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DIGITAL REHABILITATION AND WEARABLE SENSOR–BASED PHYSIOTHERAPY: EVALUATING FUNCTIONAL RECOVERY OUTCOMES IN MUSCULOSKELETAL PATIENTS IN PAKISTAN

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Abstract

Digital rehabilitation and wearable sensor–based physiotherapy have emerged as transformative innovations for improving rehabilitation outcomes by enabling continuous patient monitoring, personalized treatment, and evidence-based clinical decision-making. Despite their growing adoption in developed healthcare systems, empirical evidence regarding their effectiveness in improving functional recovery among musculoskeletal patients in developing countries, particularly Pakistan, remains limited. This study examined the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes among musculoskeletal patients in Pakistan. Specifically, it investigated the mediating role of patient engagement in rehabilitation and the moderating role of digital health literacy. Grounded in Task–Technology Fit (TTF) Theory, the study employed a quantitative, cross-sectional, explanatory research design. Primary data were collected from musculoskeletal patients receiving physiotherapy services in public and private hospitals and rehabilitation centers across Pakistan using a structured questionnaire. The proposed conceptual framework was evaluated using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings indicate that digital rehabilitation and wearable sensor–based physiotherapy significantly enhance patient engagement and functional recovery outcomes. Patient engagement was found to partially mediate the relationship between digital rehabilitation and functional recovery, suggesting that active participation in rehabilitation is a key mechanism through which digital technologies improve clinical outcomes. Furthermore, digital health literacy significantly moderated the relationship between digital rehabilitation and patient engagement, indicating that patients with higher digital competencies benefited more from wearable sensor technologies. The study extends Task–Technology Fit Theory by integrating patient engagement and digital health literacy into a comprehensive framework explaining rehabilitation effectiveness in a developing healthcare context. The findings provide important theoretical, clinical, managerial, and policy implications for healthcare administrators, physiotherapists, and policymakers seeking to accelerate digital health transformation, improve rehabilitation quality, and promote the integration of wearable sensor technologies into physiotherapy services in Pakistan.

Frontier in Medical & Health Research

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INTRODUCTION

Musculoskeletal disorders (MSDs) are among the leading causes of disability, chronic pain, and functional impairment worldwide, imposing substantial socioeconomic and healthcare burdens on individuals and health systems. According to the Global Burden of Disease Study, musculoskeletal conditions account for a significant proportion of years lived with disability, affecting mobility, productivity, and quality of life across all age groups (Cieza et al., 2021). The increasing prevalence of musculoskeletal disorders, driven by population aging, sedentary lifestyles, occupational hazards, sports injuries, and chronic diseases, has intensified the demand for effective rehabilitation services globally.

Physiotherapy plays a central role in the rehabilitation of musculoskeletal patients by restoring functional mobility, improving muscle strength, reducing pain, enhancing joint function, and promoting independent living. Conventional physiotherapy primarily relies on face-to-face clinical sessions, manual assessment techniques, therapist observations, and patient self-reporting to monitor rehabilitation progress. While these approaches have demonstrated clinical effectiveness, they often face limitations related to subjective assessment, inconsistent monitoring, limited accessibility, poor patient adherence, and resource constraints, particularly in low- and middle-income countries (World Health Organization [WHO], 2023).

Recent advances in digital health technologies have transformed rehabilitation practices through the integration of wearable sensors, mobile health (mHealth) applications, artificial intelligence (AI), Internet of Things (IoT) devices, and remote patient monitoring systems. Digital rehabilitation combines these technologies with evidence-based physiotherapy interventions to deliver personalized, continuous, and data-driven rehabilitation services. Wearable sensor–based physiotherapy enables real-time monitoring of patients' movements, gait patterns, joint angles, muscle activity, balance, and physical performance, thereby providing objective information to physiotherapists for clinical decision-making and treatment optimization (Patel et al., 2021).

Wearable technologies, including inertial measurement units (IMUs), smart watches, smart bands, pressure sensors, electromyography (EMG) devices, and motion-tracking systems, have significantly enhanced rehabilitation by allowing continuous monitoring of patient performance both inside and outside clinical settings. These technologies facilitate early detection of rehabilitation progress, improve treatment adherence, support home-based physiotherapy, and enable clinicians to adjust rehabilitation programs according to individual patient needs (Yang et al., 2022). Consequently, wearable sensor–based physiotherapy has become an important component of modern patient-centered rehabilitation.

Digital rehabilitation has gained considerable attention following the COVID-19 pandemic, during which healthcare systems increasingly adopted tele-rehabilitation and remote monitoring to ensure continuity of physiotherapy services. Emerging evidence suggests that digital rehabilitation improves patient engagement, exercise adherence, treatment accuracy, rehabilitation efficiency, and long-term functional outcomes while reducing healthcare costs and travel burdens (Brennan et al., 2023). These technologies are particularly beneficial for patients residing in geographically remote or underserved areas where access to specialized rehabilitation services remains limited.

In Pakistan, musculoskeletal disorders represent a growing public health challenge due to increasing rates of occupational injuries, road traffic accidents, aging populations, obesity, and chronic musculoskeletal diseases. Although physiotherapy services have expanded across public and private healthcare institutions, rehabilitation services continue to face numerous challenges, including shortages of qualified physiotherapists, inadequate rehabilitation infrastructure, limited access to advanced rehabilitation technologies, and insufficient long-term patient monitoring. Consequently, many patients experience delayed recovery, reduced treatment adherence, and persistent functional limitations.

Frontier in Medical & Health Research
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The healthcare sector in Pakistan has recently demonstrated increasing interest in digital health transformation through telemedicine, electronic medical records, and mobile healthcare initiatives. Nevertheless, the adoption of wearable sensor–based physiotherapy and digital rehabilitation technologies remains relatively limited. Financial constraints, inadequate technological infrastructure, limited digital literacy, and insufficient clinical evidence have hindered the widespread implementation of digital rehabilitation programs in Pakistani healthcare institutions.

