Appendix 1: Comparing the effects of prosthetic foot types on transtibial amputee ambulation and user satisfaction: A narrative review

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***Abstract*—Lower limb amputation severely affects physical and psychosocial health, reducing quality of life. Prosthetic devices are essential for restoring mobility, with various types—passive, quasi-passive, and active—differing in biomechanical performance, energy efficiency, and user satisfaction. This narrative review compares these prosthetic foot types based on biomechanical and physiological outcomes and user satisfaction.**

Analyzing 22 studies with 171 unilateral transtibial amputees (primarily males with high activity levels), we found that active prostheses might improve gait symmetry and reduce metabolic cost of transport (MTC), though results are inconsistent. Quasi-passive feet showed better ankle kinematics and push-off power but did not reliably reduce MTC. No prosthetic type consistently outperformed the others across all parameters.

Choosing the optimal prosthetic foot is complex, as advanced prostheses may have drawbacks like increased weight and cost. Further research is needed on how different prostheses affect brain function and long-term adaptation. In conclusion, while advanced prostheses offer biomechanical benefits, the choice should consider individual needs, activity levels, and cost. More inclusive studies are needed to better guide clinical decisions and prosthetic design for diverse amputee populations.

***Index Terms*—Transtibial Amputation, Ankle Prosthesis, Biomechanical Performance, Walking Gait, User Satisfaction, Energy Efficiency, Cost**

I. Introduction

The number of individuals with lower extremity amputations in the U.S. is projected to rise to 3.6 million by 2050, with major lower limb amputations expected to account for 38% of these cases[1]. Lower limb loss has a significant negative impact on physical function and psychosocial health, leading to a diminished quality of life[2]. Following such a loss, assistive devices play a crucial role in rehabilitation, aiming to restore daily activities and enhance quality of life. Among these devices, prostheses are often preferred because they allow individuals to perform daily tasks as naturally as possible. Additionally, prosthetic use can boost self-esteem by helping individuals maintain a physical appearance closer to that of able-bodied people. On the other hand, prostheses can lead to falls and secondary injuries, such as lower back pain and osteoarthritis in the intact knee and hip, which contribute to high medical costs and reduced quality of life[3]. Additionally, lower limb prostheses can complicate the performance of daily activities. This difficulty is influenced by several factors, including the type of prosthesis, the degree of prosthetic integration, the level and cause of amputation, the individual's mobility, and the presence of comorbidities. These factors can make tasks such as foot positioning, walking on flat surfaces, navigating ramps and stairs, crossing obstacles, walking on slippery surfaces, and transitioning between activities more challenging. For example, it is well-documented that walking with a lower limb prosthesis leads to deviations in gait kinetics and spatiotemporal parameters compared to able-bodied walking[4]. These deviations are often due to the loss of proprioception, sensory feedback and the prosthetic device's inability to replicate normal muscle function. Moreover, individuals with lower limb amputations often experience significant structural and functional changes in the brain post-amputation, along with a decline in both static and dynamic balance[5]. These adverse changes increase the risk of falls, which in turn negatively impact quality of life. Beyond the physical and biomechanical effects, the psychosocial impact is equally significant and can fluctuate over the years following amputation. For instance, a person's functional status strongly correlates with overall satisfaction and quality of life, while emotional factors such as depression, anxiety, body image issues, and high pain levels tend to have a detrimental effect[6]. These challenges highlight the need for ongoing research, both short- and long-term, into how technological advancements in ankle-foot prosthetics can improve quality of life.

Specifically, the ankle joint plays a pivotal role in gait by providing net positive work during late stance; especially while walking at moderate or fast speeds. Moreover, controlled platarflexion by the ankle joint regulates whole-body angular momentum to maintain

