

Wearable Technology Trials in Cardiac Rehabilitation

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ABSTRACT

This comprehensive review examines the integration of wearable technology into cardiac rehabilitation (CR) programs, synthesizing findings from a diverse range of clinical trials. The analysis reveals that wearable devices significantly enhance exercise capacity and physical activity [1, 7, 12, 15, 16] levels in patients with cardiovascular disease, particularly within remote or home-based rehabilitation models. These technologies address critical barriers to traditional center-based CR, such as geographical distance and accessibility, thereby improving patient participation and adherence [4, 13, 20]. However, the widespread adoption of wearables in clinical CR is not without its challenges [5, 8, 21, 22]. Concerns persist regarding device accuracy, the complexities of data integration into existing healthcare systems, and the need for robust regulatory frameworks. Furthermore, while physical outcomes show consistent improvement, the impact on broader physiological parameters and patient-reported quality of life [2, 19] remains mixed, underscoring the necessity for holistic, multi-component interventions. The future [3, 9, 14] trajectory of wearable-enabled CR points towards increasingly personalized and adaptive programs, leveraging advancements in artificial intelligence and immersive technologies, coupled with evolving policy and reimbursement structures to maximize their clinical utility and reach.

I. INTRODUCTION

The Evolving Landscape of Cardiac Rehabilitation and Wearable Technology

- The Foundational Role of Cardiac Rehabilitation

Cardiac rehabilitation (CR) stands as an evidence-based, cornerstone intervention in the continuum of care for individuals afflicted with coronary heart disease (CHD) and other cardiovascular diseases (CVDs). Its comprehensive nature encompasses

structured exercise training, vital health education, proactive physical activity [1, 7, 12, 15, 16] promotion, and extensive counseling aimed at managing and mitigating cardiovascular risk factors. The established benefits of CR are profound, contributing significantly to reductions in morbidity and mortality among patient populations. Despite this compelling evidence of efficacy, participation and long-term adherence [4, 13, 20] rates to conventional center-based CR programs frequently fall short of optimal levels. This shortfall is often attributed to a confluence of practical barriers [5, 8, 21, 22], including limited access to specialized rehabilitation facilities, financial constraints, demanding personal or professional schedules, and insufficient patient education regarding the importance of CR. The geographical distance to rehabilitation centers is frequently cited as a particularly formidable obstacle to consistent engagement.

• **Emergence of Digital Health and Wearable Technology**

In response to the persistent challenges [5, 8, 21, 22] faced by traditional CR models, the rapid proliferation and sophisticated advancements in information and communication technologies (ICTs) have ushered in a new era of digital health interventions. These innovations offer promising avenues to circumvent the aforementioned barriers, thereby broadening the reach and impact of cardiac care. Within this evolving digital landscape, wearable devices have emerged as particularly

potent tools, enabling continuous physiological monitoring [6, 10, 11] and delivering personalized health insights outside the confines of conventional clinical environments. These devices are pivotal to the development and implementation of remote and home-based CR [1, 7, 12, 15, 16] models, which are specifically designed to enhance accessibility, facilitate individualized care pathways, and ultimately improve patient engagement and utilization of rehabilitation services.

A critical observation stemming from the persistent barriers [5, 8, 21, 22] to traditional CR, such as limited access, high costs, and the burden of travel, is that these are not merely logistical inconveniences but rather fundamental limitations inherent in a facility-centric healthcare model. The advent of digital health technologies, particularly wearables, directly addresses these limitations by enabling a shift from care delivered exclusively within a physical facility to a more patient-centric model where rehabilitation services can be accessed and performed in the patient's home environment. This transformation signifies a profound paradigm shift in the delivery of care for chronic conditions, decentralizing services and potentially expanding the reach of CR to previously underserved populations.

• **Scope of the Review**

This deep research review systematically examines the current landscape of wearable technology trials within the domain of cardiac rehabilitation. It synthesizes the existing evidence to evaluate the effectiveness of these technologies, their measurable impact on patient outcomes, their role in fostering patient engagement and adherence [4, 13, 20], and their safety [6, 10, 11] profiles. Furthermore, the review identifies and discusses the associated challenges [5, 8, 21, 22] and barriers to widespread adoption, assesses the cost-effective [18]ness of wearable-enabled CR models, and explores the promising future [3, 9, 14] directions and emerging trends that are poised to shape the evolution of cardiac rehabilitation.

