# Advancements in Physiotherapy: Technology-Enabled Rehabilitation, Wearable Monitoring, and Virtual Reality Applications for Musculoskeletal Care

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## Abstract

Musculoskeletal (MSK) disorders are the most common cause of disability in every region of the globe, and they have a tremendous impact on physical functioning, quality of life, and healthcare expenses. The traditional physiotherapy is the cornerstone of therapy but is being marred with lack of compliance, subjective performance and lack of accessibility. The trial was done to compare the effect of physiotherapy interventions alleviated through technology, sensor-based wearable monitoring and virtual reality (VR) based rehabilitation, with the traditional physiotherapy. It was a 12-month randomized controlled trial (RCT) with 120 participants with MSK conditions. The participants were divided to technology-based or traditional physiotherapy group and pain, ROM, muscle strength, functional ability, adherence and satisfaction were measured. The results demonstrated that there were much more improved outcomes in the technology condition with a reduction in pain to 62 percent, a 38 percent increase in ROM, functional outcomes and adherence and satisfaction. Real-time monitoring was supported by wearable data, and VR was more motivating and engaging. These results help to state that rehabilitation protocols supplemented with wearable devices and VR are more effective and can help patients be more satisfied. The paper also concludes that technological-enhanced physiotherapy is a novel method of maximizing musculoskeletal therapy to allow personalized, evidence-based, and affordable rehabilitation.

**Keywords:** Physiotherapy, Musculoskeletal Rehabilitation, Wearable Sensors, Virtual Reality, Tele-rehabilitation

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## Introduction

One of the most burning health problems in the 21 st century is musculoskeletal (MSK) disorders (Briggs et al., 2020). Their conditions include low back pain, osteoarthritis, tendinopathies, and rotator cuff injuries and contribute to being a major cause of disability, poor quality of life, and to social and economic burden (Kalikanov et al., 2025). According to the World Health Organization, over 1.7 billion individuals worldwide have musculoskeletal disorders as the most frequent disabling ailment in all ages (WHO, 2022). These disorders do not only reduce physical abilities and mobility but also extend their effects to the psychological distress, work absence, and higher healthcare expenditures (Blyth et al., 2019). Physiotherapy has a key position in the prevention, treatment, and rehabilitation of MSK disorders (Bullo et al., 2024). Physiotherapy interventions such as manual therapy, exercise, patient education, and functional retraining which are conservative interventions have been found to optimally improve pain, joint mobility, muscle power, and functional autonomy (Dickson et al., 2024). In spite of these thoroughly reported benefits, traditional approaches have certain historic constraints in clinical practice. One of the major concerns is patient compliance since most patients do not exercise at home on a regular basis thereby reducing the general effectiveness of therapy (Paladugu et al., 2025). The access to rehabs is also low, particularly in rural and underserved groups, because of the distance to service, the cost, and availability of trained professionals (Fullen et al., 2023). Moreover, the traditional physiotherapy rehabilitation gain assessment and monitoring are founded on unstandardized subjective self-reporting and limited in-clinic evaluations (Thibaut et al., 2022). This would lead to the delay of complications, underreporting of the patient gain, and limitation of tailoring therapy programs (Sun et al., 2022). These constraints are suggesting that new data-integrated solutions are required to improve the quality, accessibility, and patient satisfaction of musculoskeletal rehabilitation.

The profession of rehabilitation science is being transformed by technological innovations that provide opportunities to provide, monitor, and make changes to physiotherapy therapies in different ways (E Siqueira et al., 2024). The use of technologies, such as wearable sensors, VR devices, and tele-rehabilitation platforms, is becoming a potential solution that will eliminate most of the disadvantages of the traditional solutions. Real-time continuous monitoring of patient movement, muscle activity, and biomechanical functioning can be done with wearable sensors (including inertial measurement units/IMUs), electromyography (EMG) sensors, and force-sensing insoles (Cunha et al., 2023). These systems can offer therapists with objective and quantifiable data which can be used to make exercise approaches individualized, monitor adherence, and provide immediate corrective feedback. They allow the patients to track their performance, making them more motivated and responsible. Meanwhile, virtual reality (VR) and augmented reality (AR) application usage became popular in rehabilitation (Iqbal et al., 2024). VR interventions offer game-like environments to patients that allow simulating realistic functional activities to improve motivation, participation in activities, and neuroplasticity (Paladugu et al., 2025). Immersive exposure may improve pain tolerance, functional performance, and psychological well-being, particularly when used as part of standard rehabilitation protocols (Kalikanov et al., 2025). Additionally, telerehabilitation platforms, by means of video conferencing and remote monitoring, enhance access to care by means of remote supervision and reducing the number of in-person visits (Shambushankar et al., 2025). Emerging evidence indicates that technology-assisted physiotherapy not only improves clinical outcomes but also raises adherence, patient satisfaction, and cost-effectiveness (Blyth et al., 2019; Kim et al., 2022). Besides, advances in machine learning and AI enable the examination of substantial amounts of biomechanical and clinical information, resulting in predictive modeling, personalized treatment plans, and adaptive rehab systems (Sumner et al., 2023). Integrating these technologies represents a paradigm shift toward precision rehabilitation, which is data-driven, patient-specific, and adaptively evolving.