dynamic balance during sloped walking and stair ascent/descent[7]. In subjects undergoing transtibial amputation, the ability of the ankle to facilitate the forward progression of the limb during the late stance and early swing phase remains absent. Clinical studies show that this results in the adoption of compensatory strategies by the residual and contralateral limbs; significantly increasing the metabolic energy cost compared to non-amputees. Even the most advanced prosthetic devices developed so far cannot fully replicate a biological limb's mechanics; as in controlled plantarflexion, power generation and inertial properties of the ankle joint[8]. Significant strides in terms of materials, mechanism and control system design have been made in the field of prosthetic devices giving rise to three classes of devices based on the foot mechanism; passive (Solid Ankle Cushioned Heel (SACH) Foot and Energy Storing and Return (ESR) Foot), quasi-passive and active (Powered Prosthetic Foot)[9]. The current advancements in prosthetic development are moving away from passive prostheses towards quasi-passive and active prostheses, with the aim of reducing prosthetic-related adverse events that impact quality of life[2]. This shift is a crucial aspect of lower limb prosthetic innovation. This essential aspect of lower limb prosthetic development and rehabilitation aims to restore quality of life by enhancing mobility, addressing the psychosocial challenges that follow amputation, reducing gait compensations during daily activities, and more accurately replicating the movements of an able-bodied individual. However, a systematic review comparing the benefits and drawbacks of the available ankle prosthetic devices during daily ambulatory tasks is absent. Therefore, in this literature review, we tried to compare the three classes of prostheses based on biomechanical, physiological, performance, and user satisfaction during walking gait.

II. Methods

A. Search Query

In February 2024, we performed a systematic literature review using 2 bibliographical databases; Pubmed and Web of Science, to compare the biomechanical and patient satisfaction outcomes of passive, quasi-passive and active ankle prostheses/feet. We used the following boolean combination of keywords: "comparison" AND "passive" OR "quasi-passive" AND "active" OR "powered" AND "transtibial" AND "prosthesis". The search was constrained to articles published in English. No restrictions on the publication date were used.

B. Selection Criteria

Randomised controlled trials, as well as cross-sectional, cross-over, and cohort studies, were considered. Only studies with participants with unilateral transtibial amputation were included. We excluded studies on children, upper limb amputees, bilateral transtibial amputees and transfemoral amputees. We included studies that compared passive, quasi-passive, and active ankle-foot prostheses rather than standalone studies highlighting just one type of prosthesis. Our selection strategy also aligned with reviewing the differences in the different prostheses in terms of biomechanical parameters, performance parameters, and patient satisfaction.

C. Data Extraction and Analysis

All the studies included in this review focussed on patients with unilateral transtibial amputation (TTA). The descriptive outcomes from each study following the chosen tasks performed have been presented in the form of evidence tables. We extracted data related to the type of prosthetic feet compared, tasks performed, biomechanical parameters evaluated and the results for the same.

All the biomechanical data corresponding to net metabolic cost and joint dynamics were already adjusted based on the participant inertial properties, so we made no further adjustments to the reported data prior to comparison. Based on the tasks performed by the subjects (broadly classified as walking on level terrain, uphill and downhill terrain and stair ascent/descent) the prosthetic devices were compared. All the studies included, only focussed on walking gait and the same is reflected in the review.

III. Results

A. Study selection

The search yielded 88 and 921 articles in Pubmed and Web of Science respectively. We identified the 21 unique articles from the databases and excluded irrelevant articles based on a sequential screening method (i.e. review the title, abstract and full text). Some other articles (n=1) were also included after searching references and/or the citations of the included articles using the "snowball" method. A detailed description of the process is shown as a flowchart Figure(1).

B. Study characteristics

Data from 171 participants across all the studies were compared (Table 1). The mean ± standard deviation (SD) of the participant sample size was 8 ± 3. All the studies had a predominantly male participant population (81.3%) and the participants were relatively young (mean age = 36.7 years). All the participants underwent unilateral transtibial amputation (TTA), with all of them undergoing amputation after trauma. All the participants in the included studies were categorised as community ambulators or active adults i.e. having a Medicare Functional Classification Level of K3 or K4 respectively.

95.4% of the reviewed studies compared passive and active ankle prostheses (n=21). Only one study compared passive to a quasi-passive ankle prosthesis[10].

