DOI: https://doi.org/10.62017/jkmi

Impact of Balance and Fitness Training on Fall Risk Reduction in Prosthesis Users Post-Amputation: Systematic Literature Review

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Abstrak

Latar Belakang: Risiko jatuh pada pengguna prostesis pasca amputasi masih menjadi tantangan utama dalam rehabilitasi karena berkaitan dengan gangguan keseimbangan postural, asimetri gaya berjalan, serta penurunan kepercayaan diri. Tujuan: Menganalisis dampak latihan keseimbangan dan latihan kebugaran dalam menurunkan risiko jatuh pada pengguna prostesis pasca amputasi serta memetakan tren penelitian terkini. Metode: Penelitian ini menggunakan Systematic Literature Review (SLR) dengan protokol PRISMA dan analisis bibliometrik yang dibantu oleh VOSviewer. Proses seleksi dilakukan terhadap artikel yang diterbitkan pada periode 2020–2025 dengan kriteria inklusi yang mencakup topik keseimbangan, kebugaran, dan risiko jatuh pada amputee. Dari 205 artikel awal, sebanyak 30 artikel dinyatakan memenuhi kriteria untuk dianalisis. Hasil: Hasil analisis mengidentifikasi tiga sumbu pengetahuan utama, yaitu karakteristik amputee dan pola gaya berjalan, penilaian risiko jatuh berdasarkan parameter klinis dan teknologi, serta luaran jatuh dan cedera; yang didukung oleh tema intervensi kognitif seperti action observation therapy. Distribusi artikel menunjukkan peningkatan signifikan pada tahun 2025 (30%), yang mengindikasikan fokus penelitian terkini pada rehabilitasi yang bersifat personal, pemanfaatan teknologi sensor, serta strategi latihan dual-task. Pembahasan: Sintesis hasil penelitian menegaskan bahwa latihan keseimbangan dan kebugaran efektif dalam meningkatkan stabilitas dinamis, mengurangi variabilitas langkah, dan meningkatkan kepercayaan diri. Integrasi teknologi seperti perangkat wearable, machine learning, serta kerangka klinis ERAS memperluas pilihan dalam penilaian dan implementasi program rehabilitasi. Kesimpulan: Latihan keseimbangan dan kebugaran terbukti penting sebagai pendekatan multidimensional yang tidak hanya menargetkan aspek fisik, tetapi juga aspek psikososial dan klinis, sehingga mendukung upaya pencegahan jatuh pada pengguna prostesis pasca amputasi.

***Kata kunci**: latihan keseimbangan, latihan kebugaran, risiko jatuh, pengguna prostesis*

Abstract

Background: The risk of falling among post-amputation prosthesis users remains a major challenge in rehabilitation due to its association with postural imbalance, gait asymmetry, and decreased self-confidence. Objective: To analyze the impact of balance training and fitness training on reducing the risk of falling among post-amputation prosthesis users and to map current research trends. Methods: This study used a Systematic Literature Review (SLR) with the PRISMA protocol and bibliometric analysis assisted by VOSviewer. The selection process was carried out on articles from 2020–2025 with inclusion criteria on the topics of balance, fitness, and fall risk in amputees. From 205 initial articles, 30 articles were eligible for analysis. Results: The analysis revealed three main knowledge axes, namely amputee characteristics and gait patterns, fall risk assessment based on clinical and technological parameters, and fall/injury outcomes; supported by cognitive intervention themes such as action observation therapy. The distribution of articles showed a significant increase in 2025 (30%), indicating a current research focus on personalized rehabilitation, the use of sensor technology, and dual-task exercise strategies. Discussion: The synthesis results confirm that balance and fitness training effectively improve dynamic stability, reduce step variability, and improve confidence. The integration of technologies such as wearables, machine learning, and the ERAS clinical framework expands the options for assessment and program implementation. Conclusion: Balance and fitness training are proven to be important as a multidimensional approach that targets not only physical aspects but also psychosocial and clinical aspects, thereby supporting fall prevention in post-amputation prosthesis users.

***Keywords**: balance training, fitness training, fall risk, prosthesis users*

INTRODUCTION

The risk of falling is one of the main challenges for post-amputation individuals who use prostheses, because the loss of a lower limb affects balance, coordination, and gait patterns. Falling not only causes physical injury, but also affects an individual's self-confidence, quality of life, and level of social participation. In the context of rehabilitation, fall prevention is an important aspect that must be considered so that prosthesis users can adapt optimally to their new physical condition (Miller et al., 2019). Efforts to reduce the risk of falls in post-amputation prosthesis users are often associated with training-based interventions, particularly balance training and fitness training. Both approaches have been shown to have the potential to strengthen muscles, improve proprioception, and improve postural control strategies that are weakened due to amputation. Previous literature emphasizes that physical training is not only oriented towards physical recovery, but also supports psychosocial dimensions, such as increased self-confidence and reduced anxiety about falling (Sawers & Hafner, 2018).

The need for more structured interventions is becoming increasingly urgent as the number of amputations due to chronic diseases such as diabetes mellitus and peripheral vascular disease increases, especially in developing countries. This phenomenon has implications for the increasing burden on rehabilitation services, making an evidence-based approach through systematic reviews essential for mapping the effectiveness of programs that have been implemented (Ziegler-Graham et al., 2008). A Systematic Literature Review (SLR) supported by bibliometric analysis using tools such as VOSviewer can provide a knowledge map of research trends, inter-topic relationships, and remaining research gaps. This approach allows researchers to understand the extent to which balance and fitness training have been studied in the context of prosthesis users, as well as the direction of future research development (van Eck & Waltman, 2017).

In addition, this study has academic and practical urgency. From an academic perspective, the results of SLR and mapping can contribute to strengthening the theoretical framework related to amputation rehabilitation. From a practical perspective, this study can be a reference for physiotherapists, medical personnel, and rehabilitation program designers to formulate evidence-based fall prevention strategies. Thus, this study is relevant both for the development of science and the improvement of health service quality (Highsmith et al., 2016).

This background also highlights the existence of a knowledge gap. Although a number of studies have examined rehabilitation interventions, there is still limited research that specifically focuses on the physiological and psychosocial mechanisms of balance and fitness training in the context of fall prevention in prosthesis users. Therefore, this study was conducted to fill this gap with a systematic approach and comprehensive knowledge network visualization (Gailey et al., 2019). Based on this description, the purpose of this study was to identify and analyze the impact of balance and fitness training on fall risk reduction in post-amputation prosthesis users through a systematic literature review and to map research trends and gaps with the help of VOSviewer.