Functional recovery represents the ultimate goal of musculoskeletal rehabilitation and refers to patients' ability to regain mobility, physical independence, muscle strength, joint function, and participation in daily activities following injury or illness. Functional recovery outcomes are influenced by multiple factors, including treatment quality, patient engagement, technological support, rehabilitation intensity, and adherence to prescribed exercise programs. Digital rehabilitation technologies offer significant potential for improving these outcomes by providing continuous monitoring, personalized feedback, objective performance assessment, and timely therapeutic interventions.

From a theoretical perspective, Task–Technology Fit (TTF) Theory proposes that technological innovations improve individual performance when technological capabilities effectively match task requirements (Goodhue & Thompson, 1995). Within physiotherapy, wearable sensor technologies enhance rehabilitation effectiveness by supporting therapists' clinical responsibilities while facilitating patients' active participation in rehabilitation exercises. Accordingly, digital rehabilitation technologies are expected to improve functional recovery by strengthening rehabilitation quality, patient engagement, and evidence-based clinical decision-making.

Despite the rapid expansion of digital rehabilitation globally, empirical research investigating wearable sensor–based physiotherapy within developing countries remains limited. Most existing studies have been conducted in high-income countries, while evidence regarding the effectiveness of digital rehabilitation among musculoskeletal patients in Pakistan remains scarce. Furthermore, limited research has examined how wearable sensor technologies influence functional recovery within Pakistan's healthcare context using comprehensive theoretical frameworks and quantitative empirical methods.

Therefore, this study investigates the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes among musculoskeletal patients in Pakistan. The findings are expected to contribute to rehabilitation science, physiotherapy practice, digital health research, and healthcare management while providing evidence-based recommendations for improving rehabilitation services through digital innovation.

Problem Statement

Musculoskeletal disorders are among the leading causes of disability and functional impairment worldwide, requiring effective physiotherapy interventions to restore mobility, physical function, and quality of life. Although digital rehabilitation and wearable sensor technologies have demonstrated promising outcomes in improving rehabilitation effectiveness, their adoption within Pakistan's healthcare system remains limited.

Pakistani rehabilitation services continue to face challenges including shortages of physiotherapists, limited rehabilitation facilities, inadequate long-term patient monitoring, inconsistent treatment adherence, and restricted access to advanced rehabilitation technologies. These limitations frequently result in delayed recovery, reduced functional outcomes, and increased healthcare costs for musculoskeletal patients.

Recent technological advancements have enabled physiotherapists to utilize wearable sensors and digital rehabilitation platforms for continuous monitoring of patient movement, exercise performance, and rehabilitation progress. However, empirical evidence regarding the effectiveness of these technologies in improving functional recovery among musculoskeletal patients in Pakistan remains scarce. Most existing

Frontier in Medical & Health Research
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studies have been conducted in developed healthcare systems and may not adequately reflect the institutional, technological, and socioeconomic realities of Pakistan.

Furthermore, previous research has primarily focused on the technical performance of wearable devices rather than examining how digital rehabilitation contributes to functional recovery through patient-centered rehabilitation processes. Consequently, significant theoretical and empirical gaps remain regarding the implementation and effectiveness of wearable sensor–based physiotherapy within Pakistan's healthcare environment.

Addressing these gaps is essential for informing healthcare policy, improving rehabilitation practices, supporting digital health transformation, and enhancing functional recovery outcomes among musculoskeletal patients in Pakistan.

Research Questions

How does digital rehabilitation and wearable sensor–based physiotherapy influence functional recovery outcomes among musculoskeletal patients in Pakistan?

To what extent does wearable sensor–based physiotherapy improve patient engagement during rehabilitation?

What is the relationship between patient engagement and functional recovery outcomes?

How does digital health literacy influence the effectiveness of digital rehabilitation among musculoskeletal patients?

What policy and clinical strategies can promote the adoption of wearable sensor–based physiotherapy in Pakistan's rehabilitation sector?

Research Objectives

To examine the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes among musculoskeletal patients in Pakistan.

To investigate the effect of digital rehabilitation on patient engagement during physiotherapy.

To assess the relationship between patient engagement and functional recovery outcomes.

To examine the moderating role of digital health literacy in the relationship between digital rehabilitation and patient engagement.

To develop evidence-based recommendations for strengthening digital rehabilitation services and wearable sensor adoption within Pakistan's healthcare system.

Significance of the Study

This study contributes significantly to rehabilitation science, physiotherapy, digital health, healthcare management, and health technology research.

From a theoretical perspective, the study extends Task–Technology Fit Theory by examining how wearable sensor–based physiotherapy improves functional recovery through enhanced patient engagement within a developing-country healthcare context. The proposed framework enriches digital rehabilitation literature by integrating technological, behavioral, and clinical dimensions of rehabilitation outcomes.

Empirically, the study addresses an important research gap by providing evidence regarding the effectiveness of digital rehabilitation technologies among musculoskeletal patients in Pakistan. The findings contribute to the limited body of literature examining wearable sensor–based physiotherapy within South Asian healthcare systems.

Practically, the findings provide valuable guidance for physiotherapists, rehabilitation specialists, hospital administrators, and digital health developers seeking to improve rehabilitation quality through wearable technologies, remote monitoring systems, and personalized rehabilitation programs.

From a policy perspective, the study supports Pakistan's digital health transformation initiatives by providing evidence for healthcare policymakers regarding investments in rehabilitation technologies, digital infrastructure, workforce training, and patient-centered healthcare innovation. The findings may assist government agencies and healthcare institutions in developing national strategies for integrating wearable sensor technologies into rehabilitation services.

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

Finally, the study contributes to improving patient outcomes by identifying strategies that enhance rehabilitation effectiveness, patient engagement, treatment adherence, and functional recovery, thereby promoting more accessible, efficient, and sustainable rehabilitation services throughout Pakistan.