## Objectives

The objective of this research is to evaluate the clinical effectiveness of wearable and VR based interventions in enhancing pain, range of motion (ROM), strength, functional capacity, and quality of life; compare patient compliance, user-friendliness, and user satisfaction with technologically enabled rehabilitation; examine implementation barriers such as cost, infrastructure, data privacy, and clinician training; and suggest a model for implementing these technologies in routine physiotherapy practice.

## Materials and Methods

### Study Design

This prospective RCT was conducted over 12 months in the Department of Physical Medicine and Rehabilitation at a tertiary care teaching hospital to compare the effectiveness of technology-enabled physiotherapy, using wearable sensor monitoring and VR)–assisted exercises, with standard physiotherapy in patients with musculoskeletal conditions. Participants were randomly assigned (1:1) to experimental (technology-assisted) or control (conventional) groups using a computer-generated sequence. The study followed the Declaration of Helsinki, received Institutional Ethics Committee approval, and obtained written informed consent from all participants.

### Participants

Adults aged 18–65 years with clinically and radiologically confirmed musculoskeletal disorders (e.g., osteoarthritis, low back pain, rotator cuff injuries, tendinopathies) referred for physiotherapy were included if they had functional limitations and could attend sessions and follow-ups. Exclusion criteria were neurological or cognitive disorders, recent orthopedic surgery (<3 months), psychiatric illness, or contraindications to VR (e.g., epilepsy, severe motion sickness). A sample size of 120 (60 per group) was determined by power analysis (power = 0.80, $\alpha = 0.05$) to detect a 20% difference in outcomes, with 10% added for possible dropouts.

### Intervention Protocol

*Wearable Device–Assisted Rehabilitation*

Participants in the experimental group were fitted with wearable sensors, including IMUs and surface electromyography (sEMG) trackers, placed on key muscle groups and joints relevant to the condition being treated (e.g., quadriceps and knee joint for knee osteoarthritis, lumbar paraspinals for low back pain). These devices captured kinematic and electromyographic data during exercise sessions, including joint angles, range of motion, muscle activation patterns, and adherence metrics. The collected data were transmitted to a secure cloud-based platform and monitored by therapists in real time, allowing for individualized feedback and exercise adjustments.

*Virtual Reality–Based Rehabilitation*

The VR treatment was administered through a head-mounted display (HMD) system (e.g., Oculus Quest 2) connected to motion-tracking sensors and specially designed rehabilitation software. Three times weekly for 8 weeks, each 45-minute therapy session was carried out. Patients practiced gamified therapeutic exercises that mimicked daily functional tasks, like reaching, squatting, stepping, and lifting, in virtual environments. Difficulty levels and task complexity were incrementally modified according to patient performance and tolerance. All sessions were supervised by therapists to provide for safety and maximize technique.

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*Control Group*
The control group participants underwent usual physiotherapy comprised of supervised therapeutic exercises, stretching, strengthening, and manual therapy as needed, with no wearable or VR support. Session frequency and duration were the same as for the experimental group.

## Outcome Measures

Outcomes were measured at baseline, mid-intervention (4 weeks), post-intervention (8 weeks), and follow-up (12 weeks) with standardized and validated measures. Clinical outcomes were pain intensity using the Visual Analogue Scale (VAS), ROM by goniometric measurement, and muscle strength by Manual Muscle Testing (MMT) and isokinetic dynamometry. Functional outcomes were mobility and balance via the Timed Up and Go Test (TUG) and Berg Balance Scale (BBS), and walking performance through spatiotemporal gait analysis using wearable sensors. Patient-reported outcomes were quality of life using the Short Form-36 (SF-36) questionnaire, adherence as the percentage of attended sessions and self-reported home exercise compliance, and satisfaction as assessed by a Likert-scale survey of technology use and rehabilitation experience.