METODE

This study used a systematic literature review and bibliometric analysis (Bartolini et al., 2019; Huang et al., 2020). The protocol stages used as a basis or guide were the PRISMA Protocol, which consisted of identification, screening, eligibility, and inclusion (Page et al., 2021). The bibliometric analysis procedure began with determining the research objectives, formulating the research questions, and formulating a search strategy to collect the dataset (Huang et al., 2020). This study combines the systematic SLR and bibliometric analysis stages because they have similar procedures, starting from determining the research objectives, formulating research questions, developing a search strategy for data collection, and conducting analysis. The entire series of activities in this review was carried out systematically, including the dataset search stage.

The entire series of activities during the review of this article was carried out systematically. The flow of actions specified in the design (planning section) was followed to guide the implementation of the research. A decade's worth of data sets was considered sufficient to track research developments in this field. The dataset collection phase began chronologically by (1) opening Google Scholar, ScienceDirect, or PubMed; (2) entering search keywords as listed in Table 1 in the title, abstract, and keyword search fields. The keywords used are: ("platelet-rich plasma" OR PRP) AND (injection OR therapy OR treatment) AND ("chronic tendinopathy" OR "tendon injury" OR tendinitis OR tendinosis) AND ("evidence-based review" OR systematic OR meta-analysis) ; (3) then, set the document type (articles and reviews); and (4) set the year

DOI: https://doi.org/10.62017/jkmi

(between 2020 and 2025); (5) SLR extraction where the SLR protocol formulation: Designed to answer three main questions:

1. RQ1: How can knowledge mapping related to the use of Platelet-Rich Plasma (PRP) in the treatment of chronic tendinopathies be identified through bibliometric analysis with VOSviewer?
2. RQ2: What are the biological and clinical mechanisms that explain the effectiveness of PRP injection therapy in comparing the treatment outcomes of chronic tendinopathies with conventional methods or other alternative therapies?
3. RQ3: How can the results of a literature review on the role of PRP injections in chronic tendinopathies provide implications for clinical practice, treatment guidelines, and future research directions in the field of orthopedics and musculoskeletal rehabilitation?

Meanwhile, the next process is document screening or extraction by applying the inclusion and exclusion criteria established in the previous identification stage. At this stage, all articles and reviews are extracted (screened) to determine the data suitable for SLR analysis. The selection criteria are presented in Table 1.

Table 1. Selection Criteria

No.	**Exclusion Criteria**	**Exclusion Results**
1	Articles written in English	30 Articles in languages other than English
2	Articles that do not meet the criteria (no keywords in the title, abstract, or keywords)	84 related articles
3	Duplicates	3 related articles

Data extraction using the exclusion criteria described above yielded 117 articles. The articles were then assessed for eligibility. The collected data will be evaluated using the following quality assessment criteria:

1. Was the article published in a journal listed in Google Scholar, ScienceDirect, or PubMed between 2020 and 2025?
2. Does the article cover the concept of Impact of Balance and Fitness Training on Fall Risk Reduction in Prosthesis Users Post-Amputation?

If the questions asked are correct, then the article passes the quality assessment for eligibility.

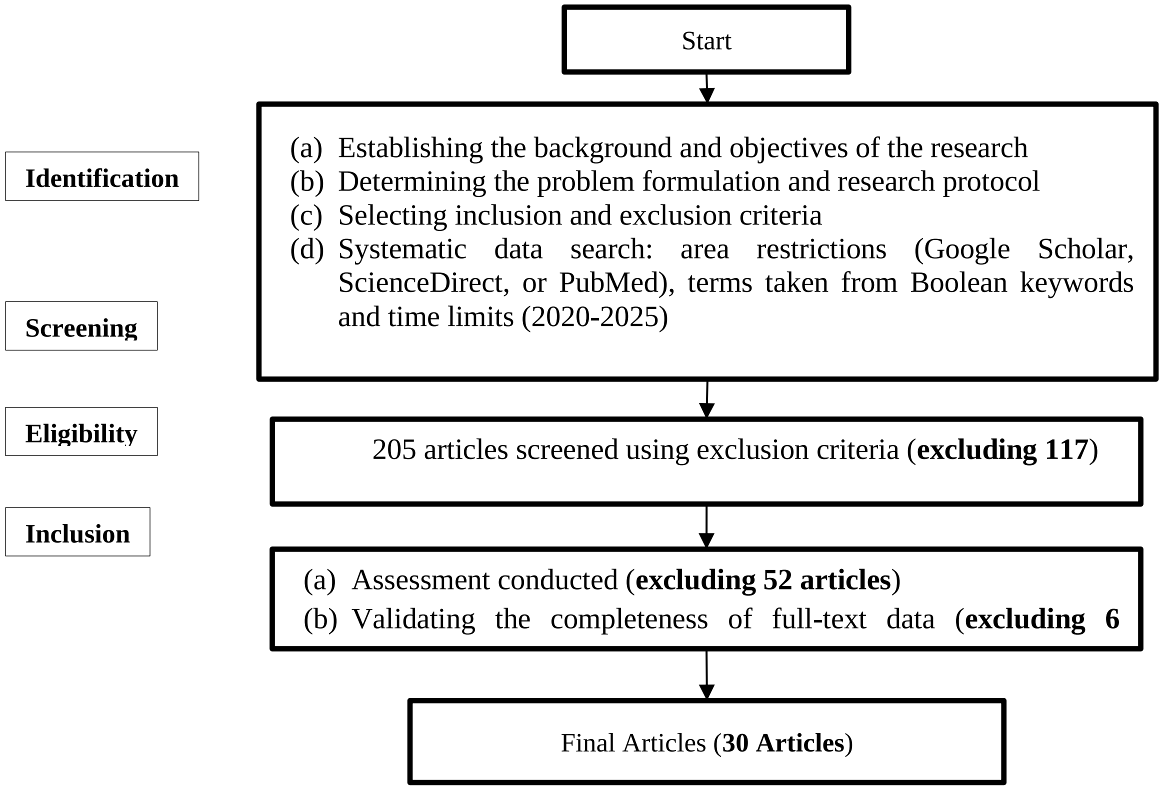

Figure 1. PRISMA Flow Diagram

The flowchart in Figure 1 summarizes the details of the SLR and bibliometric analysis in the following steps: (1) Identification of articles based on keywords. Systematic data search from Google Scholar, journal articles from 2020 to 2025 (2) in screening, 205 articles were extracted using exclusion criteria. A total of 117 articles were excluded, and 88 articles proceeded to the next level; (3) in terms of eligibility, the articles had to be validated and completed, and (4) finally, 30 full-text articles that were eligible for systematic literature analysis were included, and their content was reviewed manually. Data synthesis was continued with the extraction of article data corresponding to the Research Question (RQ) described in thematic form.

