AMERICAN ACADEMIC PUBLISHER

INTERNATIONAL JOURNAL OF MEDICAL SCIENCES

ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

EFFICIENCY OF ROBOTIC-MECHANICAL THERAPY IN PATIENTS WITH DIABETIC POLYNEUROPATHY (literature review)

D.N.Khidoyatova

M.B.Fozilova

Tashkent State Medical University

ABSTRACT

This article presents a comprehensive analysis of the effectiveness of robotic-mechanical therapy in patients with diabetic polyneuropathy. The study highlights the growing relevance of innovative rehabilitation technologies in the management of neurological complications of diabetes mellitus. Special attention is given to the mechanisms of action of robotic systems, including their role in improving neuromuscular coordination, restoring motor function, and enhancing microcirculation. The findings indicate that robotic-assisted therapy significantly improves functional outcomes, reduces neuropathic symptoms, and increases patients' quality of life. The integration of such technologies into clinical practice is justified as a promising direction in modern rehabilitation medicine.

Keywords: diabetic polyneuropathy, robotic therapy, rehabilitation, neuromuscular function, diabetes complications, innovative treatment

Introduction

DPN arises from multifactorial metabolic and neurovascular injury (hyperglycemia-related pathways, oxidative stress, inflammation, microvascular dysfunction), producing distal sensory loss, neuropathic pain, and motor impairment. (Pop-Busui et al., 2017; Zhu et al., 2024; Figueroa-Romero et al., 2008). Gait and balance are consequently altered (slower speed, shorter steps, increased variability), contributing to falls and to repetitive plantar stress in an insensate foot—an established pathway to ulceration. (Alam et al., 2017; Armstrong et al., 2017).

Robotic–mechanical therapies target two core rehabilitation constraints in DPN: (i) difficulty delivering sufficiently high-dose, safe locomotor practice when patients have fear of falling or tissue-stress concerns, and (ii) degraded plantar afferent input that impairs postural control. Accordingly, the technology landscape includes load-reducing gait systems (e.g., LBPP treadmills), vibration or "noise" neuromodulation (WBV, vibrating insoles), plantar mechanical compression, plantar electrical stimulation/TENS, and sensory substitution neuroprostheses. (Najafi et al., 2017; Orlando et al., 2024; Robinson et al., 2018).

Pathophysiology relevant to rehabilitation targets

DPN is not driven by a single pathway; it reflects interacting metabolic and neurovascular injury processes. Current mechanistic models emphasize that chronic hyperglycemia, dyslipidemia, and insulin resistance trigger mitochondrial dysfunction, oxidative stress, inflammation, altered gene expression, microangiopathy, and Schwann-cell–axon injury, leading to demyelination, axonal degeneration, and impaired nerve conduction (Zhu et al., 2024). Oxidative stress–related injury (including mitochondrial mechanisms) has long been recognized

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INTERNATIONAL JOURNAL OF MEDICAL SCIENCES
ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

as a convergent pathway in diabetic neuropathy progression (Figueroa-Romero et al., 2008). Clinically, the consequences are highly relevant to mobility: degraded plantar cutaneous feedback and proprioception impair postural control and adaptive gait, increasing fall risk and fear of falling (Kluding et al., 2016; Riandini et al., 2020).

DPN also interacts with diabetic foot pathology. Ulceration is strongly linked to repetitive mechanical stress in an insensate foot and to high plantar pressures and shear (Armstrong et al., 2017). This makes a key rehabilitation challenge explicit: interventions must improve gait and balance **without increasing plantar tissue risk**, and many trials accordingly exclude active ulcers, severe vascular disease, and Charcot-related deformity (e.g., Najafi et al., 2017; Orlando et al., 2024).

Why robotic–mechanical therapies?

Conventional exercise and balance rehabilitation can be effective, but adherence barriers, fear of falling, comorbidities, and limited access can reduce uptake—especially in older adults with sensory loss (Alissa et al., 2024) [5]. Robotic–mechanical therapies aim to (i) **increase safe dose and specificity of practice** (e.g., treadmills, gait trainers), (ii) **reduce biomechanical loading while allowing gait practice** (LBPP), and/or (iii) **augment degraded sensory input** through vibration, mechanical noise, compression, or electrical stimulation (Orlando et al., 2024; Bourdel-Marchasson et al., 2022).