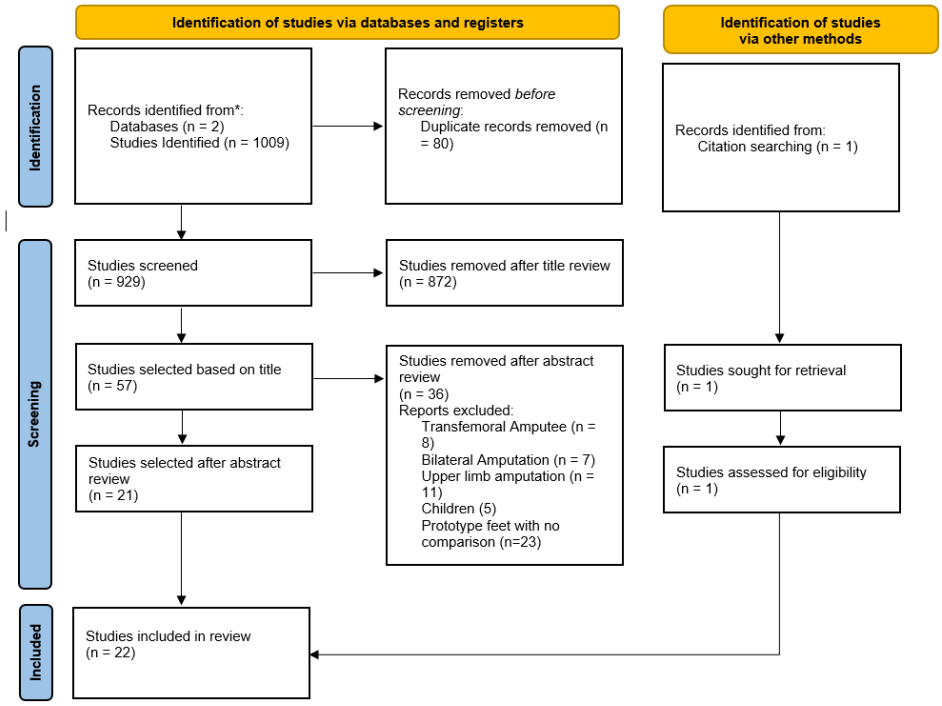

Fig. 1: Study Selection Process using the PRISMA Method

Among the studies implementing active prosthesis, 95.2% used the BiOM foot (n=20). All the passive feet studied were of the Energy Storage and Return (ESR) Foot type (n=22).

Level ground walking was the most studied ambulatory activity (n=20) followed by incline/decline walking (n=7) and stair descent/ascent climbing (n=2). All the studies (n=22) compared different biomechanical parameters such as peak ankle power, net metabolic transport cost, whole-body momentum etc. while using the different prostheses. Only one study conducted performance tests and evaluated prosthesis user satisfaction questionnaires[11].

C. Comparing prosthetic feet for level walking

Twenty studies assessed relevant biomechanical parameters to compare the different feet while participants performed level walking. When comparing passive to active feet, Montgomery and Grabowski (2018) and Esposito et al. (2014) observed a statistically significant drop in MTC when using active feet (7%-20%)[8][12]. Whereas five studies found no statistically significant reduction in MTC while using active foot when compared to their prescribed passive device[13][14][15][16][8]. Quesada et al. (2016) also used an ankle prosthetic foot emulator to evaluate the effects of assistance in the form of increasing push-off power during pre-swing. The authors found no significant changes in MTC[13]. Ingraham et al. (2018) used just an active foot (BiOM foot) and observed changes in MTC with increasing net positive work by the foot (increasing the assistance mode). They did observe a noticeable reduction in MTC with increasing assistance[17]. Mancinelli et al. (2021) and Sun et al. (2014) found that using an active/powered foot helped in replicating the ankle joint kinematics better however Fylstra et al. (2020) found no such gain[14][18][19]. Montgomery and Grabowski (2018), Esposito and Wilken (2014) and Ferris et al. (2012) indicated that active foot improved gait symmetry between the prosthetic and intact limb significantly[8][12][11]. Rabago et al. (2016) and Gates et al. (2013) reported 6% to 10% higher self-selected walking speed using the active foot[20][21]. One of these studies was performed on a custom uneven terrain showing that participants felt more comfortable with the active foot at fast speeds[21]. Based on the review the effect of an active device on the hip and knee extensor muscle activity cannot be concluded. Gates et al. (2013), Rabago et al. (2016) and Ferris et al. (2012) reported an increase in ankle range of motion with a 10° to 14° increase in ankle plantarflexion[21][20][11]. Hill and Herr (2013) and Grabowski and D'Andrea (2013) indicated a reduction in the peak ground reaction impulse on the trailing intact limb[22][23]. However, the differences in the loading rate of ground reaction impulse were not found to be statistically significant. Fylstra et al. (2020) found that the peak propulsion timing of the active foot was lagging resulting in the prosthetic limb being pushed vertically rather than anteriorly[19]. Three studies demonstrated that the peak power generated at the ankle increased significantly compared to passive and the active foot performed net positive work during stance[24][18][20]. Using the active foot,