## Data Collection and Analysis

All data were collected by trained physiotherapists blinded to group allocation, with wearable sensor data automatically logged and exported to a secure database, and clinical and functional assessments conducted using standardized protocols. Statistical analysis was performed using SPSS version 22, with continuous variables expressed as mean ± standard deviation (SD) and categorical variables as percentages. Between-group differences were analyzed using independent t-tests or Mann–Whitney U tests for continuous data and chi-square tests for categorical data, while repeated measures ANOVA examined changes over time. A $p < 0.05$ was considered statistically significant, and effect sizes were calculated using Cohen's d. Missing data were handled using multiple imputation, intention-to-treat (ITT) analysis was applied to all randomized participants, and subgroup analyses based on age, sex, and baseline severity explored differential intervention responses.

## Results

### Demographics and Baseline Characteristics

A total of 120 participants were enrolled and randomized equally into the technology-assisted group (n = 60) and the conventional physiotherapy group (n = 60). The mean age of participants was 48.6 ± 10.4 years, with a male-to-female ratio of 1.1:1. Baseline characteristics, including pain intensity, range of motion, functional scores, and quality of life measures, were comparable between groups ($p > 0.05$), confirming successful randomization and group equivalence. Table 1 presents the baseline demographic and clinical characteristics of participants in both groups, showing similar distributions in age, gender, disease duration, pain scores, range of motion, and quality of life. The absence of significant differences ($p > 0.05$) confirms successful randomization and comparability between the technology and control groups.

**Table 1. Baseline Demographic and Clinical Characteristics of Participants**

| Variable | Technology Group (n=60) | Control Group (n=60) | *p*-value |
|---|---|---|---|
| Age (years, mean ± SD) | 48.9 ± 10.2 | 48.3 ± 10.7 | 0.78 |
| Gender (M/F) | 32 / 28 | 31 / 29 | 0.85 |
| Duration of condition (months) | 14.2 ± 5.6 | 13.9 ± 5.8 | 0.74 |
| VAS Pain Score | 7.1 ± 1.2 | 7.0 ± 1.3 | 0.66 |
| Knee ROM (degrees) | 72.5 ± 12.4 | 73.1 ± 12.1 | 0.82 |
| SF-36 QoL Score | 43.2 ± 6.8 | 42.9 ± 7.1 | 0.77 |

Note: No significant differences were observed in baseline variables between groups

### Clinical Outcomes

After 8 weeks of intervention, the technology-enabled group demonstrated significantly greater improvements in pain reduction, ROM, and muscle strength compared to the control group ($p < 0.001$). Mean VAS scores decreased by 62% in the technology group versus 41% in the control group. Similarly, ROM improved by 38% versus 22%, and muscle strength gains were significantly higher. Table 2 shows significant improvements in clinical outcomes after intervention, with the technology group demonstrating greater reductions in pain, enhanced range of motion, and increased muscle strength compared to the control group. Percentage improvements were consistently higher in the technology group, and all differences were statistically significant ($p < 0.05$).

**Table 2. Changes in Clinical Outcomes Pre- and Post-Intervention**

| Outcome Measure | Technology Group (Pre/Post) | Control Group (Pre/Post) | % Improvement (Tech vs. Ctrl) | *p*-value |
|---|---|---|---|---|
| VAS Pain Score | 7.1 → 2.7 | 7.0 → 4.1 | 62% vs. 41% | <0.001 |
| ROM (degrees) | 72.5 → 100.1 | 73.1 → 89.3 | 38% vs. 22% | <0.001 |

| | | | | |
|---|---|---|---|---|
| Muscle Strength (MMT score) | 3.2 → 4.8 | 3.1 → 4.2 | 50% vs. 35% | 0.002 |

Figure 1 is the percentage change in improvement in pain alleviation, joint mobility, and muscle strength following the intervention. The technology group showed considerably greater improvements across all outcomes than the control group and demonstrated persistently greater improvements across all test measures, indicating significantly enhanced effectiveness with technology-facilitated rehabilitation.

