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REVIEW

Wearable technologies to predict and prevent and heart failure hospitalizations: a systematic review

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Heart failure (HF) is a global pandemic and accounts for substantial morbidity and healthcare expenditure, largely due to frequent hospitalizations. While traditionally HF patients are followed with intermittent clinical assessments, wearable technologies offer continuous, real-time monitoring, potentially enabling earlier detection and tailored interventions to prevent hospitalization. This systematic review evaluates the impact of non-invasive wearable devices on hospitalizations in HF. Following PRISMA guidelines, literature searches were conducted in PubMed and Scopus using keywords related to HF, hospitalization, and wearable technology on 1 March 2024, and re-run on 3 December 2024. Studies assessing the link between wearable devices and HF-related hospitalization rates were included. Data extraction covered population characteristics, study design, type of device, and hospitalization rates. Risk of bias was assessed using ROBINS-I and ROB-2 tools. Meta-analysis was attempted but not performed due to significant heterogeneity (I^2>90%). From 2247 records, eight studies involving 1823 patients were finally analysed. Devices included ReDS, VitalPatch, ZOLL LifeVest, and ZOLL-HFMS, with follow-up ranging from 30 to 646 days. Wearable devices allowed prediction of HF hospitalization within 6.5–32 days in advance. Wearable-guided therapy compared to traditional assessment showed an 89% relative reduction at 30 days in a single-blind randomized-controlled trial, and 78% and 87% reductions in 30-day and 90-day hospitalization rates in observational studies. Although these data highlight the potential of wearable devices in HF management, future research should test predefined wearable-guided treatment algorithms on strong endpoints and address cost-effectiveness and data security in large randomized-controlled trials with longer follow-up.

Registration This review was registered with PROSPERO (CRD42024519282).

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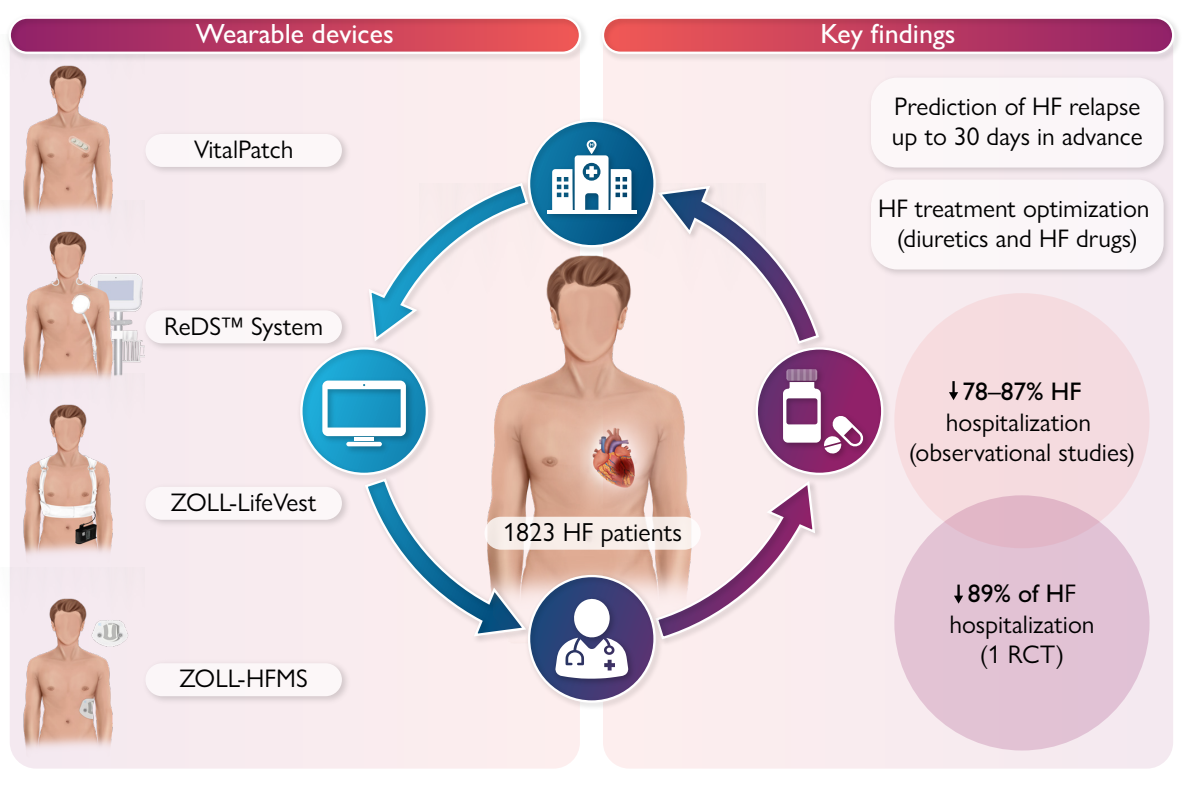
Graphical Abstract



Keywords Wearable • Sensor • TeleMedicine • Hospitalization Rate • Readmission • Hearth Failure • Systematic Review

Introduction

Wearable devices, such as smartwatches, fitness trackers, and biosensors, monitor various health parameters including vital signs, body position, physical activity and sleep, as well as different biomarkers in real time.[1–5] While initially popular for fitness tracking in healthy individuals, these devices have been recently tested for monitoring patients.[6] Indeed, their ability to collect long-term continuous data may enable the identification of trends and specific patterns in time series, not apparent from single measurements or shorter recordings.[7]

Heart failure (HF) is well-suited for wearable technologies due to its chronic nature and the presence of detectable physiological changes, such as fluid overload, altered heart, and respiratory rates, and reduced daily activity that often precede decompensation by days or weeks. This offers a window for early interventions. Traditional follow-up relies on infrequent visits, which may delay necessary treatment adjustments. In contrast, wearables may provide real-time, non-invasive monitoring, allowing clinicians to identify subtle changes and respond proactively in advance. This dynamic tracking matches the fluctuating course of HF, making wearable monitoring particularly promising.[8] Despite advancements in its management, HF remains a significant public health issue, with hospitalization for acute decompensation representing 1–2% of all hospital admissions in Western countries,[9] especially in individuals aged 65 years and over.[10] Approximately 23% of HF patients are readmitted within 30 days, and 21% within 90 days post-discharge.[11]