step-to-step transition work was observed to reduce (n=2)[18][12] but one study also found no significant differences[8]. Many studies evaluated the effect of active foot on the whole body angular momentum (H) in the sagittal, transverse and frontal planes (n=3). Among them, one study reported a decrease in sagittal plane H range[25] when using active prosthesis, while the others didn't observe any differences[26][27]. In all three studies, it was found that the transverse and frontal H ranges didn't show any difference. Out of the studies which evaluated the External Knee Abduction Moment (EKAM) (n=3), Esposito and Wilken (2014) found the peak EKAM to be similar for both types of feet whereas Grabowski and D'Andrea (2013) and Hill and Herr (2013) found it to reduce by 12.1% to 20.6% with the active device[12][23][22]. No differences were observed in the EKAM loading rate (n=3). While comparing passive to quasi-passive feet, Segal et al. (2011) reported a 41% increase in ankle push-off moment during pre-swing and a 44% increase in the push-off work done by the ankle when using the quasi-passive foot. However, they observed a 12.1% increase in the MTC for the quasi-passive foot as well[10].

D. Comparing prosthetic feet for incline/decline walking

Seven studies assessed relevant biomechanical parameters to compare the different feet while participants performed incline/decline walking. Comparing passive to active feet, Esposito et al. (2014) and Colvin et al. (2022) found no statistically significant differences in MTC while Montgomery and Grabowski (2018) reported a 13% decrease in MTC when using the active foot. Colvin et al. (2022) and Pickle et al. (2017) indicated a decrease in the hip and knee extensor activity in the trailing as well as leading intact limb[15][28]. The ankle range of motion was also found to increase when wearing the active foot (n=2)[20][11]. Rabago et al. (2016) also indicated an increase in the self-selected walking speed[20]. Montgomery and Grabowski (2018) also observed an increase in the gait symmetry between the prosthetic limb and the intact limb with the active foot compared to the passive[8]. The active feet also resulted in higher peak ankle power generation (n=2)[20][11]. The effect of the active foot on step-to-step transition work by the trailing intact limb was unclear. The sagittal H range was found to decrease when using the active foot[25]. The study included comparing passive and quasi-passive feet, did not perform the tests for incline/decline walking.

E. Comparing prosthetic feet for stair ascent/descent

Two studies assessed relevant biomechanical parameters to compare the different feet while participants performed stair ascent/descent. Similar to level walking, the ankle range of motion as well as the peak ankle power and net push-off work done by the ankle was found to increase with the active foot[11]. Gait asymmetry was found to decrease with active foot compared to passive[11]. The sagittal H range was found to be similar for both types of feet[27]. The study included comparing passive and quasi-passive feet, did not perform the tests for stair ascent/descent.

F. Comparing prosthetic feet based on performance tests

One study compared passive and active feet based on performance tasks. Tasks performed include the T-Test, Four Square Step Test and the Hill and Stair Assessment Tests. No significant differences were found when using the active foot compared to the passive[11].

G. Comparing prosthetic feet based on user satisfaction

One study compared the passive and active feet using the Prosthetic Evaluation Questionnaire and Prosthetic Preference Questionnaire. The authors found that In five out of the six Prosthetic Evaluation Questionnaire subscales, the average scores were higher for the active compared to the passive foot, but none of the differences were statistically significant. Seven out of the eleven participants favoured the active foot over the passive on the Prosthetic Preference Questionnaire with the mean ± SD being 83.6 ± 18.3 millimetres[11].

IV. Discussion

Our main objective in this review was to compare the efficacy of different types of ankle prostheses in terms of walking gait biomechanics and patient comfort. Our initial hypothesis was, that active feet improve gait kinematics and kinetics as well as reduce MTC, offsetting their inherent disadvantage of cost, complexity of construction and weight. After reviewing the included studies we could not find conclusive evidence to support our initial hypothesis from the measured outcomes; due to the high heterogeneity in the results.

When switching from passive to more advanced prostheses like the quasi-passive feet, the study did observe improvements in ankle joint kinematics as well as an increase in the ankle push-off power and the net work done. This was hypothesized to reduce the MTC as previous studies tied the lack of adequate push-off in passive devices to the increase in MTC in transtibial amputees. However, the authors found the MTC to increase by 12.1% when using the quasi-passive foot[10]. This result was claimed to be due to the higher weight, lack of subject-specific size, and stiffness of their prototype foot. The authors did a subsequent study tailoring their prosthesis to the participants' specifications. This reduced the MTC by 9% compared to conventional passive feet[29].