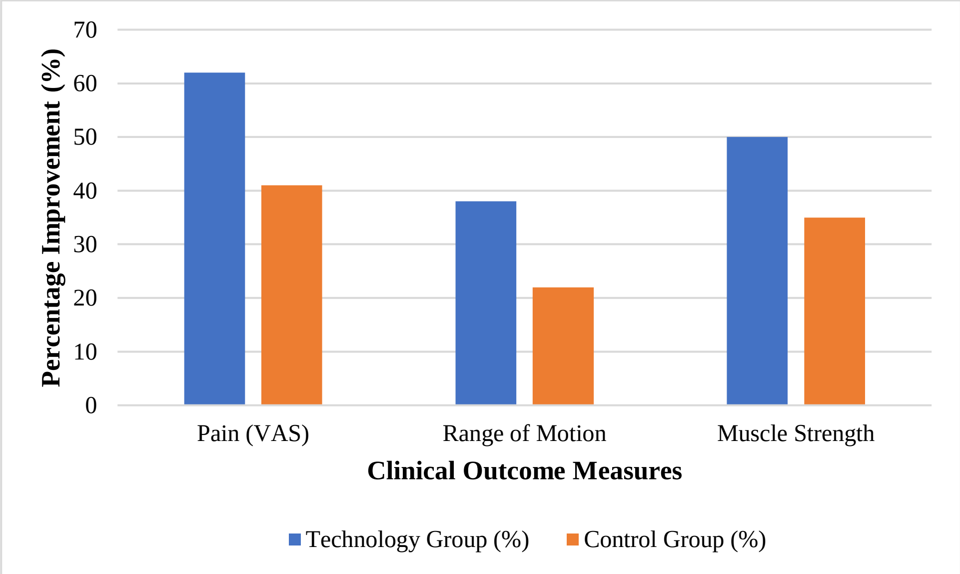


**Figure 1:** Percentage Improvement in Clinical Outcomes

### Functional Performance Metrics

Functional outcomes increased to a greater extent in the technology-assisted group. The TUG test times fell by 36% relative to 22% for the control group, whereas BBS scores rose by 31% versus 17%. Gait parameters such as step length and cadence also demonstrated better improvements. Table 3 shows remarkable improvements in functional outcomes, with the technology group demonstrating larger improvements in mobility, balance, and gait speed relative to the control group.

**Table 3. Functional Outcomes Comparison**

| Outcome Measure | Technology Group (Pre/Post) | Control Group (Pre/Post) | % Improvement (Tech vs. Ctrl) | *p*-value |
|---|---|---|---|---|
| TUG (seconds) | 16.8 → 10.7 | 17.1 → 13.3 | 36% vs. 22% | <0.001 |
| BBS Score (0–56) | 36.2 → 47.5 | 35.9 → 42.1 | 31% vs. 17% | <0.001 |
| Gait Speed (m/s) | 0.86 → 1.12 | 0.84 → 1.01 | 30% vs. 20% | 0.004 |

Figure 2 compares functional performance improvements between groups, showing that the technology-assisted group achieved greater gains in mobility, balance, and gait speed. Significant reductions in TUG times, increased BBS scores, and faster gait speeds highlight the enhanced functional recovery achieved with technology-enabled rehabilitation compared to conventional physiotherapy ($p < 0.05$).