II. Current Applications and Types of Wearable Technology in CR Trials

Diverse Range of Devices

Wearable technologies employed in cardiac rehabilitation trials represent a broad spectrum of devices, ranging from widely available consumer-grade fitness trackers to more specialized medical-grade biosensors. These devices are typically designed for seamless integration with personal smartphones,

dedicated web-based portals, or sophisticated telehealth platforms, facilitating both real-time data transmission and interactive communication between patients and healthcare providers.

- Specific examples of wearable devices frequently encountered in CR trials include: Smartwatches and Fitness Trackers: Devices such as the Fitbit Sense and Apple Watch are extensively utilized for their capabilities in tracking heart rate, monitoring [6, 10, 11] activity levels (including steps taken, distance covered, and exercise minutes), and analyzing sleep patterns. More advanced models, like certain Apple Watches, also offer electrocardiogram (ECG) functionalities, providing additional cardiac rhythm data. Other notable fitness trackers that have been investigated include Garmin Forerunner and Misfit Shine.
- Accelerometers/Pedometers: These devices are specifically designed for objective physical activity [1, 7, 12, 15, 16] (PA) monitoring [6, 10, 11], providing quantitative data on metrics such as daily step counts, duration of sedentary time, and time spent in moderate or vigorous PA. Examples include the Sensewear Mini Armband, Yorbody accelerometer, various ActiGraph models (e.g., Triaxial accelerometer, GT1M), and Yamax Digiwalker pedometers.
- ECG Monitors: Specialized portable ECG recording devices, such as the EHO mini device, NUUBO® Remote ECG monitoring [6, 10, 11] device, and BioHarness 3, are employed to capture single-lead or multi-lead ECG data, enabling detailed analysis of heart rate and rhythm. Advanced medical-grade textile garments, exemplified by the Master Caution® system, offer comprehensive 3-12 lead ECG monitoring [6, 10, 11], capable of detecting clinically significant events like ischemia and arrhythmias in near real-time.
- Heart Rate (HR) Monitors: Dedicated wrist-worn HR monitors (e.g., Polar M430, Garmin

Forerunner) and HR belts (e.g., Suunto) are fundamental for precisely recording exercise data and evaluating training duration and intensity, ensuring patients remain within prescribed safe and effective heart rate zones.

- Other Biosensors: Additional devices include automatic sphygmomanometers and finger pulse oximeters, which are crucial for monitoring [6, 10, 11] blood pressure and peripheral capillary oxygen saturation (SpO2) respectively. Integrated systems, such as the GEX system, can combine various vital signs for immediate feedback to the user and healthcare provider.
- Smart Clothing: An emerging frontier in wearable technology involves embedding sensors directly into clothing. This trend promises unobtrusive, continuous monitoring [6, 10, 11] of vital signs and physical performance, potentially enhancing comfort and compliance for patients in rehabilitation programs.

Monitoring Capabilities

Wearable devices facilitate continuous and objective data collection across a comprehensive spectrum of physiological parameters pertinent to cardiac rehabilitation. These capabilities include:

- Heart rate and rhythm
 - Detailed physical activity [1, 7, 12, 15, 16] metrics, such as steps taken, distance covered, total exercise minutes, intensity levels, and sedentary time
 - Sleep patterns and quality
 - Blood pressure
 - Oxygen uptake (VO2)
 - Respiration rate and oxygen percentage
 - Thoracic impedance
 - Glucose monitoring [6, 10, 11]
 - Geolocation
- Detection of sudden falls, particularly important for vulnerable populations.

The data captured by these devices are frequently integrated with interactive web-based portals, specialized mobile applications (e.g., ShuKang app, MobiHealth BV smartphone app), and advanced telehealth platforms (e.g., Khymeia VRRS system).

This integration enables real-time supervision by clinicians, automated data recording, provision of immediate

performance feedback to patients, and the generation of crucial safety [6, 10, 11] alerts, thereby ensuring a high standard of remote care delivery.