Table 1: Study Characteristics

Author	Prosthetic Comparison	Participant	Tasks performed	Measured parameters	Results
Mancinelli et al. 2011	Passive elastic (Ceterus by Ossur) VS Active (Powerfoot BiOM)	• Number of Subjects: 5 • Age: 39.4±9yrs • Gender: M • Weight: - • Type of amputation: Unilateral Traumatic Transtibial Amputation (TTA)	• Level walking Overground indoor track	Biomechanics: • Ankle Angles • Ankle Peak power generation (PPG) • Metabolic Transport Cost (MTC)	• Kinetic and kinematics parameters measured with BiOM closer to normal gait biomechanics • MTC reduced on average by 8.4% (not statistically significant)
Colvin et al. 2022	Passive Elastic (participants' prescribed feet) VS Active (BiOM T2)	• Number of Subjects: 10 • Age: 42±11yrs • Gender: 6M/4F • Weight: 81.3±14.7kg (with BiOM), 79.7±15kg (with prescribed feet) • Type of amputation: Unilateral TTA	• Level walking Ground • Inclined walking ±3, ± 6 and ±9 ° on a treadmill	Biomechanics: • sEMG • GRFs • MTC	• No statistically significant changes in MTC • Hip and knee extensor iEMG and peak EMG reduced with BiOM for both legs
Takahashi et al. 2014	Passive Elastic (Elation by Ossur) VS Active (BiOM)	• Number of Subjects: 12 • Age: 36yrs (amputee) 24.2±2.9yrs (healthy controls) • Gender: 6M/6F • Weight: 80.7kg (amputee), 75.3±21.8yrs (healthy controls) • Type of amputation: Unilateral TA	• Level walking Treadmill	Biomechanics: • Limb and joint kinematics • GRF	• BiOM generated higher peak power as well as performed net positive work at the ankle joint

Pickle et al. 2017	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 8 • Age: 30±8yrs • Gender: 7M/1F • Weight: 72±8kg • Type of amputation: Unilateral TTA	• Inclined walking ±3 and ±6 ° sloped walking on a treadmill	Biomechanics: • Whole body kinematics • GRF • EMG	• Power generated by contralateral and ipsilateral hamstrings reduced by 32% and 44% respectively, when using BiOM • On average rectus femoris generated 49% less power with BiOM
Montgomery and Grabowski 2018	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 10 • Age: 42±11yrs • Gender: 6M/4F • Weight: 81.3±14.7kg • Type of amputation: Unilateral TTA	• Level walking Treadmill • Inclined walking ±3, ± 6 and ±9 ° on a treadmill	Biomechanics: • Joint and limb kinematics • GRF • MTC	• No significant changes in step-to-step transition work when using BiOM • BiOM improved gait symmetry by 212% • MTC reduced by 13% for uphill walking. No significant changes for level ground walking
Kim et al. 2021	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 10 • Age: 46.5±14.9yrs • Gender: M • Weight: - • Type of amputation: Unilateral TTA	• Level walking Treadmill	Biomechanics: • EMG • MTC	• Higher activity of the ipsilateral vastus medialis and contralateral gluteus medius with BiOM • No significant changes in MTC when using BiOM
Pickle et al. 2016	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 10 • Age: 24±5yrs • Gender: 9M/1F • Weight: 91±10kg • Type of amputation: Unilateral TTA	• Level walking Treadmill • Inclined walking ±5 and ±10 ° sloped walking on a treadmill	Biomechanics: • Whole body kinematics • GRF	• 3% reduction in range of whole body angular momentum (H) in sagittal plane with BiOM • No significant changes in range of H for transverse

					and frontal planes with the different feet
Sun et al. 2014	Passive Elastic (participants' prescribed feet) VS Active (SPARKY)	• Number of Subjects: 1 • Age: - • Gender: M • Weight: 86.5kg • Type of amputation: Unilateral TTA	• Level walking 10m walkway	Biomechanics: • Kinematics with Helen-Hayes marker set • GRF	• Ankle kinematics closer to normal gait when using powered • SPARKY generated 10% more moment during the stance phase
Pickle et al. 2014	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 9 • Age: 30±6yrs • Gender: 8M/1F • Weight: 94.5±7.8kg • Type of amputation: Unilateral TTA	• Level walking • Stair ascent/descent 16step staircase with 18cm rise over 26.5cm run	Biomechanics: • Whole body kinematics • GRF	• Sagittal plane range of H were similar for both prostheses during both stair ascent and descent
Esposito et al. 2014	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 6 • Age: 29±6yrs • Gender: 5M/1F • Weight: 92.7±6.3kg (including the prosthesis) • Type of amputation: Unilateral TTA	• Level walking Treadmill • Inclined walking ±5 ° sloped walking on a treadmill	Biomechanics: • Whole body kinematics • GRF • MTC	• 53% more net trailing residual limb step-to-step transition work by BiOM • 16% lower MTC with BiOM for level walking • For inclined walking no significant differences
Gates et al. 2013	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 11 • Age: 30±5yrs • Gender: 10M/1F • Weight: 95±7.3kg • Type of amputation: Unilateral TTA	• Level walking Uneven terrain (loose rock surface)	Biomechanics: • Whole body kinematics • GRF	• 10% higher self-selected walking speed when using BiOM • No differences in step-width and step length variability