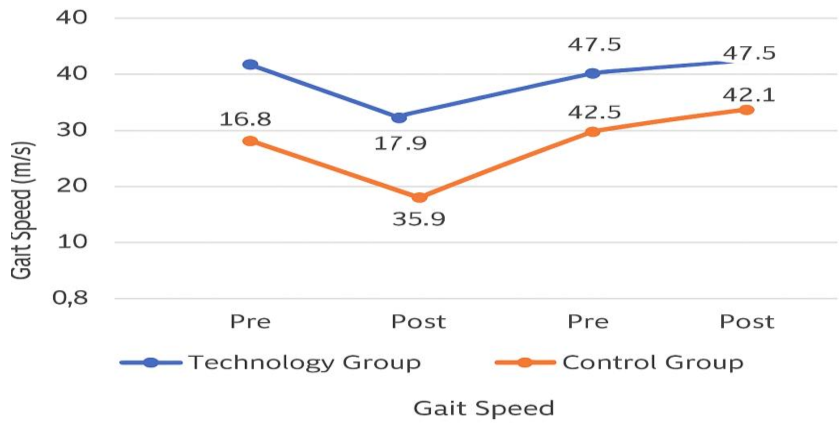


**Figure 2:** Improvements in Functional Performance Outcomes

## Wearable Data Insights

Wearable sensor data revealed excellent adherence and engagement in the technology group, with 92.4% of prescribed sessions completed compared to 78.6% in the control group ($p < 0.001$). Real-time motion data allowed therapists to detect compensatory movements in 87% of participants and make immediate corrective adjustments, enhancing exercise quality. Furthermore, daily step count and joint mobility metrics showed progressive improvements over the intervention period. Table 4 presents wearable sensor-derived insights, showing significantly higher session adherence, step counts, and daily joint mobility improvements in the technology group compared to the control group. Compensatory motion was detected in most participants, allowing real-time corrections. All differences were statistically significant ($p < 0.05$), highlighting enhanced monitoring effectiveness.

**Table 4. Wearable Sensor-Derived Insights**

| Metric | Technology Group | Control Group | *p*-value |
|---|---|---|---|
| Session adherence (%) | 92.4 ± 3.1 | 78.6 ± 4.2 | <0.001 |
| Compensatory motion detection (%) | 87.0 ± 5.4 | – | – |
| Mean step count per session | 3,412 ± 412 | 2,785 ± 520 | 0.002 |
| Average daily joint mobility increase (%) | 28.4 ± 4.7 | 19.2 ± 5.1 | 0.001 |

Figure 3 compares session adherence and activity metrics between the two groups. The technology group achieved significantly higher adherence rates, greater step counts, and larger improvements in daily joint mobility than the control group. These findings demonstrate the superior effectiveness of wearable sensor monitoring in enhancing engagement, physical activity, and rehabilitation outcomes.

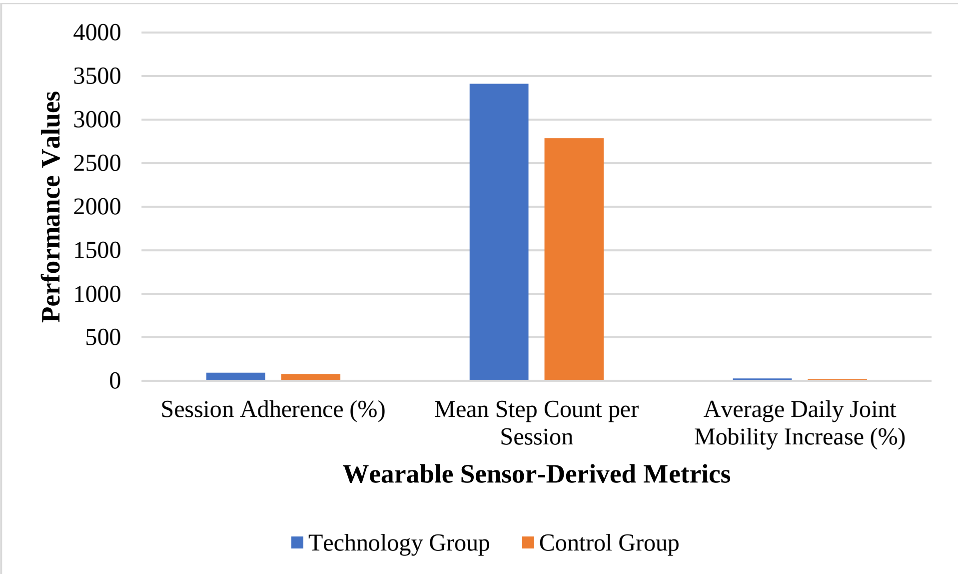


**Figure 3:** Session adherence and activity metrics comparison between groups

## VR Engagement and Adherence

The VR platform significantly enhanced patient motivation and satisfaction. Overall satisfaction scores were higher in the technology group (4.6 ± 0.5) versus the control (3.8 ± 0.7, p < 0.001). Session completion rates exceeded 90%, and qualitative feedback highlighted improved confidence, reduced fear of movement, and increased enjoyment of therapy. Table 5 shows significantly higher VR engagement and usability outcomes in the technology group, including greater session completion, higher satisfaction scores, improved self-reported confidence, and enhanced therapy enjoyment compared to the control group. All differences were statistically significant (p < 0.05), indicating superior patient experience and motivation with VR-assisted rehabilitation.