Literature Review

Digital Rehabilitation

Digital rehabilitation has emerged as a transformative approach to delivering physiotherapy and rehabilitation services by integrating digital technologies into conventional therapeutic interventions. It encompasses tele-rehabilitation, mobile health (mHealth), wearable sensors, artificial intelligence (AI), virtual reality (VR), cloud-based health platforms, and Internet of Things (IoT)-enabled monitoring systems to support patient assessment, treatment, and recovery (Brennan et al., 2023). Unlike traditional rehabilitation, digital rehabilitation enables continuous monitoring of patients beyond clinical settings, thereby improving accessibility, treatment personalization, and long-term patient management.

Recent advances in digital health have accelerated the adoption of remote rehabilitation services, particularly following the COVID-19 pandemic, which highlighted the need for technology-assisted healthcare delivery. Digital rehabilitation enables physiotherapists to monitor patient performance in real time, evaluate treatment progress objectively, provide personalized exercise prescriptions, and adjust rehabilitation plans according to individual recovery trajectories (Laver et al., 2020). Consequently, digital rehabilitation has become an important component of patient-centered healthcare systems across developed countries.

Despite these global advancements, the implementation of digital rehabilitation within Pakistan remains limited. Rehabilitation services continue to rely predominantly on conventional face-to-face physiotherapy because of limited technological infrastructure, inadequate financial resources, insufficient digital literacy among healthcare professionals, and restricted access to advanced rehabilitation equipment. These challenges underscore the importance of investigating digital rehabilitation within Pakistan's healthcare context.

Wearable Sensor–Based Physiotherapy

Wearable sensor technology represents one of the most significant innovations in contemporary physiotherapy and rehabilitation. Wearable sensors are portable electronic devices capable of continuously measuring physiological and biomechanical parameters, including body movement, gait characteristics, joint angles, muscle activity, posture, physical activity levels, balance, and exercise performance (Patel et al., 2021).

Modern wearable rehabilitation technologies include inertial measurement units (IMUs), accelerometers, gyroscopes, electromyography (EMG) sensors, pressure sensors, smart watches, smart garments, and motion-tracking systems. These technologies generate objective clinical data that support physiotherapists in evaluating rehabilitation progress while enabling personalized treatment planning.

Research demonstrates that wearable sensor–based physiotherapy significantly improves rehabilitation accuracy by replacing subjective clinical observations with quantitative performance measurements (Yang et al., 2022). Continuous monitoring enables therapists to detect deviations in rehabilitation progress early, modify exercise programs accordingly, and reduce the likelihood of treatment failure.

Furthermore, wearable sensors facilitate home-based rehabilitation by allowing patients to perform prescribed exercises independently while clinicians remotely monitor adherence and recovery. Such technologies reduce hospital visits, minimize healthcare costs, and increase accessibility for patients residing in geographically remote areas.

Functional Recovery Outcomes

Functional recovery represents the primary objective of physiotherapy for musculoskeletal disorders. It refers to the restoration of physical function, mobility, muscle strength, joint

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

flexibility, balance, endurance, and the ability to perform activities of daily living independently following injury, surgery, or chronic musculoskeletal conditions.

Functional recovery extends beyond symptom reduction by emphasizing patients' capacity to return to work, participate in social activities, and maintain an acceptable quality of life. Consequently, rehabilitation success is increasingly evaluated using patient-centered functional outcome measures rather than solely relying on clinical assessments.

Recent evidence indicates that digital rehabilitation technologies positively influence functional recovery by providing continuous feedback, personalized interventions, objective performance monitoring, and timely therapeutic adjustments (Brennan et al., 2023). Patients receiving digitally supported rehabilitation demonstrate higher treatment adherence, improved exercise performance, and faster recovery compared with those receiving conventional physiotherapy alone.

Within Pakistan, however, empirical evidence evaluating the influence of wearable sensor–based physiotherapy on functional recovery remains scarce despite increasing investments in digital healthcare infrastructure.

Patient Engagement in Rehabilitation

Patient engagement refers to the degree to which individuals actively participate in their rehabilitation process through adherence to prescribed exercises, regular communication with healthcare professionals, self-monitoring, and commitment to treatment goals. Patient engagement is widely recognized as a critical determinant of successful rehabilitation outcomes.

Digital rehabilitation technologies strengthen patient engagement by providing real-time feedback, personalized exercise reminders, motivational support, performance tracking, and interactive communication between patients and physiotherapists (WHO, 2023). Continuous access to rehabilitation information increases patients' confidence and encourages active participation throughout the recovery process.

Studies have consistently demonstrated that higher patient engagement improves exercise adherence, treatment compliance, rehabilitation efficiency, and functional recovery among musculoskeletal patients. Conversely, poor engagement contributes to delayed recovery, treatment discontinuation, and increased disability.

Wearable sensor technologies further enhance patient engagement by allowing patients to visualize rehabilitation progress through digital dashboards and performance reports. Such objective feedback promotes motivation and encourages sustained participation in rehabilitation programs.

Digital Health Literacy

Digital health literacy refers to individuals' ability to access, understand, evaluate, and effectively utilize digital health technologies for managing healthcare needs. Within digital rehabilitation, digital health literacy enables patients to operate wearable devices, interpret rehabilitation feedback, communicate through digital platforms, and follow technology-assisted physiotherapy programs.

Patients with higher levels of digital health literacy demonstrate greater confidence in using wearable technologies, better adherence to rehabilitation exercises, and improved treatment outcomes (Norman & Skinner, 2006). Conversely, limited digital competencies reduce technology acceptance and hinder effective utilization of digital rehabilitation services.

In developing countries such as Pakistan, digital health literacy varies considerably according to educational attainment, socioeconomic status, technological exposure, and geographic location. Therefore, digital health literacy is expected to influence the effectiveness of wearable sensor–based physiotherapy and digital rehabilitation interventions.

Digital Rehabilitation and Functional Recovery Outcomes

Recent rehabilitation research consistently reports positive relationships between digital rehabilitation technologies and functional

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

recovery. Wearable sensors enable physiotherapists to collect objective movement data, evaluate rehabilitation progress accurately, detect treatment deficiencies, and personalize rehabilitation strategies according to patients' clinical conditions.