					• Increased ankle plantarflexion with BiOM by 10° • No significant differences in medial-lateral margins of stability between the two device types
Esposito and Wilken, 2014	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 10 • Age: 30.2±5.3yrs • Gender: 9M/1F • Weight: 95.8±7.3 • Type of amputation: Unilateral TTA	• Level walking Overground	Biomechanics: • Whole body kinematics • GRF	• No significant difference in peak external knee abduction moment (EKAM) for the two prostheses in the sagittal plane • BiOM reduced the peak GRF by 7% at fast and moderate speeds for the contralateral limb • At fastest speed 12% GRF asymmetry seen with passive • Loading rates of the contralateral limb lower with BiOM at fast and moderate speeds
Fylstra et al. 2020	Passive Elastic (participants' prescribed feet) VS Active (BiOM T2)	• Number of Subjects: 5 • Age: 38yrs (median) • Gender: 4M/1F • Weight: 101kg (median) • Type of amputation: Unilateral traumatic TTA	• Level walking Treadmill	Biomechanics: • Whole body kinematics • GRF	• No significant improvement of the ankle joint mechanics with BiOM • Peak propulsion timing with BiOM earlier pushing the shank vertically instead of anteriorly

Au et al. 2007	Passive Elastic (Flex-Foot Ceterus and Freedom Innovations Sierra) VS Active (BiOM)	• Number of Subjects: 3 • Age: 40-57yrs • Gender: M • Weight: 71-86kg • Type of amputation: Unilateral TTA	• Level walking Overground	Biomechanics: • MTC	• BiOM reduced the MTC by 7% to 20% compared to passive
Grabowski and D'Andrea, 2013	Passive Elastic (participants' prescribed feet) VS Active (BiOM T2)	• Number of Subjects: 7 • Age: 45±6yrs • Gender: M • Weight: 99.5±10.2kg • Type of amputation: Unilateral TTA	• Level walking Treadmill	Biomechanics: • Whole body kinematics • GRF	• Peak GRF on the unaffected leg was 6.6% lower with BiOM at slow and moderate speeds • Peak EKAM of the unaffected leg was 20.6% and 12.2% lower at moderate and fast speeds • GRF and EKAM loading rates didn't differ significantly
Hill and Herr, 2013	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 2 • Age: 28, 40yrs • Gender: M • Weight: 72.1, 69.3kg • Type of amputation: Unilateral TTA	• Level walking Overground	Biomechanics: • Whole body kinematics • GRF	• With BiOM 8% reduction in peak impact GRF • 18% reduction in GRF loading rate • 8% reduction in peak heel strike impact foot pressure • 15% reduction of peak EKAM
Rabago et al. 2016	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 10 • Age: 30.2±5.3yrs • Gender: 9M/1F • Weight: 96.1±6.8kg • Type of amputation: Unilateral TTA	• Inclined walking ±5 ° sloped walking on stationary platform	Biomechanics: • Whole body kinematics • GRF	• 6% increase in self-selected walking speed with BiOM • 8% increase in ipsilateral ankle power generation

					• BiOM resulted in greater peak ankle plantarflexion (13°) and peak power generation (103%) at preswing
Ferris et al. 2012	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 11 • Age: 29.8±5.3yrs • Gender: 10M/1F • Weight: 95±7.3kg • Type of amputation: Unilateral TTA	• Level walking Overground • Inclined walking -10 ° sloped walking on a platform • Stair ascent/ descent 16 steps	Biomechanics: • Whole body kinematics • GRF Performance: • T-Test • Four Square Step Test • Hill and Stair Assessment Tests User Satisfaction: • Prosthetic Evaluation Questionnaire (EQ) • Prosthetic Preference Questionnaire (PQ)	• BiOM ankle ROM 30% greater than the passive • 12% reduction in peak plantarflexion asymmetry with BiOM • Peak ankle moment and power 40% and 125% higher with BiOM • No significant difference in performance tests • BiOM mean scores higher in 5/6 in EQ • 7/11 individuals preferred BiOM with 83.16±18.3mm difference on PQ
Quesada et al. 2016	Used prosthesis emulator to compare passive and powered ankle devices	• Number of Subjects: 6 • Age: 47±6yrs • Gender: M • Weight: 87.8±8.5kg • Type of amputation: Unilateral TTA	• Level walking Treadmill	Biomechanics: • Whole body kinematics • GRF • MTC • EMG	• No statistically significant difference in MTC