In particular, continuous monitoring via wearable technologies can help clinicians to identify patients at high-risk of decompensation or readmission, enabling timely and targeted interventions. This may reduce HF hospitalizations by facilitating early treatment optimization, either through urgent in-person visits, televisits, or remote management via dedicated digital platforms. This was clearly highlighted by studies on implantable devices, such as implantable cardioverter defibrillators (ICDs) using specific algorithms such as the HeartInsight[12] and HeartLogic,[13] or with the cardioMEMS, which enables scheduled, intermittent monitoring of pulmonary artery pressures when patients position themselves on a dedicated receiving unit.[14] In a recent systematic review and meta-analysis on different invasive haemodynamic monitoring systems, a 25% reduction in HF hospitalizations was found.[15] However, the potential impact of wearable devices, defined as any device that has to be worn either continuously or not to acquire data on the patients health, on HF hospitalization has not yet been systematically studied.

Given this gap of evidence, this systematic review aims to analyse the use of wearable devices, in HF patients and their capability to predict or prevent HF hospitalization.

Methods

This systematic review was reported following the Preferred Reporting Items for Systematic Reviews (PRISMA) approach.[16] The initial search was implemented on 01 March 2024, and re-run on 3 December 2024. The protocol was registered on PROSPERO and can be found with reference: CRD42024519282, accessible at: https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=519282. The search query consisted of terms considered pertinent by the authors, as follows.

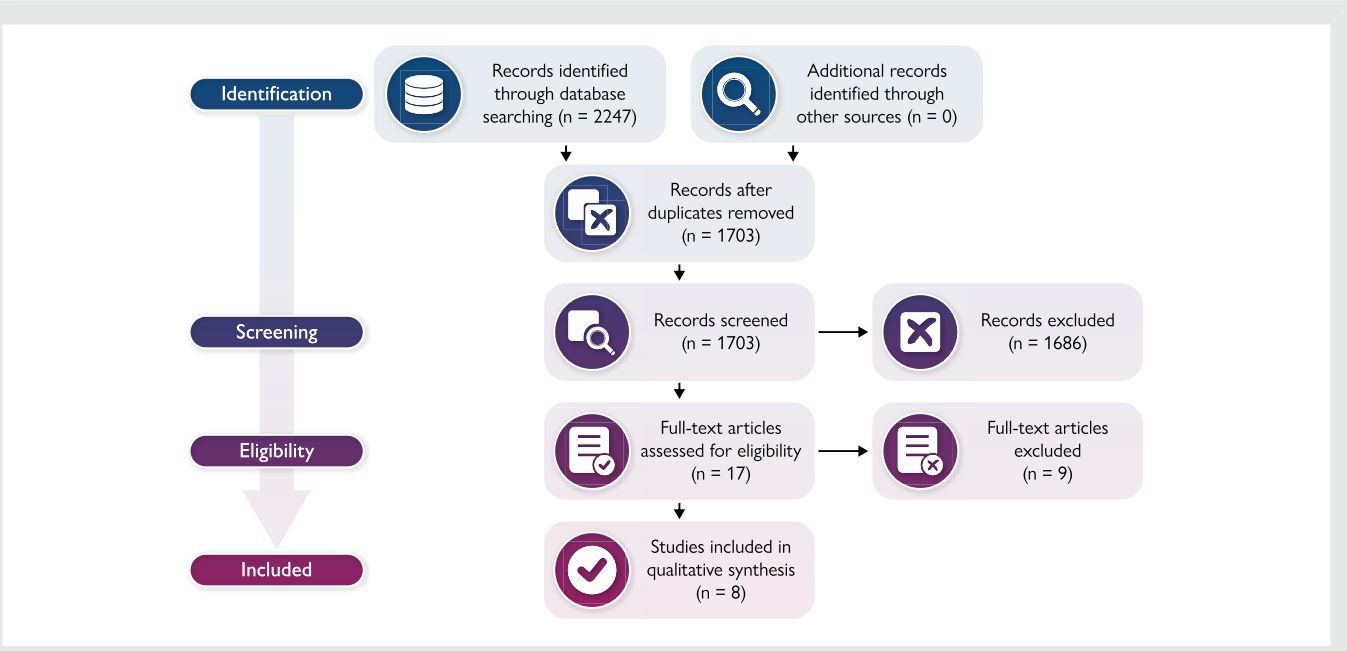


Figure 1 PRISMA flowchart—a flowchart showing the selection process of studies for the systematic review, detailing the number of records identified, screened, and included.

Search strategy

The search included peer-reviewed publications on PubMed and Scopus using the search string in Supplementary material online, *Material S-1*.

Studies included had to present original data or results referring to our aim and had to be written in English. Studies were excluded if they did not focus on the assessment of the hospitalization rates in patients with HF using wearable sensors. Systematic reviews, meta-analysis, opinion papers, and case reports, were also excluded.

Data extraction

The search string was launched first on 01 March 2024, and re-run on 11 October 2024. Data were extracted by two reviewers (F.N. and A.C.). Disagreements on extracted data were resolved through discussions between the two reviewers (F.N. and A.C.).

Descriptive variables extracted from each article were: first author, publication year, first author's affiliation country, study design, number of cases, age and sex of the population, HF aetiology (ischaemic, non-ischaemic), HF stage (A, B, C, D), recent acute decompensation (y/n), New York Heart Association (NYHA) symptoms, comorbidities, type of wearable technology, hospitalization rate for either wearable technology or traditional strategy, and difference in hospitalization rates between the two arms, if present, time from wearable notification and HF hospitalization. For any result expressed narratively, not displaying in rates the difference in hospitalization, a note column was added.

Quality assessment of selected studies

The quality assessment was performed according to the type of study analysed. All records were independently assessed by two reviewers (F.N. and A.C.), and any conflicts in evaluations were resolved through discussion. The interventional studies[17–22] were assessed with the ROBINS-I tool, whereas the two controlled studies[23,24] were evaluated using the ROB-2 tool.

Results

Records distribution

From 2247 total records (810 PubMed, 1437 Scopus), systematic screening yielded eight eligible studies for inclusion, as shown in *Figure 1*. The process involved removing duplicates and non-relevant records through title screening (2183 excluded), abstract review (48 excluded), and full-text assessment (9 excluded).

