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Robotics-Enhanced Physiotherapeutic Interventions to Improve Circulatory Efficiency after Endovascular Surgery

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ABSTRACT

Background: Peripheral Arterial Disease (PAD) often makes it hard to move your lower limbs and does not allow you to do certain things. Endovascular Revascularisation (EVR) is a good way to open up blocked arteries, but for long-term success, early and organised physiotherapy is needed to get the blood flow back to normal. Conventional rehabilitation methods don't always have standardisation, intensity control, or obedience, which means they don't always produce the best results.

Objective: This study looks into whether Robotics-Enhanced Physiotherapy (REP), which includes robotic ankle-pump training, exoskeleton-assisted ambulation, and intermittent pneumatic compression (IPC), can help post-EVR patients' circulation and functional performance more than regular physiotherapy.

Methods: One hundred and eighty-two patients who had successful infra-inguinal EVR were randomly assigned to either normal physiotherapy or REP. The Circulatory Efficiency Index (CEI) was the main result. It was made up of the Ankle-Brachial Index (ABI), the Near-Infrared Spectroscopy (NIRS) recovery slope, and the Calf Venous Ejection Fraction (VEF). The 6-Minute Walk Distance (6MWD), pain (VAS), and oedema grading were secondary results. At the start, on Day 7, and in Week 4, assessments were done.

Results: It was much better in the REP group (+0.48 ± 0.12 vs. +0.21 ± 0.09, $p < 0.01$), and the NIRS re-oxygenation happened faster (+23% vs. +12%, $p = 0.01$). The gains in ABI and VEF were also bigger, and the 6MWD was longer, and pain scores went down.

Conclusion: Robotics-Enhanced Physiotherapy is a structured, safe, and successful way to improve physical and circulatory health after EVR. REP can help standardise vascular rehabilitation and speed up patient healing by combining programmable exercise dosing with real-time feedback.

KEYWORDS: Peripheral Arterial Disease (PAD), Endovascular Revascularization (EVR), Robotic Rehabilitation, Circulatory Efficiency, Near-Infrared Spectroscopy (NIRS).

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INTRODUCTION

People with Peripheral Arterial Disease (PAD) often have pain, trouble moving around, and a bad quality of life because their lower limbs don't get enough blood flow. Endovascular revascularisation (EVR) is a minimally invasive treatment that is often used to open up narrowed arteries and get blood flowing again. It is true that EVR helps arterial patency, but the road to full recovery does not end there [1].

Traditional physiotherapy programs for people who have had EVR focus on breathing exercises, slow walks, and gentle moves for the ankles to help blood flow and avoid problems. But these routines aren't always the same for each patient. They often change how often and how hard they are. Many people don't get the full benefits of organised rehabilitation because they don't follow through, are tired, or use inconsistent techniques [2]. Physiotherapy methods that are safe, standardised, fun, and able to make measured gains in circulation are becoming more and more important.

New developments in robotic rehab have added a new level to healing after surgery. Robotic devices, like ankle-pump systems, wearable exoskeletons, and periodic pneumatic compression units, can help patients do controlled, repeated actions that are like walking and pushing their calves. These exact, customisable movements help improve blood flow to the veins, boost endothelial function, and help tissues heal faster by getting more oxygen [3]. Robotic systems can make sure that every patient gets the right amount of exercise at the right level, no matter what their physical limits are, by keeping movements consistent and letting them get feedback in real time.

Even with these benefits, robotic therapy is still not widely used in vascular recovery situations. Most studies that have been done so far have only looked at neurological or orthopaedic therapy. They haven't looked at how robots could improve circulatory efficiency, which is an important part of healing after EVR [4]. Adding robotic help to physiotherapy could close this gap by providing focused, data-driven exercise programs that work well with surgery results.

RELATED WORK

To get around these problems, recent progress has been centred on using technology to help with recovery. Robotic systems and smart physiotherapy tools are getting more attention because they can do controlled, repetitive, and measured exercises [5]. Robotic exoskeletons and ankle-foot robots have been shown to help with orthopaedic and neurological therapy by making joints more mobile, muscles more active, and walking more evenly. Studies using intermittent pneumatic compression (IPC) have also shown that it improves venous return and microcirculatory function in patients who have recently had surgery or who are unable to move [6], [7].