RESULTS AND DISCUSSION

RQ1: How can knowledge mapping related to balance and fitness training in reducing the risk of falls in post-amputation prosthesis users be identified through bibliometric analysis with VOSviewer?

Network Visualization VOSviewer maps keyword relationships into thematic clusters so that RQ1 can be answered: the knowledge map on balance and fitness training to reduce the risk of falls in post-amputation prosthesis users is organized around three axes amputee characteristics and gait patterns, fall risk assessment and gait parameters in the elderly, and fall/injury outcomes as well as two supporting axes related to action observation-based interventions and transfemoral context. This mapping confirms that exercise interventions, prosthetic design/devices, and objective-subjective assessment strategies are interconnected through longitudinal evidence, clinical trials, and sensor-based technology reviews.

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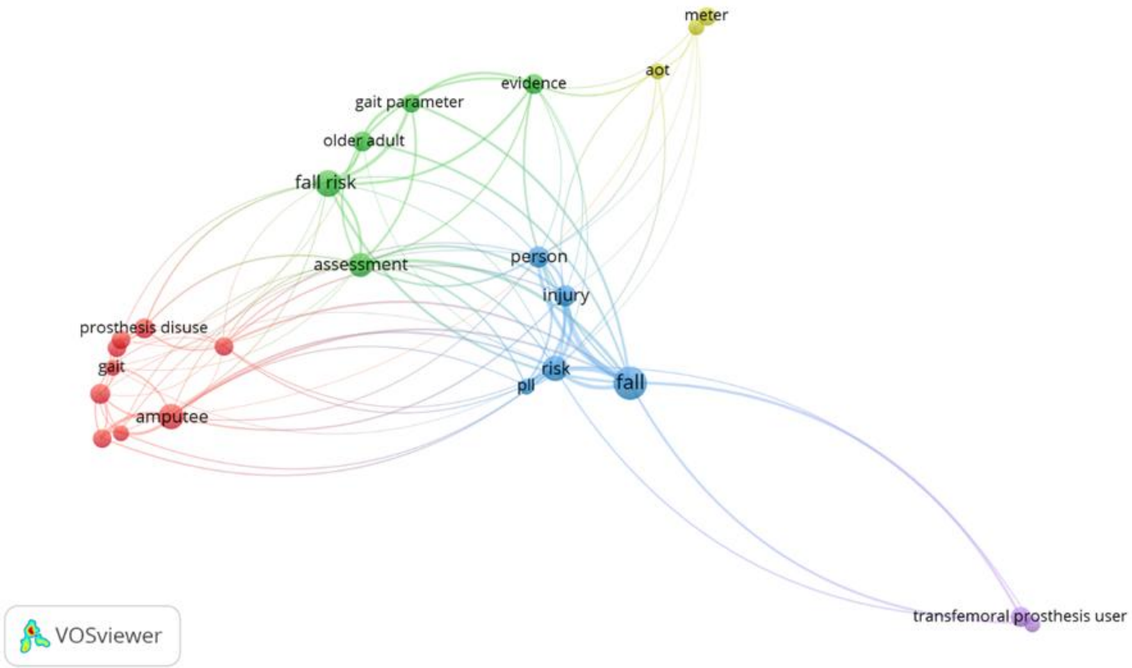

Figure 2. Network Visualization Vosviewer

The mapping results in Network Visualization describe Cluster 1 (red) connecting amputee, balance, body segment, effect, gait, individual, lower limb amputee, prosthesis disuse, and transtibial amputation. This node ties together evidence of postural control imbalance in minor lower limb amputation and the benefits of orthotics/prosthetics for stability (Acien et al., 2025), improved function after Ewing amputation (Berger et al., 2025), and increased movement asymmetry in high-demand mobility tasks compared to flat walking (Christensen et al., 2020). Dual-task training improves walking speed, mobility, cognitive function, and sleep quality in transfemoral amputees (Demirdel & Erbahçeci, 2020), while concurrent tasks affect step variability in transtibial and transfemoral amputees (Demirdel et al., 2022). Amputation level alters asymmetry and cautious gait, requiring tailored rehabilitation (Pantera et al., 2025). Trunk movement variations during sit-to-stand associated with low back pain signal the need for sensor-based movement retraining (Parr et al., 2025). Episodes of prosthesis disuse reduce balance confidence and daily steps, thereby increasing the risk of falls (Rosenblatt et al., 2021). Nonlinear cross-segmental body dynamics analysis reveals instability in acceleration/angular velocity patterns on the amputation side (Krauskopf et al., 2025). A 12-week personalized exercise program enhances somatosensory integration in postural control, though it does not always improve balance confidence (Schafer & Vanicek, 2021).

Cluster 2 (green) connects assessment, evidence, fall risk, gait parameters, and older adults. Fall risk assessment in older adults shows multi-factorial determinants such as gender, foot comorbidities, and lower extremity weakness (Bekele et al., 2020). A scoping review on elderly prosthesis users highlights the limitations of single measures; a combination of clinical tests and gait parameters is more informative (Finco et al., 2023). TUG-based virtual assessment is feasible at home to reduce the burden of therapy (DadeMatthews et al., 2024). A review of the Ten-Meter Walk Test emphasizes the role of mobile/wearable sensors and calibration for the accuracy of spatiotemporal features (Gabriel et al., 2023). Machine learning on the 2MWT/6MWT shows promise for foot-strike detection, but fall risk classification for amputees remains challenging (Juneau et al., 2022). In older adults, progressive exercise difficulty does not always provide extra gains beyond standard programs, effects are highly influenced by baseline and age (dos Santos et al., 2025). PNF techniques such as rhythmic stabilization provide acute effects on

TUG/FRT (Lamp et al., 2023). Pain, balance confidence, functional mobility, and prosthetic side reach are associated with recurrent fall risk and are modifiable factors (Seth et al., 2023).

