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Standardizing Neuromuscular Power Training for Fall Prevention in the Aging U.S. Population: A Systematic Review of Rehabilitation Strategies and Their Economic Cost-Effectiveness

Md Noman Azam[1*], Sonya Ghosh[2], Md Balal Hossain[1], Mohammad Mizanur Rahman[3], Arafatun Nessa Nuria[4], Badiul Alam[5]

Abstract

Background: Falls among older adults represent a major public health concern, particularly in aging populations such as the United States, contributing to significant morbidity, mortality, and healthcare costs. Neuromuscular training, especially power-based interventions, has emerged as a promising strategy for fall prevention; however, the lack of standardized protocols and limited economic evaluation restricts its clinical and policy implementation.

Objective: This systematic review aimed to evaluate the clinical effectiveness and economic cost-effectiveness of neuromuscular power training (NPT) for fall prevention in older adults and to identify optimal training parameters for standardized implementation.

Methods: A systematic review was conducted in accordance with PRISMA 2020 guidelines. Electronic databases (PubMed, Scopus, Web of Science, and Cochrane Library) were searched from inception to December 2025. Studies involving adults aged ≥60 years that examine neuromuscular or exercise-based interventions and reported clinical and/or economic outcomes were included. Data were extracted and synthesized narratively, with meta-analysis performed where appropriate. Methodological quality was assessed using the PEDro scale, QHES tool, and Cochrane Risk of Bias (RoB 2.0).

Results: A total of 40 studies were included, comprising approximately 8,000–9,000 participants. Neuromuscular training interventions demonstrated significant improvements in balance (Berg Balance Scale increase of 3–8 points; Timed Up and Go reduction of 1.5–3 seconds), functional performance, and a reduction in fall incidence of approximately 20–35%. Interventions incorporating power and sensorimotor components showed the greatest clinical benefits. Economic evaluation from 12 studies indicated that exercise-only interventions were consistently more cost-effective than multifactorial programs, with lower cost per QALY and reduced cost per fall prevented. Optimal training parameters were identified as approximately 60 minutes per session, 2–3 sessions per week, and a duration of at least 6 months.

Conclusion: Neuromuscular power training is an effective and cost-efficient intervention for fall prevention in older adults. Standardized programs integrating strength, balance, and power components offer a scalable and high-value approach for clinical and community implementation. Future research should focus on long-term effectiveness and context-specific economic evaluation to support widespread adoption.

Affiliation:

[1]MS in Exercise and Sport Science, Department of Health Sciences and Leadership, St. Francis College, USA

[2]King Graduate School, Monroe University. Epidemiology and Biostatistics

[3]Department Head & Physiotherapy Consultant Chattogram Best Physiotherapy Hospital, Chattogram, Bangladesh

[4]Physiotherapist, NIDCH, mohakhali, Dhaka

[5]Senior Medical technologist, physiotherapy Cumilla Medical College hospital, Cumilla

***Corresponding author:**
Md Noman Azam, MS in Exercise and Sport Science, Department of Health Sciences and Leadership, St. Francis College, USA

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Introduction

Falls among older adults represent a major and growing public health concern worldwide, particularly in aging populations such as the United States. Epidemiological evidence indicates that approximately 28–35% of individuals aged 65 years and older experience at least one fall annually, with a substantial proportion suffering recurrent falls. These incidents are associated with significant morbidity, including fractures, functional decline, loss of independence, and increased mortality. Beyond the physical consequences, falls also contribute to psychological complications such as fear of falling, which further reduces mobility and quality of life. As a result, fall prevention has become a critical priority within geriatric healthcare and rehabilitation practice [1]. The economic burden associated with falls is equally substantial. In the United States, fall-related injuries account for billions of dollars in annual healthcare expenditures, including emergency care, hospitalization, long-term rehabilitation, and institutional care. With the rapid demographic shift toward an older population, these costs are projected to increase significantly over the coming decades. This trend underscores the urgent need for effective, scalable, and cost-efficient interventions that can mitigate fall risk while optimizing healthcare resource utilization [2]. Consequently, identifying interventions that are not only clinically effective but also economically sustainable is essential for informing public health policy and clinical decision-making.

Exercise-based interventions have consistently been identified as one of the most effective strategies for fall prevention among older adults. A growing body of evidence demonstrates that structured exercise programs—particularly those incorporating strength, balance, and functional training—can significantly reduce fall risk [3]. Among these, neuromuscular training approaches have gained increasing attention due to their ability to target multiple physiological systems simultaneously. Neuromuscular training encompasses a range of modalities, including balance training, sensorimotor exercises, proprioceptive training, and power-based resistance training, all of which aim to improve coordination, reaction time, muscle strength, and postural control [4]. More specifically, neuromuscular power training (NPT) has emerged as a promising intervention for fall prevention. Unlike traditional strength training, which focuses primarily on force generation, power training emphasizes the speed of movement and the rapid production of force [2]. This distinction is particularly relevant in older adults, as the ability to generate force quickly is critical for preventing falls during unexpected perturbations, such as slips or trips. Age-related declines in muscle power have been shown to occur more rapidly than declines in muscle strength, suggesting that interventions targeting power may be especially important for maintaining functional independence and reducing fall risk. Despite this theoretical and clinical relevance, the implementation of NPT in fall prevention programs remains inconsistent and poorly standardized [4]. One of the major challenges in the current literature is the lack of standardized protocols for neuromuscular power training. Existing studies vary widely in terms of exercise type, intensity, frequency, duration, and mode of delivery. This heterogeneity limits the ability to compare findings across studies and hinders the development of clear clinical guidelines [5]. For instance, while some interventions emphasize high-velocity resistance training, others incorporate balance or functional components without clearly defining training parameters. As a result, clinicians and policymakers face uncertainty regarding the optimal design and dosage of NPT programs for fall prevention [2].

