

REVIEW

Role of Wearable Devices in the Current Era of Healthcare



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Abstract: Wearable technologies, including smartwatches, fitness trackers, wearable electrocardiographic monitoring systems, and biosensor-based devices, are increasingly being integrated into modern healthcare because of their ability to provide continuous and real-time physiological monitoring. These devices can support early mobilization, facilitate remote patient monitoring, encourage patient engagement, and aid in the early detection of postoperative complications. In cardiac surgical patients, wearable devices may help identify arrhythmias such as atrial fibrillation, monitor heart rate variability, oxygen saturation, respiratory rate, sleep quality, and physical activity levels, thereby enabling clinicians to recognize physiological deterioration at an early stage. Continuous monitoring through wearable systems may contribute to faster intervention, reduction in hospital stay, lower readmission rates, and improved post-operative recovery outcomes. Beyond cardiac surgery, wearable technologies have demonstrated potential applications in cardiology, diabetes management, pulmonary rehabilitation, oncology, sports medicine, neurological disorders, and mental health monitoring. These devices may improve chronic disease management by enabling long-term monitoring outside the hospital setting and promoting personalized healthcare delivery. Furthermore, wearable technologies support telemedicine and home-based rehabilitation programs, which have become increasingly important in recent years. Despite these promising advantages, several limitations continue to restrict their widespread clinical adoption. Challenges related to device accuracy, motion artifacts, battery life, sensor reliability, patient compliance, interoperability, and data privacy remain important concerns. Additional large-scale studies are required to validate their safety, reliability, cost-effectiveness, and long-term clinical benefits. This review discusses the evolution, applications, benefits, and limitations of wearable devices, with special emphasis on their role in postoperative cardiac care and remote health monitoring.

Keywords: wearable devices, cardiology, arrhythmia, atrial fibrillation, postoperative care

1. Introduction and Background

1.1. Introduction

Postoperative monitoring plays a vital role in the outcome of cardiac surgery patients. Enhanced recovery after surgery (ERAS) is a topic of interest in the era of minimally invasive cardiac surgery. Early mobilization and increased physical activity are core components of enhanced recovery programs. Mobilization of patients following heart surgery is a laborious process because of several invasive monitoring lines, multiple inotropic support, and more discomfort with standard midline sternotomy than with minimally invasive cardiac surgery. Prolonged immobilization can lead to deep vein thrombosis, lung infection, delirium, atelectasis, and pleural effusion. Early mobilization as part of the recovery and on-time discharge has been shown to minimize hospital-acquired infection, pressure injuries, delirium, and pleural effusion.

Wearable devices and remote monitoring have been shown to be beneficial in major abdominal surgery, in which patients with higher median cumulative step count had significantly shorter hospital stay and lower morbidity [1]. Conventional objective measuring methods are often uncomfortable for patients, so it's essential for us to introduce simple methods that are more patient friendly. Those devices should be accurate and reliable enough to replace the cumbersome conventional monitoring system.

Wearable devices can also measure the step count and motivate the patient in reaching target step counts and hence in early mobilization and early recovery. Accurate measurement of foot-steps mobilized is not easy to follow up in a hospital setting, and it is more subjective. Wearable devices give an objective measurement of steps taken. This is only true if certain/strict measures are taken by the wearer as some wearables are also prone to wrong readings. For example, with smartwatches, sitting down and swinging the arm with a significant displacement can trick the gyroscope into measuring step counts incorrectly. Desaturation or tachycardia while mobilizing can be detected earlier before the patient develops tachypneic and thereby helps in guiding the limit of physical activity. Arrhythmias like atrial fibrillation (AF) and ventricular fibrillation (VF) can be detected earlier using telemetry-monitored electrocardiogram (ECG) monitoring. Blood sugar monitoring in diabetic patients can be obtained

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without multiple pricks and can aid in the management of insulin dosage and blood glucose level in postoperative patients.

