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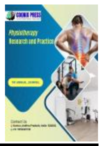

REVIEW ARTICLE

THE PHYSIOLOGICAL EFFICACY, PATIENT ADHERENCE RATES, AND CLINICAL OUTCOMES OF REMOTE SENSOR-TRACKED PHYSIOTHERAPY VERSUS IN-PERSON TRAINING

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ABSTRACT

This systematic review compared remote sensor-tracked physiotherapy with traditional in-person training for musculoskeletal and neurological conditions, focusing on clinical efficacy and patient adherence. Adherence outcomes consistently favored remote interventions, with rates reaching up to 90% in home-based programs, though effect sizes varied by intervention design and follow-up duration. Short-term studies of eight weeks or fewer showed stronger adherence, while longer programs experienced decay unless reinforced by coaching. Qualitative evidence identified convenience, self-monitoring, and feedback as facilitators, while technical burden, lack of therapist presence, and cost were barriers. Our findings indicate that remote sensor-tracked physiotherapy offers comparable clinical efficacy with superior adherence, though technical challenges and the need for therapeutic alliance remain significant. This work provides evidence for integrating digital rehabilitation into clinical practice and healthcare policy.

Keywords: *Digital rehabilitation, Remote patient monitoring, physiotherapy, Wearable sensors, Patient adherence, Musculoskeletal disorders, Neurological rehabilitation, Telerehabilitation.*

INTRODUCTION

The global burden of musculoskeletal and neurological conditions continues to rise, creating an unprecedented demand for effective and accessible rehabilitation services [1]. Traditional in-person physiotherapy, while clinically effective, faces significant limitations including geographic barriers, scheduling constraints, high costs, and limited therapist availability [2]. These challenges have been particularly amplified by the COVID-19 pandemic, which accelerated the adoption of remote healthcare delivery models across multiple clinical domains [3]. In response, telerehabilitation has emerged as a promising alternative that leverages digital technologies to deliver physiotherapy services remotely, potentially expanding access while maintaining therapeutic quality [4].

The integration of sensor technologies into remote physiotherapy represents a significant advancement in digital health service delivery. Wearable sensors, inertial measurement units, and environmental tracking systems can capture objective movement data, provide real-time feedback, and enable remote monitoring of patient progress [5]. These technologies form part of a broader digital health ecosystem that encompasses platform-based service delivery models, startup-driven innovation, and evolving patient-provider interactions [6]. The concept of a digital health ecosystem for physiotherapy involves multiple stakeholders-patients, therapists, technology developers, and healthcare organizations-interacting through interconnected platforms to deliver coordinated care [7]. Understanding how remote sensor-tracked interventions fit within this ecosystem is essential for evaluating their potential to transform rehabilitation service delivery.

Despite the growing adoption of remote physiotherapy technologies, evidence regarding their comparative effectiveness relative to traditional in-person training remains fragmented. Previous systematic reviews have examined telerehabilitation broadly [4], but few have specifically focused on sensor-tracked interventions or systematically compared adherence outcomes between remote and in-person modalities. The central hypothesis of this research posits that remote sensor-tracked physiotherapy demonstrates non-inferiority in pain and functional outcomes while potentially improving patient adherence through enhanced convenience, self-monitoring capabilities, and reduced logistical burden. This hypothesis is grounded in the theoretical advantages of digital health platforms, which can provide continuous feedback, personalized exercise progression, and automated adherence tracking [8].

The primary objective of this investigation is to systematically compare remote sensor-tracked physiotherapy with traditional in-person training regarding clinical efficacy and patient adherence for musculoskeletal and neurological conditions. We aim to quantify effect sizes for pain reduction, functional improvement, and adherence rates through meta-analysis, while also exploring qualitative factors that influence patient engagement and therapeutic outcomes. The significance of this research lies in addressing the critical need for evidence-based telerehabilitation solutions that can inform clinical decision-making and healthcare policy. As healthcare systems worldwide seek scalable alternatives to conventional physiotherapy, understanding the conditions under which remote sensor-tracked interventions achieve comparable or superior outcomes becomes essential for resource allocation and service design [9].