Ingraham et al. 2018	Active (BiOM) at different powered assist levels	• Number of Subjects: 10 • Age: 41.7±15.5yrs • Gender: M • Weight: 92.9±19.5 • Type of amputation: Unilateral TTA	• Level walking Treadmill	Biomechanics: • Whole body kinematics • GRF • MTC	• Increasing power assist reduced MTC
Andrea et al. 2014	Passive Elastic (participants' prescribed feet) VS Active (BiOM)	• Number of Subjects: 8 • Age: 47±8yrs • Gender: - • Weight: 98.6±9.7kg • Type of amputation: Unilateral TTA	• Level walking Treadmill	Biomechanics: • Whole body kinematics • GRF	• No significant differences in H range in all the planes
Segal et al. 2011	Passive Elastic (participants' prescribed feet) VS Quasi-passive (Controlled Energy Storage and Return (CESR) Foot)	• Number of Subjects: 7 • Age: 52.3±12yrs • Gender: M • Weight: 80.9±9.9kg • Type of amputation: Unilateral TTA	• Level walking Overground and treadmill	Biomechanics: • Whole body kinematics • GRF • MTC	• CESR resulted in 41% increase in peak ankle power compared to passive • CESR increased push-off work by 44% • CESR increased MTC by 12.1%

The advantages of transitioning from quasi-passive to active feet are unclear as no study has conducted experiments to compare them thus far. The evaluation of the biomechanical and performance measures when switching from passive to active prosthesis have been mixed. During level walking active devices did improve gait symmetry compared to passive feet although being significantly less than able-bodied gait. Gait asymmetry has been indicated to result in adaptive behaviours which increase the activity of the related muscles in the contralateral intact limb and further increase the metabolic cost. Thus theoretically this should result in a reduction in MTC when using active feet. However, five studies found no significant drop in MTC when using active feet compared to passive. This was assumed to be due to less time familiarising with the device. All the participants in those studies previously used passive ESR feet and although short-term familiarization training trials were conducted, the long-term effects need to be studied. Moreover, no reduction in MTC, even with a significant increase in the ankle push-off work as well as an increase in the net positive work done by the ankle when using the active feet, indicates augmenting or restoring ankle push-off work does not affect the overall walking energy economy. This decoupling might be a result of the lack of individualised tuning of the powered prosthesis and thus the effects of alternate tuning or control of the peak propulsion push-off torque by the active feet need to be observed[13]. Also compared to conventional passive devices, active devices weigh significantly more. Studies show that a 1 kg mass placed at the foot can increase the MTC by 8-9% during walking[29]. An increase in EKAM results in the development of early-onset knee osteoarthritis. Thus since EKAM in the intact limb has been seen to increase due to the adopted compensatory mechanisms after TTA, authors conducted experiments to see whether an active device can mitigate this. Majority of the studies indicate that peak EKAM in the intact knee reduced by 12.2% to 20.6% subject to the walking speed; when using the active prosthesis. This shows that active prosthesis can reduce dependence on the intact limb and associated risk of developing osteoarthritis. However, no significant differences were observed when comparing the loading rate of the EKAM. While the physical performance of the active and passive prostheses produced similar results, user satisfaction needs to be evaluated to assess the long-term adaptability of the device. In the study done by Ferris et al. (2012), Prosthetic Preference Questionnaire responses show that participants had a preference for the active device (BiOM Foot)[11]. This result was assumed to be due to the net positive work done by the foot in terms of additional plantarflexion during push-off and its perceived benefits on subject gait. Thus based on the above comparative results it is difficult to ascertain whether the benefits of using an active prosthesis will significantly outweigh its passive counterpart. In the included studies the prostheses were evaluated with an emphasis on walking biomechanics, primarily addressing abnormal movement patterns that can be corrected in the short term by using the prosthesis. However, these movement patterns are influenced by a complex interaction between biomechanical factors and the brain, highlighting the brain's crucial role in controlling and executing human gait. Research using magnetic resonance imaging has shown that amputation leads to thinning of the premotor cortex and visuomotor areas, along with reduced white matter integrity in the premotor region opposite the site of amputation, and within the bilateral connection between the premotor cortices. These brain changes can disrupt movement planning, coordination of eye and limb movements, and perception-action coupling[2]. Amputation also alters limb representation in the primary motor and somatosensory cortices and reduces connectivity among various brain regions, including the primary motor cortex, somatosensory cortex, basal ganglia, thalamus, and cerebellum[2]. These changes may result in impaired motor control and balance, increasing the risk of falls. Interestingly, none of the studies in this review examined the impact of different prosthetic ankle-foot devices on brain function. Given the short duration of prosthetic comparison experiments, the lack of observed effects would not be surprising, as neuroplasticity is a gradual process requiring ample time for adaptation. Understanding how neuroplasticity relates to different prosthetic types could provide valuable insights into improving the quality of life for individuals with lower limb amputations.