Multiple monitoring lines in postoperative patients keep them anxious and have an effect on their recovery. With the advent of minimally invasive cardiac surgery, minimizing the duration of hospital stay is very important. Wearable devices help in overcoming the hindrance of multiple monitoring lines. The role of wearable devices in postoperative follow-up after cardiac surgery has been studied and has shown early detection of complications and prevented rehospitalization [2].

Continuous monitoring during physical activity helps in early detection of ischemia, tachycardia, and hypoxia and thereby can adjust the dose of rate control drugs and antianginal drugs. Monitoring of immediate postoperative cardiac surgery patients using wearable medical-grade devices can have a great impact in the era of minimally invasive cardiac surgery for early mobilization and recovery [3].

With advances in technology, remote monitoring of postoperative cardiac surgery patients can be easily made feasible. But the effect of these monitors on patient outcomes is to be studied further and has yet to be established.

Wearable devices can also continue monitoring during physical activity, so they can aid in the earlier detection of complications. Literature has shown the advantage of early detection of perioperative complications and a decrease in length of hospital stay [4]. But there is a lacuna in establishing the safety and reliability of wearable devices. Here, we compare the wearable device with routine invasive monitoring in the cardiac critical care unit in postoperative patients in terms of accuracy, reliability, and safety in patient management.

1.2. History of wearable devices

Devices worn or affixed to the body that track activity levels, monitor physiological factors, and offer real-time health insights are referred to as wearable technologies. An important turning point in wearable technology was the Hamilton Pulsar's 1972 debut, which also introduced the first digital watch and signaled the merging of fashion and technology. A significant advancement in fitness tracking was made in 2008 with the introduction of Fitbit. By enabling users to monitor physical activity, heart rate (HR), and sleep habits, this cutting-edge gadget helped people make better decisions and lead healthier lives. With the introduction of wearable glucose monitors and Apple Watches with ECG capabilities, the healthcare industry underwent a dramatic change in 2017. These gadgets gave people the ability to better track their health, providing insightful information and enabling early intervention. Sensor-enabled smart apparel gained popularity in 2019 because it enables users to track physical performance, monitor vital signs, and maximize sports training schedules. This invention promised to improve wearers' comfort and performance by fusing fashion and technology. In 2020, Elon Musk's Neuralink project explored the field of brain-machine interfacing and offered the possibility of controlling a gadget directly with thoughts [5]. This innovative technology had the potential to help people with disabilities and transform human-computer interaction. Daskivich et al.'s [6] careful investigation of wearable activity trackers (WATs) resolves a long-standing conundrum for the first time. In this study, 100 patients undergoing major inpatient surgeries had their postoperative ambulation measured using activity monitors. By demonstrating that a step count of up to 1000 on the first postoperative day is associated with a lower probability of a

prolonged length of stay, the authors identified patients who are at risk for extended lengths of stay.

2. Uses of Wearables in Healthcare

2.1. Physical activity and language monitoring

Long-term inactivity is associated with a number of health problems. A wearable gadget that vibrates after 20 minutes of sitting was created by Frank et al. [7] to see if reminders could help students with their posture. Although it was unclear how the reminders affected students' health, the study found that they were helpful in changing their behavior.

Choo et al. [8] studied the use of cellphones and wearable technology to monitor language usage in a different study. To keep an eye on mother-child communication, they employed a Language Environment Analysis (LENA). Mothers received feedback from the gadget, which assisted them in modifying their communication styles. Mothers who participated in the study said the information helped them communicate with their kids more effectively.

2.2. Mental status monitoring and depression management

The use of wearable technology with sensors that measure physiological indicators, such as skin conductance and HR, to track mental health, especially stress, is growing.

Borisov et al. [9] showed that the feasibility of unobtrusive, real-time cognitive load monitoring, highlighting its potential for adaptive systems in education, human-computer interaction, and workplace environments, while also pointing to challenges in generalization and real-world deployment.