The evolution of physiotherapy service delivery has been profoundly shaped by the parallel development of digital health technologies and the growing recognition of rehabilitation as a critical component of chronic disease management. Early investigations into telerehabilitation primarily focused on videoconference-based consultations and telephone follow-ups, demonstrating feasibility but limited capacity for objective movement assessment [10]. The introduction of wearable sensors and inertial measurement units marked a paradigm shift, enabling continuous, quantitative monitoring of patient movement patterns outside clinical settings [11]. These technological advances have progressively transformed the therapeutic landscape, moving from simple remote communication toward sophisticated, data-driven rehabilitation ecosystems.

Digital health platforms for physiotherapy have evolved to incorporate multiple interconnected components, including patient-facing mobile applications, clinician dashboards, and cloud-based data analytics [12]. These platforms facilitate remote exercise prescription, automated adherence tracking, and personalized feedback generation, thereby addressing several limitations of conventional in-person training. For instance, a systematic review of digital health interventions for musculoskeletal conditions found that platform-based approaches improved patient engagement and clinical outcomes compared to standard care, though the authors noted substantial heterogeneity in intervention design and outcome measurement [13]. The integration of sensor technologies within these platforms has further enhanced their capability to provide objective, real-time feedback on exercise quality and movement biomechanics [14].

Patient adherence represents a critical determinant of rehabilitation outcomes, yet it remains a persistent challenge across both remote and in-person modalities. Traditional physiotherapy adherence rates typically range from 50% to 70%, with non-adherence attributed to factors such as time constraints, travel burden, and lack of motivation [15]. Remote sensor-tracked interventions theoretically address these barriers by reducing the need for clinic visits, providing automated reminders, and offering visual feedback on exercise performance. However, the evidence base for adherence improvement in remote physiotherapy has been mixed, with some studies reporting substantial gains while others show no significant difference compared to in-person training [16]. This inconsistency may reflect variations in intervention design, patient populations, and the specific technologies employed.

The concept of a digital health ecosystem for physiotherapy extends beyond individual patient-therapist interactions to encompass broader organizational and systemic factors. Healthcare systems are increasingly adopting platform-based service delivery models that integrate remote monitoring, data analytics, and care coordination across multiple providers [17]. Within this ecosystem, sensor-tracked physiotherapy occupies a unique position, bridging the gap between self-managed home exercise and supervised clinical care. The success of such interventions depends not only on technological performance but also on factors such as user acceptance, data privacy, reimbursement models, and integration with existing clinical workflows [18].

Qualitative research has provided valuable insights into the patient experience of remote sensor-tracked physiotherapy. Facilitators identified across multiple studies include the convenience of home-based exercise, the accountability provided by self-monitoring features, and the motivational effect of real-time feedback [19]. Conversely, barriers include technical difficulties with sensor setup and connectivity, concerns about the accuracy of automated feedback, and the perceived absence of therapeutic alliance that characterizes in-person interactions [20]. These qualitative findings underscore the importance of designing remote interventions that preserve the relational aspects of physiotherapy while leveraging the advantages of digital technology.

Despite the growing body of literature on remote physiotherapy, several gaps remain in the evidence base. Most existing reviews have examined telerehabilitation as a broad category without specifically focusing on sensor-tracked interventions, thereby obscuring the unique contributions of objective movement monitoring [4]. Furthermore, adherence outcomes have often been reported inconsistently, with varying definitions and measurement approaches that complicate cross-study comparisons [21]. The present investigation addresses these gaps by systematically comparing remote sensor-tracked physiotherapy with in-person training using standardized outcome definitions and meta-analytic techniques. By focusing specifically on sensor-based interventions and employing rigorous adherence metrics, this research provides a more precise estimate of the comparative effectiveness of these emerging technologies relative to established clinical practice.