Artificial intelligence integrated with wearable technologies further enhances rehabilitation by predicting recovery trajectories, identifying high-risk patients, and supporting evidence-based clinical decision-making. These capabilities improve rehabilitation efficiency while reducing unnecessary clinical visits and healthcare expenditures (Topol, 2019).

Systematic reviews indicate that wearable sensor–based rehabilitation improves mobility, muscle strength, balance, gait performance, exercise adherence, and quality of life among patients with musculoskeletal disorders (Laver et al., 2020). Nevertheless, most empirical evidence originates from developed healthcare systems, limiting its applicability to resource-constrained environments such as Pakistan.

Digital Rehabilitation in Pakistan

Pakistan's rehabilitation sector has experienced gradual modernization through increased adoption of telemedicine, electronic medical records, and digital healthcare initiatives. However, wearable sensor–based physiotherapy remains at an early stage of implementation.

Several barriers continue to restrict digital rehabilitation adoption, including inadequate technological infrastructure, limited healthcare funding, insufficient professional training, lack of digital rehabilitation policies, and disparities in healthcare accessibility between urban and rural areas.

Despite these constraints, increasing smartphone penetration, internet accessibility, and governmental interest in digital healthcare present opportunities for integrating wearable sensor technologies into physiotherapy practice. Evidence-based research examining these technologies within Pakistan is therefore essential to support healthcare planning and policy development.

Research Gap

Although digital rehabilitation and wearable sensor technologies have demonstrated considerable potential in improving rehabilitation outcomes internationally, important research gaps remain. Existing studies have predominantly focused on stroke rehabilitation, neurological disorders, sports medicine, or orthopedic surgery in developed countries, while relatively little empirical evidence exists regarding musculoskeletal rehabilitation in developing healthcare systems.

Within Pakistan, research investigating wearable sensor–based physiotherapy remains extremely limited. Most previous studies have emphasized technological feasibility rather than evaluating how digital rehabilitation influences functional recovery through patient engagement within a comprehensive theoretical framework.

Furthermore, limited studies have examined the moderating influence of digital health literacy on rehabilitation outcomes, despite its growing importance in digital healthcare adoption. Consequently, there is insufficient empirical evidence explaining the mechanisms through which wearable sensor–based physiotherapy improves functional recovery among musculoskeletal patients in Pakistan.

This study addresses these theoretical and empirical gaps by developing an integrated framework examining the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes through the mediating role of patient engagement and the moderating role of digital health literacy.

Underpinning Theory

Task–Technology Fit (TTF) Theory

This study is grounded in Task–Technology Fit (TTF) Theory**,** proposed by Goodhue and Thompson (1995)**.** The theory argues that technology enhances individual performance when its capabilities effectively align with the tasks users are required to perform. According to TTF Theory, technological adoption alone does not guarantee improved outcomes; rather, superior performance occurs when technological features adequately support users' task requirements.

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

Within physiotherapy, rehabilitation tasks involve patient assessment, movement analysis, exercise prescription, progress monitoring, clinical decision-making, and continuous evaluation of functional improvement. Wearable sensor technologies provide real-time biomechanical data, objective movement analysis, exercise monitoring, and performance feedback that directly support these rehabilitation activities.

From the patient's perspective, wearable sensors facilitate exercise adherence, self-monitoring, personalized feedback, and continuous communication with physiotherapists, thereby improving engagement throughout the rehabilitation process. When these technological capabilities effectively match rehabilitation tasks, patients are expected to achieve superior functional recovery outcomes.

In the context of Pakistani healthcare, TTF Theory provides a strong theoretical explanation for understanding how digital rehabilitation technologies contribute to improved rehabilitation performance despite existing resource constraints. Hospitals and rehabilitation centers possessing appropriate technological infrastructure, trained physiotherapists, and digitally engaged patients are more likely to realize the full benefits of wearable sensor–based physiotherapy.

Accordingly, TTF Theory provides a comprehensive theoretical foundation for examining the relationships among digital rehabilitation, patient engagement, digital health literacy, and functional recovery outcomes within Pakistan's evolving digital healthcare environment.

Research Hypotheses (Concise)

H1: Digital rehabilitation and wearable sensor–based physiotherapy positively influence patient engagement in rehabilitation.

H2: Digital rehabilitation and wearable sensor–based physiotherapy positively influence functional recovery outcomes.

H3: Patient engagement in rehabilitation positively influences functional recovery outcomes.

H4: Patient engagement mediates the relationship between digital rehabilitation and wearable sensor–based physiotherapy and functional recovery outcomes.

H5: Digital health literacy positively moderates the relationship between digital rehabilitation and wearable sensor–based physiotherapy and patient engagement, such that the relationship is stronger at higher levels of digital health literacy.

H6: Digital rehabilitation and wearable sensor–based physiotherapy positively influence functional recovery outcomes through the mediating role of patient engagement under conditions of high digital health literacy (moderated mediation).

Methodology

Research Design

This study employed a quantitative, cross-sectional, explanatory research design to examine the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes among musculoskeletal patients in Pakistan. The study further investigated the mediating role of patient engagement in rehabilitation and the moderating role of digital health literacy. A quantitative approach was considered appropriate because it enabled the objective measurement of latent constructs and the empirical testing of the proposed hypotheses. The cross-sectional design facilitated data collection at a single point in time from patients receiving physiotherapy services, while the explanatory design was suitable for examining causal relationships among the study variables. The proposed conceptual framework was analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) because of its suitability for evaluating complex mediation and moderation models involving multiple latent constructs.

Population

The target population comprised adult musculoskeletal patients receiving physiotherapy and rehabilitation services at public and private tertiary-care hospitals, rehabilitation centers,

Frontier in Medical & Health Research
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orthopedic clinics, and specialized physiotherapy facilities across Pakistan.

Eligible participants included patients diagnosed with musculoskeletal conditions such as low back pain, neck pain, osteoarthritis, rheumatoid arthritis, sports injuries, fractures, joint replacement rehabilitation, ligament injuries, and other orthopedic disorders. Only patients who had undergone physiotherapy treatment involving digital rehabilitation technologies or wearable sensor-assisted physiotherapy for at least four weeks were included in the study.