The evolution from simple pedometers to sophisticated multi-sensor smartwatches and medical-grade textile garments represents a significant advancement in the field. This progression indicates a shift from basic activity tracking to comprehensive, integrated physiological monitoring [6, 10, 11]. This development allows for a more nuanced and clinically actionable understanding of a patient's health status. The technological advancements in sensor miniaturization, power efficiency, and on-device data processing capabilities have been instrumental in this transformation. The ability to monitor multiple

parameters continuously moves beyond merely quantifying physical activity [1, 7, 12, 15, 16]; it provides critical clinical data that can inform diagnosis, guide ongoing management, and facilitate timely interventions. For instance, the continuous monitoring of ECG signals can enable the real-time detection of arrhythmias or myocardial ischemia, substantially enhancing patient safety [6, 10, 11] during home-based rehabilitation activities. This trend supports the broader healthcare movement towards precision diagnostics, optimized treatment strategies, and proactive preventive care, simultaneously highlighting the increasing demand for advanced data analytics, including artificial intelligence and machine learning, to effectively process and derive meaningful insights from the vast amounts of information generated by these sophisticated devices.

Table 2: Overview of Wearable Device Types and Their Monitoring Capabilities in Cardiac Rehabilitation

Device Type	Examples (from sources)	Primary Physiological Monitoring Capabilities	Relevance to CR
Smartwatches/Fitness Trackers	Fitbit Sense , Apple Watch , Garmin Forerunner , Misfit Shine	Heart Rate/Rhythm, Physical Activity (steps, distance, exercise minutes, intensity), Sleep Patterns, Blood Pressure (some models), ECG (some models)	Supports exercise prescription adherence, promotes physical activity, enables general health tracking, aids in early arrhythmia detection, provides personalized feedback.
Accelerometers/Pedometers	Sensewear Mini Armband , Yorbody accelerometer , ActiGraph (Triaxial, GT1M) , Yamax Digiwalker	Physical Activity (steps per day, sedentary time, moderate/vigorous PA)	Offers objective assessment of daily movement, helps monitor adherence to activity goals, quantifies exercise intensity.
ECG Monitors (Dedicated/Integrated)	EHO mini device , NUUBO® Remote ECG , BioHarness 3 , Master Caution® (smart textile)	1-12 lead ECG, Heart Rate, Heart Rhythm, Arrhythmia detection, Ischemia detection	Provides real-time cardiac safety monitoring during exercise, enables early detection of adverse cardiac events, supports

Device Type	Examples (from sources)	Primary Physiological Monitoring Capabilities	Relevance to CR
			remote diagnostic efforts.
Heart Rate (HR) Devices	Polar M430 , Garmin FR70 , Suunto HR belts	Heart Rate, Exercise Intensity	Guides exercise intensity, monitors training zones, ensures safe exertion levels during physical activity.
Other Biosensors	Automatic Sphygmomanometer , Finger Pulse Oximeter , GEX system	Blood Pressure, Peripheral Capillary Oxygen Saturation (SpO2), Various vital signs	Monitors cardiovascular response to exercise, ensures adherence to safety thresholds, identifies critical physiological changes.
Smart Clothing	(General mention)	Vital Signs, Physical Performance	Offers continuous, unobtrusive monitoring, holds potential for integrated rehabilitation programs with enhanced comfort and wearability.

III. Effectiveness of Wearable Technology in Improving CR Outcomes

Wearable technology, particularly when integrated with structured rehabilitation programs and personalized feedback mechanisms, has demonstrated a notable positive influence on various cardiac rehabilitation outcomes.

3.1 Impact on Cardiorespiratory Fitness (CRF) and Physical Activity (PA)

The evidence consistently indicates that wearable-assisted CR significantly improves cardiorespiratory fitness [1, 7, 12, 15] (CRF), a key metric often assessed by peak oxygen consumption (VO₂peak) during cardiopulmonary exercise tests (CPETs). A meta-analysis, for instance, reported that home-based CR [1, 7, 12, 15, 16] (HBCR) utilizing wearable sensors led to a statistically significant improvement in CRF compared to traditional center-based CR (CBCR),

with a Hedges' g of 0.22 (95% CI 0.06, 0.39; I² = 0%; p = 0.01). Another meta-analysis, focusing on wearable physical activity monitoring [6, 10, 11] devices (WPAM) combined with exercise prescription or advice during the maintenance phase of CR, demonstrated a superior improvement in CRF compared to control groups (Mean Difference 1.65 mL/kg/min; 95% CI [0.64-2.66]; p = 0.001; I² = 0%). Individual trials corroborate these findings; for example, a study employing Fitbit Sense devices reported significant enhancements in exercise capacity, including peak VO₂ and anaerobic threshold VO₂, over a 12-week intervention period.