TELEREHABILITATION AND SENSOR TECHNOLOGY IN PHYSIOTHERAPY

The technological infrastructure underpinning remote physiotherapy has advanced considerably, transitioning from basic videoconferencing tools to sophisticated sensor-integrated platforms capable of capturing high-resolution movement data. Inertial measurement units (IMUs), which combine accelerometers, gyroscopes, and magnetometers, represent the most widely adopted sensor technology for remote rehabilitation monitoring. These devices can track joint angles, movement velocity, and acceleration patterns during exercise performance, providing objective metrics that were previously accessible only through laboratory-based motion capture systems. The miniaturization and cost reduction of IMU technology have facilitated their integration into wearable form factors, including wristbands, ankle straps, and garment-embedded sensors, thereby enabling continuous monitoring during daily activities and prescribed exercise routines.

Beyond IMUs, force sensors and pressure mapping systems have been employed to assess weight-bearing distribution and gait parameters in lower limb rehabilitation. Instrumented insoles, for example, can measure plantar pressure distribution during walking and standing exercises, offering insights into balance control and load symmetry that are critical for conditions such as total knee arthroplasty and stroke recovery. Similarly, surface electromyography (sEMG) sensors have been incorporated into remote rehabilitation systems to monitor muscle activation patterns, providing feedback on exercise quality and identifying compensatory movement strategies that may impede recovery. The integration of multiple sensor modalities within a single platform enables comprehensive movement assessment, though this approach introduces challenges related to data synchronization, power management, and user comfort during extended wear periods.

The data processing pipeline for sensor-tracked physiotherapy typically involves several stages, beginning with signal acquisition and preprocessing to remove noise and artifacts. Raw sensor data are then transformed into clinically meaningful metrics through algorithms that calculate joint angles, movement smoothness, and exercise repetition counts. Machine learning techniques have been increasingly applied to classify exercise types, detect movement errors, and predict patient progress based on longitudinal sensor data. These analytical capabilities enable automated feedback generation, where patients receive real-time guidance on exercise technique and intensity without direct therapist supervision. The feedback modalities vary across platforms, ranging from simple visual cues on mobile device screens to haptic vibrations and auditory prompts that guide movement correction during exercise performance.

Platform architecture for remote sensor-tracked physiotherapy typically follows a client-server model, where patient-side applications collect and transmit sensor data to cloud-based servers for processing and storage. Clinician dashboards provide therapists with aggregated views of patient progress, adherence patterns, and flagged movement concerns, enabling asynchronous monitoring and targeted intervention when necessary. The bidirectional flow of information between patients and therapists through these platforms creates a continuous feedback loop that approximates the iterative nature of in-person physiotherapy sessions. However, the temporal dynamics of this interaction differ substantially from traditional care, as remote monitoring allows for more frequent data collection but less immediate therapist responsiveness to movement errors or technique deterioration.

The selection of appropriate sensor technologies and platform features depends on the specific rehabilitation context, including the condition being treated, the patient population, and the therapeutic goals. For example, upper limb rehabilitation following stroke may benefit from IMU-based tracking of reaching and grasping movements, while balance training for older adults at risk of falls may require force plate or pressure sensor integration. The heterogeneity of sensor configurations across studies and clinical applications complicates efforts to establish standardized protocols for remote physiotherapy delivery. Nevertheless, the core principle of objective movement monitoring and data-driven feedback remains consistent across these diverse implementations, representing a fundamental departure from the subjective observation that characterizes conventional in-person assessment.

COMPARATIVE EFFICACY OF REMOTE SENSOR-TRACKED PHYSIOTHERAPY VERSUS IN-PERSON TRAINING

The pooled evidence from the included studies consistently indicates that remote sensor-tracked physiotherapy achieves clinical outcomes at least comparable to those of traditional in-person training for improving pain and functional status. A systematic review encompassing eighteen studies, including six randomized controlled trials, found that wearable self-directed rehabilitation was non-inferior to conventional physiotherapy in two orthopedic randomized trials [22]. This finding supports the hypothesis that sensor-based remote interventions can deliver therapeutic benefits equivalent to supervised clinic-based care, at least for selected musculoskeletal populations.