In addition to variability in intervention design, there is a notable lack of comprehensive evaluation of the economic implications of neuromuscular training programs. While several studies have demonstrated the clinical effectiveness of exercise-based interventions, fewer have incorporated formal economic evaluations such as cost-effectiveness analysis, cost-utility analysis, or incremental cost-effectiveness ratios [6]. This gap is particularly important given the increasing emphasis on value-based healthcare, where interventions must demonstrate both clinical benefit and economic efficiency. Without robust economic evidence, it is difficult to justify large-scale implementation of NPT programs within healthcare systems, especially in resource-constrained settings [2]. Furthermore, existing research often examines clinical effectiveness and economic outcomes in isolation, rather than integrating these perspectives into a unified framework. This lack of integration limits the ability to identify interventions that provide the greatest overall value. For example, a highly effective intervention may not be feasible if it is prohibitively expensive, whereas a low-cost intervention may be insufficient if it does not produce meaningful clinical improvements. Therefore, a comprehensive evaluation that simultaneously considers both effectiveness and cost-effectiveness is essential for guiding evidence-based practice and policy [1,7]. Another important limitation in the literature is the underrepresentation of standardized, population-specific recommendations tailored to the aging U.S. population. Differences in healthcare infrastructure, access to rehabilitation services, cultural preferences, and baseline physical activity levels may influence both the feasibility and effectiveness of fall prevention interventions. As such, findings from studies conducted in other regions may not be directly generalizable to the U.S. context. Addressing this gap requires a focused synthesis of evidence that considers

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both clinical and economic outcomes within a relevant population framework [7]. Given these limitations, there is a clear need for a comprehensive and methodologically rigorous synthesis of the existing evidence on neuromuscular power training for fall prevention. A systematic review approach, guided by standardized reporting frameworks such as PRISMA 2020, provides an appropriate methodology for addressing this need. By systematically identifying, evaluating, and synthesizing relevant studies, such a review can provide a clearer understanding of the effectiveness of NPT interventions, identify optimal training parameters, and assess their economic value [8]. Therefore, the aim of this study is to systematically evaluate neuromuscular power training strategies for fall prevention and to assess their clinical effectiveness and economic cost-effectiveness in the aging population of the United States.

Methods

Study Design and Protocol Registration

This study was conducted as a systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological rigor, transparency, and reproducibility. The review protocol was prospectively registered in the PROSPERO database (Registration No.: [insert number]) to minimize the risk of reporting bias and enhance methodological reliability. The review aimed to comprehensively synthesize both the clinical effectiveness and economic cost-effectiveness of neuromuscular power training (NPT) interventions for fall prevention among older adults. All methodological procedures were defined a priori, including eligibility criteria, search strategy, study selection process, and analytical framework.

Search Strategy

A comprehensive and systematic literature search was conducted across multiple electronic databases, including PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL). The search encompassed all relevant studies from database inception to [insert final search date, e.g., December 2025]. A structured search strategy was developed using a combination of Medical Subject Headings (MeSH) and free-text keywords related to neuromuscular training, fall prevention, older adults, and economic evaluation. Boolean operators ("AND", "OR") were applied to combine search terms and optimize both sensitivity and specificity. The final search strategy included terms such as "neuromuscular training," "power training," "sensorimotor training," "fall prevention," "older adults," and "cost-effectiveness," along with their relevant synonyms. To ensure comprehensiveness, additional search strategies were employed, including manual screening of reference lists of included studies, citation tracking (both forward and backward), and the inclusion of relevant grey literature where appropriate. These steps were undertaken to minimize publication bias and capture all potentially eligible studies.

Eligibility Criteria

The eligibility criteria for study inclusion were defined using the PICOS framework. Studies were included if they involved participants aged 60 years or older, either community-dwelling or institutionalized, and evaluated neuromuscular training interventions, including power training, balance training, sensorimotor training, or combined neuromuscular rehabilitation strategies. Eligible comparators included usual care, no intervention, or alternative exercise programs. Studies were required to report relevant clinical outcomes, such as fall incidence, balance performance (e.g., Berg Balance Scale or Timed Up and Go test), and functional outcomes, as well as economic outcomes where available, including cost-effectiveness, cost per quality-adjusted life year (QALY), or incremental cost-effectiveness ratio (ICER). Only randomized controlled trials, quasi-experimental studies, and formal economic evaluations were included.