Psychiatric conditions like depression can be screened for, diagnosed, and tracked with the help of wearable technology. In one study, bipolar patients' autonomic state was evaluated using heart rate variability (HRV) and wearable textile technology. Another proposed a depression monitoring system that enhances HRV feature extraction from ECG data using an application-specific system-on-chip to increase the accuracy of depression recognition. These technologies present viable options for automated, real-time mood state monitoring in both healthy and diseased settings. The review emphasizes the potential of integrating wearables with AI-driven systems for real-time emotional feedback, while also discussing key challenges like data privacy, accuracy, and user engagement in digital health contexts [10].

2.3. Sports medicine

The use of wearables to improve athletic performance and training is growing. Damji et al. [11] showed that commercial wearable technology can accurately identify jump heights and track jump loads in professional volleyball players. These gadgets are useful tools in sports medicine to enhance performance and reduce injury risk because they can measure HR, workloads, and functional movements.

Son et al. [12] demonstrated a fuzzy logic-based technique to detect heat stroke while exercising in hot weather. Their system can monitor the risk of heat stroke and notify users by analyzing inputs from ambient sensors and wearable technology. The system's capacity to prevent heat-related illnesses during physical exercise was validated by the testing results.

2.4. Patient management

By facilitating the early detection of issues in health, wearable technology can provide better hospital patient care. The development of point-of-care diagnostic equipment is made possible by wireless connectivity [13]. For instance, in emergency medical situations, wearable sensors continuously track ambient variables like temperature and harmful chemicals, and vital indications like HR, body temperature, and oxygen levels. By sending data to medical professionals, these gadgets improve patient care.

Furthermore, by monitoring activity levels, wearables aid in managing chronic conditions by assisting patients in better self-management and health. By offering unbiased data, these gadgets help people better monitor their routines, nutrition, and weight [14].

2.5. Cancer

Basen-Engquist et al. [15] reported that physical activity levels are among the lowest among endometrial cancer survivors, and they frequently experience obesity rates of up to 70%. Lifestyle changes, however, can lead to better health results. Rossi et al. [16] assessed the Fitbit AltaTM's validity and acceptability in a broad sample of endometrial cancer survivors. Despite data showing low activity levels, the study concluded that individuals embraced the gadget well. In a similar vein, breast cancer survivors have been using WATs to reduce inactivity and enhance physical activity. Wearable programs can enhance physical activity in this population and effectively promote home-based rehabilitation, as demonstrated by Reo et al. [17] and Keats et al. [18].

2.6. Chronic pulmonary diseases

Chronic obstructive pulmonary disease necessitates ongoing treatment and rehabilitation. Tey et al. [19] created a multimodal sensor-based remote rehabilitation system for patients with persistent respiratory issues. The system offered pulmonary patient-specific coaching, progress tracking, and exercise tracking. Initial findings demonstrated that the system could use sensory data to provide precise exercise recommendations. Its cost-effectiveness and comfort for healthcare rehabilitation require more research.

2.7. Diabetes management

Monitoring variables like medication, exercise, food, and stress are necessary for effective diabetes treatment. Real-time, individualized care is being advanced by consumer technology including wearables, sensors, and smartphone apps [20]. The wearable artificial pancreas, which employs a closed-loop system with an insulin pump and glucose monitor, is a noteworthy example. According to recent research, closed-loop control enhances type I diabetes glucose management. Wearable technology has the potential to improve self-care and save healthcare costs. One example is sweat-based glucose monitors [21].

2.8. Cardiology

For patients with cardiac issues, wearable technology has been created to monitor the heart and enable mHealth

apps. Low-power wearable ECG monitoring devices have been developed [22]. A lot of wearable technology measures HRV. Pan et al. [23] demonstrate the system's potential for real-time cardiovascular assessment and stress monitoring, suggesting promising applications in personalized healthcare, while noting challenges related to durability, stability, and large-scale deployment.