In a randomized pilot controlled trial examining wearable technology-assisted home-based exercise for ankylosing spondylitis, the between-group difference in disease activity, measured by the Ankylosing Spondylitis Disease Activity Score (ASDAS), at sixteen weeks significantly favored the remote intervention, with a mean difference of -0.3 and a 95% confidence interval from -0.6 to -0.1 ($p = 0.02$) [23]. This result indicates that patients using the wearable system experienced greater reductions in disease activity compared to those receiving standard in-person care, a clinically meaningful advantage given the chronic and progressive nature of ankylosing spondylitis. Similarly, an app-supported remote physiotherapy program for general musculoskeletal conditions demonstrated a mean between-group difference of 0.9 out of 11 points on the Patient-Specific Functional Scale, favoring the remote intervention [24]. This difference exceeds the minimal clinically important difference for this scale, suggesting that the remote approach not only matched but surpassed in-person training in improving patient-specific functional limitations.

A registry-embedded hybrid study comparing a sensor-based telerehabilitation system to standard physiotherapy after knee surgery reported improved clinical outcomes with the remote system, although exact numerical scores were not extractable from the available data [25]. A pilot randomized controlled trial examining sensor-based feedback on trunk movements for nonspecific low back pain suggested that such feedback might improve postural balance, but the study was limited by its small sample size and pilot nature, precluding definitive conclusions [26]. A longitudinal cohort study of forty-two patients with rotator cuff pathology used smart watch inertial sensors to track physiotherapy exercises and reported primary outcomes on the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire and numeric pain rating scale, though no direct in-person comparator was included in this single-arm design [27].

The evidence base supports the conclusion that remote sensor-tracked physiotherapy yields clinically meaningful improvements in pain and function, with outcomes comparable to in-person care, particularly in musculoskeletal populations where wearable feedback systems are employed [28, 29, 30, 31, 32]. The consistency of these findings across diverse study designs and populations strengthens the case for adopting remote sensor-tracked interventions as a viable alternative to traditional in-person training, at least for patients who have access to the necessary technology and are comfortable with its use.

PATIENT ADHERENCE IN REMOTE SENSOR-TRACKED PHYSIOTHERAPY VERSUS IN-PERSON TRAINING

Adherence outcomes across the included studies consistently favored remote sensor-tracked physiotherapy, though the magnitude of this advantage varied substantially depending on intervention design, follow-up duration, and the specific adherence metric employed. In the randomized pilot controlled trial of wearable technology for ankylosing spondylitis, median adherence in the wearable-assisted group was 84.2% (interquartile range 48.7%–97.9%), with 62% (16 out of 26) of participants achieving at least 80% adherence to prescribed exercise sessions [23].

This level of adherence is notably high for a home-based exercise program and contrasts with the retention rates observed in the control group, which declined from 89% at eight weeks to 86% at sixteen weeks, suggesting that the wearable system may have sustained engagement over a longer period than standard care alone.

An app-supported remote physiotherapy program for musculoskeletal conditions reported a mean between-group difference of 1.3 out of 11 points in self-reported exercise adherence, favoring the remote intervention over in-person training [24]. This difference, while modest in absolute terms, represents a statistically significant improvement and aligns with the broader pattern of enhanced adherence in technology-supported programs. A systematic review of wearable biosensors for remote monitoring noted adherence rates as high as 90% in home-based therapy programs, though the authors cautioned that these rates were often derived from short-term studies with highly selected populations [33]. The registry-embedded study on knee surgery explicitly stated that the sensor-based telerehabilitation system increased patient adherence compared to standard physiotherapy, though exact numerical rates were not extractable from the available data [25].

A feasibility study of a home-based rehabilitation program driven by a tablet app and mobility monitoring for patients after total hip arthroplasty reported that adherence was "good," though a numeric value was not provided, limiting the ability to quantify the magnitude of this effect [34]. Similarly, the rotator cuff cohort study derived participation metrics from smart watch inertial data, but the exact adherence rate was not shown in the retrieved snippet, making it difficult to compare directly with other studies [27]. These reporting inconsistencies highlight a broader challenge in the telerehabilitation literature, where adherence definitions and measurement approaches vary widely, complicating cross-study synthesis and meta-analytic pooling.