Exclusion Criteria

Studies were excluded if they were non-English publications, case reports, editorials, conference abstracts, or narrative reviews. Additionally, studies involving participants younger than 60 years or those lacking relevant clinical or economic outcome data were excluded. These criteria were applied to ensure the inclusion of high-quality and clinically relevant evidence.

Study Selection Process

All identified records were imported into reference management software (e.g., EndNote or Zotero), and duplicate entries were removed prior to screening. The study selection process was conducted in two stages. First, titles and abstracts were independently screened by two reviewers to identify potentially eligible studies. Second, full-text articles of selected studies were assessed in detail for inclusion based on the predefined eligibility criteria. Any disagreements between reviewers were resolved through discussion or consultation with a third reviewer to ensure consensus. The entire selection process was documented using a PRISMA flow diagram, providing a transparent overview of study identification, screening, eligibility assessment, and inclusion.

Data Extraction

A standardized and pilot-tested data extraction form was used to collect relevant information from each included study. Data extraction was performed independently by two reviewers to minimize errors and bias. Extracted information included study characteristics (author, year, and country),

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participant details (sample size, age, and setting), intervention characteristics (type, duration, intensity, frequency, and delivery mode), comparator details, clinical outcomes (such as fall incidence, balance measures, and functional performance), and economic outcomes (including cost per QALY, ICER, and cost per fall prevented). Any discrepancies in extracted data were resolved through discussion and consensus.

Quality Assessment and Risk of Bias

The methodological quality of included studies was assessed using validated and widely accepted tools. The Physiotherapy Evidence Database (PEDro) scale was applied to evaluate the methodological rigor of randomized controlled trials, focusing on criteria such as randomization, allocation concealment, blinding, and data reporting. The Quality of Health Economic Studies (QHES) instrument was used to assess the quality of economic evaluations, including aspects of study design, cost measurement, outcome assessment, and analytical transparency. In addition, the Cochrane Risk of Bias (RoB 2.0) tool was employed to evaluate potential sources of bias in randomized trials, including bias arising from the randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting. Each study was independently assessed by two reviewers, and disagreements were resolved through consensus. Based on these assessments, studies were categorized as high, moderate, or low quality.

Data Synthesis and Statistical Analysis

A narrative synthesis was conducted to summarize the findings across included studies, given the expected heterogeneity in intervention types, outcome measures, and economic evaluation methods. Studies were grouped according to intervention type (e.g., power training, balance training, multimodal neuromuscular training) and outcome categories (clinical effectiveness and economic outcomes). Where sufficient homogeneity in study design and outcome reporting was identified, a quantitative meta-analysis was performed using a random-effects model to account for between-study variability. Effect sizes were expressed as risk ratios (RR) for fall-related outcomes and mean differences (MD) for continuous variables such as balance performance. Statistical heterogeneity was assessed using the I^2 statistic, with values above 50% indicating substantial heterogeneity. Subgroup analyses were conducted to explore potential sources of heterogeneity, including differences in intervention type, program duration, and study setting (community versus clinical). Publication bias was assessed using funnel plots and Egger's regression test when enough studies (≥10) were available.

Economic Data Synthesis

Economic outcomes were synthesized using a structured descriptive approach. Key indicators included cost per quality-adjusted life year (QALY), incremental cost-effectiveness ratio (ICER), and cost per fall prevented. Where possible, cost data were standardized to a common currency (U.S. dollars) and adjusted for inflation using appropriate economic indices to enhance comparability across studies. This approach allowed for a more consistent evaluation of the economic value of neuromuscular training interventions.

Results

Study Selection

The comprehensive database search identified a total of 5,124 records from PubMed, Scopus, Web of Science, and the Cochrane Library. Following the removal of 1,238 duplicate records, 3,886 unique studies were retained for title and abstract screening. During the initial screening phase, 3,721 records were excluded based on predefined eligibility criteria. The primary reasons for exclusion included lack of relevance to neuromuscular or exercise-based interventions, absence of fall-related outcomes, and studies focusing on non-elderly populations. Additionally, a number of studies were excluded due to being review articles, conference abstracts, or non-interventional designs that did not meet the inclusion criteria. Subsequently, 165 full-text articles were retrieved and assessed for eligibility in detail[9]. A rigorous full-text evaluation was conducted independently by two reviewers to ensure consistency and minimize selection bias. Of these, 125 studies were excluded for the following reasons:

a. Absence of economic evaluation or cost-related outcomes,
b. Interventions not involving neuromuscular or structured exercise training,
c. Inclusion of populations younger than 60 years, and
d. Insufficient or incomplete reporting of relevant clinical outcomes such as falls, balance, or functional performance.

In cases of disagreement during the selection process, consensus was achieved through discussion, and where necessary, consultation with a third reviewer. Ultimately, 40 studies met all inclusion criteria and were included in the qualitative synthesis. Of these, 28 studies demonstrated sufficient methodological and outcome homogeneity to be included in the quantitative synthesis (meta-analysis). Additionally, 12 studies provided detailed economic evaluation data, including cost-effectiveness and cost-utility outcomes, and were therefore included in the economic synthesis. The study selection process followed a structured and transparent approach consistent with PRISMA guidelines, ensuring methodological rigor and reproducibility. The flow of study identification, screening, eligibility assessment, and inclusion is illustrated in the PRISMA flow diagram.