Outside of a lab or clinical context, wearable technology measures a patient's heart activity. Without affecting the patient's everyday activities, heart assessments can be carried out at a number of commonplace locations. To evaluate the 3D sternal seismocardiogram in daily life, for instance, researchers created a textile-based wearable device that allows for the discrete collection of ECG, respiration, and accelerometric data. Additionally, a continuous, portable ballistocardiogram sensor that may be worn in the ear was created by Da He et al. [24]. Important details about heart contractility and its regulation can be obtained from the ear devices.

Since its initial use in clinical settings in 2001, the wearable cardioverter defibrillator (WCD) has diversified its scope of indications. The WCD is a backup strategy for preventing sudden arrhythmic death until the need for an implanted cardioverter defibrillator is evident or the arrhythmic risk is thought to be minimal or non-existent [25].

Nantume et al. [26] investigated the viability of employing a wireless digital watch as a wearable surveillance device to track patients' vital signs. The wearable technology and conventional clinical monitors were contrasted by the researchers. The findings demonstrated that approximately 80% of patients received accurate HR readings from the tested wearable device, and the comparison was statistically significant, suggesting that there was satisfactory general agreement between the novel device and the clinical monitor. Despite the fact that the recorded HRs were marginally lower than the norm for continuous ECG monitoring, a personal fitness tracker device can be utilized to monitor patients' HRs.

2.9. Wearable devices

Wearable devices have been commonly used recently in healthcare for various purposes. Wearables are tiny, body-worn computers with seamless integration [27]. These are used in healthcare in monitoring, assisting with diagnosis, and engaging patients in healthcare [28]. There are many different kinds of gadgets, such as activity trackers, wrist watches, chest bands, and even more specialized ones that can test for cancer cells or measure electrolyte levels [29].

HR, activity, and sleep monitoring are all frequently tracked with wearable technology. Newly created wearable technology permits blood pressure and ECG monitoring and can offer affordable ways to treat hypertension, screen for cardiac arrhythmias, and perform other clinical and lifestyle interventions.

According to Mizuno et al.'s [30] literature review, wearable technology is a promising and novel approach to postsurgical patient observation. They monitor and detect early complications, give objective outcomes assessment, enhance patient safety, and possibly lower healthcare costs by remotely assessing a variety of health metrics.

However, the accuracy of these devices has not been extensively studied till date.

3. Advantages of Wearable Devices

3.1. Early mobilization

The results of cardiac surgery patients are greatly influenced by postoperative surveillance. A new area of focus during the time of minimally invasive cardiac surgery is ERAS [31]. The 2019 guidelines for ERAS in cardiac surgery were provided by Engelman et al. [32]. Enhanced rehabilitation programs should include early mobilization and increased physical activity, according to Ljungqvist et al.'s [33] 2017 ERAS guidelines. Early mobilization after cardiac surgery has been shown to enhance respiratory muscle strength, ventilation/perfusion ratio, ventilation, and functional ability [34, 35].

Studies have also revealed that patients felt constrained by oxygen lines, tubes, surgical drains, and constant vital sign monitoring while they were in the hospital [36, 37]. Many intrusive lines, particularly in patients recovering from heart surgery, prevent the patient from being mobilized as soon as possible. Patients frequently find conventional objective measuring techniques uncomfortable; thus, it is critical that we provide straightforward techniques that are more accommodating to patients. These gadgets ought to be precise and dependable enough to take the place of the laborious traditional monitoring approach.

Both Ripollés-Melchor et al.'s [38] and Kanejima et al.'s [39] systematic reviews showed favorable impacts on functional capacity and were deemed safe and practicable for critically ill patients.

In a systematic study in 2017, Ramos dos Santos et al. [40] found that, when compared to control groups receiving no treatment, the early mobilization groups had reduced rates of surgical complications, improved functional ability, and shorter hospital stays. However, no intervention stood out as being better when compared to other mobilization protocols.