Cluster 3 (blue) connects falls, injuries, persons, pll, and risk. Person-step exposure-based longitudinal analysis clarifies that groups with limited walking ability have higher incidence of falls/injuries when standardized to step exposure (Chihuri et al., 2021). A case series of stumbles in transfemoral patients shows that the mid-swing phase is most at risk for falls and recovery strategies differ from healthy controls, suggesting the need for task-specific strength/skill training and prosthetic/exoskeleton assistance (Eveld et al., 2022). The ERAS perioperative care framework for major amputation emphasizes a coordinated care pathway across phases to mitigate complications and restore function (McGinigle et al., 2024). In pediatric neurology populations, the four-square step test indicates dynamic balance as a sensitive indicator of fall risk (Cui et al., 2025), a message that can be translated to young amputees. Reviews and meta-analyses of action observation therapy (AOT) show benefits across several ICF domains (Ryan et al., 2021), consistent with the neurophysiological basis of mirror mechanisms supporting fall prevention through motor behavior regulation (Rizzolatti et al., 2021). The role of rehabilitation physicians as care navigators is crucial for maintaining continuity of patient goals from pre-amputation to the long term (Donaghy et al., 2024).

Cluster 4 (yellow) connects AOT, meter, and quality. This node links AOT interventions and meter-based tests as indicators of mobility quality. Evidence from AOT in musculoskeletal/neurological conditions shows improvements in specific walking function and speed, but dose parameters still vary (Ryan et al., 2021; Rizzolatti et al., 2021). Ten-/Six-Minute Walk Tests combined with phone/wearable sensors enable high-quality remote monitoring (Gabriel et al., 2023) and align with virtual TUG assessments (DadeMatthews et al., 2024). At the service level, the ERAS consensus offers perioperative quality standards for major amputations (McGinigle et al., 2024). Specific exercises such as Pilates reformer also show improved cognitive function in sedentary women, with potential relevance for dual-tasking in amputee rehabilitation (Özeren et al., 2024).

Cluster 5 (purple) connects stumble and transfemoral prosthesis users. The focus is on recovery responses when stumbling: more falls occur during the mid-swing phase and in older users; inadequate elevating/lowering strategies and insufficient prosthetic step support are triggers (Eveld et al., 2022). Dual-task training and exposure to specific motor tasks help automate strategies and reduce the cost of dual tasks (Demirdel & Erbahçeci, 2020; Demirdel et al., 2022). Differences in asymmetry and cautious gait between transfemoral and transtibial amputees require training protocols tailored to the level of amputation (Pantera et al., 2025). A bio-inspired auto-adaptive framework for passive knee prostheses demonstrates reduced fatigue and high fall prevention, pointing toward the development of devices that support functional training (Asif et al., 2025). On the other hand, variable gait training in AFO users shows potential for improving step stability/accuracy an idea that could be adopted as a variable training paradigm for the prosthetic community (van Duijnhoven et al., 2025). Finally, a scoping review on postural control imbalance reinforces the need for high-quality research to integrate devices and exercises into clinical decision-making (Acien et al., 2025).

Overlay Visualization in VOSviewer highlights the chronology of topic emergence: dark colors (left scale) mark early themes, while green–yellow colors mark recent themes. In this way, the map helps answer the direction of research evolution on "Impact of Balance and Fitness Training on Fall Risk Reduction in Prosthesis Users Post-Amputation": the general issue of "fall–injury–risk" appears first, followed by the bridge "assessment–gait parameter–older adult," and finally the specific issues of amputation and rehabilitation practices (amputee, gait, prosthesis disuse) gain prominence.

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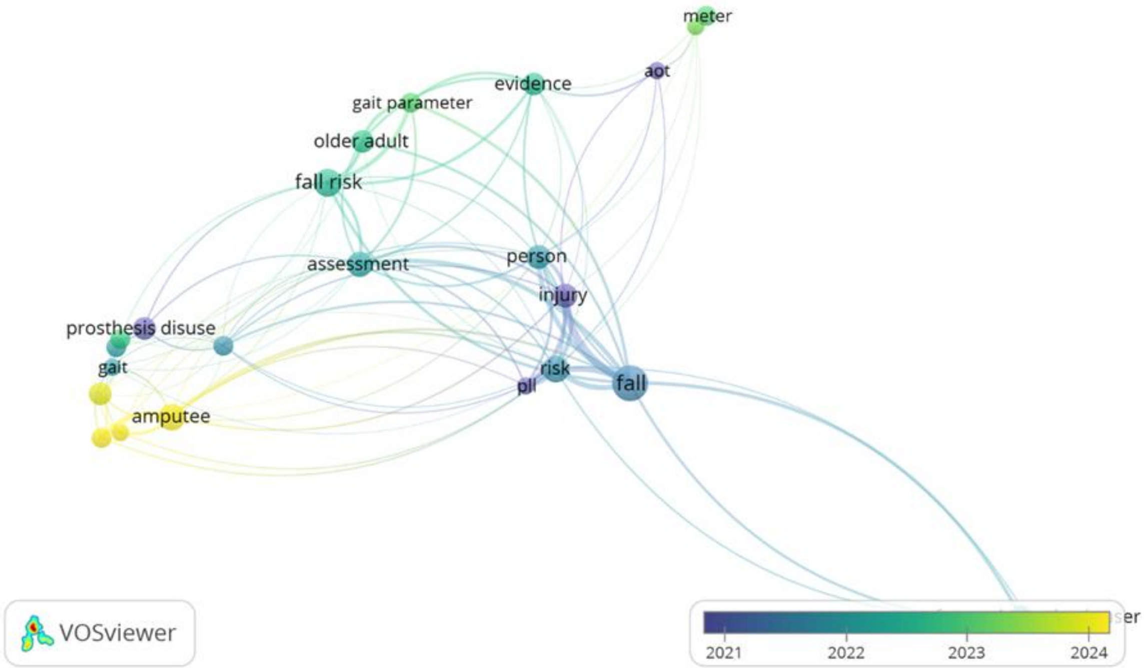

Figure 3. Overlay Visualization Vosviewer

Node fall, risk, injury, pll appears blue-purple an indication of the initial theme (around 2020–2021) that focused on quantifying the risk of falls and injuries in the general population with lower limb loss. This network is closely connected to person as an individual exposure node. The middle period (around 2022–2023) is marked by a shift to green–cyan nodes: assessment, fall risk, gait parameters, older adults, and meters. This phase shows a strengthening of measurement methodologies TUG/10-MWT/6-MWT, mobile phone/wearable sensors, and clinical trials which serve as a link between fall outcomes and intervention design. Most recently (yellow), the amputee and gait nodes are on the lower left, signifying a new focus on prosthesis-specific exercise practices and walking strategies; nearby, prosthesis disuse is colored green-cyan, reminding us of issues of balance confidence and functional regression when the device is not in use. The AOT node remains darker (early–mid), providing the context for neurocognitive interventions that are later integrated into the assessment and physical exercise phases. The warming color pattern from the "fall–risk" center towards "amputee–gait" indicates research maturation: from risk description to optimization of balance/fitness training, device adaptation, and sensor-based monitoring.

