amputations on sloped terrains. Many of the findings with regard to joint kinetics focused on lessened compensatory strategies and physical demand on the contralateral limb. This may indicate that these devices could be used to alleviate compensatory ambulatory strategies in people where they are especially pronounced.

The powered assistance of PAFPs likely lessens the power and moment generation load on the other joints and contributes to the reduced metabolic expenditure when using these devices on slopes. This reduced metabolic cost to sloped walking will likely lead to physically demanding activities such as hiking to become more accessible to those with transtibial amputations.

This class of device may perform well on some terrains and for certain tasks and not others. Given the variability in performance of the devices across different slopes this seems like it might be the case. Assessing exactly when these devices cross the threshold of performance over their passive counterparts would be useful to not only determine when these devices are useful but in what way. While there seem to be very distinct benefits to PAFPs, they remain heavy, bulky, and constrained by the quality of their controller. They also remain fairly understudied outside of a controlled lab setting. In the case of slope walking, these drawbacks seem to be outweighed by the benefits.

4.1 Limitations/Further Research

The primary limitations of this review is the limited availability of literature on this specific topic of powered ankle prostheses in sloped walking. While this field is evolving, there is little research exploring the key outcomes measures such as kinetics, kinematics, and metabolic costs of uphill walking with powered ankle prosthesis remains unexplored. The results of the review relied on a small pool of literature to extract. These articles overlapped one another, using the same participants, groups, and intervention strategies. This overlap of literature limits the diversity of reliable articles for the findings and poses challenges in generalizability.

The literature following this topic has multiple limitations in methodology and study design. All of the studies found had small sample sizes of less than 10 participants, which limits the generalizability of the findings. Many studies have fixed walking speeds of 1.25m/s, which may not reflect real-world variations in gait parameters. The acclamation periods were short for adaptation to the powered ankle (12 hours), so the affected limb was unable to take full advantage of the powered prosthesis. In addition, the studies were performed within a controlled laboratory setting. These limitations in the literature hinder the ability to draw a conclusion about the powered ankle in various settings within day-to-day life.

Future research of this topic should include more diverse populations and real-world scenarios. As the field progresses as well as technology, additional research into advancement of prosthetic design with improved energy efficiency, and adaptability should be explored. Furthermore, the use of larger cohort studies, and different prosthetic designs will address the gaps within the research and provide a stronger foundation for the field.

5 Conclusion

Our review of studies exploring the effects of the powered ankle prosthesis on sloped/inclined surfaces revealed the potential benefits and limitations. The powered ankle prosthesis has been shown to have significant improvements in gait kinematics, reduction of compensatory strategies, and improvement of metabolic cost compared to the passive prosthesis. The key results of the review included improvement in ankle power push-off, reduction in metabolic cost, and work symmetry on steeper inclines. These advances in technology suggest that the powered ankle can improve quality of life and independence in individuals with unilateral transtibial amputations.

References

[1] C. R. C. Walker, R. R. Ingram, M. G. Hullin, S. W. McCreath, Lower limb amputation following injury: a survey of long-term functional outcome, Injury 25 (6) (1994) 387–392. doi:10.1016/0020-1383(94)90132-5. URL https://www.sciencedirect.com/science/article/pii/0020138394901325

[2] D. A. Winter, S. E. Sienko, Biomechanics of below-knee amputee gait, Journal of Biomechanics 21 (5) (1988) 361–367. doi:10.1016/0021-9290(88)90142-X. URL https://www.sciencedirect.com/science/article/pii/002192908890142X

[3] D. J. Sanderson, P. E. Martin, Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking, Gait & Posture 6 (2) (1997) 126–136. doi:10.1016/S0966-6362(97)01112-0. URL https://www.sciencedirect.com/science/article/pii/S0966636297011120

[4] R. L. Waters, J. Perry, D. Antonelli, H. Hislop, Energy cost of walking of amputees: the influence of level of amputation, JBJS 58 (1) (1976) 42. URL https://journals.lww.com/jbjsjournal/abstract/1976/58010/Energy_cost_of_walking_of_amputees__the_influence.7.aspx

[5] C. Gauthier-Gagnon, M.-C. Grisé, D. Potvin, Enabling factors related to prosthetic use by people with transtibial and transfemoral amputation, Archives of Physical Medicine and Rehabilitation 80 (6) (1999) 706–713. doi:10.1016/S0003-9993(99)90177-6.