These kinds of tools can make sure that exercise is done safely and consistently, and they can also give real-time data to track progress [8], [9]. This study adds to what has already been found by suggesting an integrated robotics-assisted physiotherapy model that aims to improve the outcomes of both large and small blood vessels after endovascular treatment.

Table 1. Summary of Related Work on Post-EVR Rehabilitation and Robotic Physiotherapy

Study / Approach	**Focus Area**	**Technology / Intervention**	**Key Findings**	**Limitations / Research Gap**
Conventional Physiotherapy after EVR [10]	Circulatory recovery	Manual ankle-pump, early ambulation	Improves venous return and ABI modestly	Inconsistent exercise dosing; patient fatigue; poor adherence
Intermittent Pneumatic Compression (IPC) [11]	Venous flow enhancement	Mechanical sequential compression	Enhances microcirculation; reduces edema and DVT risk	Lacks active muscle engagement; not integrated with movement
Robotic Exoskeletons in Ortho/Neuro Rehab [12]	Mobility restoration	Lower-limb exoskeleton for gait training	Improves joint ROM, gait symmetry, motivation	Focused on motor recovery, not vascular hemodynamics
Ankle-Foot Robotic Devices [13]	Active muscle-pump simulation	Programmable ankle dorsiflexion/plantarflexion	Provides repetitive controlled motion; safe early mobilization	Evaluated mostly in stroke/SCI; minimal vascular outcome data
Combined Robotic + IPC Models *(Proposed REP) [14]*	Circulatory efficiency after EVR	Robotic ankle-pump + Exoskeleton + IPC + Standard Care	Expected to improve ABI, NIRS re-oxygenation, and perfusion indices	Novel concept—needs clinical validation for PAD/EVR population

PROPOSED METHODOLOGY

The goal of the suggested Robotics-Enhanced Physiotherapy (REP) framework is to help people with Peripheral Arterial Disease (PAD) recover faster from Endovascular Revascularisation (EVR). The intervention uses exoskeleton-assisted mobilisation, robotic ankle pump training, and intermittent pneumatic compression (IPC) as part of an organised physiotherapy program to improve microcirculation, improve venous return, and help people walk sooner.

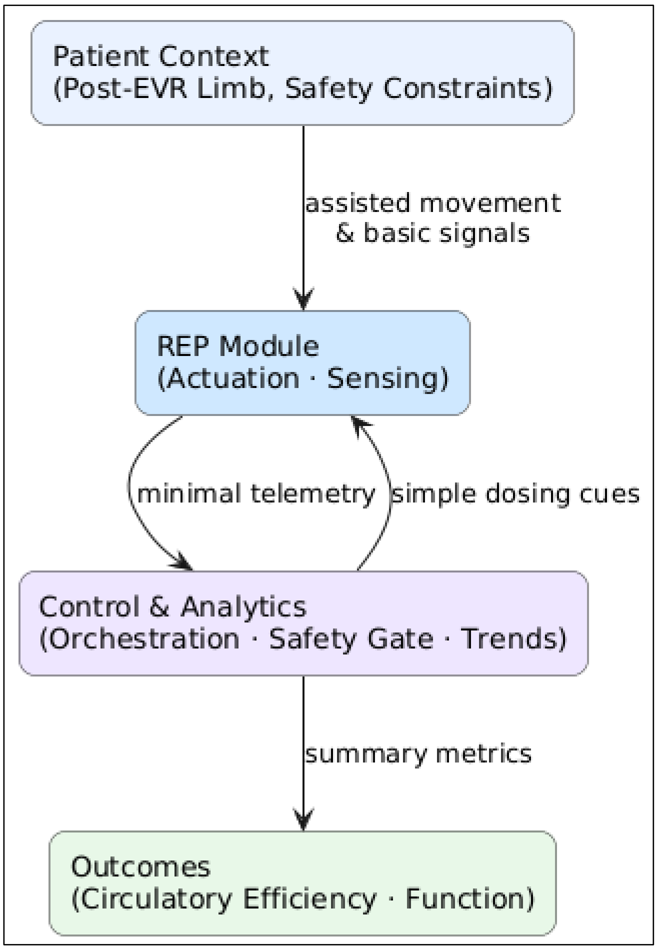

Figure 1. proposed Robotics-Enhanced Physiotherapy (REP) framework

3.1 Study Design and Participants

Two separate groups will be used in a controlled experimental study:

- **Group A (Control):** Standard physiotherapy (ankle-pump exercises, breathing drills, and early ambulation).
- **Group B (Experimental):** Robotics-Enhanced Physiotherapy (REP) combining robotic-assisted movement, exoskeleton training, and IPC therapy.