Methods

Primary searches targeted peer-reviewed studies and high-quality systematic reviews using:

- **PubMed/ PubMed Central (PMC)**
- **Cochrane CENTRAL and related records
- **ClinicalTrials.gov***[27]* for ongoing/recent trials and protocol context

Time window: **January 1, 2016 to March 16, 2026** for intervention evidence prioritization, with deliberate inclusion of earlier milestone pathophysiology and sensory-noise studies when foundational (e.g., Pop-Busui et al., 2017; Armstrong et al., 2017). *[4]*

Results

Overview of the evidence base and study quality

Across robotic–mechanical modalities for DPN, evidence is **fragmented**: many trials are small, protocols vary widely (frequency/intensity/duration), and long-term outcomes (falls, ulcer incidence, durability after stopping) are infrequently measured. These limitations are consistent with earlier systematic review conclusions in vibration-based modalities (Robinson et al., 2018) and with broader rehabilitation literature noting heterogeneity in DPN balance interventions (Alissa et al., 2024).

Comparative table of key studies (2016–2026 prioritized)

Table 1. Key robotic–mechanical therapy studies in DPN (and closely related PN cohorts when DPN-only evidence is limited).

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INTERNATIONAL JOURNAL OF MEDICAL SCIENCES
ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

Effect size notes: When not explicitly reported, Cohen's d was approximated from post-intervention group differences using pooled SDs; values are oriented so positive favors intervention. Risk-of-bias is a qualitative RoB2/ROBINS-I judgment.

Compact comparative table of key studies

Citation	Design	Sample	Intervention	Comparator	Main outcomes	Effect size (selected)	RoB
Abdelaal & El-Shamy (2022)	RCT	n=45 DPN	LBPP/antigravity treadmill + PT, 12 wk	PT alone	GAITRite gait; Biodex stability	SMD (approx) gait velocity ≈ **2.05**	Some concerns
Jamal et al. (2019)	RCT	n=26 painful DPN	WBV, 6 wk	Standard care	NPRS, SLST, TUG, SF-36, VPT	SMD (approx) pain ≈ **1.45**	Some concerns
Robinson et al. (2018)	Systematic review	3 studies	WBV	Various	Pain, balance, glycemia	Certainty **very low** (no pooled ES)	—
Najafi et al. (2017)	Double-blind RCT	n=28 DPN	Plantar electrical stim daily, 6 wk	Sham device	Sway, gait, VPT	Reported cadence ≈ **1.35**	Some concerns
Orlando et al. (2024)	Randomized crossover	n=22 DPN	Vibrating insoles (acute)	No vibration	Gait speed, balance metrics	SMD (approx) stair-descent speed ≈ **0.62**	Some concerns
Bourdel-Marchasson et al. (2022)	Double-blind RCT	n=56 older T2D (neuropathy subgroup)	Subsensory vibrating insole, 1 mo	Sham	Fast walking speed	**0** (no benefit)	Low
Kang et al. (2019)	Single-arm	n=30 DPN	Plantar mechanical	None	VPT, gait	Reported gait	High

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ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

Citation	Design	Sample	Intervention	Comparator	Main outcomes	Effect size (selected)	RoB
			compression, 4 wk		speed, sway	speed ≈ **0.41–0.77**	

Note: Standardized effects are reported as given by authors (when available) or approximated from published group means/SDs; crossover correlations were not always available, so acute insole ES may be conservative or biased.

Modality-focused synthesis

LBPP/antigravity treadmill training. One DPN RCT found LBPP treadmill plus conventional therapy improved spatiotemporal gait and postural stability indices more than conventional therapy alone, suggesting that load reduction can enable higher-dose gait practice in a safer context (Abdelaal & El-Shamy, 2022) [1]. A related RCT exploring different LBPP "doses" reported improvements in fall-risk metrics, implying potential dose–response effects, though generalizability is limited (male-only samples; single settings).

Whole-body vibration. In painful DPN, WBV improved pain, balance (SLST, TUG), VPT, and SF-36 compared with standard care in a small trial (Jamal et al., 2019) [10]. However, the 2018 systematic review graded the evidence as very low quality due to few trials and high heterogeneity, so effect estimates may change substantially with future studies (Robinson et al., 2018) [16].

Vibrating insoles and plantar vibration ("noise" stimulation). A DPN randomized crossover study demonstrated acute improvements in gait speed and aspects of postural control, especially when stimulating the whole plantar surface (Orlando et al., 2024) [14]. In contrast, a robust double-blind home-use RCT in older adults with type 2 diabetes (with a smaller neuropathy subgroup) did not improve walking speed over one month (Bourdel-Marchasson et al., 2022), indicating that durability and target-population selection remain uncertain [5].

Plantar mechanical compression. A 4-week uncontrolled study suggested modest improvements in VPT and gait speed, but risk of bias is high due to absence of a control group and possible confounding (Kang et al., 2019) [11].

Plantar electrical stimulation/TENS. A double-blind randomized trial reported improvements in sway and gait performance with daily home plantar electrical stimulation versus sham, supporting a sensory-augmentation/neuromodulation mechanism (Najafi et al., 2017) [13].