All included studies are reported in *Table 1*. One article was from Germany (12.5%),[17] one from Israel (12.5%),[18] four (50%)[19–21,25] from the USA, one from Japan (12.5%)[22] and one from Spain (12.5%).[23] Four studies were categorized as cohort studies,[17,19–21] two as pre–post studies,[18,25] and they were all evaluated to be at low risk of bias using the ROBIN-I tool. Two studies[22,23] were classified as either a randomized control trial (RCT)[23] or concurrent-control trial[25] and were evaluated at low and moderate risk of bias respectively, using the ROB-2 tool. Quality appraisal is shown in Supplementary material online, *Material S-2*.

In this study, a proportion meta-analysis was attempted, nonetheless, results are not presented, as heterogeneity was found to be too high ($I^2 > 90\%$).

Studies synthesis

The eight included studies accounted for a total of 1823 patients. Patient characteristics, HF aetiology, comorbidities, and baseline treatments of the different studies are reported in *Table 2*. While some studies[19–21] also included hospitalizations for various causes, only HF-related readmissions were considered in the analysis, in accordance with the research protocol.

All included studies considered discharge from a HF hospitalization as an inclusion criterion. Exclusion criteria varied across studies, but often included individual morphometric characteristics, such as body mass index values lower <15–22 or >30–39 kg/m^2, or height <140–155 cm or >190 cm,[18,22,23] and the impossibility to wear the device due to skin damages or allergies.[20,21] Also participants with specific medical conditions that could interfere with accurate measurements or treatment compliance, such as severe scoliosis,[22] active pulmonary disorders,[18,19] focal lung lesions,[18] and recent major cardiac events[17,18,23] were excluded. Cognitive impairments,[20,21] including documented history of dementia or delirium, were also listed as exclusion criteria. Nomoto *et al.*[22] also considered the inability to maintain a seated position or tolerate the measurement device over a short time period. Additionally, some studies excluded patients with implanted

Table 1 Summary of included studies—a summary table detailing the characteristics of the included studies, including author, year, technology used, number of patients, and results

Title	First author	Technology used	Continuous monitoring	Number of patients	Control group	Results
Evaluation of remote dielectric sensing (ReDS) technology-guided therapy for decreasing heart failure re-hospitalizations[18]	O. Amir	ReDS™ Wearable System	No	50	No	Hospitalization rate at 90 days: 16% when using the wearable system vs. 120% in the pre-intervention period
Early use of remote dielectric sensing after hospitalization to reduce heart failure readmissions[19]	A. Lala	ReDS™ Wearable System	No	220	Yes n. 140	Hospitalization rate at 30 days: 2.6% in the intervention group vs. 11.80% in the control group
Influence of decompensated heart failure on cardiac acoustic biomarkers: impact on early readmissions[17]	J.W. Erath	ZOLL-LifeVest wearable cardioverter-defibrillator (WCD)	Yes	671	No	Event rate at 90 days: 12% when using the WCD vs. 7–18% reported in the literature
Continuous wearable monitoring analytics predict heart failure hospitalization: the LINK-HF multicentre study[21]	J. Stehlik	Wearable biosensors 'VitalPatch'	Yes	100	No	Hospitalization rate at 90 days: 24% when using the wearable system vs. 30% reported in the literature
Continuous remote patient monitoring: evaluation of the heart failure cascade soft launch[20]	W.N. Chi	Wearable biosensors 'VitalPatch'	Yes	5	No	Hospitalization rate at 30 days: 20% when using the wearable system vs. 25% reported in the literature
Remote dielectric sensing before and after discharge in patients with ADHF: the ReDS-SAFE HF trial[23]	J. Alvarez-Garcia	ReDS™ Wearable System	No	100	Yes n. 50	Hospitalization rate at 30 days: 2% in the intervention group vs. 18% in the control group
Clinical implications of remote dielectric sensing-guided management[22]	Y. Nomoto	ReDS™ Wearable System	No	183	Yes n. 138	Hospitalization rate at 646 days: 5% in the intervention group vs. 27% in the control group
Impact of a novel wearable sensor on heart failure rehospitalization: an open-label concurrent-control clinical trial[25]	J. P. Boehmer	ZOLL-LifeVest wearable cardioverter-defibrillator (WCD)	Yes	249	Yes n. 245	Hospitalization rate at 90 days: 13% in the intervention group vs. 20% in the control group

Table 2 Characteristics of included studies—a comprehensive breakdown of patient demographics, heart failure aetiology, ejection fraction, New York Heart Association classification, baseline therapies, and comorbidities

Author	Alvarez-Garcia *et al.*	Amir *et al.*	Chi *et al.*	Erath *et al.*	Lala *et al.*	Nomoto *et al.*	Stehlik *et al.*	Boehmer *et al.*
Number of cases	50 (total: 100)	50	5	671	80 (total: 220)	45 (total: 183)	100	249 (total: 494)
Age	67 ± 14	73.8 ± 10.3	60–89	61 ± 13	65.2 ± 13.2	80 (77–84)	68.4 ± 10.2	≤65 years: controls: 47.3% cases: 39.8% 65 years: controls: 52.7% cases: 60.2%
Sex	70% M 30% F	62% M 38% F	20% M 80% F	77% M 23% F	66.3% M 33.7% F	58% M 42% F	98% M 2% F	42.2% F 57.8% M
NYHA symptoms	III and IV	II: 10% III: 74% IV: 16%	III: 100%	I: 8% II: 57% III: 26% IV: 2% Unknown: 7%	II: 25.7% III: 67.6% IV: 6.8%	N/A	II: 25% III: 55% IV: 20%	I/II: 17.3% III: 36.1% IV: 17.3% NA: 29.3%
Ejection fraction	HFrEF: 57% HFmrEF: 12% HFpEF: 31%	HFmrEF/HFpEF (HF > 40%): 40% HFrEF: 60%	HFrEF: 40% HFpEF: 60%	HFrEF: 100%	HFrEF: 66.2%	N/A	HFrEF: 74% HFpEF: 26%	HFrEF: 42.2% HFmrHF/HFpEF: 54.6% NA: 3.2%
HF state	Acute: 25% Chronic: 76%	Chronic: 100%	*De novo*: 20% Chronic: 80%	N/A	N/A	*De novo*: 39% Chronic: 61%	Chronic: 100%	Chronic: 100%
Baseline therapies	Loop diuretic agents 92% Dose of furosemide, mg/day 156 ± 23 Thiazides 8% Loop diuretic agent + thiazides 8% RAAS inhibitors 60% β-blockers 88% MRAs 38% SGLT2 inhibitor 44%	ARB/ARNI: 40% β-blockers: 43% Thiazide: 5% Loop diuretics: 46% Statins: 42% MRAs: 13%	Pacemaker 20%	β-blockers: 93.3% ACEI/ARB/ARNI: 83% Diuretics: 87.7%	ARNIs: 15.9% ACEI/ARB: 49.6% MRAs: 41.8% β-blockers: 84.1% Calcium channel blockers: 7.7% Loop diuretics: 86.4% Thiazides: 5.5% Inotropes: 6.4%	β-blockers: 4.44% MRAs: 2.22% SGLT2 inhibitor: 4.44% Diuretics: 100%	β-blockers: 80% ACEI/ARB/ARNI: 59% Loop diuretics: 92% Aldosterone antagonist: 24% Anticoagulants: 47% Nitrate: 36% Pacemaker: 15% CRT: 8% ICD: 25%	β-blockers: 81.1% ACEI: 19.3% ARB: 46.2% ARNI: 29.3% MRA: 25.3% SGLT2 inhibitor: 13.7% Diuretic agent: 89.2%