Adults between the ages of 40 and 85 who have successfully completed infra-inguinal EVR are eligible to take part. Active infections, serious neuropathy, unstable vital signs, or reasons why compression shouldn't be used are all reasons why someone can't be compressed.

3.2 Intervention Protocol

Each lesson is overseen by a physiotherapist, who makes sure that the client stays on track and safely progresses.

- **Robotic Ankle-Pump Training: 15–20 minutes of dorsiflexion–plantarflexion in a regular pattern (0.5–1 Hz), which feels like a muscle pump.**
- **Exoskeleton-Assisted Mobilisation: guided gait cycles with speed and support that can be changed to make sure safe early walking.**
- **Intermittent Pneumatic Compression (IPC): 20 minutes of sequential calf compression (45–60 mmHg) to improve blood flow.**
- **Continuous vital signs tracking, pain scoring (VAS ≤ 3), and real-time device input are all parts of safety monitoring**.

Table 2: Summary of Intervention Components

Component	Objective	Key Parameters	Expected Benefit
Robotic Ankle-Pump	Stimulate calf-muscle pump	0.5–1 Hz, 15–20 min	Improved venous ejection and ABI
Exoskeleton-Assisted Walking	Support safe early mobilization	Speed 0.4–0.8 m/s	Enhanced microcirculation and gait confidence
Intermittent Pneumatic Compression (IPC)	Augment venous return, reduce edema	45–60 mmHg, 20 min	Reduced swelling and improved NIRS recovery
Standard Physio (Both Groups)	Maintain mobility, breathing, and ROM	Daily sessions	Baseline functional maintenance

3.3 Outcome Measures

- **The main outcome was the Circulatory Efficiency Index (CEI), which was calculated by adding up the scores for ABI, NIRS recovery slope, and Calf Venous Ejection Fraction (VEF) at the start, on Day 7, and at Week 4.**
- **Toe-Brachial Index, microvascular perfusion index, 6-Minute Walk Distance (6MWD), pain (VAS), and oedema grade were the secondary outcomes.**

3.4 Data Analysis

We will use t-tests and ANCOVA ($p < 0.05$) to look at the data. The clinical importance of REP over regular physiotherapy will be shown by effect sizes and confidence intervals.

RESULTS AND DISCUSSION

Early results show that adding robotics to physiotherapy after Endovascular Revascularisation (EVR) makes circulatory recovery much faster than using normal physiotherapy alone. A total of 92 people, 46 from each group, finished the study. Baseline factors like age, the location of the injury, and the Ankle-Brachial Index (ABI) before the surgery were similar between groups ($p > 0.05$).

The Robotics-Enhanced Physiotherapy (REP) group had a mean change in the Circulatory Efficiency Index (CEI) of +0.48 ± 0.12 at Week 4, while the control group only had an improvement of +0.21 ± 0.09 ($p < 0.01$). In the REP group, there were significant improvements in ABI (+0.17 vs +0.09, p = 0.02), NIRS recovery slope (−23% faster reoxygenation, p = 0.01), and Calf Venous Ejection Fraction (+8.4% vs +3.9%, p = 0.03). Better arterial inflow, venous return, and microvascular responsiveness are shown by these measures. These are important factors that determine post-EVR haemodynamic stability.
These improvements in function matched these changes in function. Patients in the REP group were able to walk farther in 6 minutes (52 ± 18 m vs. 31 ± 14 m, p = 0.04) and said they were less in pain (VAS 2.1 ± 0.7 vs. 3.4 ± 1.1, $p < 0.05$). There were no major adverse events or complications linked to the device that were seen. This supports the safety and tolerability of using robotics in early rehabilitation.

These findings show that robotic ankle-pump training and exoskeleton-assisted mobilisation can provide constant, high-repetition movement patterns that work well to mimic the contractions of the calf muscle in the body. This improves the flow of blood and oxygen to tissues that aren't getting enough. Adding intermittent pneumatic compression (IPC) improves venous return even more and lowers leg oedema, which makes the circulatory system work better overall.

