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THE ROLE OF WEARABLE TECHNOLOGY AND TELEREHABILITATION IN OPTIMIZING POST-OPERATIVE ACL RECOVERY: A FRAMEWORK FOR EQUITABLE ACCESS

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ABSTRACT

Background: Anterior Cruciate Ligament (ACL) rupture is a debilitating injury requiring prolonged rehabilitation. The traditional clinic-based model of care presents significant socioeconomic barriers, including geographic distance and indirect costs, which contribute to suboptimal adherence and inequitable outcomes.
Objective: This descriptive review outlines a comprehensive framework integrating wearable sensor technology and telerehabilitation to optimize post-operative ACL recovery and democratize access to care.
Methods: We synthesized recent literature (2015–2025) focusing on the efficacy of remote monitoring, sensor validation, and the economic impact of telerehabilitation.
Results: Current evidence demonstrates that telerehabilitation is clinically non-inferior to standard face-to-face therapy regarding range of motion and functional milestones. Wearable sensors (IMUs) and mobile applications provide valid, objective data that enhances patient adherence through "digital visibility," bridging the gap between prescribed and actual exercise dosage. Furthermore, economic analyses indicate that this model significantly reduces patient-borne costs, establishing it as a dominant strategy for equitable healthcare delivery.
Conclusion: Integrating digital health technologies into ACL rehabilitation offers a scalable solution to the "rehabilitation gap." By combining objective data with remote access, this framework mitigates social determinants of health, ensuring that high-quality recovery is accessible regardless of a patient's geographic or financial status. A hybrid model utilizing these tools is recommended as the future standard of care.

KEYWORDS
ACL Rehabilitation, Telerehabilitation, Wearable Technology, Health Equity, Digital Health

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Introduction

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Anterior Cruciate Ligament (ACL) rupture is one of the most common and debilitating knee injuries, particularly affecting young, athletic individuals [1]. The incidence of these injuries, and subsequent ACL reconstruction (ACLR) surgeries, has seen a significant rise globally, especially among adolescent populations [2]. While the surgical technique is the first crucial step, the ultimate success of the intervention—defined by a return to pre-injury activity levels and the prevention of long-term sequelae—is overwhelmingly dependent on a protracted, 9- to 12-month post-operative rehabilitation program [3].

This structured physiotherapy is critical for restoring neuromuscular control, symmetrical strength, and psychological readiness to return to sport. Failure to adequately complete this demanding process is directly linked to inferior patient-reported outcomes, higher rates of re-injury, and the early onset of post-traumatic osteoarthritis [4, 21]. Despite its established importance, adherence to long-term ACL rehabilitation protocols is notoriously poor [5]. The traditional model of care, which demands frequent (often 2-3 times per week) in-person clinic visits, creates significant logistical and financial burdens for patients [5, 6].

These burdens are not distributed equally; they function as significant social determinants of health (SDOH) that create profound inequities in access to care [7]. Patients in rural or remote areas may lack geographic access to specialized sports physiotherapists. For many others, the indirect costs—such as transportation, childcare, and, most critically, lost wages from taking time off work—make consistent attendance economically untenable [6, 7]. This results in a two-tiered system where patients with greater financial resources, geographic advantages, and flexible work schedules are inherently more likely to achieve an optimal recovery.

The rapid maturation and validation of digital health technologies offer a powerful solution to this equity gap. The integration of wearable sensor technology (e.g., inertial measurement units) with telerehabilitation platforms provides a new paradigm for care delivery [8]. Wearable sensors can provide objective, real-time data on movement quality, range of motion, and adherence at home, while mHealth platforms can connect the patient to the provider, irrespective of location [9].

However, the true value of this technology is not merely in its data collection, but in its potential to democratize access to high-quality care. This descriptive paper outlines a comprehensive framework that integrates wearable technology and telerehabilitation to optimize post-operative ACL recovery. We argue that this framework is an essential, scalable strategy for mitigating socioeconomic and geographic barriers, thereby advancing health equity in musculoskeletal rehabilitation.

Literature Review

2.1. The "Black Box" of Traditional Rehabilitation and Adherence

The traditional rehabilitation model is heavily reliant on supervised in-clinic exercises and patient self-reporting of their home exercise program (HEP). This "black box" of at-home recovery is a critical point of failure. Studies consistently show a discrepancy between what patients report and their actual adherence. For example, Walker et al. (2020) highlighted that barriers such as lack of motivation and logistical issues significantly impede adherence to home protocols [5]. This lack of objective insight prevents clinicians from addressing key psychological barriers such as kinesiophobia (fear of re-injury), which are known to negatively impact recovery outcomes but are difficult to monitor without continuous data [22].

2.2. Validation of Wearable Technology for Objective Monitoring

Wearable technology, particularly inertial measurement units (IMUs), has emerged as a validated solution to this monitoring deficit. Shuai et al. (2022) assessed the reliability of inertial measurement systems and confirmed they provide valid quantification of lower extremity joint angles during functional movements, demonstrating high consistency with optical motion capture [12]. Beyond passive monitoring, these sensors facilitate active intervention. Gokeler et al. (2019) emphasized that integrating principles of motor learning with technology can support neuroplasticity [17].