Table 2. Frequency of Articles Based on Year of Publication

Year of Publication	Frequency (f)	Percentage
2020	4	13.3%
2021	5	16.7%
2022	3	10.0%
2023	4	13.3%
2024	5	16.7%
2025	9	30.0%
Total	30	100

The annual distribution shows an increase in research output, peaking in 2025 with 9 articles (30%), followed by 2021 and 2024 with 5 articles each (16.7%), then 2020 and 2023: 4 articles each (13.3%), and 2022: 3 articles (10.0%). This trend is consistent with the color gradation on the map: yellow–green nodes (themes 2024–early 2025), particularly amputee, gait,

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and connections to assessment, indicate a strengthening of current research on balance training, gait parameters, and evidence-based rehabilitation strategies for prosthesis users. Meanwhile, the dominance of blue/purple in the fall–risk–injury nodes reflects the conceptual foundation of the early decade, which was later translated into assessment protocols and interventions. In other words, the frequency table confirms the apparent shift in focus on the overlay: quantification of risk ( ) → standardization of assessment (intermediate) → implementation of exercises and optimization of prosthesis user function (current).

Table 3. Article Summary

No	Author (Year)	Research Objectives	Research Methods & Objects	Results & Conclusions
1	Acien et al. (2025)	Synthesizing research on postural control in minor lower limb amputations and balance-enhancing interventions.	Scoping review of 15 studies (n=288) using biomechanics, functional tests (FRT, TUG), and questionnaires.	There are postural deficits and increased fall risk; custom orthotics and prosthetics can improve performance; high-quality studies are needed.
2	Asif et al. (2025)	Developing an adaptive bio-inspired framework for passive knee prosthesis movement.	Development research with sensors and damping control; deep learning architecture for gait phase classification.	Classification accuracy of 94.44%; reduction in hip hike and fatigue; 95% fall prevention; improved function for passive prosthesis users.
3	Bekele et al. (2020)	Assessing the magnitude of fall risk and related factors among urban elderly in Gondar, Ethiopia.	Cross-sectional study (n=607); TUG; bivariate and multivariate logistic regression.	Fall risk 38.2%; factors: female, foot problems, lower limb weakness, depression, walking aids; protective diabetes medication.
4	Berger et al. (2025)	Comparing functional outcomes post-Ewing amputation vs. preoperative condition, normative TTA, and healthy individuals.	Intervention cohort (22 patients; 26 EAs); tests: 10MWT, TUG, 6MWT, FRT & PROM ~1 year.	Post-amputation outcomes improved significantly; better than normative TTA on some tests and comparable to ABAs on 10MWT & TUG.
5	Chihuri et al. (2021)	Quantifying fall risk & injury in amputees based on person-step exposure ( ).	Prospective cohort with 5 monthly visits (n=10); StepWatch4; GEE Poisson.	Limited walkers have an IRR of 6.10 and an injury rate of 8.56 vs. the community; step-based metrics improve the precision of risk estimation.
6	Christensen et al. (2020)	Comparing movement asymmetry in low- vs. high-mobility tasks after TTA.	Kinematics/kinetics analysis during flat walking & stair climbing; TTA vs control; ANCOVA.	Asymmetry increases when climbing stairs (knee moment, GRF, etc.); high-demand tasks need to be the focus of rehabilitation/prosthetics.
7	Cui et al. (2025)	Assessing dynamic balance, motor	Cross-sectional study (n=92; 5–15 years);	85.9% had fallen/year; FSST accurately identified

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		function, and fear of falling as indicators of fall risk in children with DMD.	FSST, MFM-32, 6MWT, TFTs, FOF.	recurrent falls (AUC 0.856–0.890; cut-off 10.41 s); MFM/TFTs had limited discrimination.
8	DadeMatthews et al. (2024)	Exploring virtual functional mobility assessment in lower limb prosthesis users.	Descriptive observational study (n=12); mobility survey & TUG via online platform.	Average TUG of 11.0±2.9 s (faster than TTA reference); negative correlation with functional status; virtual assessment is feasible.
9	Demirdel & Erbahçeci (2020)	Testing the effects of dual-task balance training on TF amputees.	RCT (N=20) single-task vs dual-task, 12 sessions/4 weeks; 1-leg stance, FSST, TUG, 10MWT, MoCA, PSQI.	Both groups improved; dual-task superior in dual-task performance, mobility, speed, cognition, and sleep quality.
10	Demirdel et al. (2022)	Comparing the effects of concurrent cognitive vs. motor tasks on gait in TTA/TF and healthy individuals.	Treadmill ST, CDT, MDT; 20 TTA, 13 TF, 20 healthy; variability analysis.	MDT increased step length variability in amputees; motor load → greater variability (potential fall risk).
11	Donaghy et al. (2024)	Presenting the role of physiatrists in the management of lifelong limb loss.	Clinical review & evidence-based practice framework across phases of care.	Mapping the interdisciplinary coordination role from pre-amputation to long-term care; emphasizing patient-centered goals.
12	dos Santos et al. (2025)	Testing the effectiveness of progressive exercise difficulty levels for balance and gait in the elderly.	RCT (n=22) 12 weeks; EG with progression vs CG without progression; BBS, TUG, mDGI; ANCOVA.	No group effect; improvements occurred in both groups; baseline values & age predicted changes.
13	Eveld et al. (2022)	Identifying factors contributing to falls in TF prosthesis users when stumbling on the healthy side.	Case series (n=6); early/mid/late swing phase perturbations; strategy and kinematic analysis.	15/26 stumbles → falls; older age and mid-swing phase most at risk; recommendations for training/device support for elevating/step strategies.
14	Finco et al. (2023)	Mapping clinical fall risk assessment in elderly lower limb prosthesis users.	Scoping review of 19 studies; clinical outcome measures & gait parameters.	No single effective measure; combination of assessments & prospective data needed for evidence-based protocols.
15	Gabriel et al. (2023)	Reviewing mobile/wearable devices for Ten Meter Walk Test analysis.	Systematic review (PRISMA) of multiple databases; NLP for screening.	The most relevant chronometer and accelerometer; the importance of calibration and integration of environmental sensors;