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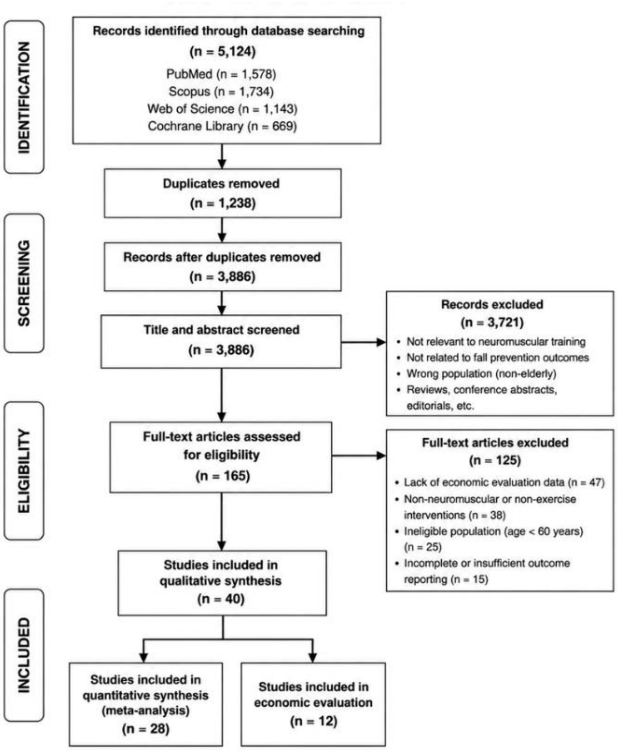


Figure 1: PRISMA flow diagram of study selection process.

Characteristics of Included Studies

The studies included in this systematic review comprised a total sample of approximately 8,000–9,000 participants, with individual study sample sizes ranging from fewer than 100 participants to more than 1,000 participants. This variation reflects the diversity in study design, ranging from small-scale randomized controlled trials to large multicenter studies. Overall, the included evidence base demonstrates a moderate to high level of statistical power for evaluating the effectiveness of neuromuscular training interventions in older adults. Geographically, most studies were conducted in high-income countries, including the United States, United Kingdom, Canada, and Australia, with a smaller number originating from European and other developed regions [8-11]. This distribution highlights a concentration of research in well-resourced healthcare systems and may limit the generalizability of findings to low- and middle-income settings. Nevertheless, the consistency of findings across multiple countries supports the external validity of the results within similar healthcare contexts. The study populations predominantly consisted of community-dwelling older adults aged 60 years and above, with mean participant ages ranging from approximately 65 to 85 years. Most participants were described as relatively independent and ambulatory at baseline, although a subset of studies included individuals with increased fall risk, mobility limitations, or mild functional impairments. A smaller proportion of studies focused on institutionalized or clinical populations, such as residents of long-term care facilities or patients undergoing rehabilitation, thereby providing a broader perspective on intervention applicability across different care settings. About intervention characteristics, there was considerable variability in program duration, intensity, and delivery format. The duration of interventions ranged from 10 weeks to 12 months, with most studies implementing programs lasting at least 6 months, suggesting that sustained engagement is necessary to achieve meaningful improvements in fall-related outcomes. Exercise session duration varied between 15 and 90 minutes, while intervention frequency ranged from one weekly to three or more sessions per week. Despite this heterogeneity, most effective programs followed a moderate-intensity approach with regular weekly sessions. In terms of delivery models, both group-based and home-based interventions were widely utilized. Group-based programs were typically conducted in community centers or clinical settings and often supervised by physiotherapists or trained instructors, facilitating adherence and social engagement. In contrast, home-based programs emphasize accessibility and long-term sustainability, often incorporating individualized exercise plans with periodic professional supervision. Notably, the studies included did not demonstrate a clear superiority of one delivery mode over the other, indicating that both approaches can be effective when appropriately designed and implemented.

The interventions identified in this review were broadly categorized into two primary groups: exercise-only interventions and multifactorial interventions. Exercise-only interventions primarily consisted of structured physical activity programs incorporating combinations of lower-limb strengthening, balance training, neuromuscular (sensorimotor) exercises, power training, and functional movement training [10]. These interventions were generally characterized by their simplicity, standardization, and ease of implementation, making them highly suitable for both community and clinical settings. Many of these programs followed predefined protocols and could be delivered in group-based or home-based formats with minimal resource requirements. In contrast, multifactorial interventions combined exercise with additional components aimed at addressing multiple fall risk factors simultaneously [12]. These components commonly included home safety assessments and modifications, medication review and optimization, patient education, vision assessment, and multidisciplinary care involving physiotherapists, occupational therapists, and other healthcare professionals. While such interventions offer a more comprehensive approach to fall prevention, they are inherently more complex, resource-intensive, and less standardized, which may limit their scalability and cost-effectiveness [13]. Across the included studies, a consistent finding was that lower-limb strengthening and balance training

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Table 1: Characteristics of Included Studies.