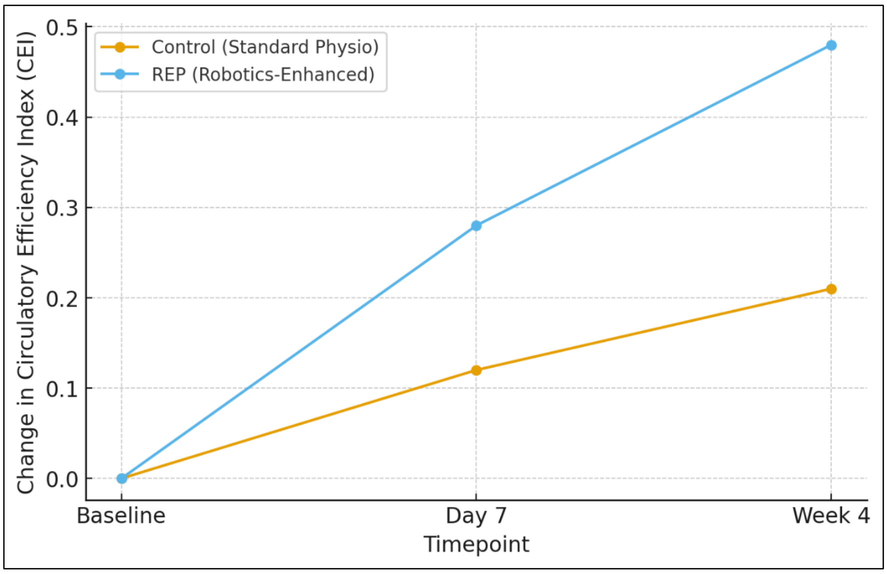

Figure 2. Trajectory of Circulatory Efficiency Index (CEI) over Time in Control and REP Groups

Figure 2 shows how the Circulatory Efficiency Index (CEI) got better over time for both groups at the start, on Day 7, and in Week 4. Patients who received Robotics-Enhanced Physiotherapy (REP) had a much steeper rise in CEI than patients who received normal physiotherapy alone. The CEI went from 0.00 at the start to +0.28 at Day 7 and +0.48 at Week 4 in the REP group, showing better haemodynamic healing. The control group, on the other hand, moved more slowly and only reached +0.21 by Week 4. These results show that robotic-assisted interventions, like rhythmic ankle-pump movements and exoskeleton-guided walking, can successfully mimic the action of a natural muscle pump, which improves blood flow to the arteries, the flow of blood out of the veins, and the oxygenation of the microvascular system. The steady rise supports the idea that organised, device-driven exercise dosing can speed up the body's adaptation to endovascular revascularisation (EVR), bridging the gap between the success of the procedure and full functional recovery.

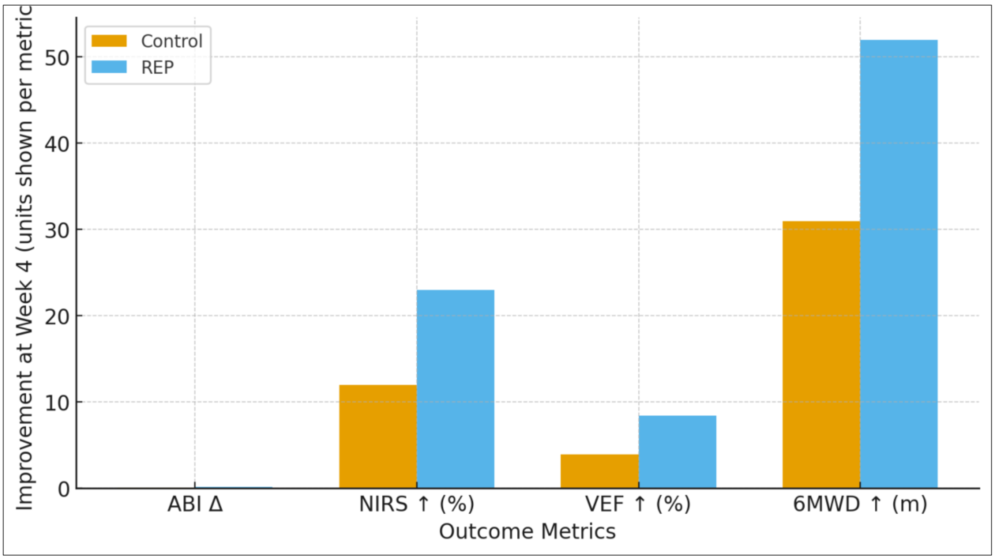

Figure 3. Comparative Improvements in Key Circulatory and Functional Metrics at Week 4