The process of mobilizing patients following cardiac surgery is time-consuming because several inotropic support lines, multiple invasive monitoring lines, and more discomfort are associated with conventional midline sternotomy than with minimally invasive cardiac surgery [41]. Extended immobilization may result in delirium, atelectasis, pleural effusion, lung infection, and deep vein thrombosis [40].

3.2. Shorter hospital stay

The South American Guidelines for Cardiovascular Rehabilitation state that low-intensity exercises and patient education, such as light walking with personalized progressions and passive mobilization, are the main components of phase I cardiac rehabilitation [42]. It has been demonstrated that early mobilization reduces hospital stay, delirium, pressure injuries, hospital-acquired infections, and pleural effusions.

The advantages of wearable technology and remote monitoring in major abdominal surgery were examined by Wolk et al. [43] in June 2019. Patients' hospital stays were noticeably shorter, and their morbidity was lower when their median cumulative step count was higher.

3.3. Remote vital monitoring

According to research by Posthuma et al. [44], patients on medical and surgical wards can benefit from remote vital monitoring as it can aid in the early identification of patient decline.

According to Amin et al. [45], wearable device technologies provide a practical and objective way to continually and remotely monitor patients after surgery, which may improve patient safety, lower medical expenses, and improve continuity of care. Wearables may reduce hospital stays by facilitating early discharge, saving both time and money (Figure 1).

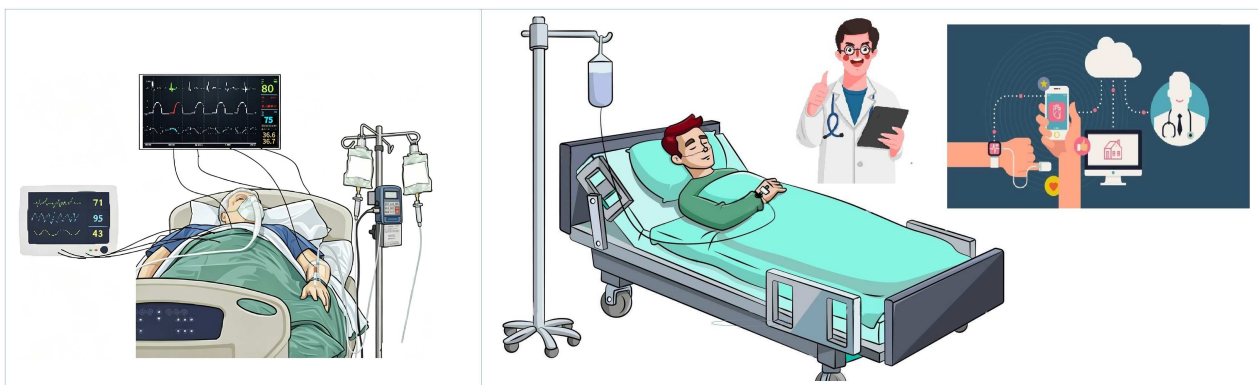
3.4. Early detection of complications

In 2018, Ghomrawi et al. [46] found a correlation between the beginning of postoperative problems and a decline in mobility scores assessed by wearable technology, with detection taking place before medical attention is sought.

Additionally, Mobbs et al. [47] presented a case showing how wearable device data, when combined with radiologic and clinical assessment, can be useful in identifying a postoperative problem and facilitating prompt management.

According to research by Çoban [48], continuous monitoring can reveal saturation fall and tachycardia in postoperative patients that are missed by the Early Warning Score. This discovery could aid in the prevention of clinical repercussions and early detection.

Figure 1
Remote monitoring



The continuous monitoring device did not consistently deliver HR in line with nurse assessments, according to Breteler et al. [49]. Temperature and respiratory rate (RR) accuracy were not within allowable bounds. Improved signal processing may be able to overcome the system's limitations. Errors in the manually recorded data present an opportunity to appreciate the time restrictions faced by nursing personnel, particularly with regard to manual RR and HR measurement procedures, and to increase understanding of the need for manual observations.