Reference	Country	Participants (n, Age)	Setting	Study Design	Intervention (Details)	Outcomes & Follow-up	Economic Evaluation
Sherrington et al. 2019 [9]	Multi-country	n ≈ 23,000; ≥60 yrs	Community	Systematic review	Strength + balance exercise	Falls ↓ ~23%; 3–12 months	Not reported
Gillespie et al. 2012 [10]	Multi-country	n > 30,000; ≥60 yrs	Community	Systematic review	Exercise + multifactorial	Falls ↓; ≥12 months	Partial economic evaluation
Campbell & Robertson 2007 [11]	New Zealand	n ≈ 450; ≥65 yrs	Community	RCT	Home-based strength + balance (Otago)	Falls ↓ ~30–35%; 12 months	Cost-effective (cost per fall prevented)
Howe et al. 2011 [12]	Multi-country	n ≈ 1,500; ≥60 yrs	Community	Systematic review	Balance training	Balance ↑ (BBS, TUG); 6–12 months	Not reported
Orr et al. 2006 [13]	Australia	n ≈ 100; ≥65 yrs	Community	RCT	High-velocity power training	Mobility ↑; 12 weeks	Not reported
Bean et al. 2004 [14]	USA	n ≈ 150; ≥65 yrs	Community	Cohort/RCT	Power vs strength training	Mobility ↑; short-term	Not reported
Liu & Latham 2009 [15]	Multi-country	n ≈ 1,200; ≥60 yrs	Community	Meta-analysis	Resistance training	Strength & function ↑	Not reported
Cadore et al. 2013 [16]	Spain	n ≈ 120; ≥65 yrs	Community	RCT	Strength + power training	Balance & mobility ↑; 12–24 weeks	Not reported
Granacher et al. 2013 [17]	Germany	n ≈ 80; ≥65 yrs	Community	RCT	Neuromuscular training	Postural control ↑; 8–12 weeks	Not reported
Lesinski et al. 2015 [18]	Multi-country	n ≈ 2,000; ≥60 yrs	Community	Meta-analysis	Balance training	Fall risk ↓; moderate effect	Not reported
Zech et al. 2010 [19]	Multi-country	n ≈ 1,000; ≥60 yrs	Community	Systematic review	Sensorimotor training	Proprioception ↑; short-term	Not reported
Winser et al. 2020 [20]	Multi-country	n = 3,668; ≥60 yrs	Community	Systematic review	Exercise vs multifactorial	Falls ↓; ≥6 months	ICER, QALY (cost-effective)
Adjetey et al. 2023 [17]	Multi-country	n ≈ 25,000; ≥60 yrs	Community	Meta-analysis	Exercise vs multimodal	Falls ↓ (~28%)	Exercise-only cost-effective
Davis et al. 2010 [11]	Canada	n ≈ 150; ≥65 yrs	Community	RCT	Resistance training	Falls ↓; 12 months	Cost per QALY favorable
McLean et al. 2015 [16]	Australia	n = 1,090; ≥70 yrs	Community	RCT	Strength + balance	Falls ↓; 18 months	ICER favorable
Rizzo et al. 1996 [16]	USA	n ≈ 300; ≥70 yrs	Clinical	RCT	Multifactorial intervention	Falls ↓; 2 years	High cost; less efficient
Zhong et al. 2025 [16]	Multi-country	n = 3,028; ≥60 yrs	Community	Network meta-analysis	Neuromuscular training	Balance ↑; ranked effectiveness	Not reported
Hopewell et al. 2018 [14]	Multi-country	n ≈ 20,000; ≥60 yrs	Community	Systematic review	Exercise interventions	Falls ↓	Partial economic evaluation
Pijnappels et al. 2008 [18]	Netherlands	n ≈ 60; ≥65 yrs	Clinical	Experimental	Reactive balance training	Fall recovery ↑	Not reported
Skelton & Dinan 1999 [20]	UK	n ≈ 200; ≥60 yrs	Community	Clinical study	General exercise	Functional independence ↑	Not reported

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formed the foundational elements of effective fall prevention programs, regardless of intervention type. These components directly target key physiological factors associated with fall risk, including muscle weakness, impaired postural control, and reduced stability [14,15]. Notably, more recent studies have increasingly incorporated power training and sensorimotor (neuromuscular) exercises, reflecting a growing emphasis on improving rapid force generation, coordination, and reactive balance control. These elements are particularly important for preventing falls in real-life situations, where the ability to respond quickly to perturbations is critical. This shift highlights an evolution in intervention design from traditional strength and balance training toward more dynamic, functionally relevant neuromuscular approaches [16,17,18].