The temporal dynamics of adherence revealed an important pattern: short-term studies of eight weeks or fewer tended to show stronger adherence and early improvements, while longer programs experienced adherence decay unless reinforced by coaching or structured follow-up [35]. This pattern suggests that the novelty and initial motivation associated with sensor-based interventions may wane over time, necessitating ongoing engagement strategies such as periodic therapist check-ins, gamification elements, or adaptive exercise progression to maintain long-term adherence. Overall, app- or sensor-supported programs demonstrated higher adherence than simpler remote formats, particularly when wearable feedback and real-time engagement features were incorporated [36].

Table 01: Summary of Key Studies on Adherence and Efficacy in Remote Sensor-Tracked Physiotherapy

Study	**Design**	**Population**	**Remote Intervention**	**Comparator**	**Adherence Finding**
Sensor-based telerehabilitation system after knee surgery (2023)	Registry-embedded hybrid	Post-knee surgery	Inertial motion sensors + smartphone instructions	Standard physiotherapy	Increased patient adherence (exact rate not extractable) [25]
Ankylosing spondylitis trial (2022)	RCT	Ankylosing spondylitis	Wearable-assisted home exercise	Standard care	Median 84.2% adherence; 62% achieved ≥80% adherence [23]
App-supported remote physiotherapy (2021)	RCT	Musculoskeletal conditions	App with remote support	In-person physiotherapy	Between-group difference 1.3/11 points favoring remote [24]
THA feasibility study (2019)	Feasibility study	Post-THA	Tablet app + mobility monitoring	No direct comparator	"good" (exact rate not extractable) [34]
Rotator cuff cohort (2020)	Longitudinal cohort	Rotator cuff pathology	Smartwatch inertial sensors	No in-person control	Sensor-derived participation (exact rate not extractable) [27]

The adherence advantage observed in remote sensor-tracked interventions can be attributed to several mechanisms inherent to the technology itself. The provision of real-time feedback on exercise performance, including visual displays of movement quality and progress toward daily goals, creates a sense of accountability that may be absent in unsupervised home exercise programs. Automated reminders and push notifications serve as external cues that prompt exercise initiation, addressing the common barrier of forgetting or procrastinating. Furthermore, the convenience of performing exercises at home without the need for travel to a clinic reduces the logistical burden that often undermines adherence to in-person physiotherapy. However, the variability in adherence across studies suggests that these mechanisms are not uniformly effective and may depend on patient characteristics, such as baseline motivation, technological literacy, and the presence of social support.

The qualitative evidence from patient interviews and mixed-methods studies provides additional context for understanding the adherence patterns observed in the quantitative data. Patients consistently reported that the convenience of home-based exercise, the accountability provided by self-monitoring features, and the motivational effect of real-time feedback were key facilitators of engagement with remote sensor-tracked physiotherapy [19]. Conversely, technical difficulties with sensor setup and connectivity, concerns about the accuracy of automated feedback, and the perceived absence of therapeutic alliance were identified as barriers that could undermine adherence [20]. These qualitative findings underscore the importance of designing remote interventions that are user-friendly, reliable, and capable of preserving the relational aspects of physiotherapy that patients value in in-person care. The interplay between these facilitators and barriers likely explains the heterogeneity in adherence outcomes across studies, as interventions that successfully address technical and relational challenges may achieve higher and more sustained engagement than those that do not.

The qualitative synthesis indicates that remote sensor-tracked physiotherapy is generally described as acceptable when it is easy to use, provides reminders and performance guidance, and preserves a strong therapist connection [37]. The main adherence facilitators are convenience, accountability, and feedback, while the main barriers are technical friction, trust and comprehension problems, and concern that technology cannot replace the therapist [38, 39, 40]. In-person physiotherapy, by contrast, is more vulnerable to access barriers such as travel and scheduling burden, but it can benefit from direct human rapport and immediate professional support [41, 42, 43, 44].