Wearable devices can also measure the step count and motivate the patient in reaching target step counts and hence in early mobilization and early recovery [50]. Keeping a track of the precise measurement of footsteps mobilized in a hospital setting is challenging and more subjective. The objective measurement of steps taken is provided by wearable technology [51].

According to Solomou et al. [52], wearable technology makes it possible to capture an array of health metrics, including HR, body temperature, and physical activity, in a discrete, continuous, and distant manner. It may also be possible for these devices to enhance the early detection of complications following surgery, which offers better patient outcomes and less expensive healthcare.

According to a study by Hiraoka et al. [53], telemetry-monitored ECG monitoring can be used to identify arrhythmias such as VF and AF earlier. It is possible to obtain blood sugar monitoring in diabetic patients without the need for repeated needle sticks, and it can help postoperative patients control their insulin dosage and blood glucose levels [54].

Research has demonstrated the early diagnosis of problems and prevention of rehospitalization in the postoperative follow-up period following heart surgery by the use of wearable devices [45].

4. Limitations

Sui et al. [55] noted in their study that companies find it challenging to integrate resources as they trust their core items to create their own rules and regulations in the absence of industry norms and laws. Therefore, it is necessary to establish and implement new regulatory standards.

According to Koralli and Mouzakis [56], on the one hand, the existing wearable devices' low sensor specificity raises the possibility of overdiagnosis of benign nonsignificant signals, which could result in misdiagnoses, pointless tests, and anxiousness. However, a delayed diagnosis and treatment plan could arise from the omission of potentially clinically relevant traits due to insufficient sensor sensitivity.

Pentapati [57] has said that poor battery life and limited storage are challenging factors in implementing wearable devices in healthcare.

Wearable health devices can collect a variety of user data, such as location, lifestyle preferences, and health information, according to Guk et al. [58]. This may increase the likelihood of tampering and leakage. Strategies to safeguard data and increase public trust must be developed.

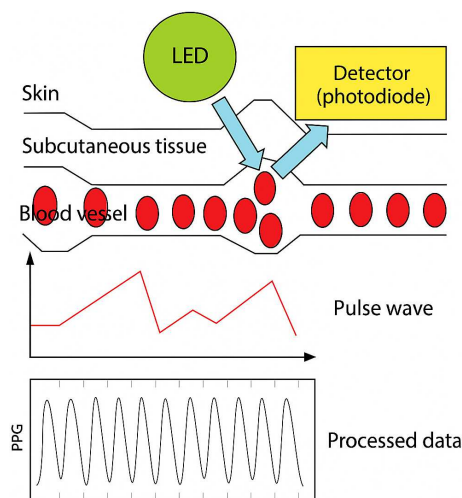
5. Parameters

5.1. Photoplethysmography (PPG)

Wearable technology that tracks HR, heart rhythm, and SpO₂ frequently uses PPG. PPG may eventually be used in various medical settings, such as blood pressure monitoring and vascular ageing. PPG sensors are of use in Wristwatch, wrist band, or eyeglasses, which are suitable for long-term continuous

noninvasive monitoring on the fingers, ear lobes, forehead, or chest. These optical sensors assess blood volume variations in the microvascular bed, a measurement that is commonly made using a pulse oximeter. Measurements of light transmitted or reflected to a photodiode, sensitive changes in vascular distention, and variations in pulse pressure in the arteries and arterioles in the subcutaneous tissue are all signs of the cardiac cycle. With this data, beat-to-beat pulse signal measurement can be interpreted via sensor fusion, which aggregates a variety of physiological markers (Figure 2).