Patients younger than 18 years of age, individuals with severe neurological disorders, cognitive impairments, or communication difficulties that could affect questionnaire responses were excluded from the study.

Sampling Technique

A multistage stratified purposive sampling technique was employed.

Initially, healthcare institutions were stratified into public and private hospitals, rehabilitation centers, and physiotherapy clinics to ensure proportional representation of different healthcare sectors. Subsequently, purposive sampling was used to recruit musculoskeletal patients who had direct experience with digital rehabilitation platforms or wearable sensor–based physiotherapy during their treatment.

This sampling approach ensured that respondents possessed sufficient knowledge and practical experience to evaluate digital rehabilitation technologies and their rehabilitation outcomes.

Sample Size

A total of 450 structured questionnaires were distributed among eligible musculoskeletal patients receiving physiotherapy services across selected healthcare institutions in Pakistan.

Following data screening for incomplete responses, missing values, duplicate entries, and multivariate outliers, 402 valid questionnaires were retained for final statistical analysis, representing an effective response rate of approximately **89.3%**.

The final sample size exceeded the minimum recommendations proposed by Hair et al. (2022) for Structural Equation Modeling and provided sufficient statistical power to estimate the proposed mediation and moderation effects.

Data Collection Procedures

Primary data were collected using a structured, self-administered questionnaire adapted from previously validated measurement scales reported in rehabilitation science, physiotherapy, digital health, and healthcare technology literature.

Prior to the main survey, the questionnaire underwent expert evaluation by senior physiotherapists, orthopedic specialists, rehabilitation physicians, digital health experts, and academic researchers to establish content validity and contextual relevance. Minor modifications were incorporated to improve clarity, readability, and cultural appropriateness.

A pilot study involving 40 musculoskeletal patients was conducted to evaluate questionnaire reliability, wording, response consistency, and completion time. Feedback obtained during the pilot study resulted in minor revisions before administration of the final questionnaire.

Ethical approval was obtained from the relevant institutional ethics committee, while formal permissions were secured from participating hospitals and rehabilitation centers. Eligible participants were informed about the study objectives, voluntary participation, confidentiality, anonymity, and their right to withdraw from the study at any stage without consequences. Written informed consent was obtained prior to questionnaire administration.

Questionnaires were distributed during routine physiotherapy sessions with assistance from trained research assistants and physiotherapists. Completed questionnaires were reviewed immediately to minimize missing responses. Subsequently, the collected data were coded and entered into IBM SPSS Statistics 29 for preliminary analysis and SmartPLS 4 for measurement and structural model evaluation.

Instruments/Measures

Data were collected using a structured questionnaire consisting of two sections.

Frontier in Medical & Health Research

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The first section obtained respondents' demographic and clinical information, including age, gender, educational level, occupation, duration of musculoskeletal condition, type of injury, rehabilitation duration, hospital type, and previous experience using wearable rehabilitation technologies.

The second section measured the study constructs using previously validated reflective scales adapted from rehabilitation and digital health literature. All questionnaire items were measured using a five-point Likert scale, ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

Measurement Constructs

Construct	Number of Items	Adapted From
Digital Rehabilitation and Wearable Sensor–Based Physiotherapy	7	Patel et al. (2021); Yang et al. (2022)
Patient Engagement in Rehabilitation	6	WHO (2023); Brennan et al. (2023)
Digital Health Literacy	5	Norman and Skinner (2006)
Functional Recovery Outcomes	7	Cieza et al. (2021); Laver et al. (2020)

The questionnaire assessed participants' perceptions regarding digital rehabilitation quality, wearable sensor usability, rehabilitation adherence, patient participation, digital competency, mobility improvement, pain reduction, physical functioning, and overall rehabilitation effectiveness.

Reliability and Validity

The psychometric properties of the measurement model were evaluated following established guidelines for PLS-SEM.

Internal consistency reliability was assessed using Cronbach's Alpha (α) and Composite Reliability (CR). Values greater than 0.70 were considered acceptable indicators of construct reliability (Hair et al., 2022).

Convergent validity was examined using indicator factor loadings and Average Variance Extracted (AVE). Standardized loadings exceeding 0.70 and AVE values above 0.50 confirmed satisfactory convergent validity.

Discriminant validity was evaluated using the Fornell–Larcker Criterion, cross-loadings, and the Heterotrait–Monotrait Ratio (HTMT). HTMT values below 0.85 demonstrated adequate discriminant validity among the latent constructs.

Content validity was established through comprehensive literature review and expert assessment by physiotherapy professionals, rehabilitation specialists, orthopedic consultants, and digital health researchers. Construct validity was further confirmed through Confirmatory Factor Analysis (CFA) before estimation of the structural model.

To minimize common method bias, several procedural remedies were implemented, including respondent anonymity, randomized questionnaire items, standardized survey instructions, and the use of validated measurement instruments. Harman's Single-Factor Test and Variance Inflation Factor (VIF) analysis indicated that common method variance did not pose a significant threat to the study findings.

The structural model was evaluated using bootstrapping with 5,000 resamples. Hypothesis testing included assessment of standardized path coefficients (β), t-values, p-values, coefficients of determination (R^2), effect sizes (f^2), predictive relevance (Q^2), standardized root mean square residual (SRMR), mediation effects, moderation effects, and confidence intervals. This comprehensive analytical procedure ensured the reliability, validity, and robustness of the empirical findings.

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

Data Analysis

Respondents' Demographic Profile

A total of 402 valid questionnaires were analyzed after data screening. Table 1 summarizes the demographic characteristics of the respondents.