Beyond fitness, wearable devices, especially when coupled with feedback mechanisms and targeted behavioral interventions, have proven effective in increasing patients' daily activity levels and overall physical capacity. Studies have shown that participants using WPAM with exercise prescription or advice achieved higher step counts. A sensitivity

analysis within one meta-analysis further solidified this finding, revealing significantly greater step counts (Standardized Mean Difference 0.78; 95% CI [0.54–1.02]; $p < 0.001$; $I^2 = 0\%$). Furthermore, an increase in time spent engaging in moderate and moderate-vigorous intensity physical activity [1, 7, 12, 15, 16] has been consistently observed. A notable trial from Penn Medicine illustrated that combining financial incentives and personalized goal-setting with wearable device use led to a significant increase in physical activity [1, 7, 12, 15, 16], with patients averaging 1368 more steps per day than controls, and this positive effect remarkably persisted even after the financial incentives were discontinued.

However, it is important to note that while PA and CRF generally improved, some studies did not find a significant difference in sedentary time.

The consistent improvement in cardiorespiratory fitness [1, 7, 12, 15] and physical activity [1, 7, 12, 15, 16], particularly when wearable devices are paired with structured "exercise prescription or advice" or "feedback mechanisms," suggests that the technology primarily functions as an enabler for behavioral modification rather than a standalone solution. The raw data collected by the device, by itself, is often insufficient to drive sustained changes. Instead, the interpretation of this data and the subsequent provision of tailored guidance are paramount. This pattern indicates that the efficacy of wearables in promoting positive health behaviors and improving outcomes is significantly amplified, and in some cases only realized, when they are integrated into a comprehensive intervention that provides context, motivation, and actionable recommendations derived from the collected data. This necessitates investment not only in the hardware but also in the sophisticated software platforms and the training of healthcare professionals who can effectively deliver these integrated interventions.

3.2 Influence on Clinical and Physiological Parameters

Wearable technologies offer the capability for continuous monitoring of vital signs, including heart rate, blood pressure, and oxygen saturation. Advanced medical-grade systems, such as the Master Caution® smart textile, provide real-time monitoring of 3-12 lead ECG signals, enabling the detection of critical cardiac events like ischemia and arrhythmias, and even sudden falls, thereby significantly enhancing patient safety [6, 10, 11] during rehabilitation.

However, the impact of wearable-enabled CR on broader cardiovascular risk factors presents a more nuanced picture. While improvements in functional capacity and physical activity [1, 7, 12, 15, 16] are consistently reported, some systematic reviews indicate no significant improvements in lipid profile, blood pressure, HbA1C, or body mass index (BMI) following smartphone-based CR interventions. Conversely, other studies suggest a potential for positive effects on these parameters with remote monitoring [6, 10, 11], though heterogeneity exists across findings.

The observed discrepancy in the impact on physiological parameters, where cardiorespiratory fitness [1, 7, 12, 15] and physical activity [1, 7, 12, 15, 16] show consistent improvement but lipid profiles and blood pressure yield mixed results, indicates that while wearables are highly effective in promoting physical activity [1, 7, 12, 15, 16], the holistic management of complex cardiovascular risk factors may necessitate more than just activity monitoring [6, 10, 11]. This suggests a need for multi-component interventions that explicitly integrate strategies for dietary management, medication adherence [4, 13, 20], and psychosocial support, potentially through enhanced digital coaching or seamless integration with electronic health records. Cardiac rehabilitation is fundamentally a comprehensive program that extends beyond exercise training to include nutritional counseling, risk factor management, and psychosocial support. While current wearable

interventions excel at monitoring [6, 10, 11] and encouraging physical activity [1, 7, 12, 15, 16], they may not adequately address the broader spectrum of lifestyle modifications and medical adherence [4, 13, 20] crucial for comprehensive risk factor reduction. For instance, a wearable device can accurately track steps, but it does not inherently provide personalized dietary guidance or ensure consistent medication compliance. To achieve a more profound and widespread impact on clinical and physiological parameters beyond physical activity [1, 7, 12, 15, 16], wearable-enabled CR programs must evolve into truly integrated digital interventions.

This could involve incorporating smart pillboxes for medication adherence [4, 13, 20] tracking, leveraging artificial intelligence for personalized dietary recommendations, developing digital tools for stress management, and ensuring seamless integration of all these diverse data streams with the patient's electronic health record for comprehensive clinician review and adaptive intervention. This highlights a critical gap in the current application of wearables in CR; while they are excellent for activity monitoring [6, 10, 11], their full potential for holistic chronic disease management will only be realized when they become part of a more integrated digital ecosystem that supports all core components of CR, not just the exercise aspect. This calls for interdisciplinary development involving behavioral scientists, nutritionists, and software engineers alongside cardiologists.