Figure 2
Photoplethysmography



The two primary components of a PPG signal are the pulsatile alternating current, which results from variations in arterial blood volume that modulate light absorption, and the quasi-static direct current, which represents light transmitted from static venous blood, arterial blood, skin, and tissue. PPG can be measured using either reflectance or transmission. In transmission mode, the photo detector detects light passing through the material, which is positioned at the opposite location of the light source. The sensor must be placed on the body in a location that allows for the identification of transmitted light. Only the body's extremities—such as the fingertip or earlobe—may be used as the measurement point. The position of the gadget, which may obstruct daily activities, is the biggest drawback of the transmission technique. In reflectance mode, the photodiode detects light that is scattered back from bone, tissues, or blood vessels, indicating that the photodiode and light source are on the same side. A user-friendly monitoring strategy is made possible by the measurement sites' freedom from locational restrictions, in contrast to the transmission mode. Common measuring locations include the forehead, forearm, ankle, and wrist [59].

Green LEDs/infrared light-emitting diodes (IR-LEDs) are the main light sources in the majority of PPG sensors. While oxyhemoglobin and deoxyhemoglobin are typically measured for oxygen absorption using green light, IR-LEDs are most frequently used to measure more deeply concentrated blood flow in specific body parts, like the muscles [60]. A distinctive wristwatch PPG probe, which used the patient's ulnar and radial arteries as the common measuring site in place of the blood capillaries, was developed [61]. The suggested device included a variety of

sensors, IR-LEDs, and photo transistors to increase the PPG signal's accuracy and sensitivity.

A technique to lessen the negative effects of motion artifacts (MA) on PPG signal quality was presented by Zwahlen et al. [62]. Another similar method was also presented to eliminate motion artifacts by employing two reflecting pulse signals from a single green LED sensor [63].

It is discovered that biological, cardiovascular, and sensor-related factors significantly affect PPG signals. Muscle movement and tissue dilatation are examples of inner tissue alterations that can result from tissue modifications brought on by intentional or involuntary motions. These movements will cause the receiving light to change, producing a new signal. Variations in the way light propagates through tissues are caused by an individual's anatomy, organ sizes, and the volume of fluids stored by the tissues [64]. The displacement of the sensor is another element that can alter the signal. Movements of the body and physical activity may cause the sensor to move from its original position. The sensors' movement modifies the light's path, which has an impact on the signals [65]. The amount of pressure the gadget applies to the skin regulates the strength of the signal that is received.

PPG technology has become more and more popular as a substitute HR monitoring method in recent times. This is mostly because of its ease of operation, comfort, compliance, and affordability [66]. However, the major limitation is that these sensors function accurately when in direct contact with the skin and are also very much susceptible to MA due to hand movements, especially in wristbands, leading to inaccurate monitoring of the PPG signals during regular everyday activities and physical activity. Skin complexion, moisture, and tattoos are also suggested to impact PPG precision [67]; however, one study reported comparable device performance across the entire spectrum of skin tones [68]. Other variables, including background noise in the environment, could potentially have an impact on the PPG signal collection and, in turn, the HR estimation accuracy [69].

5.2. Heart rate

Long-term research has demonstrated a correlation between resting tachycardia and cardiovascular disease as well as unfavorable clinical outcomes, establishing the well-established link between HR and cardiovascular risk [70].

Measurements from smart watches based on PPG offer more convenient continuous monitoring. When compared to telemetry in healthy humans, modern devices often use peak detection algorithms, which, despite individual device accuracy variances, yield median error ranges of less than 5% [71]. The miniaturization of PPG sensors has made it possible to include them in other common clothing items, such as eyeglasses and rings [72]. Unusual rhythms, such as premature atrial or ventricular contractions and AF, can provide PPG readings that differ from the underlying electrical activity, confusing peak identification algorithms. This may result in inaccurate HR readings. In this regard, sophisticated algorithms have been devised to minimize PPG signal mistakes [73]. Nowadays, smartwatches come with limited rate and rhythm analysis software in addition to ECG recording capabilities [74]. Additionally, developing self-powered wearables and using triboelectric nano generator technology with pulse detecting capabilities makes promising advanced continuous heart rate monitoring systems for an extended time period [75]. The mechanical movement is transformed into energy and an ECG-like signal by a self-sustaining sensor that acquires biomechanical energy released by the pulse of the radial artery. Darker skin tones may make it more difficult for