Continued

Table 2 *Continued*

Author	Alvarez-Garcia *et al.*	Amir *et al.*	Chi *et al.*	Erath *et al.*	Lala *et al.*	Nomoto *et al.*	Stehlik *et al.*	Boehmer *et al.*
Comorbidities	Hypertension	CAD	AF	Hypertension	Hypertension	Hypertension	CAD	CKD
	Diabetes	Diabetes	CAD	Diabetes	AF	Dyslipidaemia	Diabetes	COPD
	COPD		COPD	COPD	Diabetes	Diabetes	AF	Diabetes
	CKD		Diabetes	Sleep apnoea	COPD	AF	Anaemia	
			CKD	CKD	CKD	CAD	COPD	
			Cancer	Sudden cardiac arrest	CAD	Valvular disease		
			Anxiety			History of stroke		
			Hypertension	Myocardial infarction				

AF, atrial fibrillation; ARB, angiotensin receptor blocker; ARNI, angiotensin receptor-neprilysin inhibitor; CAD, coronary artery disease; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; CRT, cardiac resynchronization therapy; HFmrEF, heart failure with mid-range ejection fraction; HFpEF, heart failure with preserved ejection fraction; HFrEF, heart failure with reduced ejection fraction; MRAs, mineralocorticoid receptor antagonist; RAAS, renin-angiotensin-aldosterone system; SGLT2, sodium-glucose cotransporter 2.

cardiac devices,[17,23] those who received[23] or were waiting for[17] a heart transplant, or individuals with a life expectancy of <1 year.[17,23]

Most patients were classified within NYHA Classes II and III, and HFrEF was the predominant HF phenotype across studies. Acute on chronic HF cases were more frequent, although two studies[20,23] reported a subset with new-onset HF. Baseline treatments were similar across studies, with high usage of β-blockers, angiotensin-converting enzyme inhibitors/angiotensin receptor blockers/angiotensin receptor-neprilysin inhibitors, and loop diuretics, alongside a smaller portion using pacing devices including cardiac resynchronization therapy (CRT). The most common comorbidities were hypertension, atrial fibrillation (AF), diabetes, and coronary heart disease. Two studies[17,25] reported data about ischaemic and non-ischaemic HF aetiology, though aetiology and American Heart Association classification data were generally unreported.

The included studies in the analysis used various wearable sensor technologies, represented in *Table 3*.

Impact of wearable technologies on heart failure hospitalization

Among the included studies, one was a randomized-controlled trial,[23] three included control groups: one used a concurrent-control group,[25] one used pre-enrolment historical data as control,[18] and one employed a blinded comparison where clinicians could not access patients' wearable data.[22] Two studies compared their results with literature-reported averages,[17,20] and one study was observational with no control group.[21] All the included studies are summarized in *Table 1*.

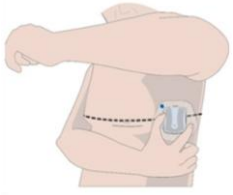
In a single-blind randomized-controlled trial, Alvarez-Garcia *et al.*[23] evaluated ReDS-guided therapy vs. routine management in 101 patients with acute decompensated HF. The ReDS group showed significantly better outcomes at 30 days post-discharge compared to the standard care, with a 90% lower relative risk of a composite endpoint including unplanned acute decompensated HF visits, HF hospitalizations, or death [2% vs. 20%, HR: 0.094, 95% confidence interval (CI): 0.012–0.731, $P = 0.003$]. This was largely driven by HF readmissions, which were reduced by 89% (2% vs. 18%, $P = 0.016$).

Boehmer *et al.*[25] in their trial evaluated the Zoll HFMS system, a novel wearable radiofrequency sensor, in 249 patients. While this device is primarily marketed as a wearable defibrillator for sudden cardiac death prevention, Boehmer *et al.*[25] specifically utilized its continuous monitoring capabilities to detect early signs of HF decompensation, making it relevant to our review's focus on prediction of HF hospitalization. The study compared standard care with blinded device data vs. treatment guided by sensor data. In the intention to treat analysis, intervention arm showed a 38% relative risk reduction in HF readmissions at 90 days post-discharge (13% vs. 20%, HR: 0.62, CI unreported, $P = 0.03$). Furthermore, total hospitalization days were reduced by 28% (from 392 to 281 days), and quality of life was improved in the intervention group, as expressed by a 12-point increase KCCQ-12 questionnaire.

Lala *et al.*'s study[19] retrospectively analysed 220 patients discharged after hospital admission for HF, and evaluated 30-day readmission rates: 80 patients used the ReDS non-invasive monitoring technology in the intervention group to guide diuretic treatment according to a prespecified algorithm, and 140 patients received standard therapy as a control group. The intervention group showed a 78% lower 30-day hospitalization rate compared with the control group (2.6% vs. 11.8%, HR: 0.21 CI: 0.05–0.89; $P = 0.04$).