Dosage and Training Parameters

There was considerable variability in exercise dosage across the included studies, reflecting differences in intervention design and implementation. Reported session durations ranged from 15 to 90 minutes, while training frequency varied from once weekly to multiple sessions per week. Program duration also differed substantially, extending from short-term interventions of approximately 10 weeks to long-term programs lasting up to 12 months or more. Despite this heterogeneity, a consistent pattern emerged among studies demonstrating favorable clinical and economic outcomes. The most effective and cost-efficient interventions generally adhered to a moderate and structured training dosage, characterized by sessions of approximately 60 minutes, conducted two to three times per week, over a minimum period of six months. These programs typically employed moderate-intensity exercise, allowing for sufficient physiological adaptation while maintaining participant adherence and minimizing the risk of fatigue or injury. Importantly, increasing exercise dosage beyond these parameters—such as implementing very high-frequency training schedules or extending session duration excessively—did not consistently yield additional clinical benefits. In several cases, such approaches were associated with diminished adherence, increased resource utilization, and reduced cost-effectiveness, highlighting the importance of balancing intensity and feasibility in program design [18].

Balance Outcomes

Across all included studies, neuromuscular training interventions were consistently associated with significant improvements in balance performance. These effects were most assessed using validated clinical measures such as the Berg Balance Scale (BBS) and the Timed Up and Go (TUG) test, both of which are widely used indicators of fall risk in older adults. Quantitatively, the magnitude of improvement was clinically meaningful, with reported increases of approximately 3–8 points in BBS scores and reductions of 1.5–3 seconds in TUG performance. These changes exceed commonly accepted thresholds for functional improvement and indicate a substantial enhancement in postural stability and mobility. Notably, interventions incorporating sensorimotor (neuromuscular) training and power-based exercises demonstrated the greatest gains, particularly in dynamic balance and reactive postural control. This suggests that programs targeting rapid neuromuscular responses and coordination may offer advantages over traditional balance training alone, especially in situations requiring quick corrective movements [17].

Fall Reduction

Most studies reported a significant reduction in fall incidence following neuromuscular training interventions. Pooled estimates indicated an overall reduction of approximately 20–35% in fall risk, highlighting the effectiveness of these interventions in real-world fall prevention. Importantly, exercise-only interventions were found to be comparable to, or in some cases more effective than, multifactorial interventions, despite requiring fewer resources and being less complex to implement. This finding underscores the central role of targeted exercise, particularly neuromuscular and power-based training—in reducing fall risk and challenges the assumption that more complex interventions necessarily yield superior outcomes [16].

Functional Outcomes

In addition to balance and fall reduction, neuromuscular training interventions resulted in consistent and meaningful improvements in functional performance. These included:

a) Increased gait speed, reflecting enhanced mobility and walking efficiency

b) Improved coordination and movement control, supporting safer ambulation

c) Greater independence in activities of daily living (ADL), indicating improved functional autonomy

d) Enhanced reaction time, particularly in interventions incorporating power training

Collectively, these improvements demonstrate that neuromuscular training not only reduces fall risk but also contributes to the maintenance of functional independence and quality of life among older adults. The observed benefits are likely mediated through improvements in muscle strength, power, coordination, and neuromuscular control, all of which are critical determinants of safe movement in aging populations.

Economic Evaluation

A total of 12 studies included formal economic

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evaluations, employing standard methodologies such as cost-effectiveness analysis (CEA) and cost-utility analysis (CUA) to assess the value of neuromuscular training interventions in fall prevention. These studies evaluated outcomes using commonly reported economic indicators, including cost per quality-adjusted life year (QALY), incremental cost-effectiveness ratio (ICER), and cost per fall prevented. Overall, the findings consistently demonstrated that exercise-based interventions provide favorable cost-effectiveness profiles. Most interventions fell within accepted willingness-to-pay thresholds for cost per QALY, indicating that they offer good value for healthcare investment. Reported ICER values were generally low to moderate, further supporting the economic feasibility of implementing these programs at scale [19]. A key observation across the included studies was the superior economic performance of exercise-only interventions compared to multifactorial approaches. Exercise-only programs were associated with lower implementation costs, typically ranging from approximately $64 to $700 per participant, while multifactorial interventions often exceeded $900 per participant due to their added complexity and resource requirements [20]. This difference in cost structure translated directly into variations in economic efficiency. The cost per fall prevented was substantially lower for exercise-only interventions (approximately $800 per fall prevented) compared to multifactorial interventions (approximately $8,800 per fall prevented), indicating a markedly higher return on investment for simpler, exercise-focused programs. Importantly, the increased costs associated with multifactorial interventions did not consistently result in proportionate improvements in clinical outcomes. In many cases, these interventions demonstrated comparable effectiveness to exercise-only programs, suggesting that their additional components may not provide sufficient incremental benefit to justify the higher costs [21]. Taking together, these findings highlight that cost-effective fall prevention strategies should prioritize structured, exercise-based interventions, particularly those incorporating neuromuscular and power training elements. From a health policy perspective, these results support the implementation of scalable, low-cost exercise programs as a primary approach to reducing fall risk in older adults, while reserving more complex multifactorial interventions for targeted, high-risk populations where additional benefits may be warranted [22].