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				sample size limitations.
16	Juneau et al. (2022)	Classification of fall risk in amputees using smartphone sensor data 2MWT/6MWT.	LSTM foot-strike detection; RF risk classification (n=80).	High FS accuracy; 76.3% correct risk classification, but <50% for those who fell in the last 6 months; improvement needed.
17	Krauskopf et al. (2025)	Assessing gait stability and regularity across body segments in amputees.	Biomechanics on a 3-speed treadmill; 15-segment IMU; Lyapunov exponent & fuzzy entropy; PPCA.	Amputees are less stable (especially at low speeds) and less adaptive; holistic disruption of gait/balance.
18	Lamp et al. (2023)	Comparing the acute effects of PNF RS vs. SR techniques on balance in elderly women.	3-group RCT (RS, SR, control); 15-minute sessions; TUG, FRT, stabilometry.	RS & SR reduce TUG time & increase FRT; RS reduce COP speed; easy method & potential to prevent falls.
19	McGinigle et al. (2024)	Establishing ERAS/SVS consensus for perioperative care of major lower extremity amputations.	International expert consensus; 33 structured recommendations from pre- to post-operative care.	An ERAS framework specific to amputation for coordinating care and improving outcomes.
20	Mollà-Casanova et al. (2024)	Evaluating the effects of mirror neuron activation therapy (MNAT) on elderly function.	SR/MA 13 RCTs (11 quantitatively analyzed).	MNAT > control for function, balance, walking speed; adding MNAT to exercise was inconsistent.
21	Özeren et al. (2024)	Testing the effects of Pilates reformer on cognitive function in sedentary women.	RCT (n=44) 6 weeks; Stroop test, right-left discrimination, PSQI.	Significant improvement in several Stroop scores vs. control; not significant in right-left discrimination & sleep quality.
22	Pantera et al. (2025)	Impact of amputation level on gait asymmetry and "cautious gait".	Retrospective; 49 amputees (22 TTA, 27 TFA) vs. 30 controls; Zebris pressure mat.	Asymmetry increased with amputation level; TFA: greater step width, double support, and CoP ML; need for personalized rehabilitation.
23	Parr et al. (2025)	The effect of low back pain on ML trunk movement variation during sit-to-stand in TTA.	Study used IMU; 58 TTA (28 with LBP, 30 without); 5 STS repetitions.	STS time was the same, but ML trunk motion variation was greater in LBP; accelerometer metrics could distinguish trunk control.
24	Rizzolatti et al. (2021)	Summarizing the role of mirror mechanisms & AOT for recovery/maintenance of motor skills.	A broad narrative review across clinical conditions & fall prevention.	AOT is beneficial in many conditions; potential fall prevention & personalization with modern technology.

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25	Rosenblatt et al. (2020)	The role of podiatrists in assessment and fall risk reduction.	Review 2014–2019; focus on clinical assessment and intervention.	Importance of medical history, foot evaluation/deformities; interventions: shoe modifications, exercises, analgesia, surgery, referrals.
26	Rosenblatt et al. (2021)	Impact of not wearing a prosthesis on balance confidence in long-term TTA users (case study).	Case report of a 76-year-old man; pre- vs. post-4 months of no/limited use; various measures of balance/activity.	Balance confidence ↓19%, walking speed ↓12%, steps/day ↓19%; intervention needed to restore confidence.
27	Ryan et al. (2021)	Effectiveness of AOT in the rehabilitation of neurological and musculoskeletal conditions.	SR 36 RCT (n=1405); several meta-analyses.	Strong evidence for stroke and Parkinson's disease; moderate evidence for orthopedics and MS; heterogeneous therapeutic parameters → no standard dose yet.
28	Schafer & Vanicek (2021)	Effects of a 12-week personalized exercise program on postural control and confidence in LLA.	Block-RCT (n=14; 7 exercise, 7 control); SOT, MCT, ABC.	Significant improvement in SOT under difficult conditions in the exercise group; no change in ABC; controls tended to become more asymmetrical.
29	Seth et al. (2023)	Risk factors associated with recurrent falls in adults with lower limb amputation.	Cross-sectional study (n=83); pain (back/residual/sound), ABC, PLUS-M, FRT, mFSST.	Widespread pain (LBP + both legs), low confidence, poorer mobility & shorter prosthetic reach → increased risk of repeated falls.
30	van Duijnhoven et al. (2025)	Does variable gait training improve stability in AFO users with neuromuscular disorders?	Pilot study (n=3) 3 sessions of interactive treadmill training; evaluation of step variability & target-stepping accuracy, balance, fear of falling.	Step variability decreased (step time −38%, length −26%, width −22%); target accuracy ↑; unclear on balance/perception scores; larger study needed.

A summary of 30 articles in the table shows that research related to The Analysis Study of Diagnosis and Management of Prevalence, Diagnosis and Surgical Management of Hip Fracture is closely related to the themes of amputation, risk of falling, and rehabilitation strategies. Early studies such as Bekele et al. (2020), Christensen et al. (2020), and Rosenblatt et al. (2020) emphasized the prevalence of falls in the elderly and the role of the clinical assessment. The following year, the focus shifted to person-step-based risk quantification (Chihuri et al., 2021), the effects of AOT (Ryan et al., 2021; Rizzolatti et al., 2021), and personalized training (Schafer & Vanicek, 2021). A significant leap occurred in 2022–2023 with studies on transfemoral stumbling (Eveld et al., 2022), risk classification using sensors (Juneau et al., 2022), and a scoping review of prosthesis assessment in the elderly (Finco et al., 2023), plus contributions from Gabriel et al. (2023), Lamp et al. (2023), and Seth et al. (2023) highlighting wearables, PNF techniques, and pain and confidence factors. The 2024–2025 period is marked by an explosion of research: virtual assessment (DadeMatthews et al., 2024), ERAS consensus (McGinigle et al., 2024), mirror neuron therapy (Mollà-Casanova et al., 2024), Pilates reformer (Özeren et al., 2024), and the framework for physical therapy care (Donaghy et al., 2024). Meanwhile, recent publications reinforce the biomechanical and personalized rehabilitation aspects, such as Acien et al. (2025), Asif et al. (2025), Berger et al. (2025), Cui et al. (2025), dos Santos et al. (2025), Krauskopf et al. (2025), Pantera et al. (2025), Parr et al. (2025), and van Duijnhoven et al. (2025). The entire literature shows an evolution from risk description towards diagnostic innovation, technology-based assessment, and relevant surgical and rehabilitation management strategies to understand the dynamics of hip fracture diagnosis and management.