Nomoto *et al.*[22] evaluated the impact of ReDS-guided management in 183 patients hospitalized for cardiovascular diseases, comparing outcomes between two groups: a blind period group, where ReDS values were collected but not revealed to clinicians (standard care was followed without ReDS guidance), and an open period group, where ReDS measurements were used to guide treatment, particularly in adjusting diuretic doses. During the median follow-up of 646 days,

Table 3 Outline of wearable devices used—an outline of wearable devices, including the type of technology employed and variables measured

Wearable device	Technology used	Parameters measured or derived
VitalPatch  Credits to VitalConnect, via Diagnostic and Interventional Cardiology (www.dicardiology.com)	The VitalPatch is designed as a single-use, adhesive patch that incorporates advanced biosensor technology for continuous vital sign monitoring.[20,21] The device integrates sophisticated ECG sensors, accelerometers, and impedance measuring components, utilizing Bluetooth technology for seamless data transmission to a secure monitoring platform. The system includes real-time alert capabilities that notify clinicians when abnormal patterns are detected.	ECG waveform, heart rate, heart rate variability, arrhythmia burden, respiratory rate, body posture, activity levels, skin temperature, gross activity assessments, walking patterns, sleep monitoring, and body tilt measurements.[20,21]
ReDS™ Wearable System  Credits to Sensible Medical Innovations, Inc. (https://sensible-medical.com/solution/)	The ReDS Wearable System employs advanced electromagnetic signal technology in a vest-like format.[18,19,23,25] The system utilizes specialized sensors that emit and receive electromagnetic signals to assess fluid content in the thoracic cavity. It features rapid processing capabilities, delivering results within 90 s, and includes a connected app interface that provides real-time notifications to healthcare providers when fluid levels exceed predetermined thresholds.	Intrathoracic fluid content.[18,19,23,25]
ZOLL-LifeVest wearable cardioverter-defibrillator (WCD)  Credits to ZOLL Medical Corporation (www.lifevest.zoll.com)	The ZOLL LifeVest[23] is a wearable cardioverter-defibrillator that monitors heart rhythm and delivers shocks for life-threatening arrhythmias. It also continuously monitors CABs, which detect alterations in heart sounds and vibrations associated with variations in ventricular filling pressures. The device utilizes an algorithm that analyses acoustic signals to identify patterns indicative of fluid accumulation and early signs of HF decompensation.	Surface ECG, cardiohaemic vibrations, electromechanical activation time (EMAT), S3 strength.
ZOLL-HFMS (Heart Failure Monitoring System)  Credits to ZOLL Medical Corporation (https://cardiac.zoll.com/medical-professionals/heart-failure-management-system)	The system uses radar waves from a chest-worn sensor to detect changes in thoracic fluid levels by analysing signal delays and strength. Its high sensitivity to tissue hydration enables early detection of interstitial oedema, signalling heart failure decompensation days before symptoms arise.[22]	Thoracic fluid index, heart rate, respiration rate, activity levels, posture, heart rhythm via ECG.[22]

CABs, cardiac acoustic biomarkers; ECG, electrocardiogram; EMAT, electromechanical activation time; ReDS, remote dielectric sensing; WCD, wearable cardioverter-defibrillator.

patients in the open period group had a 82% lower cumulative incidence of the primary outcome (all-cause death or HF admission) compared with the blind period group (5% vs. 27%, $P = 0.018$), mainly driven by reduced HF hospitalization.

Amir *et al.*[18] followed 50 acute decompensated HF patients using ReDS technology for 90 days post-discharge. ReDS alerts prompted diuretic dose changes (89% increases and 8% decreases) and neurohormonal therapy adjustments (3%). During ReDS-guided management,

90-day hospitalization rates decreased by 87% compared to pre-ReDS periods (HR 0.07, 95% CI 0.01–0.54, $P = 0.01$) and 79% vs. post-ReDS periods (HR 0.11, 95% CI 0.014–0.88), respectively.

Erath *et al.*'s was the largest study,[17] involving 671 patients with decompensated HF (left ventricular ejection fraction <35%), followed-up after hospital discharge with the ZOLL-LifeVest for 90 days. The population showed a 12% hospitalization rate at 90 days, in line with the event rate of 7–18% reported in the literature in similar populations. The algorithm detected HF future events with a median of 32 days in advance (IQR = 11–45). Notably, in this study no variation in HF management was planned, since the study aim was simply to test the predictive power of the algorithm (sensitivity of 69%, specificity of 60%, positive predictive value 19%, and a negative predictive value of 94%).

Stehlik *et al.*[21] performed a study involving 100 patients, using the VitalPatch sensor and a machine learning analysis (similarity-based modelling). Their results showed a 90-day hospitalization rate of 24%. The platform used was able to detect precursors of readmission for HF 6.5 (4.2–13.7) days before exacerbation (76–88% sensitivity and 85% specificity). Stehlik *et al.*[21] reported compliance issues in 13 out of 100 patients with the VitalPatch device.

Chi *et al.*[20] conducted a study with five patients using the VitalPatch sensor and Multivariate Change Index. They reported a 30-day readmission rate of 20%, compared to a 25% average rate they found in literature.[23] The study was simply a pilot used to modify and fine-tune the workflow process and study protocol. Chi *et al.* also reported compliance issues in one out of five patients with the VitalPatch device.

Discussion

Emerging evidence, as collected and summarized in the current review, indicates that wearable technologies offer substantial potential for predicting and preventing HF deterioration and reducing hospitalization rates. By continuously monitoring key physiological parameters, such as heart rate, respiratory rate, physical activity, and fluid status, these wearables could detect early signs of worsening HF. This seems to enable timely interventions and personalized care adjustments, allowing healthcare providers to address potential issues before HF patients escalate into acute events.