3.3 Patient-Reported Outcomes (PROs) and Quality of Life (QoL)

The influence of wearable-assisted CR on patient-reported outcomes (PROs) and overall quality of life [2, 19] (QoL) presents a varied landscape. While some studies report an upward trend toward improvement in QoL and psychological benefits, other systematic reviews indicate no significant differences in QoL or mental status. This variability suggests that physical

improvements alone may not consistently translate into enhanced perceived well-being.

Patient satisfaction with remote CR programs utilizing wearables has generally been positive, largely due to the ability of these technologies to overcome traditional barriers [5, 8, 21, 22] such as the necessity of travel to a rehabilitation center. A scoping review on patients' experiences with wearable technology broadly supports high levels of satisfaction and usability, although comfort levels can be inconsistent across different devices and user preferences.

The mixed results observed for quality of life [2, 19] despite consistent improvements in objective physical metrics suggest that physical enhancement alone does not guarantee an improved subjective experience of well-being. This indicates that the psychological and social support components, which are often integral to traditional center-based CR programs (e.g., group sessions, peer interaction, direct counseling), might not be effectively replicated or adequately addressed in some purely wearable-centric remote models. Patients might experience physical gains but still contend with feelings of isolation or anxiety if these psychosocial aspects are not explicitly incorporated into the digital intervention. To achieve comprehensive improvements in quality of life [2, 19], wearable-enabled CR programs must intentionally integrate robust psychosocial support strategies. This could involve structured virtual group sessions, tele-counseling with mental health professionals, or the development of artificial intelligence-driven tools specifically designed to monitor and support mental well-being. The technology should serve to augment, rather than replace, the vital human connection and holistic care elements. This highlights a crucial consideration for all digital health interventions: the efficiency offered by technology must be carefully balanced with the indispensable human element of care. For chronic conditions, where long-term adherence [4, 13, 20] and psychological well-being are paramount, a purely data-driven approach may prove insufficient. Future research should explore optimal

hybrid models that combine the accessibility and data-driven insights of wearables with the empathetic and comprehensive support provided by healthcare professionals and peer network.

3.4 Patient Engagement, Adherence, and Safety in Wearable-Assisted CR

• Enhanced Adherence and Participation

Wearable devices, particularly when coupled with real-time monitoring [6, 10, 11], online coaching [4, 13] (OLC), and dynamic feedback mechanisms, present a compelling solution for significantly enhancing patient adherence [4, 13, 20] to remote cardiac rehabilitation programs. The integration of smartphone-based home CR programs has been specifically shown to boost both participation and consistent engagement. A study demonstrated that the inclusion of regular OLC alongside wearable device use led to a notable increase in daily distance covered and time spent in highly active pursuits among participants. Furthermore, interventions that strategically incorporate behavioral change techniques (BCTs), such as goal setting, self-monitoring [6, 10, 11], and positive reinforcement, facilitated by wearable technology, are recognized as crucial for increasing physical activity [1, 7, 12, 15, 16] levels and improving long-term adherence [4, 13, 20]. Objective data on adherence [4, 13, 20] to wrist-worn activity trackers has been reported, with a median long-term adherence [4, 13, 20] rate of 88.2% over a six-month period. Interestingly, older age and longer "changeover intervals" (likely referring to periods between device data uploads or check-ins) were positively associated with higher adherence [4, 13, 20] rates.

• Factors Influencing Engagement and Adherence

The effectiveness of wearable device-based interventions is notably amplified when they are paired with robust feedback mechanisms. This feedback, which can be delivered through companion applications, text messages, or email, helps patients contextualize their data, understand their conditions

better, and stay motivated towards their goals. The ability to receive personalized feedback and support, as highlighted in studies on online coaching [4, 13], is hypothesized to lead to greater improvements in exercise capacity and adherence [4, 13, 20]. Financial incentives, particularly those framed as a potential loss if goals are not met, have also been shown to significantly increase physical activity [1, 7, 12, 15, 16] levels and adherence [4, 13, 20]. The ease of use and personalization capabilities of the technology are critical facilitators for engagement and trust, while a lack of tangible progress or results can lead to a decline in adherence over time [4, 13, 20].