URL https://www.sciencedirect.com/science/article/pii/S0003999399901776

[6] S. R. Koehler-McNicholas, E. A. Nickel, J. Medvec, K. Barrons, S. Mion, A. H. Hansen, The influence of a hydraulic prosthetic ankle on residual limb loading during sloped walking, PLOS ONE 12 (3) (2017) e0173423, publisher: Public Library of Science. doi:10.1371/journal.pone.0173423.
URL https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0173423

[7] F. Sup, H. A. Varol, M. Goldfarb, Upslope Walking With a Powered Knee and Ankle Prosthesis: Initial Results With an Amputee Subject, IEEE Transactions on Neural Systems and Rehabilitation Engineering 19 (1) (2011) 71–78, conference Name: IEEE Transactions on Neural Systems and Rehabilitation Engineering. doi:10.1109/TNSRE.2010.2087360.
URL https://ieeexplore.ieee.org/abstract/document/5604320

[8] S. Culver, H. Bartlett, A. Shultz, M. Goldfarb, A Stair Ascent and Descent Controller for a Powered Ankle Prosthesis, IEEE Transactions on Neural Systems and Rehabilitation Engineering 26 (5) (2018) 993–1002, conference Name: IEEE Transactions on Neural Systems and Rehabilitation Engineering. doi:10.1109/TNSRE.2018.2819508.
URL https://ieeexplore.ieee.org/abstract/document/8325301

[9] H. M. Herr, A. M. Grabowski, Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation, Proceedings of the Royal Society B: Biological Sciences 279 (1728) (2011) 457–464, publisher: Royal Society. doi:10.1098/rspb.2011.1194.
URL https://royalsocietypublishing.org/doi/full/10.1098/rspb.2011.1194

[10] S. Au, M. Berniker, H. Herr, Powered ankle-foot prosthesis to assist level-ground and stair-descent gaits, Neural Networks 21 (4) (2008) 654–666. doi:10.1016/j.neunet.2008.03.006.
URL https://www.sciencedirect.com/science/article/pii/S0893608008000683

[11] J. R. Jeffers, A. M. Grabowski, Individual Leg and Joint Work during Sloped Walking for People with a Transtibial Amputation Using Passive and Powered Prostheses, Frontiers in Robotics and AI 4, publisher: Frontiers (Dec. 2017). doi:10.3389/frobt.2017.00072.
URL https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2017.00072/full

[12] N. T. Pickle, J. M. Wilken, J. M. Aldridge Whitehead, A. K. Silverman, Whole-body angular momentum during sloped walking using passive and powered lower-limb prostheses, Journal of Biomechanics 49 (14) (2016) 3397–3406. doi:10.1016/j.jbiomech.2016.09.010.
URL https://linkinghub.elsevier.com/retrieve/pii/S002192901630985X

[13] E. Russell Esposito, J. M. Aldridge Whitehead, J. M. Wilken, Step-to-step transition work during level and inclined walking using passive and powered ankle–foot prostheses, Prosthetics and Orthotics International 40 (3) (2016) 311–319, publisher: SAGE Publications Ltd STM. doi:10.1177/0309364614564021.
URL https://doi.org/10.1177/0309364614564021

[14] A. E. Ferris, J. M. Aldridge, C. A. Rábago, J. M. Wilken, Evaluation of a Powered Ankle-Foot Prosthetic System During Walking, Archives of Physical Medicine and Rehabilitation 93 (11) (2012) 1911–1918. doi:10.1016/j.apmr.2012.06.009.
URL https://www.sciencedirect.com/science/article/pii/S0003999312004327

[15] N. T. Pickle, A. M. Grabowski, J. R. Jeffers, A. K. Silverman, The Functional Roles of Muscles, Passive Prostheses, and Powered Prostheses During Sloped Walking in People With a Transtibial Amputation, Journal of Biomechanical Engineering 139 (111005) (Oct. 2017). doi:10.1115/1.4037938.
URL https://doi.org/10.1115/1.4037938

[16] C. A. Rábago, J. Aldridge Whitehead, J. M. Wilken, Evaluation of a Powered Ankle-Foot Prosthesis during Slope Ascent Gait, PLoS ONE 11 (12) (2016) e0166815. doi:10.1371/journal.pone.0166815.
URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5157979/

[17] G. Fu, W. Zhu, H. Wang, Y. Huang, J. Zhu, L. Ruan, Q. Wang, A Robotic Transtibial Prosthesis With Equilibrium-Adjustable Parallel Springs to Improve Energy Efficiency in Slope Walking, IEEE/ASME Transactions on Mechatronics (2024) 1–12Conference Name: IEEE/ASME Transactions on Mechatronics. doi:10.1109/TMECH.2024.3431277.

URL `https://ieeexplore.ieee.org/document/10645488`

[18] J. R. Montgomery, A. M. Grabowski, Use of a powered ankle-foot prosthesis reduces the metabolic cost of uphill walking and improves leg work symmetry in people with transtibial amputations, Journal of the Royal Society, Interface 15 (145) (2018) 20180442. `doi:10.1098/rsif.2018.0442`.