Table 1: Demographic Characteristics of Respondents (n = 402)

Variable	Category	Frequency	Percentage (%)
Gender	Male	218	54.2
	Female	184	45.8
Age	18–30 Years	126	31.3
	31–45 Years	173	43.0
	46–60 Years	82	20.4
	Above 60 Years	21	5.3
Hospital Type	Public	231	57.5
	Private	171	42.5
Rehabilitation Duration	1–3 Months	146	36.3
	4–6 Months	164	40.8
	Above 6 Months	92	22.9
Musculoskeletal Condition	Low Back Pain	123	30.6
	Osteoarthritis	104	25.9
	Sports Injury	81	20.1
	Fracture Rehabilitation	61	15.2
	Others	33	8.2

The demographic profile indicates that 54.2% of the respondents were male and 45.8% were female. The largest proportion (43.0%) belonged to the 31–45-year age group, reflecting the economically active population frequently affected by musculoskeletal disorders. More than half of the respondents (57.5%) received rehabilitation services from public hospitals, while 40.8% had participated in rehabilitation programs for four to six months. Low back pain was the most common musculoskeletal condition (30.6%), followed by osteoarthritis (25.9%). The demographic distribution suggests that the sample adequately represented patients undergoing physiotherapy and rehabilitation in Pakistan.

Descriptive Statistics

Table 2: Descriptive Statistics

Construct	Mean	Standard Deviation	Skewness	Kurtosis
Digital Rehabilitation & Wearable Sensor–Based Physiotherapy	4.12	0.61	-0.41	-0.36
Patient Engagement	4.01	0.64	-0.39	-0.28
Digital Health Literacy	3.84	0.69	-0.24	-0.44
Functional Recovery Outcomes	4.06	0.62	-0.35	-0.31

Frontier in Medical & Health Research

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Respondents reported favorable perceptions regarding digital rehabilitation and wearable sensor–based physiotherapy (M = 4.12), indicating high acceptance of digital rehabilitation technologies. Functional recovery outcomes also demonstrated a relatively high mean score (M = 4.06), followed by patient engagement (M = 4.01). Digital health literacy recorded the lowest mean (M = 3.84), suggesting opportunities to strengthen patients' digital competencies. Skewness and kurtosis values remained within acceptable limits (±2), indicating that the data satisfied the assumption of normality.

Reliability and Convergent Validity

Table 3: Reliability and Convergent Validity

Construct	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Digital Rehabilitation & Wearable Sensor–Based Physiotherapy	0.926	0.940	0.721
Patient Engagement	0.911	0.928	0.683
Digital Health Literacy	0.894	0.920	0.657
Functional Recovery Outcomes	0.918	0.934	0.706

The reliability analysis confirmed excellent internal consistency for all constructs, with Cronbach's Alpha values ranging from 0.894 to 0.926. Composite Reliability values exceeded the recommended threshold of 0.70, while Average Variance Extracted (AVE) values were greater than 0.50. These findings confirm that the measurement model possessed satisfactory reliability and convergent validity.

Discriminant Validity

Table 4: Fornell–Larcker Criterion

Construct	DRWSP	PE	DHL	FRO
Digital Rehabilitation & Wearable Sensor–Based Physiotherapy	**0.849**			
Patient Engagement	0.671	**0.826**		
Digital Health Literacy	0.548	0.586	**0.810**	
Functional Recovery Outcomes	0.624	0.702	0.567	**0.840**

The square roots of the AVE values (shown in bold) exceeded the correlations among the latent constructs, confirming satisfactory discriminant validity. Therefore, each construct measured a unique theoretical concept without significant overlap.

Structural Model Assessment

Bootstrapping with 5,000 resamples was conducted to evaluate the proposed hypotheses.

Table 5: Direct Effects

Hypothesis	Structural Path	β	t-value	p-value	Decision
H1	DRWSP → Patient Engagement	0.684	16.12	<0.001	Supported
H2	DRWSP → Functional Recovery Outcomes	0.274	4.96	<0.001	Supported
H3	Patient Engagement → Functional Recovery Outcomes	0.492	9.84	<0.001	Supported

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

The structural model revealed that digital rehabilitation and wearable sensor–based physiotherapy significantly enhanced patient engagement (β = 0.684, p < 0.001), supporting H1. Digital rehabilitation also exerted a significant positive influence on functional recovery outcomes (β = 0.274, p < 0.001), supporting H2. Furthermore, patient engagement significantly improved functional recovery outcomes (β = 0.492, p < 0.001), confirming H3. These findings indicate that active patient participation is an important contributor to successful rehabilitation.

Mediation Analysis

Table 6: Indirect Effects

Hypothesis	Indirect Relationship	β	t-value	p-value	Decision
H4	DRWSP → Patient Engagement → Functional Recovery Outcomes	0.336	7.25	<0.001	Supported

The mediation analysis indicated that patient engagement significantly mediated the relationship between digital rehabilitation and functional recovery outcomes (β = 0.336, p < 0.001). This finding suggests that wearable sensor–based physiotherapy improves functional recovery not only directly but also indirectly by increasing patients' participation, adherence, and commitment to rehabilitation exercises.

Moderation Analysis

Table 7: Moderating Effect of Digital Health Literacy

Hypothesis	Interaction Effect	β	t-value	p-value	Decision
H5	DRWSP × Digital Health Literacy → Patient Engagement	0.198	4.13	<0.001	Supported

Digital health literacy significantly moderated the relationship between digital rehabilitation and patient engagement (β = 0.198, p < 0.001). Patients with higher levels of digital health literacy benefited more from wearable sensor–based physiotherapy because they were better able to understand, utilize, and engage with digital rehabilitation technologies.

Moderated Mediation Analysis

Table 8: Conditional Indirect Effect

Hypothesis	Conditional Indirect Effect	β	t-value	p-value	Decision
H6	DRWSP → Patient Engagement → Functional Recovery Outcomes (High Digital Health Literacy)	0.371	6.08	<0.001	Supported

The moderated mediation analysis demonstrated that the indirect effect of digital rehabilitation on functional recovery through patient engagement became significantly stronger under conditions of high digital health literacy. This finding indicates that patients who possess better digital competencies derive greater rehabilitation benefits from wearable sensor technologies.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Coefficient of Determination (R^2)

Table 9: Coefficient of Determination

Endogenous Variable	R^2	Interpretation
Patient Engagement	0.468	Moderate
Functional Recovery Outcomes	0.652	Substantial

The proposed structural model explained 46.8% of the variance in patient engagement and **65.2**% of the variance in functional recovery outcomes. These values indicate satisfactory predictive accuracy and demonstrate that digital rehabilitation, patient engagement, and digital health literacy collectively explain a substantial proportion of rehabilitation success among musculoskeletal patients.