Continuous monitoring has become fundamental to improve HF outcomes.[24] Implantable devices, like the CardioMEMS device, have shown strong predictive capabilities for HF decompensation,[24] while multisensor systems such as HeartLogic™ have shown to enable timely interventions.[26] Meta-analyses have confirmed these benefits. Iaconelli *et al.*[15] reported a 25% reduction in HF hospitalizations with invasive monitoring vs. standard care, while Lindenfeld *et al.*[27] found a 36% decrease in HF hospitalizations and 25% reduction in overall mortality using invasive devices. These benefits matched those obtained by implementing newer pharmacological interventions like sacubitril-valsartan[28] and sodium-glucose cotransporter-2 inhibitors,[29,30] or those seen with CRT.[31] Very recently, Scholte *et al.*[32] found that patients with advanced HF benefited more from invasive monitoring systems, while stable patients achieved good outcomes using simpler non-invasive approaches. However, even in advanced stages, wearable devices may allow earlier detection of decompensations, leading to less severe admissions and shorter hospital stays, ultimately reducing costs and resource use.

Implantable devices have limitations: not all patients meet criteria, some face surgical risks or infections,[33] and high costs can be a barrier. Simple asynchronous monitoring of vital parameters during follow-up focuses on single time-point assessments rather than temporal trends. In this respect, the HHH study,[34] a multi-country RCT, compared standard care with three asynchronous monitoring strategies: monthly calls, weekly vital sign transmission, and monthly 24-hour cardiorespiratory monitoring. Despite high compliance, no significant reduction in HF hospitalizations was observed. Fudim *et al.*[35] introduced the Bodyport cardiac scale, integrating biomarker analysis like impedance plethysmography into daily routines. Results on HF readmissions are pending.

Wearable technologies may bridge the gap, offering a non-invasive, cost-effective alternative. Indeed, they have shown already promise in cardiovascular care, especially in early diagnosis, as demonstrated by the Apple Heart Study,[36] which identified AF in over 400 000 participants. Despite HF being a prevalent condition well-suited for wearable devices, evidence remains sparse. Our review found only eight studies from 2247 records, involving 1823 HF patients, and only one RCT. This gap between potential and (high quality) evidence highlights the need for more research. Future studies should prioritize larger RCT and pragmatic designs to keep pace with rapidly advancing technologies, including AI integration, as noted by Myhre *et al.*[37]

Among the studies that met our criteria, the ReDS-guided studies[18,19,22,23] not only reported reduced readmissions but also provided insights into non-invasive monitoring-guided interventions in HF management. Though ReDS is not a continuous wearable technology but rather a non-invasive, home-based, and on-demand monitoring tool requiring patient compliance for periodic measurements, it shows how even intermittent assessment of key physiological parameters can effectively guide HF therapy. These studies revealed two pivotal strategies for therapeutic intervention: precise volume management and optimized titration HF life-saving medications. The first strategy emphasizes dynamic diuretic management, aligning with growing evidence that appropriate decongestion is clinically relevant.[38] Concurrently, wearable-guided monitoring enabled more aggressive uptitration of disease-modifying therapies, in line with the evidences provided by the STRONG-HF[39] and PIONEER-HF[40] trials. Furthermore, these technologies could transcend the limitations of traditional fixed-dose regimens, allowing treatment to adapt in real time to the patient's evolving clinical status, facilitating not only drug uptitration in new-onset and decompensated HF but also careful down-titration in case of hypotension with or without renal hypoperfusion during warmer months,[41] infections, or inflammatory events.[42]

Despite the promising clinical outcomes, the economic implications of wearable technologies in HF management remains unexplored. In the USA, the annual median HF-specific hospitalization cost is estimated to be around $15 879 per patient,[43] while in European countries, in-patient costs range from $5000 to $18,000, representing 1–2% of total healthcare expenditures.[44] The observed reductions in hospitalization rates across studies (78–89%) suggest substantial potential for healthcare cost savings. Despite promising findings, the widespread clinical adoption of wearable and non-invasive technologies to reduce HF hospitalizations has been limited by several factors. There is a notable lack of high-quality evidence, with only one out of eight studies being a large-scale randomized-controlled trial, which hinders definitive conclusions about clinical benefits and cost-effectiveness. In addition, cost and reimbursement challenges, inadequate data processing infrastructures, and issues related to patient adherence and clinical workflow integration further impede progress.[45] Therefore, future research should systematically evaluate these aspects to enable more effective and scalable implementation.

Future research should prioritize the development of well-designed, rigorous RCTs that include diverse patient populations, with balanced gender representation, larger sample sizes, and clear inclusion/exclusion criteria.[46] To fully harness the potential of wearables, future research should aim for a multiparametric approach that integrates diverse key physiological signals into accurate predictive algorithms, similar to those employed within implantable devices.[47,48] Furthermore, future studies should examine a broad spectrum of clinically relevant outcomes (hospitalization and/or cardiovascular mortality), assess cost-effectiveness and healthcare resource utilization, and incorporate extended follow-up periods to capture long-term benefits and any limitations associated with wearable technologies.[49]

Limitations

While this systematic review indicates potential benefits of wearable devices in reducing HF hospitalizations, a few limitations must be acknowledged. The small number of studies ($n = 8$) and the limited number of RCTs (one 1 of 8) introduce selection bias and limit the strength of our conclusions. Short follow-up periods (30–90 days) and small sample sizes—with only two studies[17,25] including over 100 patients—restrict generalizability. The lack of control groups in some studies,[17–19] relying instead on literature-reported averages, may not provide reliable benchmarks. Significant gender disparity, with a predominance of male participants (75%) in four studies,[17–19,21] limits applicability to the broader HF population, since disease manifestations and treatment responses differ between genders.[29,30]

Conclusions

This systematic review highlights the potential of non-invasive wearable devices in improving HF management by aiding decompensation detection and reducing hospitalizations. When combined with clinical treatment algorithms, these devices may support interventions like volume management and HF medication titration, offering a lower-cost alternative to invasive methods for high-risk patients. While still in early stages, wearable technology shows promise for reducing hospitalizations and improving outcomes, with significant advancements anticipated in the coming years, given high-quality studies exploring technical challenges, including privacy issues, data processing, administrative innovation, and meaningful clinical integration will consolidate these preliminary findings.

Lead author biography

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Supplementary material

Supplementary material is available at *European Heart Journal – Digital Health*.