RQ2: What physiological and psychosocial mechanisms explain the effectiveness of balance and fitness training programs in reducing the risk of falls in post-amputation prosthesis users, and what factors influence their success?

The performance of the exercise program stems from the recovery of sensorimotor integration that is disrupted after amputation. Postural control imbalance arises due to the loss of proprioceptive input, changes in load strategy, and mechanical limitations of the artificial limb, resulting in decreased functional test scores and increased risk of falling; appropriate orthotic and prosthetic interventions can improve stability and smoother load transitions during functional tasks (Acien et al., 2025). Localized stability disturbances across body segments, particularly at low walking speeds, reveal irregular dynamic patterns on the amputation side and indicate targets for exercise to enhance movement regularity and stability (Krauskopf et al., 2025). Movement asymmetry becomes more pronounced during high-demand mobility tasks such as stair climbing, so training should target knee joint moments, ground reaction forces, and ankle angles to reduce interlimb disparities (Christensen et al., 2020). Differences in amputation level affect step width, double support phase, and center of pressure deviation, so exercise design must adapt to stabilization needs in transfemoral versus transtibial amputations (Pantera et al., 2025). Neuromuscular reorganization following procedures such as Ewing amputation followed by rehabilitation also showed improvements in TUG, 10MWT, and 6MWT performance, indicating that modulation of afferent input and efferent control through exercise can be clinically meaningful (Berger et al., 2025).

The effectiveness of exercise is supported by higher-level neural mechanisms that optimize motor planning and processing. Activation of the mirror neuron system through action observation therapy facilitates the acquisition and maintenance of motor skills and has the potential to prevent physically impactful events such as falls, especially when appropriately combined with functional activities (Rizzolatti et al., 2021). Synthesis evidence shows that AOT is beneficial in a number of neurological and musculoskeletal conditions, although dosage parameters still vary, so balance training needs to be combined with a structured observation-action protocol (Ryan et al., 2021). In older adults, mirror neuron activation therapy can improve function, balance, and walking speed, meaning that movement-based training can enhance the quality of physical training (Mollà-Casanova et al., 2024). The dual-task approach, which trains cognitive and motor processing simultaneously, improves mobility, walking speed, and cognitive status, so that the efficacy of training comes not only from strength and flexibility but also from the automation of attention responses while walking (Demirdel & Erbahçeci, 2020). Improved executive function following exercise-based interventions such as Pilates reformer further supports the hypothesis that cognitive modulation plays a role in postural control and environmental navigation (Özeren et al., 2024), while dynamic balance tests such as the Four Square Step Test serve as sensitive indicators for mapping changes in fall risk related to motor skills and posture control (Cui et al., 2025).

Biomechanical and technological explanations bridge the gap between mechanisms and outcomes. Recovery responses when stumbling on a transfemoral prosthesis are influenced by the swing phase and the capacity to generate sufficient hip or knee flexion; strength training and task-specific skill can improve both elevating and lowering strategies, and device or exoskeleton support can help initiate prosthetic swing safely (Eveld et al., 2022). Variable training in orthosis users improves step stability and target-stepping accuracy, indicating that exposure to diverse walking conditions accelerates locomotor control adaptation (van Duijnhoven et al., 2025). Bio-inspired frameworks that adapt damping and utilize sensor signals improve passive knee motion patterns, reduce hip hike and fatigue, and demonstrate high fall prevention rates, suggesting that integrating adaptive devices can enhance training outcomes (Asif et al., 2025). Risk classification using machine learning-processed 2MWT or 6MWT data provides additional insights into relevant step parameters, although accuracy for the past six months' fall history still needs improvement to be useful as exercise feedback (Juneau et al., 2022). The ecosystem of wearable-based assessment and teleassessment, including accelerometers and virtual platforms that monitor TUG or 10MWT, expands the scope of exercise progress monitoring and the quality of spatiotemporal data underpinning program adjustments (Gabriel et al., 2023; DadeMatthews et al., 2024), while the person-step exposure-based approach improves the precision of risk estimation so that exercise intensity can be measured more accurately according to daily walking capacity (Chihuri et al., 2021).

Psychosocial dimensions form the basis for successful intervention. Low balance confidence is associated with recurrent falls, while low back pain, residual limb pain, and healthy limb pain increase the likelihood of falling; these findings emphasize the need for exercise modules that target pain reduction, improved functional mobility, and expanded reach on the prosthetic side (Seth et al., 2023). Periods of not using the prosthesis decrease balance confidence, walking speed, and daily step count, so support during the wound phase and graded return-to-use strategies are needed to prevent regression in participation (Rosenblatt et al., 2021). A 12-week personalized program has been shown to reduce dependence on visual input and improve somatosensory interpretation, although it does not always immediately increase confidence scores, indicating that education and counseling need to go hand in hand with physical training (Schafer & Vanicek, 2021). Population factors such as gender, foot problems, lower extremity weakness, depression, and use of walking aids increase the risk of falls in older adults ( ), making screening for comorbidities and podiatric intervention part of the exercise package (Bekele et al., 2020). The acute effects of PNF techniques such as rhythmic stabilization reduce TUG time and increase FRT range, which can serve as a gateway to building initial success and motivating continued exercise participation (Lamp et al., 2023), while progression in difficulty level should consider baseline values and age, as the greatest response occurs in participants with lower baselines (dos Santos et al., 2025).

The success of the program is also influenced by clinical management and service standards. The ERAS framework for major amputations sets out recommendations from pre-admission to post-surgery to ensure consistent recovery of function and readiness for exercise across all phases of care (McGinigle et al., 2024). The role of the rehabilitation physician as a cross-disciplinary coordinator ensures that patient goals align with exercise selection, device adjustments, and long-term follow-up plans to control secondary risk factors (Donaghy et al., 2024). Podiatry's contribution in evaluating foot deformities, modifying shoes, and timely therapy referrals enriches the multifactorial management that supports exercise success (Rosenblatt et al., 2020). Scoping review evidence emphasizes that no single measure adequately identifies fall risk in older prosthesis users, so success requires a combination of clinical tests and gait parameters as the basis for decision-making (Finco et al., 2023). Monitoring trunk control with sensors during sit-to-stand tasks can also guide movement retraining and device adjustments, especially when low back pain limits medial-lateral control (Parr et al., 2025).