**Table 5. VR Engagement and Usability Outcomes**

| Parameter | Technology Group | Control Group | *p*-value |
|---|---|---|---|
| Session completion (%) | 91.8 ± 3.5 | 79.2 ± 4.8 | <0.001 |
| Satisfaction (5-point scale) | 4.6 ± 0.5 | 3.8 ± 0.7 | <0.001 |
| Self-reported confidence (%) | 89.2 ± 4.3 | 75.4 ± 5.1 | 0.002 |
| Therapy enjoyment rating (%) | 92.5 ± 3.7 | 78.6 ± 4.9 | <0.001 |

## Discussion

This study aimed to investigate the effectiveness of technology-enabled physiotherapy interventions, specifically wearable sensor-based monitoring and VR assisted rehabilitation, compared to conventional physiotherapy approaches in patients with MSK conditions. The findings provide robust evidence that integrating wearable technologies and VR significantly enhances clinical outcomes, functional recovery, patient adherence, and overall rehabilitation experiences. The outcomes evidenced that the technology-supported group recorded superior improvement in pain alleviation, joint ROM, and muscle strength over the traditional group. Reduction in pain by 62% (VAS), improvement in ROM by 38%, and improvement in muscle strength by 50% indicate the clinical relevance of these interventions. This was closely followed by functional outcomes which showed a drastic enhancement in mobility (TUG test), balance (BBS) and gait performance. Also, sensor data of wearable sensors also showed improved compliance and engagement, but VR interventions were associated with improved satisfaction, confidence, and enjoyment ratings. These findings are consistent with the past research. Kalikanov et al. (2025) reported that VR-based rehab has proven to be significantly more effective than standard therapy in terms of pain and function improvement in various MSK conditions, and the effect size is much higher than normal use of standard therapy. Similarly, Blyth et al. (2019) demonstrated that the digital therapy significantly increases patient self-reported outcomes, such as pain, mobility, and quality of life. The wearable monitoring technologies have been also promising in terms of improving adherence, and providing real-time feedback, which ultimately results in the improvement of exercise performance and speed of recovery (Sun et al., 2022). The current research is in alignment with these results and elaborates them, showing the synergistic impact of the combination of wearable technologies together with immersive VR interventions to one rehabilitation program.

The enhanced results of the presented research can be attributed to the variety of underlying processes associated with technology-guided rehabilitation (Capecci et al., 2024). Wearable sensors are objective, real-time monitors of patient performance, and they can measure joint angles, quality of movement, muscle activity, and compliance to an exercise accurately (Cunha et al., 2023). Real-time feedback enables immediate correction of compensatory movements, minimizing the likelihood of injury and maximizing therapeutic loading, while objective data enable individualized adjustments to rehabilitation protocols, such that exercises remain suitably challenging and specific to the patient's recovery phase (Sun et al., 2022). Virtual reality provides an immersive, interactive environment that enhances neuroplasticity, the brain's capacity to reorganize itself in response to new stimuli and by simulating functional activities, VR-based rehabilitation stimulates cortical reorganization, motor learning, and sensory integration (Paladugu et al., 2025). The gamification of exercises further enhances motivation and repetition, two essential components of motor relearning (Kalikanov et al., 2025), and engagement in meaningful, goal-directed tasks within virtual environments has also been linked to improved cognitive involvement, which may accelerate recovery and enhance functional outcomes. Behavioral engagement is another critical determinant of rehabilitation success, and conventional physiotherapy often suffers from low adherence due to repetitive and monotonous exercises (Dickson et al., 2024). In contrast, technology-enabled interventions increase patient motivation through interactive feedback, gamified tasks, and measurable progress tracking (Fullen et al., 2023), and the significant differences in adherence rates observed in this study, 92.4% in the technology group vs. 78.6% in the control, demonstrate the impact of enhanced patient engagement on treatment outcomes. Additionally, VR interventions positively influence psychosocial dimensions of rehabilitation by creating immersive, goal-oriented experiences that reduce kinesiophobia (fear of movement), enhance self-efficacy, and foster a sense of achievement (Paladugu et al., 2025), contributing to sustained participation, improved confidence, and a more positive rehabilitation experience, as reflected in the significantly higher satisfaction scores reported by the technology group in this study.