Author contributions

Francesca Noci (Methodology, Data curation, Formal analysis, Writing—original draft), Angelo Capodici (Methodology, Data curation, Formal analysis, Writing—original draft), Sabina Nuti (Validation, Writing—review & editing), Claudio Passino (Validation, Writing—review & editing), Michele Emdin (Validation, Writing—review & editing), and Alberto Giannoni (Conceptualization, Supervision, Writing—review & editing)

Data availability

As a review article, this study is based on an analysis of previously published data. All used data are cited within the manuscript and its supplementary files. No new data were created, and the datasets from the primary studies were not available to the authors.

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References

1. Tully J, Dameff C, Longhurst CA. Wave of wearables: clinical management of patients and the future of connected medicine. *Clin Lab Med* 2020;**40**:69–82.
2. Mizuno A, Changolkar S, Patel MS. Wearable devices to monitor and reduce the risk of cardiovascular disease: evidence and opportunities. *Annu Rev Med* 2021;**72**:459–471.
3. Düking P, Achtzehn S, Holmberg HC, Sperlich B. Integrated framework of load monitoring by a combination of smartphone applications, wearables, and point-of-care testing provides feedback that allows individual responsive adjustments to activities of daily living. *Sensors (Basel)* 2018;**18**:1632.
4. Düking P, Hotho A, Holmberg HC, Fuss FK, Sperlich B. Comparison of non-invasive individual monitoring of the training and health of athletes with commercially available wearable technologies. *Front Physiol* 2016;**7**:71.
5. O'Donoghue J, Herbert J. Data management within mHealth environments: patient sensors, mobile devices, and databases. *J Data Inf Qual* 2012;**4**:1–20.
6. Dhingra LS, Aminorroaya A, Oikonomou EK, Parrish R, Navar AM, Khan SS, *et al.* Use of wearable devices in individuals with or at risk for cardiovascular disease in the US, 2019 to 2020. *JAMA Netw Open* 2023;**6**:e2316634.
7. Sunny JS, Patro CPK, Karnani K, Anand A, Manoj BS, Verma PK, *et al.* Anomaly detection framework for wearables data: a perspective review on data concepts, data analysis algorithms, and prospects. *Sensors (Basel)* 2022;**22**:756.
8. Singhal A, Cowie MR. The role of wearables in heart failure. *Curr Heart Fail Rep* 2020;**17**:125–132.
9. Nieminen MS, Brutsaert D, Dickstein K, Drexler H, Follath F, Harjola VP, *et al.* EuroHeart Failure Survey II (EHFS II): a survey on hospitalized acute heart failure patients: description of population. *Eur Heart J* 2006;**27**:2725–2736.
10. Blecker S, Paul M, Taksler G, Ogedegbe G, Katz S. Heart failure-associated hospitalizations in the United States. *J Am Coll Cardiol* 2013;**61**:1259–1267.
11. Alsulymani AS, Ashram W, Alghamdi A, Alshaalan MA, Alyahya FA, Alattas AA, *et al.* Risk factors for readmission in heart failure within 90 days. *Cureus* 2023;**15**:e50236.
12. Botto GL, Sinagra G, Bulava A, Doring M, Giannotti-Santoro M, Kalinic H, *et al.* Predicting worsening heart failure hospitalizations in patients with implantable cardioverter-defibrillators: is it all about alerts? A pooled analysis of nine trials. *Europace* 2024;**26**:euae032.
13. Feijen M, Egorova AD, Beeres SLMA, Treskes RW. Early detection of fluid retention in patients with advanced heart failure: a review of a novel multisensory algorithm, HeartLogic. *Sensors (Basel)* 2021;**21**:1361.
14. Abraham WT, Adamson PB, Bourge RC, Aaron MF, Costanzo MR, Stevenson LW, *et al.* Wireless pulmonary artery haemodynamic monitoring in chronic heart failure: a randomised controlled trial. *Lancet* 2011;**377**:658–666.
15. Iaconelli A, Pellicori P, Caiazzo E, Clancy JA, Clark AL, Cosmi F, *et al.* Implanted haemodynamic telemonitoring devices to guide management of heart failure: a review and meta-analysis of randomised trials. *Clin Res Cardiol* 2023;**112**:1007–1019.
16. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, *et al.* The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;**372**:n71.
17. Erath JW, Wanczura P, Wranicz J, Gatzke N, Mikus G, Rieger A, *et al.* Influence of decompensated heart failure on cardiac acoustic biomarkers: impact on early readmissions. *ESC Heart Fail* 2020;**7**:4198–4205.
18. Amir O, Ben-Gal T, Weinstein JM, Schliamser J, Burkhoff D, Abbo A, *et al.* Evaluation of remote dielectric sensing (ReDS) technology-guided therapy for decreasing heart failure rehospitalizations. *Int J Cardiol* 2017;**240**:279–284.
19. Lala A, Barghash MH, Giustino G, Alvarez-Garcia J, Konje S, Parikh A, *et al.* Early use of remote dielectric sensing after hospitalization to reduce heart failure readmissions. *ESC Heart Fail* 2021;**8**:1047–1054.
20. Chi WN, Reamer C, Gordon R, Schussler JM, Cheeran D, Allen Ziegler S, *et al.* Continuous remote patient monitoring: evaluation of the heart failure cascade soft launch. *Appl Clin Inform* 2021;**12**:1161–1173.