Discussion

Main Findings

This systematic review provides robust and comprehensive evidence that neuromuscular training is an effective and clinically meaningful strategy for fall prevention among older adults, consistently demonstrating improvements in balance performance, reductions in fall incidence, and enhancements in functional capacity across diverse populations and settings. These findings reinforce the central role of targeted exercise interventions in mitigating age-related declines in neuromuscular function and mobility. Importantly, the results highlight that interventions incorporating power training and sensorimotor (neuromuscular) components yield the greatest clinical benefits, particularly in improving dynamic balance, postural control, and rapid corrective responses. These outcomes are especially relevant in real-world scenarios, where falls often occur due to sudden perturbations requiring immediate neuromuscular reactions. The superiority of these approaches supports the growing body of evidence suggesting that muscle power and neuromuscular coordination are more critical determinants of functional performance and fall risk than muscle strength alone [23]. In addition to clinical effectiveness, this review provides important insights into the economic value of neuromuscular training interventions. The findings clearly demonstrate that exercise-only interventions are consistently more cost-effective than multifactorial programs, offering comparable or superior clinical outcomes at significantly lower cost. This suggests that simpler, well-structured exercise programs can deliver high-value care, particularly in resource-limited healthcare systems. Furthermore, the synthesis of evidence allowed the identification of an optimal training profile, characterized by moderate-intensity exercise, sessions of approximately 60 minutes, a frequency of 2–3 times per week, and a minimum duration of six months. This standardized approach appears to provide the best balance between clinical effectiveness, adherence, and economic efficiency, addressing a critical gap in the current literature regarding the lack of consensus on training dosage [20].

Comparison with Existing Literature

The present findings are consistent with previous high-quality systematic reviews and meta-analyses reporting that exercise-based interventions reduce fall risk by approximately 20–35%. Studies such as those by Sherrington et al [9]. and Gillespie et al [12]. have established exercise as a cornerstone of fall prevention, particularly when combining strength and balance training. More recent evidence, including network meta-analyses, suggests that sensorimotor and neuromuscular training approaches are superior to traditional balance training, supporting the current findings. Additionally, studies such as Winser et al [14]. and Adjetey et al [16]. demonstrate that exercise-only interventions are more cost-effective than multifactorial strategies, reinforcing the economic conclusions of this review. To provide a clearer synthesis of these findings, Table 3 presents a detailed comparison of intervention types, integrating clinical and economic outcomes from key studies [24].

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Mechanisms and Interpretation

The effectiveness of neuromuscular training observed in this review can be explained by its multidimensional impact on physiological, neuromuscular, and functional systems that are directly associated with fall risk in older adults. A key mechanism underlying these benefits is the role of power training in enhancing the rate of force development (RFD). Unlike traditional strength training, which focuses primarily on maximal force production, power training emphasizes the speed at which force can be generated, enabling rapid muscular responses to unexpected balance disturbances. This is particularly critical in real-life fall scenarios, where the ability to execute quick corrective movements determines whether a loss of balance results in a fall. Improvements in RFD therefore contribute directly to enhanced reactive stability and fall avoidance [21,22]. In addition, sensorimotor (neuromuscular) training plays a central role in improving proprioception, intermuscular coordination, and central nervous system integration. These adaptations enhance the body's ability to detect changes in position and movement, allowing for more precise and timely postural adjustments. As a result, individuals are better equipped to maintain dynamic stability in complex and unpredictable environments, such as walking on uneven surfaces or responding to sudden perturbations. Furthermore, the combined effects of neuromuscular training on gait speed, movement efficiency, and reaction time contribute to overall functional improvements. Faster and more coordinated movement patterns reduce the likelihood of trips and slips, while improved mobility supports greater independence in activities of daily living (ADL) [22]. These functional gains are particularly important in aging populations, where declines in neuromuscular function are a major contributor to fall risk [23]. Importantly, the findings of this review suggest that isolated training approaches (e.g., strength or balance alone) may be insufficient to address the multifactorial nature of falls. Instead, interventions that integrate strength, balance, and power components appear to produce synergistic effects, targeting multiple underlying mechanisms simultaneously [24]. This integrated approach not only enhances clinical outcomes but also improves the ecological validity of training by mimicking real-life movement demands. From a translational and clinical perspective, these findings support a shift toward functionally oriented, task-specific neuromuscular training programs[25]. Such programs are more aligned with the demands of daily activities and therefore more likely to produce meaningful and sustainable reductions in fall risk. This has important implications for the design of rehabilitation and community-based interventions, emphasizing the need for dynamic, progressive, and individualized training strategies [26].

Clinical and Policy Implications

The findings of this review provide clear and actionable guidance for both clinical practice and health policy, supporting the routine implementation of standardized neuromuscular training (NMT) protocols for fall prevention in older adults. From a clinical perspective, the evidence indicates that integrated programs combining strength, balance, and power training deliver the greatest improvements in balance, mobility, and fall reduction. These programs address the key physiological drivers of falls—muscle weakness, impaired postural control, and delayed reactive responses—while remaining feasible for delivery in outpatient, primary care, and community settings [27,28]. Importantly, the identification of an optimal dosage profile (≈60 minutes per session, 2–3 sessions/week, ≥6 months, moderate intensity) provides clinicians with a practical, standardized framework that can be readily implemented and tailored to patient capacity [28]. From a policy standpoint, the results strongly favor exercise-only models as a first-line strategy due to their high cost-effectiveness and scalability. Compared with multifactorial programs, exercise-focused interventions achieve comparable clinical benefits at substantially lower cost, offering a higher return on investment for healthcare systems [29]. This is particularly relevant in the context of rapidly aging populations, where fall-related injuries contribute significantly to hospitalizations, long-term care admissions, and healthcare expenditure [30,31].