RQ3: How can the results of the literature review on balance and fitness training interventions for post-amputation prosthesis users provide implications for clinical rehabilitation practices, health policy development, and fall prevention program implementation strategies?

Literature review supports clinical practice that combines task-specific balance training, strengthening, and attention training. Dual-task training that integrates cognitive and motor components improves mobility, walking speed, and sleep quality in transfemoral users, so that clinical programs can include task automation modules to cope with environmental distractions (Demirdel & Erbahçeci, 2020). The influence of motor tasks on step variability in transtibial and transfemoral users provides a rationale for gradually increasing motor load and assessing dual-task cost during progression (Demirdel et al., 2022). A 12-week personalized program targeting somatosensory interpretation showed improvements in challenging sensory conditions, which can be adopted as a core post-prosthesis fitting package (Schafer & Vanicek, 2021). PNF techniques such as rhythmic stabilization are suitable for use as a rapid intervention to trigger early improvements in functional balance and serve as an on-ramp to more complex exercises (Lamp et al., 2023). Asymmetry differences due to amputation level and increased asymmetry during high-demand tasks require a stratified protocol based on transfemoral or transtibial amputation and the inclusion of stair climbing or elevation changes from the intermediate phase of rehabilitation (Pantera et al., 2025; Christensen et al., 2020).

Technology integration broadens the scope of services and streamlines monitoring. The use of mobile phone sensors and wearable devices for 10MWT or 6MWT improves the availability of spatiotemporal data, but calibration and integration of environmental sensors are necessary to maintain accuracy outside the laboratory (Gabriel et al., 2023). Machine learning models for foot strike detection and fall risk classification can be used as supportive screening, while recognizing limitations in identifying recent fallers so clinicians continue to prioritize multimodal assessment (Juneau et al., 2022). Teleassessment of mobility through an online platform administering the TUG demonstrates feasibility and has the potential to reduce visit burden, allowing remote services to complement in-person rehabilitation (DadeMatthews et al., 2024). Accelerometer metrics for trunk control during sit-to-stand facilitate core exercise adjustments, particularly in individuals with low back pain affecting medial-lateral control (Parr et al., 2025). Cross-segmental nonlinear dynamics analysis helps clinicians identify safe walking speeds and exercise transition points, such as prioritizing stability at low speeds before progression (Krauskopf et al., 2025).

Implications for device development and financing policies stand out from the latest study. The adaptive control framework in passive knee prostheses shows reduced fatigue and fall prevention, suggesting the benefits of funding support for smart devices compatible with clinical exercise modules (Asif et al., 2025). Improved function after Ewing amputation underscores the importance of surgical pathways that support agonist-antagonist muscle interactions so that rehabilitation exercises result in better functional transfer to daily activities (Berger et al., 2025). Stumble response analysis in transfemoral amputees suggests policy investment in strength training and task-specific motor skill programs, as well as access to swing-supporting exoskeletons as part of fall prevention (Eveld et al., 2022). Variable training that reduces step variability in orthosis users provides a rationale for including variable modules and interactive training tools in therapy funding packages (van Duijnhoven et al., 2025). Findings on postural deficits in minor amputations and the benefits of custom orthotic and prosthetic devices reinforce recommendations for repeated device adjustment services throughout the rehabilitation journey (Acien et al., 2025).

The public health perspective emphasizes cross-setting risk screening. The magnitude of fall risk in community-dwelling older adults is influenced by gender, foot problems, leg weakness, depression, and the use of assistive devices, so prevention programs require collaboration between primary care and rehabilitation services to address intrinsic and extrinsic factors simultaneously (Bekele et al., 2020). Dynamic balance tests such as the FSST have been shown to be sensitive in identifying recurrent fallers in pediatric neurology populations, which may inspire screening packages for young prosthesis users with appropriate adaptations (Cui et al., 2025). Widespread pain, balance confidence, functional mobility, and prosthetic side range of motion are associated with recurrent falls, making pain education, graded activity therapy, and functional range of motion exercises part of the standard of care (Seth et al., 2023). The role of podiatry in evaluating deformities and modifying footwear addresses gaps in distal musculoskeletal interventions often overlooked in fall prevention packages (Rosenblatt et al., 2020). Evidence synthesis on assessment indicates the need for a combination of clinical measures and gait parameters, so screening policies should not rely on a single test tool (Finco et al., 2023).

Sustainable implementation requires clear clinical governance, team education, and tiered support. The ERAS consensus for major amputations provides a perioperative care map that prepares individuals for the exercise phase ( ), reduces practice variation, and accelerates the achievement of early functional goals (McGinigle et al., 2024). The role of the physiatrist as a cross-phase care coordinator ensures continuity of patient goals, interdisciplinary coordination, and timely referral navigation to podiatry, occupational therapy, or pain services, ultimately facilitating the adoption of fall prevention protocols (Donaghy et al., 2024). AOT-based interventions can be positioned as a component of motor education that enhances exercise readiness, with evidence of benefit in the ICF domain, although dosage parameters still need to be established for routine practice (Rizzolatti et al., 2021; Ryan et al., 2021). Mirror neuron activation therapy in older adults combined with functional activities shows improvements in walking function and speed, while the cognitive components of exercises such as Pilates reformer can strengthen attention and response control while walking in crowded environments (Mollà-Casanova et al., 2024; Özeren et al., 2024). Scheduling progression of difficulty should consider baseline values and age, as the greatest response is observed in participants with low baseline values, thereby making clinical resource allocation more targeted and efficient (dos Santos et al., 2025).

CONCLUSION

This study shows that balance and fitness training have a significant impact on reducing the risk of falls in post-amputation prosthesis users through improved stability, sensorimotor strengthening, and improved gait strategy. Structured and adaptive exercise programs have been shown to help minimize intrinsic and extrinsic risk factors while improving the quality of life of prosthesis users.

The literature review emphasizes the importance of technological support, such as wearable devices, machine learning, and virtual assessment, which can strengthen early risk detection and exercise progress monitoring. The combination of traditional clinical tests with technology-based methods provides a stronger basis for determining targeted interventions for each individual.

The implications of this study extend beyond clinical rehabilitation practices to health policy development. The integration of care frameworks such as ERAS, the role of physiatrists as coordinators, and policy support for financing adaptive devices ( ) are important steps in expanding implementation. These findings underscore the need for a multidimensional approach that integrates biomechanical, technological, psychosocial, and governance aspects to optimize amputation rehabilitation and fall prevention in the future.

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