V. Generalizability of Results

All the participants included in the studies underwent amputation due to past trauma, were relatively young, male (81.3%) and fairly active with daily ambulation levels of K3 or K4. This is not reflective of the general demographic of patients with transtibial amputation. For instance, none of the participants underwent amputation due to dysvascular disease and can be classified as limited ambulators (K1 or K2 level) based on their activity level in the included studies, compared to the dysvascular transtibial amputee population (80%) and the prosthesis users classified as limited ambulators in clinical practice (44%)[30]. The focus on higher-level amputees might lead to an unintentional bias in prosthetic design and research, where the needs and preferences of lower-level amputees are underrepresented or overlooked. This could result in the development of prosthetic solutions that are not well-suited to the majority of amputees who fall within the K1 or K2 categories. Moreover, the reported proportion of male participants is not representative of the amputees by sex (65% male)[30]. Given these limitations, the inferences drawn from the included

studies cannot be generalised for dysvacular amputees, women, old individuals or people at low levels of community ambulation. Studies included in this report do not consider the cost and accessibility of the prostheses. In low-income countries, simpler and cheaper prostheses like the Solid Ankle Cushion Heel (SACH) foot are predominantly used[9]. Although they are biomechanically inferior compared to the ESR and quasi-passive feet, they are significantly more affordable. Moreover, Higher-level prosthetics designed for K3 or higher amputees tend to be more expensive and may not be cost-effective or reimbursable for lower-level amputees. This could limit the practical utility of findings from K3-focused studies for a broader population.

VI. Clinical Implications

The metabolic energy cost is crucial for determining the efficiency of a prosthesis. Active ankle prostheses, which often include powered components, were observed to reduce the energy expenditure required for walking, especially on level terrain. This can be beneficial for amputees with higher activity levels (e.g., K3 or K4). However, for those with lower activity levels (e.g., K1 or K2), the added weight and complexity of active devices might not justify the potential energy savings. Angular momentum plays a role in maintaining balance and preventing falls. Active prostheses, with their ability to provide powered propulsion and more dynamic control, can help regulate angular momentum more effectively than passive devices in the sagittal plane. This might be particularly important for patients at risk of falls or those with compromised balance. Passive prostheses often result in significant gait asymmetry due to their lack of adaptability and responsiveness. This asymmetry can lead to compensatory mechanisms, which may cause long-term musculoskeletal issues. Active feet are generally more effective at reducing gait asymmetry by providing propulsion and adapting to various walking speeds and terrains, leading to a more natural and symmetric gait. Clinically, this can reduce the risk of secondary injuries, such as joint pain or osteoarthritis in the intact limb. Selecting the appropriate prosthesis based on stability and gait symmetry can reduce the risk of long-term complications such as joint degeneration, muscle overuse, and chronic pain, particularly in the intact limb.

VII. Conclusion

This review examined the differences in quality of life among individuals with lower limb amputations using passive, quasi-passive, and active prostheses, based on biomechanical, physiological, performance, and user satisfaction. Quasi-passive and active prostheses in some studies were found to enhance biomechanical functions like reduction in MTC, increase in stability in the sagittal plane, closer replication of normal gait kinematics etc. compared to passive ankle-foot prostheses. While the short-term therapeutic benefits of more advanced prostheses have been demonstrated, inconsistencies in outcome measures persist. The impact of the brain on prosthetic function is underexplored, and the long-term benefits are still uncertain. Further research into these areas could potentially enhance the quality of life for people with lower limb amputations.

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