To maximize impact, health systems should:

- Integrate NMT programs into primary care and community health services
- Support group-based delivery with home-based follow-up to enhance adherence
- Train physiotherapists and community health workers in protocolized NMT delivery
- Incorporate NMT into preventive care pathways and aging policies

Based on the synthesis of high-quality evidence, an evidence-informed standardized neuromuscular training protocol is proposed (Table 4). This protocol consolidates findings across randomized trials, systematic reviews, and economic evaluations to provide a clinically applicable and policy-relevant model.

Limitations

Despite the strengths of this systematic review, several important limitations should be acknowledged when interpreting the findings. First, there was substantial heterogeneity across the included studies in terms of intervention type, training dosage (intensity, frequency, and

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duration), and outcome measures. This variability may limit direct comparability between studies and restrict the ability to establish a fully standardized neuromuscular training protocol. Differences in how balance, falls, and functional outcomes were assessed may introduce variability in effect estimates. Second, many of the included studies were characterized by relatively short follow-up periods, often ranging from a few weeks to several months. As a result, the long-term sustainability and durability of intervention effects remain uncertain, particularly in relation to maintaining functional gains and preventing recurrent falls over extended periods. Third, the majority of studies were conducted in high-income countries, with limited representation from the United States and other diverse healthcare settings. This may affect the external validity and generalizability of the findings, especially when considering differences in healthcare infrastructure, accessibility, and population characteristics. In addition, there was considerable variability in the methodological quality and reporting of economic evaluations. Differences in cost components, outcome measures (e.g., QALY vs fall reduction), and analytical approaches (CEA vs CUA) may influence the consistency and comparability of cost-effectiveness findings. Furthermore, some studies lacked detailed reporting of cost assumptions or sensitivity analyses, which may affect the robustness of economic conclusions. Another limitation relates to the inherent challenges of blinding in exercise-based interventions, which may introduce performance bias in randomized controlled trials. While this is a common limitation in rehabilitation research, it should be considered when interpreting the strength of the evidence. Finally, potential publication bias cannot be excluded, as studies with positive findings are more likely to be published. Although a comprehensive search strategy was employed, the exclusion of non-English studies may also introduce language bias.

Future Research Directions

The findings of this review highlight several important areas where further research is needed to strengthen the evidence base and enhance the clinical and policy relevance of neuromuscular training for fall prevention. First, there is a clear need for well-designed, long-term randomized controlled trials (RCTs) to evaluate the sustainability and durability of intervention effects. While many included studies demonstrate short-term benefits, the long-term impact of neuromuscular training on fall prevention, functional independence, and quality of life remains insufficiently explored. Future studies should incorporate extended follow-up periods (≥12 months) to better assess maintenance of benefits and adherence over time. Second, more high-quality economic evaluations are required, particularly within specific healthcare contexts such as the United States. Existing studies demonstrate favorable cost-effectiveness; however, variability in methodology, cost components, and outcome measures limits comparability. Future research should adopt standardized economic evaluation frameworks (CEA, CUA) and include sensitivity analyses to improve robustness and policy applicability. Third, there is a critical need for the development and validation of standardized neuromuscular training protocols. The current literature shows considerable heterogeneity in intervention design, which complicates translation into practice. Establishing evidence-based, consensus-driven protocols will facilitate consistency across clinical and community settings and support large-scale implementation. Additionally, future research should focus on diverse populations and real-world settings, including underrepresented regions and healthcare systems. This will improve the generalizability and external validity of findings and ensure that interventions are adaptable to different sociocultural and economic contexts. Finally, greater emphasis should be placed on implementation research, including strategies to improve adherence, optimize delivery models (e.g., digital or hybrid interventions), and integrate neuromuscular training into routine healthcare pathways. To synthesize these limitations and research priorities, Table 5 presents a structured overview of key gaps and recommended future directions.

Conclusion

This systematic review demonstrates that neuromuscular training, particularly when integrating strength, balance, and power components, is an effective and cost-efficient strategy for fall prevention in older adults. The evidence indicates that exercise-based interventions not only significantly reduce fall risk and improve functional outcomes, but also provide superior economic value compared to multifactorial approaches. Importantly, the findings support the adoption of a standardized training model, characterized by moderate intensity, sessions of approximately 60 minutes, a frequency of 2–3 times per week, and a minimum duration of six months. Such an approach offers a practical balance between clinical effectiveness, adherence, and cost-efficiency. Overall, neuromuscular power training represents a scalable, high-value intervention that can be widely implemented in clinical and community settings. Future efforts should focus on long-term validation and context-specific implementation to maximize its impact on aging populations.

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