Model Fit Assessment

Table 10: Model Fit Indices

Fit Index	Obtained Value	Recommended Value	Assessment
SRMR	0.056	< 0.08	Good Fit
NFI	0.921	> 0.90	Good Fit
RMS Theta	0.094	< 0.12	Acceptable

The model fit indices indicate that the proposed structural model adequately fits the observed data. The SRMR value of 0.056 is below the recommended threshold of 0.08, while the NFI exceeds 0.90. Additionally, the RMS Theta value falls within the acceptable range, confirming the robustness and overall adequacy of the measurement and structural models.

The findings suggest that digital rehabilitation and wearable sensor–based physiotherapy significantly improve functional recovery outcomes among musculoskeletal patients in Pakistan. The results indicate that wearable technologies enhance rehabilitation effectiveness by increasing patient engagement, which serves as a critical mechanism linking digital rehabilitation to improved physical recovery. Moreover, digital health literacy strengthens patients' ability to benefit from wearable sensor technologies, emphasizing the importance of digital competencies in modern rehabilitation programs. These findings support Task–Technology Fit Theory, demonstrating that rehabilitation technologies produce superior outcomes when they effectively align with rehabilitation tasks and patients possess the necessary digital capabilities to utilize them effectively.

Discussion

The findings of this study demonstrate that digital rehabilitation and wearable sensor–based physiotherapy significantly improve functional recovery outcomes among musculoskeletal patients in Pakistan through enhanced patient engagement, while digital health literacy strengthens this relationship. These findings support the Task–Technology Fit (TTF) Theory, which argues that technological innovations improve individual performance when their capabilities effectively align with users' task requirements (Goodhue & Thompson, 1995). In the context of physiotherapy, wearable sensor technologies complement rehabilitation tasks by providing objective movement analysis, continuous performance monitoring, and real-time feedback, thereby facilitating more effective rehabilitation outcomes.

The positive relationship between digital rehabilitation and patient engagement indicates that wearable sensor technologies encourage patients to participate more actively in rehabilitation programs. Real-time performance monitoring, personalized exercise feedback, and remote communication with physiotherapists increase patients' motivation, treatment

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

adherence, and commitment to prescribed rehabilitation exercises. This finding is consistent with previous studies reporting that digital rehabilitation improves patient participation and treatment compliance through continuous monitoring and interactive rehabilitation platforms (Brennan et al., 2023; Laver et al., 2020). Increased patient engagement is particularly important in musculoskeletal rehabilitation because successful recovery largely depends on consistent exercise adherence and active patient involvement throughout the rehabilitation process.

The study further revealed that digital rehabilitation and wearable sensor–based physiotherapy exert a direct positive influence on functional recovery outcomes. This finding suggests that wearable technologies enable physiotherapists to make more accurate clinical assessments, monitor patient progress objectively, and personalize rehabilitation interventions according to individual recovery patterns. These results are consistent with previous research demonstrating that wearable sensors improve mobility, balance, muscle strength, gait performance, and overall physical functioning among patients with musculoskeletal disorders (Patel et al., 2021; Yang et al., 2022). Continuous monitoring also facilitates early identification of rehabilitation deficiencies, allowing timely modifications to treatment plans that ultimately enhance recovery outcomes.

Patient engagement was found to significantly influence functional recovery outcomes, indicating that active participation serves as a fundamental determinant of rehabilitation success. Patients who consistently adhered to prescribed exercises, communicated regularly with physiotherapists, and actively monitored their rehabilitation progress demonstrated superior improvements in mobility, pain reduction, and functional independence. This finding supports rehabilitation literature emphasizing that patient-centered care and self-management behaviors are critical components of effective physiotherapy interventions (World Health Organization [WHO], 2023).

The mediation analysis revealed that patient engagement serves as a significant mechanism through which digital rehabilitation improves functional recovery outcomes. Rather than influencing rehabilitation solely through technological innovation, wearable sensor–based physiotherapy enhances recovery by increasing patients' motivation, adherence, and active participation in rehabilitation activities. This finding extends previous rehabilitation research by demonstrating the behavioral pathway through which digital technologies improve clinical outcomes. It also reinforces the assumptions of Task–Technology Fit Theory by illustrating that technological effectiveness depends not only on system capabilities but also on users' engagement with technology-supported tasks.

The moderating effect of digital health literacy indicates that patients possessing higher levels of digital competence derive greater benefits from wearable sensor technologies. Individuals who were capable of operating digital devices, interpreting rehabilitation feedback, and utilizing mobile rehabilitation platforms demonstrated stronger engagement and improved functional recovery. This finding aligns with previous studies suggesting that digital literacy is an essential prerequisite for successful digital health implementation (Norman & Skinner, 2006). In developing healthcare systems such as Pakistan, disparities in digital literacy may therefore influence the effectiveness of wearable rehabilitation technologies.

The moderated mediation findings further suggest that the indirect influence of digital rehabilitation on functional recovery through patient engagement becomes significantly stronger when patients possess high digital health literacy. This finding highlights that successful digital rehabilitation requires not only advanced technology but also adequate patient education and technological preparedness. Healthcare institutions implementing wearable sensor technologies should therefore integrate patient digital literacy programs into rehabilitation services to maximize treatment effectiveness.

Overall, the findings provide strong empirical evidence supporting the effectiveness of digital

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

rehabilitation and wearable sensor–based physiotherapy within Pakistan's healthcare context. The study contributes to rehabilitation science by demonstrating that technological innovation, patient engagement, and digital health literacy collectively improve functional recovery among musculoskeletal patients. Given Pakistan's growing burden of musculoskeletal disorders and limited rehabilitation resources, digital rehabilitation offers a promising strategy for expanding access to high-quality physiotherapy services while improving clinical outcomes.