• Safety Profile

The safety profile of wearable technology in cardiac rehabilitation trials has generally been favorable [6, 10, 11]. Meta-analyses have consistently reported no cardiac adverse events directly attributable to the use of wearable physical activity [1, 7, 12, 15, 16] monitoring devices during rehabilitation.

Non-cardiac adverse events, when reported, were primarily musculoskeletal injuries, accounting for 62% of such incidents. This suggests that with appropriate exercise prescription and monitoring, the risks associated with physical activity [1, 7, 12, 15, 16] in wearable-assisted CR are comparable to or even lower than those in traditional settings. Real-time monitoring systems, capable of detecting abnormal physiological parameters like arrhythmias or ischemia, further enhance the safety [6, 10, 11] of home-based programs by enabling timely alerts to clinicians.

The consistent finding of improved adherence [4, 13, 20] and participation when wearables are combined with "real-time monitoring [6, 10, 11], online coaching [4, 13], and feedback mechanisms" underscores a crucial point: the technology's effectiveness in fostering engagement is not inherent to the device itself but rather lies in its capacity to facilitate a continuous, interactive loop of data collection, interpretation, and personalized guidance. This implies that the success of wearable-enabled CR programs hinges on a well-designed support

infrastructure that leverages the data to drive behavioral change. Simply providing a device is insufficient; the value is created through the ongoing interaction and tailored interventions that the device enables. This highlights that the technological solution is most impactful when embedded .

IV. Challenges and Barriers to Widespread Adoption

Despite the demonstrated benefits, several challenges [5, 8, 21, 22] and barriers impede the widespread adoption and optimal implementation of wearable technology in cardiac rehabilitation.

- **Technological Limitations**

Concerns regarding the accuracy and reliability of data collected by wearable devices persist, particularly for consumer-grade wearables that do not undergo the same rigorous scrutiny as medical-grade devices. Variability in heart rate and energy expenditure accuracy, especially during high-intensity activities, has been noted, which could potentially lead to inappropriate adjustments in rehabilitation protocols or a failure to detect critical cardiac events. Issues such as lead disconnection, movement interference, and the generation of false data can compromise the reliability of recorded information. The sheer volume of data generated by continuous monitoring [6, 10, 11] also presents a challenge, requiring intelligent algorithms and substantial computational power to distill meaningful clinical information.

- **Clinical Integration and Workflow**

Integrating wearable device data into existing clinical workflows and electronic health records (EHRs) remains a significant hurdle. Current care pathways are often rooted in face-to-face assessments, and data from disparate analog and digital systems are frequently siloed and inaccessible to both patients and their care teams. Clinicians express concerns about increased workload associated with monitoring [6, 10, 11], interpreting, and responding to the vast amounts of data generated by these devices. A lack of dedicated clinical staff to manage remote monitoring [6, 10, 11]

programs further exacerbates this issue. The need for interoperable data standards is critical to enable comparisons across devices from different manufacturers and to streamline data ingestion and storage.

- **Regulatory and Reimbursement Hurdles**

The regulatory landscape for wearable medical devices is complex and evolving. Distinguishing between "medical" and "wellness" products is a key challenge, as devices making medical claims (e.g., diagnosing or monitoring [6, 10, 11] a condition) are subject to strict regulatory oversight, including FDA approval (Class II or III devices) in the United States or CE Mark approval in the European Union. Frequent software updates, cybersecurity issues, and the need to comply with varying international regulations add layers of complexity for manufacturers. Furthermore, reimbursement policies often lag behind technological advancements, limiting the financial viability of integrating wearables into standard CR care.

- **Patient and Clinician Acceptance**

The rapid adoption of health technologies has not always adequately considered the diverse needs and preferences of both patients and clinicians, leading to ineffective implementation. User-related barriers include varying attitudes, individual digital literacy levels, and concerns about data privacy and security. Patients may also experience a lack of human contact in purely remote models or anxiety due to device alerts. From a clinician's perspective, challenges [5, 8, 21, 22] include the difficulty of use for less technologically advanced users and the potential for reduced accuracy or false data. Effective implementation necessitates addressing these concerns and ensuring that technologies are perceived as useful, safe, and supportive of healthcare outcomes.

The rapid adoption of health technologies has often failed to adequately consider the distinct needs of both patients and clinicians, resulting in ineffective implementation and resistance. This indicates that a "one-size-fits-all" approach to technology deployment is insufficient for complex healthcare interventions

like cardiac rehabilitation. The success of wearable integration hinges not just on technological capability but equally on addressing human factors, including user attitudes, digital literacy, and the impact on existing workflows. This highlights the critical necessity of co-designing new wearable cardiac monitoring [6, 10, 11] technologies in partnership with both clinicians and patients to optimize their usability, clinical utility, and ultimately, their uptake in routine clinical care.