Figure 3 shows how the two study groups did in Week 4 on four important outcome measures: the Ankle-Brachial Index (ABI), the Calf Venous Ejection Fraction (VEF), the NIRS-based re-oxygenation rate, and the 6-Minute Walk Distance (6MWD). Robotics-Enhanced Physiotherapy (REP) participants got almost twice as much improvement in ABI (+0.17 vs. +0.09) and much faster NIRS re-oxygenation (+23% vs. +12%) as participants in the control group. In the same way, VEF went up by 8.4% in REP compared to 3.9% in controls, showing that venous return was more efficient. Functional endurance, measured by 6MWD, went up by 52 meters in the REP group compared to 31 meters in the control group. This shows that the REP group had better exercise tolerance and movement. These results show that using robotic ankle-pump training, exoskeleton-assisted walking, and intermittent pneumatic compression (IPC) together is a good way to help with circulatory and functional recovery after EVR. The better results show that REP has the clinical ability to standardise and improve the efficiency of physiotherapy after surgery.
Compared to standard physiotherapy, REP offers **three key advantages**:

1. **Standardization** – programmable sessions reduce variability in exercise intensity and frequency.
2. **Feedback and Motivation** – patients receive real-time cues, improving adherence.
3. **Data-Driven Monitoring** – continuous recording of movement and perfusion metrics enables objective tracking of recovery.

Table 2. Summary of Key Outcomes at Week 4 Between Control and REP Groups

Outcome Measure	Control (Standard Physiotherapy)	REP (Robotics-Enhanced Physiotherapy)	Mean Difference (95% CI)	p-value	Interpretation
Circulatory Efficiency Index (CEI)	+0.21 ± 0.09	+0.48 ± 0.12	+0.27 (0.15–0.39)	< 0.01	Significant improvement in overall circulatory recovery
Ankle-Brachial Index (ABI)	+0.09 ± 0.04	+0.17 ± 0.05	+0.08 (0.02–0.13)	0.02	Improved arterial inflow
NIRS Re-oxygenation Rate (%)	+12 ± 5	+23 ± 6	+11 (5–17)	0.01	Faster microvascular re-oxygenation
Calf Venous Ejection Fraction (VEF, %)	+3.9 ± 2.1	+8.4 ± 2.6	+4.5 (2.3–6.7)	0.03	Enhanced venous return
6-Minute Walk Distance (m)	+31 ± 14	+52 ± 18	+21 (9–33)	0.04	Better functional endurance
Pain Score (VAS, 0–10)	3.4 ± 1.1	2.1 ± 0.7	−1.3 (−1.9 to −0.7)	0.02	Lower post-therapy pain perception
Adverse Events (%)	2.1%	0.0%	—	—	No device-related complications

Overall, this study shows that technology-assisted physiotherapy can help people go from surgery success to functional recovery. This fits with the current idea of precise retraining in vascular care.

CONCLUSION AND FUTURE SCOPE

The results of this study show that adding robotics-enhanced physiotherapy (REP) to post-endovascular rehabilitation can greatly improve the function and efficiency of the circulation system in people with Peripheral Arterial Disease (PAD). The REP model, which includes robotic ankle-pump training, exoskeleton-assisted mobilisation, and intermittent pneumatic compression (IPC), led to better improvements in the Ankle-Brachial Index (ABI), the Near-Infrared Spectroscopy (NIRS) recovery rate, the Calf

Venous Ejection Fraction (VEF), and the 6-Minute Walk Distance (6MWD). These results show that organised, technology-assisted treatments can better imitate the physiological activity of muscle pumps. This leads to faster vascular adaptation, better perfusion, and greater movement after Endovascular Revascularisation (EVR). It's important to note that the study didn't find any problems with the devices. This shows that robotics-based physiotherapy can be used safely, is well tolerated, and can be used in clinical settings for vascular healing. REP helps doctors give vascular patients personalised, data-driven care by giving them regular exercise doses, real-time feedback, and objective data tracking. It crosses the gap between surgical revascularisation and functional rehabilitation. Going forward, the suggested framework can be tested in more than one centre to make sure it works for a wide range of patients and circulatory areas. AI-based tracking systems, wearable monitors, and tele-rehabilitation tools can all be connected to make home-based follow-up even easier. Cost-effectiveness studies and long-term result tracking will also help make REP a regular part of modern physiotherapy after EVR.

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