21. Stehlik J, Schmalfuss C, Bozkurt B, Nativi-Nicolau J, Wohlfahrt P, Wegerich S, *et al.* Continuous wearable monitoring analytics predict heart failure hospitalization: the LINK-HF multicenter study. *Circ Heart Fail* 2020;**13**:e006513.
22. Nomoto Y, Imamura T, Izumida T, Narang N, Kinugawa K. Clinical implications of remote dielectric sensing-guided management. *J Clin Med* 2024;**13**:2906.
23. Alvarez-Garcia J, Lala A, Rivas-Lasarte M, Parikh A, Giustino G, Barghash MH, *et al.* Remote dielectric sensing before and after discharge in patients with ADHF: the ReDS-SAFE HF trial. *J Am Coll Cardiol HF* 2024;**12**:695–706.
24. Brugts JJ, Radhoe SP, Clephas PRD, Brouwer TF, Brugts HF, Versteeg H, *et al.* Remote haemodynamic monitoring of pulmonary artery pressures in patients with chronic heart failure (MONITOR-HF): a randomised clinical trial. *Lancet* 2023;**401**:2113–2123.
25. Boehmer JP, Cremer S, Abo-Auda WS, Harb SC, Abraham WT, Wieselthaler GM, *et al.* Impact of a novel wearable sensor on heart failure rehospitalization: an open-label concurrent-control clinical trial. *JACC Heart Fail* 2024;**12**:2011–2022.
26. Gardner RS, Singh JP, Stancák B, Neelagaru S, Nahlawi M, Verga T, *et al.* HeartLogic multisensor algorithm identifies patients during periods of significantly increased risk of heart failure events: results from the MultiSENSE study. *Circ Heart Fail* 2018;**11**:e004669.
27. Lindenfeld J, Costanzo M, Zile M, Abraham WT, Adamson PB, Bahrami T, *et al.* Implantable hemodynamic monitors improve survival in patients with heart failure and reduced ejection fraction. *J Am Coll Cardiol* 2024;**83**:682–694.
28. McMurray JJ, Packer M, Desai AS, Gong J, Lefkowitz MP, Rizkala AR, *et al.* Angiotensin-neprilysin inhibition versus enalapril in heart failure. *N Engl J Med* 2014;**371**:993–1004.
29. McMurray JJV, Solomon SD, Inzucchi SE, Køber L, Kosiborod MN, Martinez FA, *et al.* Dapagliflozin in patients with heart failure and reduced ejection fraction. *N Engl J Med* 2019;**381**:1995–2008.
30. Packer M, Anker SD, Butler J, Filippatos G, Pocock SJ, Carson P, *et al.* Cardiovascular and renal outcomes with empagliflozin in heart failure. *N Engl J Med* 2020;**383**:1413–1424.
31. Anand IS, Carson P, Galle E, Song R, Boehmer J, Ghali JK, *et al.* Cardiac resynchronization therapy reduces the risk of hospitalizations in patients with advanced heart failure: results from the Comparison of Medical Therapy, Pacing and Defibrillation in Heart Failure (COMPANION) trial. *Circulation* 2009;**119**:969–977.
32. Scholte NTB, Gürgöze MT, Aydin D, Rohde D, van der Harst P, Andresen D, *et al.* Telemonitoring for heart failure: a meta-analysis. *Eur Heart J* 2023;**44**:2911–2926.
33. Uslan DZ, Gleva MJ, Warren DK, Mela T, Chung MK, Gottipaty V, *et al*. Cardiovascular implantable electronic device replacement infections and prevention: results from the REPLACE Registry. *Pacing Clin Electrophysiol* 2012;**35**:81–87.
34. Mortara A, Pinna GD, Johnson P, Maestri R, Capomolla S, La Rovere MT, *et al.* Home telemonitoring in heart failure patients: the HHH study (Home or Hospital in Heart failure). *Eur J Heart Fail* 2009;**11**:312–318.
35. Fudim M, Yazdi D, Egolum U, Alashi A, Rodriguiz RM, Fang JC, *et al.* Use of a cardiac scale to predict heart failure events: design of SCALE-HF 1. *Circ Heart Fail* 2023;**16**:e010012.
36. Perez MV, Mahaffey KW, Hedlin H, Rumsfeld JS, Garcia A, Ferris T, *et al.* Large-scale assessment of a smartwatch to identify atrial fibrillation. *N Engl J Med* 2019;**381**:1909–1917.
37. Myhre PL, Tromp J, Ouwerkerk W, Gerber Y, Chow SL, Gastelurrutia P, *et al.* Digital tools in heart failure: addressing unmet needs. *Lancet Digit Health* 2024;**6**:e755–e766.
38. Heidenreich PA, Bozkurt B, Aguilar D, Allen LA, Byun JJ, Colvin MM, *et al.* 2022 AHA/ACC/HFSA guideline for the management of heart failure: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Circulation* 2022;**145**:e895–e1032.
39. Mebazaa A, Davison BA, Chioncel O, Mebazaa A, Davison BA, Chioncel O, *et al.* Safety, tolerability and efficacy of up-titration of guideline-directed medical therapies for acute heart failure (STRONG-HF): a multinational, open-label, randomised trial. *Lancet* 2022;**400**:1938–1952.
40. Velazquez EJ, Morrow DA, DeVore AD, Duffy CI, Ambrosy AP, McCague K, *et al.* Angiotensin-neprilysin inhibition in acute decompensated heart failure. *N Engl J Med* 2019;**380**:539–548.
41. Narita K, Hoshide S, Kario K. Seasonal variation in blood pressure: current evidence and recommendations for hypertension management. *Hypertens Res* 2021;**44**:1363–1372.
42. Liu Y, Li J, Xiao S, Liu Y, Bai M, Gong L, *et al.* Revolutionizing precision medicine: exploring wearable sensors for therapeutic drug monitoring and personalized therapy. *Biosensors (Basel)* 2023;**13**:726.
43. Urbich M, Globe G, Pantiri K, Heisen M, Bennison C, Wirtz HS, *et al.* A systematic review of medical costs associated with heart failure in the USA (2014–2020). *Pharmacoeconomics* 2020;**38**:1219–1236.
44. Hessel FP. Overview of the socio-economic consequences of heart failure. *Cardiovasc Diagn Ther* 2021;**11**:254–262.
45. Gregório C, Agostinho JR, Rigueira J, Santos R, Pinto FJ, Brito D. From wristbands to implants: the transformative role of wearables in heart failure care. *Healthcare* 2024;**12**:2572.
46. An MW, Duong Q, Le-Rademacher J, Mandrekar SJ. Principles of good clinical trial design. *J Thorac Oncol* 2020;**15**:1277–1280.
47. Calò L, Bianchi V, Ferraioli D, Santini L, Martino A, Sette A, *et al.* Multiparametric implantable cardioverter-defibrillator algorithm for heart failure risk stratification and management: an analysis in clinical practice. *Circ Heart Fail* 2021;**14**:e008134.
48. Stevenson LW, Ross HJ, Rathman LD, Boehmer JP. Remote monitoring for heart failure management at home. *J Am Coll Cardiol* 2023;**81**:2272–2291.
49. International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use. General considerations for clinical studies. *ICH Harmonised Guideline* 2021;**E8**:1–39.