A APPENDIX

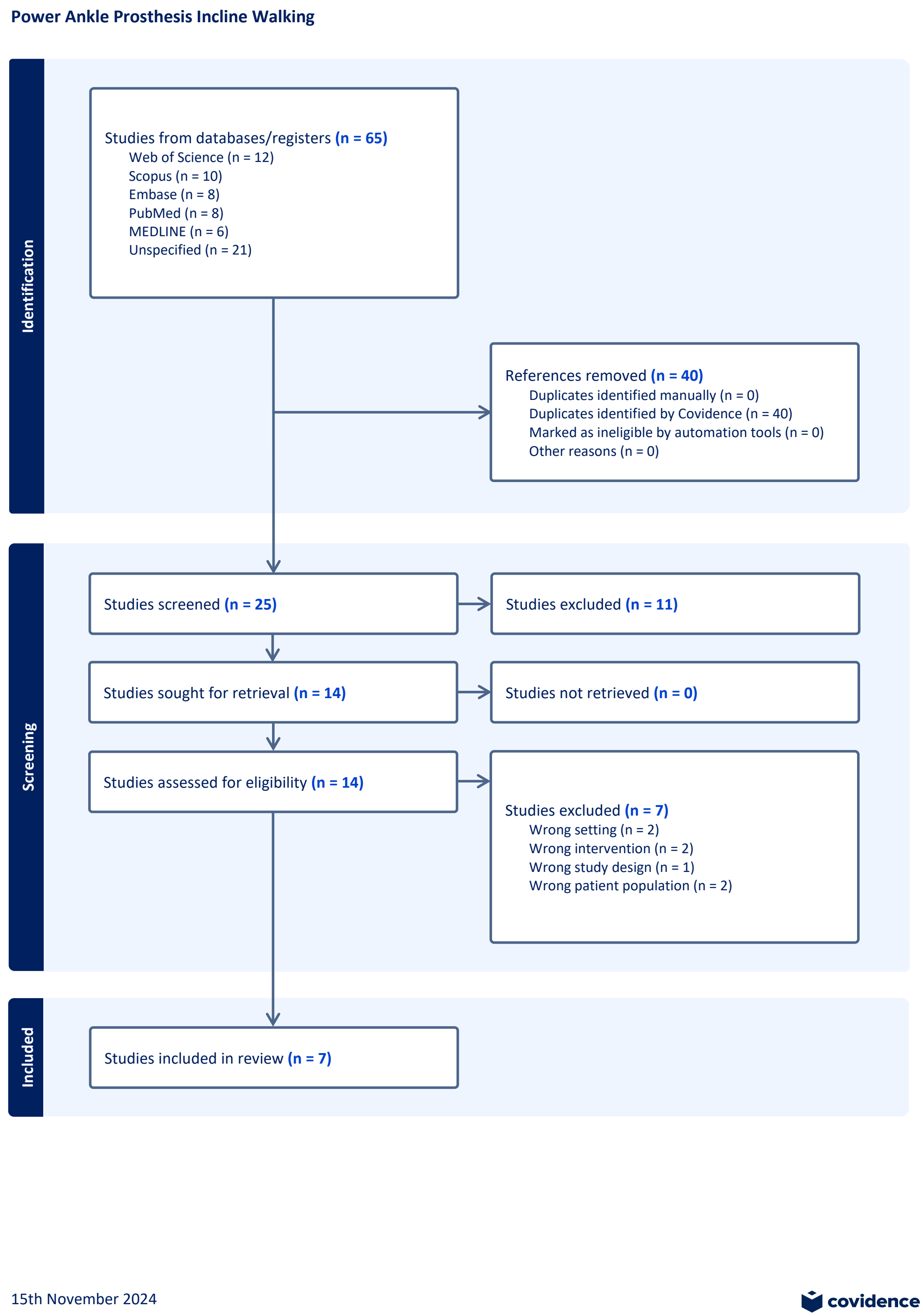

Figure 1. Covidence literature review flowchart

Citation	Article	Group	Total Sample Size	Mean Age (years)	Prosthesis	Walking Speed	Ramp/ Treadmill	Incline/ Decline
(15)	Pickle 2017	Silverman	8	45 (11)	BiOM	1.25 m/s	Treadmill	0°, ±3°, ±6°
(12)	Pickle 2016	Silverman	10	30 (5)	BiOM	1.25 m/s	Treadmill	0°, ±5°, ±10°
(18)	Montgomery 2018	Grabowski	10	42 (11)	BiOM	1.25 m/s	Treadmill	0°, ±3°, ±6°, ±9°
(11)	Jeffers 2017	Grabowski	10	42 (11)	BiOM	1.25 m/s	Treadmill	0°, ±3°, ±6°, ±9°
(17)	Guoxiang 2024	Wang	5	47.4 (12.7)	Experimental Device	0.9 m/s	Treadmill	±5°
(16)	Rábago 2016	Wilken	10	30.2 (5.3)	BiOM	Fr = 0.16	Ramp	+5°
(13)	Esposito 2015	Wilken	6	29 (6)	BiOM	Fr = 0.16	Ramp	+5°

Table 1 Experimental protocol by paper

Citation	Hip Kinetics	Knee Kinetics	Ankle Kinetics	Metabolic Cost
(15)	X	X		
(12)	X	X		
(18)				X
(11)			X	X
(17)			X	X
(16)	X	X	X	
(13)			X	X

Table 2 Outcome metrics by paper