Conclusion

This study examined the influence of digital rehabilitation and wearable sensor–based physiotherapy on functional recovery outcomes among musculoskeletal patients in Pakistan by investigating the mediating role of patient engagement and the moderating role of digital health literacy. The findings demonstrate that digital rehabilitation significantly improves patient engagement and functional recovery outcomes, confirming the growing importance of wearable sensor technologies in modern physiotherapy practice.

Patient engagement emerged as an important mediating mechanism through which digital rehabilitation enhanced functional recovery. The findings further revealed that digital health literacy strengthened the effectiveness of wearable sensor–based physiotherapy, indicating that patients with greater digital competencies benefited more substantially from digital rehabilitation technologies.

The study extends Task–Technology Fit Theory by demonstrating that wearable sensor technologies contribute to superior rehabilitation outcomes when they effectively support rehabilitation tasks and when patients possess the digital capabilities necessary to utilize these technologies. The integrated framework provides new empirical evidence regarding the interaction between technology, patient behavior, and rehabilitation outcomes within a developing-country healthcare context.

Overall, the study concludes that digital rehabilitation and wearable sensor–based physiotherapy represent effective strategies for improving rehabilitation quality, increasing patient engagement, enhancing functional recovery, and supporting digital transformation within Pakistan's healthcare system. However, maximizing these benefits requires simultaneous investments in technological infrastructure, patient education, professional training, and supportive healthcare policies.

Implications

Theoretical Implications

This study contributes to rehabilitation science, digital health, and physiotherapy literature by extending Task–Technology Fit Theory within the context of wearable sensor–based rehabilitation. It demonstrates that patient engagement serves as an important mediating mechanism linking digital rehabilitation with functional recovery outcomes, while digital health literacy enhances the effectiveness of technology-assisted rehabilitation. The proposed framework enriches existing knowledge by integrating technological, behavioral, and clinical dimensions of rehabilitation.

Practical Implications

The findings suggest that physiotherapists should incorporate wearable sensor technologies into rehabilitation programs to improve patient monitoring, personalize treatment plans, and enhance exercise adherence. Healthcare providers should also encourage patient engagement through continuous digital feedback, remote monitoring, and individualized rehabilitation support.

Managerial Implications

Hospital administrators and rehabilitation managers should invest in wearable sensor technologies, tele-rehabilitation platforms, and digital rehabilitation infrastructure to improve service quality and operational efficiency. Continuous professional development programs should be organized to enhance physiotherapists' competencies in digital rehabilitation technologies and data-driven clinical decision-making.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Policy Implications

Healthcare policymakers should develop national strategies promoting the integration of digital rehabilitation into Pakistan's healthcare system. Public investment should focus on expanding digital infrastructure, improving rehabilitation accessibility in rural areas, establishing clinical guidelines for wearable technologies, and promoting equitable access to digital rehabilitation services. Policies supporting digital health literacy and reimbursement for tele-rehabilitation services would further facilitate widespread adoption.

Recommendations

Healthcare institutions should gradually integrate wearable sensor–based physiotherapy into routine rehabilitation services to improve continuous patient monitoring and personalized treatment planning.

Physiotherapists should receive regular professional training on wearable technologies, digital rehabilitation platforms, artificial intelligence applications, and remote patient monitoring systems.

Hospitals should establish tele-rehabilitation programs that enable patients to continue physiotherapy at home while remaining under continuous clinical supervision.

Government agencies should invest in digital health infrastructure and provide financial incentives to encourage healthcare institutions to adopt wearable rehabilitation technologies.

Patient education programs should be developed to improve digital health literacy, enabling patients to effectively utilize wearable devices, mobile applications, and digital rehabilitation platforms.

Healthcare organizations should strengthen collaborations with universities, technology companies, rehabilitation centers, and digital health developers to promote innovation in physiotherapy and rehabilitation technologies.

Future rehabilitation programs should integrate artificial intelligence, predictive analytics, and personalized rehabilitation algorithms to optimize patient recovery and improve healthcare efficiency.

Limitations and Future Directions

Despite its contributions, the study has several limitations that should be considered when interpreting the findings.

First, the study employed a cross-sectional research design, which limited the ability to establish causal relationships over time. Future studies should adopt longitudinal designs to evaluate changes in functional recovery throughout different stages of rehabilitation.

Second, the study focused exclusively on musculoskeletal patients receiving physiotherapy in Pakistan. Consequently, the findings may not be generalizable to patients with neurological disorders, cardiopulmonary conditions, pediatric rehabilitation, or rehabilitation settings in other countries. Future research should investigate digital rehabilitation across diverse clinical populations and healthcare systems.

Third, data were collected using self-reported questionnaires, which may be affected by social desirability bias and subjective perceptions. Future investigations should combine survey responses with objective clinical outcome measures such as gait analysis, range of motion, muscle strength assessments, wearable sensor data, and standardized functional performance tests.

Fourth, although this study examined digital rehabilitation, patient engagement, digital health literacy, and functional recovery, future research should incorporate additional variables such as technology acceptance, trust in digital health systems, perceived usefulness, rehabilitation self-efficacy, organizational support, therapist competence, patient satisfaction, quality of life, and long-term treatment adherence to develop more comprehensive explanatory models.

Future studies should also compare rehabilitation outcomes across public and private hospitals, urban and rural healthcare facilities, and different wearable sensor technologies to identify contextual factors influencing rehabilitation effectiveness.

Finally, researchers are encouraged to employ advanced analytical approaches such as longitudinal Structural Equation Modeling (SEM), multilevel modeling, multigroup analysis, artificial neural networks, machine learning

Frontier in Medical & Health Research

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techniques, and mixed-methods research designs to provide deeper insights into digital rehabilitation and wearable sensor–based physiotherapy. Such research will contribute to the development of evidence-based rehabilitation policies and support the sustainable digital transformation of physiotherapy services in Pakistan and other developing healthcare systems.

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