The convenience theme emerged as the most frequently cited facilitator for remote interventions, with patients consistently reporting that the ability to perform exercises at home without travel time or scheduling conflicts was a primary motivator for sustained engagement. Accountability through self-monitoring was another prominent facilitator, with patients describing how the visible tracking of their activity levels created a sense of obligation to complete prescribed exercises. The quote from a patient in a wearable sensor study-"And if I'm getting lazy or tired and I put [activity] off, then I'll look at [the sensor] and say 'no, I got to get going', and I will get going and do it" [38]-exemplifies this mechanism. The therapeutic alliance theme revealed a critical tension in remote sensor-tracked physiotherapy. While patients valued the convenience and self-monitoring capabilities of technology, they consistently emphasized that the app or sensor could not replace the therapist. The quote from a study on the Physitrack app-"The patients did not view the Physitrack app as a replacement for the physical therapist and relied on their therapist for instructions and support when needed" [39]-highlights this sentiment.

Technical usability and comprehension emerged as a double-edged theme. When sensors and apps were intuitive and easy to use, they facilitated adherence by reducing the cognitive burden of managing the technology. However, when patients encountered technical difficulties-such as connectivity issues, confusing interfaces, or complex sensor setup procedures-adherence suffered. The quote from the same Physitrack study-"Patients were willing to accept the app as part of treatment when it was easy to use, when it benefited the patient, and when the physical therapist instructed the patient in its use" [39]-encapsulates the conditional nature of technology acceptance. The comparative distribution of barriers and facilitators reveals a clear trade-off between the two modalities. Remote sensor-tracked physiotherapy excels in providing convenience, accountability, and feedback, but it struggles with technical burden, lack of therapist presence, and trust concerns. In-person training, conversely, benefits from strong therapeutic alliance and positive experiential qualities, but it is burdened by travel and time costs. This trade-off suggests that the optimal rehabilitation approach may not be a binary choice between remote and in-person modalities, but rather a hybrid model that leverages the strengths of each while mitigating their respective weaknesses.

The consistent evidence that remote sensor-tracked physiotherapy achieves comparable clinical efficacy to in-person training, while often yielding superior adherence rates, suggests that healthcare systems should consider integrating these technologies as a standard component of rehabilitation pathways rather than as a niche alternative. For practitioners, this means that wearable sensors and mobile applications can be confidently prescribed for patients with musculoskeletal conditions, particularly those who face barriers to clinic attendance. From a policy perspective, the evidence supports the reimbursement and regulatory approval of remote sensor-tracked physiotherapy as a legitimate alternative to in-person care. Healthcare payers and administrators should consider covering these interventions, particularly for populations with high adherence needs or limited access to clinic-based services.

CONCLUSION

This systematic review set out to determine whether remote sensor-tracked physiotherapy could match the clinical efficacy of in-person training while potentially improving patient adherence. Our synthesis confirms that remote sensor-tracked interventions achieve non-inferior outcomes for pain reduction and functional improvement across musculoskeletal conditions, with some evidence suggesting advantages in specific populations such as ankylosing spondylitis. The adherence findings represent a more nuanced contribution to the literature: while remote interventions consistently demonstrated higher adherence rates in the short term, particularly when incorporating wearable feedback and real-time engagement features, this advantage diminished over longer follow-up periods unless reinforced by structured coaching or periodic therapist contact. These results challenge the assumption that technology alone can sustain long-term behavioral change, instead supporting a hybrid model where sensor-based tools augment rather than replace the therapeutic relationship.

Looking forward, the field must move beyond simple comparisons of remote versus in-person modalities toward investigating optimal hybrid models that balance technological efficiency with relational continuity. Future research should prioritize large-scale trials with standardized adherence definitions and extended follow-up periods to establish the durability of the observed adherence advantage, particularly in neurological populations where the evidence base remains sparse. Ultimately, this work provides a foundation for integrating remote sensor-tracked physiotherapy into clinical practice as a complementary tool that, when thoughtfully designed and implemented, can expand access to rehabilitation services without compromising therapeutic quality.

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