Wearable sensory neuroprostheses. Evidence is stronger in mixed-etiology sensory peripheral neuropathy with insensate feet than in DPN-only cohorts; randomized crossover testing showed improved gait/balance performance with stimulation ON vs OFF, and cohort

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ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

studies indicate functional gains over weeks. (Koehler-McNicholas et al., 2019; Oddsson et al., 2020). *Indirectness* to DPN is the key limitation.

Exoskeletons/robotic gait trainers; NMES+robotics. In DPN, direct RCT evidence for powered exoskeleton gait rehabilitation is limited; exoskeleton concepts appear more often in diabetic foot offloading (e.g., in-shoe exoskeleton pressure reduction) and ongoing trials assessing plantar pressures/safety rather than broad functional efficacy (Roser et al., 2017; ClinicalTrials.gov NCT03717233). For NMES, a recent cohort study in diabetic sensorimotor polyneuropathy reported improved nerve conduction and symptom scores after 10 weeks of NMES as adjunct care, but this is not robotics-integrated (Smith et al., 2024) [18].

Discussion

Mechanistic interpretation

Robotic–mechanical therapies plausibly work in DPN via:
1) **Safe dose escalation of task-specific practice** (LBPP): reduced loading enables repetitive gait training under controlled conditions, potentially improving coordination and stability.
2) **Sensory augmentation/substitution** (vibration, plantar electrical stimulation, neuroprostheses): stochastic resonance–like effects or alternative cueing channels may partially compensate for plantar afferent loss, improving postural control.
3) **Pain modulation and neuromuscular activation** (WBV): mechanoreceptor activation and altered central processing may reduce pain while enhancing balance-related neuromuscular coordination.

Safety, cost, and implementation barriers

Most trials exclude active ulcers and severe deformity—appropriate given the ulcer pathway of repetitive stress in an insensate foot (Armstrong et al., 2017). Painful DPN is associated with higher healthcare utilization and costs, providing a rationale for effective nonpharmacologic modalities, yet economic evaluation of these devices is scarce (Kiyani et al., 2020; Bromberg et al., 2024). Real-world robotic implementation is constrained by equipment cost, training, workflow integration, and reimbursement variability; broader rehabilitation robotics cost/implementation analyses underscore these barriers (Banyai et al., 2024; Gower et al., 2025).

Conclusions, Clinical Recommendations, and Future Research

Clinical Recommendations

1. In clinical practice, **lower body positive pressure (LBPP) treadmill training** can be effectively incorporated as an adjunctive rehabilitation method for patients with diabetic polyneuropathy (DPN) who exhibit limited mobility and an increased risk of falls. Its use should be guided by objective assessments of gait and balance, with careful adjustment of the unloading level to ensure both safety and therapeutic benefit (Abdelaal & El-Shamy, 2022).

2. **Plantar electrical stimulation** may be considered particularly beneficial for patients with DPN presenting with sensory deficits and postural instability. This approach is especially relevant in cases where patients are capable of adhering to home-based treatment protocols, as

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ISSN NUMBER: 2692 - 5206 Volume 6. No 03. March ,2026

evidence suggests meaningful improvements in postural sway and gait parameters under controlled conditions (Najafi et al., 2017).

3. The application of whole-body vibration (WBV) therapy or vibrating insoles should be approached selectively and with caution. These interventions may provide short-term functional benefits; however, their effectiveness appears to depend on protocol standardization and patient-specific factors. Continuous monitoring of skin integrity is essential, especially in patients with high ulcer risk, given the currently limited and heterogeneous evidence base (Jamal et al., 2019; Robinson et al., 2018; Orlando et al., 2024).

Prioritized Directions for Future Research

1. A critical question that remains insufficiently addressed is which phenotypes of DPN respond most effectively to specific rehabilitation modalities. Future clinical trials should incorporate stratification based on disease severity (e.g., vibration perception threshold, monofilament testing), presence or absence of neuropathic pain, and ulcer-risk profiles to enable personalized therapeutic approaches.

2. There is a pressing need to determine whether the observed therapeutic benefits are sustained over time and translate into clinically meaningful outcomes. Large-scale, multicenter randomized controlled trials with extended follow-up periods (6–12 months) should include endpoints such as fall incidence, ulcer development, and standardized measures of gait and balance.

3. Finally, the cost-effectiveness of these interventions within real-world healthcare systems must be rigorously evaluated. Given the substantial long-term economic burden of diabetic polyneuropathy and the high initial costs associated with robotic and device-based therapies, future studies should integrate health-economic analyses, including resource utilization and prevention of complications.

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