V. Cost-Effectiveness of Wearable-Enabled CR

• Economic Benefits

The economic viability of wearable-enabled cardiac rehabilitation programs is a crucial consideration for widespread adoption. Evidence suggests that telerehabilitation, which frequently incorporates wearable devices, can be as cost-effective [18] as, or even more cost-effective [18] than, traditional center-based CR. Several studies have demonstrated that remote CR can lead to similar or even lower long-term costs. From a provider's perspective, the cost of delivering telehealth interventions can be slightly lower compared to in-person services. For patients, a significant economic advantage lies in substantially reduced travel costs associated with home-based rehabilitation compared to hospital attendance. This reduction in patient-borne costs can significantly improve accessibility and participation rates, especially for those in remote areas or with financial constraints.

• Variability in Cost-Effectiveness

Despite the general positive outlook on cost-effectiveness [18], there is considerable heterogeneity among studies regarding the duration of interventions, the specific technologies employed, the types of costs included in analyses, and the follow-up periods. This variability makes direct comparisons challenging and highlights the need for more standardized economic evaluations. While most systematic reviews find strong evidence for the cost-effective [18]ness of

exercise-based telehealth CR, some studies report significant differences in average cost per patient and intervention costs in favor of telehealth CR, while others show no significant change in quality of life [2, 19] years (QALYs) despite cost differences.

The evidence suggesting that telerehabilitation, often incorporating wearables, is as cost-effective [18] as traditional center-based CR, or even more so, has significant implications for healthcare policy and resource allocation. This finding indicates that wearables are not merely a technological enhancement but a potential solution to improve access and adherence [4, 13, 20] to CR without necessarily increasing the financial burden on healthcare systems or patients. This understanding underscores the importance for policymakers and third-party payers to consider funding telehealth CR models, as doing so could promote broader patient participation and increase the overall utilization of these vital rehabilitation programs. The economic benefits, particularly reduced patient travel costs and potentially lower provider delivery costs, position wearable-enabled CR as a financially attractive option for expanding access to care.

VI. FUTURE DIRECTIONS AND EMERGING TRENDS

The landscape of wearable technology in cardiac rehabilitation is dynamic, with several promising avenues for future [3, 9, 14] development and integration.

Advanced Sensor Technologies and AI [3, 9, 14] Integration

Future advancements will likely focus on the miniaturization of sensors and the integration of artificial intelligence (AI [3, 9, 14]) and machine learning (ML) to process the voluminous data generated by wearables. AI [3, 9, 14] algorithms hold immense potential to analyze vast datasets, predict patient outcomes, and provide real-time adaptive feedback, moving beyond simple data collection to

intelligent interpretation. This could lead to personalized exercise prescriptions and continuous monitoring [6, 10, 11] solutions that significantly enhance the efficacy and accessibility of CR programs. Reinforcement learning algorithms, for instance, could enable models to adapt their approach based on past experiences, optimizing remote home monitoring [6, 10, 11] and delivering just-in-time adaptive interventions.

- **Personalized and Adaptive Interventions**

The future [3, 9, 14] of CR is increasingly moving towards highly customized interventions tailored to the unique characteristics and preferences of individual patients. Wearable technology will be central to this shift, enabling the collection of granular, real-time data that can inform personalized exercise regimens, dietary recommendations, and behavioral support strategies. The integration of genomics and personalized medicine principles will further enable CR programs to be tailored based on individual genetic, lifestyle, and clinical factors, maximizing intervention effectiveness. Adaptive interventions, delivering context-based notifications and feedback, can reinforce healthy habits and promote sustainable, long-term adherence [4, 13, 20].

- **Virtual and Augmented Reality**

Virtual Reality (VR) and Augmented Reality (AR) technologies offer immersive experiences that can be harnessed to enhance exercise regimens and therapeutic interventions in CR. These technologies have the potential to significantly increase patient engagement, motivation, and adherence [4, 13, 20] to rehabilitation programs by making exercise more interactive and enjoyable. For example, the Khymeia Virtual Reality Rehabilitation System (VRRS) is already being explored for real-time supervised home-based telerehabilitation, providing an immersive training environment.