Clinical practice implications from this study are profound, especially against the backdrop of transforming healthcare models focusing on personalized, data-driven, and accessible care (Chustecki, 2024). The better results obtained by the technology-assisted group indicate that wearable sensors and VR systems need to be made part of routine rehabilitation protocols for MSK disorders, since inclusion of such systems would not only enhance clinical outcomes but also increase patient satisfaction and participation (Chaplin et al., 2023). Wearable monitoring systems can be used as adjunct devices during supervised sessions and remote monitoring between visits, while VR interventions can enhance conventional exercises with variability, complexity, and motivation to therapy sessions (Bateni et al., 2024). Combined with the immersive nature of VR, wearable devices have the potential to generate new prospects in the domain of home rehabilitation and application in telehealth due to their capability to capture and communicate real-time information. These technologies may be used to supplement telerehabilitation, which has already been shown to be effective in a number of studies (Shambushankar et al., 2025), so that patients do the prescribed exercises at home but the therapists have the remote control over them, give some feedback, and change the programs with reference to objective evaluation, which will result in minimization of health costs, increased access to care, and continuation of rehabilitation in the underserved cohorts. The information provided by wearable devices and VR devices can as well be used to determine patient-specific patterns, recovering patterns, and customizing therapy plans (Sumner et al., 2023), and individualized strategies can enhance performance by providing interventions that are customized to meet individual needs, capacity, and performance. Integration of artificial intelligence (AI) in the future may also further advance personalization through automated interpretation of data and adaptive suggestions. In addition, technology-assisted rehabilitation promotes inter-disciplinary collaboration among physiotherapists, biomedical engineers, data scientists, and software developers, and this inter-disciplinary collaboration is critical to developing clinical innovation, optimizing device functionality, and translating emerging technologies into daily practice.

## Limitations

While the study shows promising results, several limitations must be acknowledged. The sample size, though statistically adequate, was small and may limit generalizability, requiring larger multicenter trials. The 12-week follow-up might not reflect long-term outcomes, so extended assessments are needed. Wearable and VR systems faced challenges like sensor drift, calibration errors, user discomfort, and high costs, which may restrict widespread use. Additionally, while assessors were blinded, participants knew their group assignments, potentially introducing performance bias. Future research should include larger, diverse populations, longer follow-ups, improved device reliability, cost-effective solutions, and enhanced blinding strategies to strengthen the evidence and ensure broader clinical applicability of technology-enabled physiotherapy interventions in musculoskeletal rehabilitation.

## Future Directions

Future research should focus on integrating AI algorithms into wearable and VR platforms to enable real-time decision-making, predictive analytics, and adaptive exercise recommendations, allowing personalized interventions and early detection of setbacks. Digital twin technology can simulate musculoskeletal responses, optimizing therapy strategies. Large, multicenter RCTs with diverse populations and longer follow-ups are needed to establish robust evidence for effectiveness, scalability, and cost-efficiency. Integration with telemedicine, EHRs, and multidisciplinary care will enhance coordination and remote management. Additionally, exploring psychosocial and cognitive impacts, including motivation, adherence, mood, and cognitive function, is essential to designing comprehensive rehabilitation programs that address both physical and psychological needs.

## Conclusion

Technology-enhanced physiotherapy interventions, combining wearable monitoring and virtual reality, showed substantial superiority over conventional practices in musculoskeletal rehabilitation. Impressive improvements were achieved in pain reduction, range of motion, muscle strength, mobility, balance, walking speed, and patient satisfaction. Information acquired through wearable devices increased exercise accuracy and adherence, while interaction with VR environments increased motivation, lowered kinesiophobia, and promoted frequent use. Functional gains achieved with these interventions highlight the potential of technology to address long-standing issues such as poor adherence, self-reported progress tracking, and insufficiency in accessing care. Integration with real-time feedback and objective monitoring also allowed for individualized adjustments to therapy, ensuring targeted and effective rehabilitation interventions. Moreover, the feasibility of remote monitoring and home-based rehabilitation widens the reach of care, offering scalable solutions for underserved populations. The application of artificial intelligence and predictive analytics would also optimize outcomes further by making the treatment planning personalized to the individual patient and adaptive rehabilitation programs. Although device costs, technical limitations, and clinician training limitations are yet challenges, the evidence is that technology-enhanced physiotherapy represents a paradigm shift in musculoskeletal disease management. Its integration into standard procedures would perhaps enhance clinical effectiveness, enhance patient involvement, and revolutionize the delivery of rehabilitation in the clinical and home settings.

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