2.3. Efficacy and Feasibility of Telerehabilitation

Concurrent with the rise of sensors, telerehabilitation has matured into a mainstream care delivery model. A 2024 survey by Gardner et al. highlighted that telerehabilitation provides a viable mechanism to bridge the post-operative supervision gap [9]. Importantly, Fricke et al. (2025) outlined in the ORSOME-II study that telerehabilitation using dedicated sensor systems (Orthelligent HOME) offers significant medical benefits, aiming to establish a new standard for post-ACLR recovery that rivals traditional methods in effectiveness [13].

2.4. The Synergistic Gap: Integrating Data and Access

While wearable sensors and telerehabilitation are individually validated, their true potential lies in synergistic integration. Schmidt et al. (2025) provided compelling evidence for this hybrid approach, demonstrating that combining a digital health application with standard care *significantly enhances* rehabilitation outcomes compared to standard care alone, suggesting that the digital component acts as a critical "force multiplier" in recovery [15].

Results

1. Study Characteristics and Participant Demographics

The analysis included data from recent randomized controlled trials (RCTs) and systematic reviews published between 2015 and 2025. The demographics across included studies reflected the typical ACL reconstruction (ACLR) population—young, active adults. A global overview by Liang et al. (2024) confirms that the primary demographic remains adolescents and young adults, who are "digital natives" and highly receptive to mHealth interventions [2].

2. Clinical Efficacy: Range of Motion (ROM) and Functional Recovery

Evidence indicates that telerehabilitation is highly effective, particularly in the initial stages of recovery. Turchetta et al. (2025) conducted a study focusing on the early post-operative period and found that telerehabilitation is effective in restoring range of motion and meeting early functional milestones, proving that remote supervision is safe and viable immediately following surgery [14].

Recent studies utilizing digital monitoring have demonstrated superiority when combined with traditional care. Schmidt et al. (2025) reported that patients who utilized a digital health application in conjunction with standard therapy achieved significantly better rehabilitation outcomes than those receiving standard care alone. This indicates that the continuous engagement provided by the app drives superior functional gains [15].

3. Patient-Reported Outcome Measures (PROMs)

Subjective knee function and quality of life were assessed using standard scoring systems (e.g., IKDC, KOOS).

Outcomes: Most studies support a non-inferiority conclusion. Pastora-Bernal et al. (2018) highlighted that patients in telerehabilitation groups achieved comparable quality of life scores to those in face-to-face groups [14]. Moreover, Liao et al. (2023) observed that patients using an AI-assisted smart brace (Tele-AI group) during the COVID-19 pandemic were able to maintain rehabilitation progress despite the lack of physical access to clinics, achieving satisfactory functional scores [19].

4. Adherence and Care Models

Adherence Rates*:* Objective data monitoring reveals high adherence in digitally supported programs. The protocols described by Fricke et al. (2025) utilizing the Orthelligent HOME system rely on "digital visibility" to maintain high patient engagement, ensuring that the prescribed exercise dosage is actually met [13].

Models of Care: The integration of these technologies requires a shift in physiotherapy frameworks. Cottrell and Russell (2020) argue that telehealth for musculoskeletal physiotherapy is not just a substitute but a distinct modality that, when implemented correctly, can effectively manage complex conditions through modified delivery models that ensure both accessibility and clinical rigor [18].

5. Cost-Effectiveness Analysis

Economic analysis consistently favors telerehabilitation, driven by reductions in personnel and travel costs. Pastora-Bernal et al. (2018) conducted a review of cost-effectiveness and found that telerehabilitation strategies offer substantial cost savings for both the healthcare system and the patient (due to reduced travel and time off work) while maintaining equivalent clinical effectiveness [14].

6. Technological Validity of Remote Monitoring

The validity of the tools used to capture this data—wearable sensors and smartphone apps—has been rigorously established.

Discussion

Clinical Equivalence and Enhanced Recovery The primary concern regarding remote rehabilitation has historically been the fear of substandard outcomes. However, the recent data from Turchetta et al. [14] demonstrates efficacy in the critical early phases. Moreover, Schmidt et al. [15] go further, showing that digital tools do not just equal standard care but can *enhance* it. This suggests that the future standard of care should be a "digital-hybrid" model.

The Hybrid Imperative Despite the technological success, the framework proposed by Cottrell and Russell [18] suggests that telehealth should be viewed as a complementary tool within musculoskeletal physiotherapy. While sensors validated by Shuai et al. [12] provide the necessary data, the clinical interpretation and management strategies outlined by Fricke et al. [13] ensure that this data translates into tangible medical benefits.

Conclusions

The comprehensive analysis of current literature substantiates that the integration of wearable technology and telerehabilitation constitutes a transformative paradigm shift in post-operative ACL management. This framework moves beyond the limitations of the traditional, clinic-centric model to offer a solution that is clinically effective, economically efficient, and socially equitable.

Clinical Viability: The evidence overwhelmingly supports the non-inferiority of telerehabilitation compared to standard face-to-face care. As demonstrated by recent reviews, remote monitoring—when supported by validated sensors—ensures that critical milestones are achieved safely.

Democratizing Access: Perhaps the most significant contribution of this framework is its potential to dismantle socioeconomic barriers. By drastically reducing the indirect costs associated with travel and lost wages, digital rehabilitation addresses the "two-tiered" system of care.

Future Directions: Ultimately, the adoption of wearable-supported telerehabilitation is a present necessity. Future efforts must now focus on standardizing reimbursement policies and integrating these digital workflows into routine clinical practice to ensure this equitable promise is fully realized.

Disclosure
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Software: Karol Demel, Adrian Dyląg, Jakub Król
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