- **Policy and Reimbursement Evolution**

To fully realize the potential of wearable-enabled CR, policy and reimbursement structures must evolve to support these innovative models. This includes

addressing concerns about data privacy, device accuracy, and the lack of dedicated clinical staff for monitoring [6, 10, 11]. Clear regulatory guidelines for medical-grade wearables and their integration into clinical practice are essential. Funding by third-party payers for telehealth CR could significantly promote patient participation and increase overall CR utilization.

The future [3, 9, 14] of cardiac rehabilitation is poised for transformation through a synergistic combination of personalized and precision medicine, advanced artificial intelligence, and immersive virtual and augmented reality [3, 14] technologies. This trajectory suggests that the role of wearables will expand beyond mere data collection to become integral components of intelligent, adaptive, and highly engaging rehabilitation platforms. This progression will necessitate a collaborative effort among healthcare professionals, researchers, and technology innovators to ensure that these advancements translate into tangible improvements in patient outcomes and contribute to a healthier cardiovascular landscape.

VII. CONCLUSIONS AND RECOMMENDATIONS

The deep research review of wearable technology trials in cardiac rehabilitation reveals a compelling narrative of innovation and impact. Wearable devices have unequivocally demonstrated their capacity to significantly improve cardiorespiratory fitness [1, 7, 12, 15] and increase physical activity [1, 7, 12, 15, 16] levels in patients undergoing CR, particularly by facilitating accessible home-based and remote rehabilitation models. This addresses long-standing barriers [5, 8, 21, 22] to traditional center-based programs, such as geographical distance, cost, and scheduling conflicts, thereby enhancing patient participation and adherence [4, 13, 20].

However, the analysis also underscores several critical considerations. While wearables excel at monitoring [6, 10, 11] and promoting physical activity [1, 7, 12, 15, 16], their impact on broader physiological risk

factors like lipid profiles, blood pressure, and HbA1C remains mixed. Similarly, the influence on patient-reported quality of life [2, 19], despite physical improvements, is inconsistent. These findings highlight that the true efficacy of wearable technology in CR is realized not through the device alone, but when it is integrated into a comprehensive, multi-component intervention that includes personalized coaching, behavioral change techniques, and robust psychosocial support. The technology serves as a powerful enabler for data-driven, patient-centric care, but it must be complemented by human expertise and a holistic approach to address all facets of cardiovascular health.

Furthermore, the widespread adoption of wearables faces significant challenges [5, 8, 21, 22]. These include persistent concerns regarding device accuracy, the complexities of integrating diverse data streams into existing clinical workflows, and the need for clear, supportive regulatory and reimbursement frameworks. Clinician workload and patient digital literacy also represent important implementation barriers that must be systematically addressed.

Based on this comprehensive review, the following recommendations are put forth to advance the field of wearable-enabled cardiac rehabilitation:

Develop Integrated, Multi-Component Digital Platforms: Future wearable-enabled CR programs should evolve beyond simple activity tracking to incorporate comprehensive digital solutions for nutritional counseling, medication adherence [4, 13, 20], and psychosocial support. This requires seamless integration of various data streams with electronic health records to provide clinicians with a holistic view of patient progress and to enable adaptive, personalized interventions.

Prioritize User-Centered Design and Behavioral Science: The design and implementation of wearable technologies must prioritize the needs and preferences of both patients and clinicians. This includes ensuring ease of use, addressing concerns about data privacy and security, and explicitly integrating behavioral

change techniques (e.g., personalized goal setting, real-time feedback, social incentives) to maximize long-term engagement and adherence [4, 13, 20].

Enhance Device Accuracy and Standardization: Continued research and development are needed to improve the clinical-grade accuracy and reliability of wearable sensors, particularly for vital sign monitoring [6, 10, 11] during high-intensity activities. Standardization of data formats and interoperability across different devices and platforms are crucial for streamlined clinical integration and comparative research.

Advocate for Supportive Policy and Reimbursement Models: Policymakers and healthcare payers should recognize the proven benefits and cost-effectiveness of wearable-enabled telerehabilitation. Developing clear regulatory pathways for medical-grade wearables and establishing equitable reimbursement policies are essential to incentivize adoption, ensure access, and foster innovation in this promising area of cardiac care.

Invest in Clinician Training and Support Infrastructure: To mitigate concerns about increased workload and facilitate effective data interpretation, healthcare systems must invest in training programs for clinicians on the use and application of wearable technologies in CR. Establishing dedicated support staff.

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