wearables to detect HR, according to research by Koerber et al. [76] in a systematic review. According to a 2016 study by Ge et al. [77] in India with 50 healthy volunteers, there was minimal difference between the Apple Watch and the Polar chest strap when the individuals were not doing anything physically demanding, with a maximum error of about 2%. On the one hand, the walking activity varied by 10% and the aerobic exercises by 7%. Showed that when the subjects were not involved in any demanding activities, there was minimal difference between the Apple Watch and the Polar chest strap, and the maximum inaccuracy was only 2%. On the other hand, the walking exercise varied by 10%, while the cardiac activities varied by 7%.

In the resting state, the mean absolute difference in HR between the devices and ECG was 4.6 ± 8.4 bpm in normal sinus rhythm (NSR) and 7.0 ± 11.8 bpm in AF. The discrepancy was even greater at maximal exercise— 13.8 ± 18.9 bpm in NSR vs. 28.7 ± 23.7 bpm in AF ($p < 0.001$).

Quinn et al. [78] in 2024 found that the device underestimated the true HR in 62% of cases and overestimated it in 25% of cases of patients who had undergone major abdominal surgery. In 2024, Helmer et al. [79] conducted a randomized controlled trial on 34 patients, 12 of whom had urological procedures and 22 of whom had non-cardiac thoracic cases. They found that the Apple Watch had the best correlation of HR measurements, meeting the clinical gold standard requirements ($r = 0.98$; $p < 0.001$). Garmin and Withings came in second and third, respectively, with ($r = 0.97$; $p < 0.001$ and 0.95 ; $p < 0.001$) [79, 80].

Thijs et al. [81] examined the gradual improvement in activity levels between two groups of patients who had Coronary Artery Bypass Grafting (CABG) (as determined by a Fitbit Charge activity tracker). Twelve patients in the first group underwent traditional off-pump CABGs, while 10 patients in the second group underwent robotically aided minimally invasive bypass surgery. Group 1's average length of stay for acute care was about 7 days (range 5–15), while Group 2's average length of stay was 6 days (range 4–12). In the first week following hospital discharge, Group 1's median daily step count was 1110 (range 739–10 195), while Group 2's was 3715 (range 1637–6720). This difference was not statistically significant, as indicated by $p = 0.06$.

Kroll et al. [82] compared HR and sleep data from a commercially available wearable device with data from cardiac telemetry and sleep questionnaires in patients in intensive care units (ICUs) in 2017.

When used to identify tachycardia, the devices demonstrated a high specificity and moderate sensitivity; however, they performed better in individuals with sinus rhythm [83].

In order to discover problems early and mobilize patients as soon as possible, they compared the vital signs of patients who had cardiac surgery after surgery using wearable technology and invasive monitoring.

5.3. Arrhythmias

Arrhythmias are an important cause of morbidity and death following cardiac surgery. The most prevalent cardiac rhythm problem following surgery is atrial tachyarrhythmia. Brady arrhythmias and ventricular arrhythmias are less common. PPG can calculate a wide array of physiological characteristics, such as cardiac output, blood pressure, HR, and peripheral capillary oxygen saturation (SpO_2). These PPG capabilities pave the way for the creation of novel ambulatory diagnostic instruments that facilitate the early detection of cardiac disorders, such as arrhythmia [84].

5.4. Atrial fibrillation (A-fib)

A common and potentially lethal side effect of heart surgery is postoperative atrial fibrillation (POAF), which occurs in 20–55% of cases. In over 90% of patients with POAF, the postoperative systemic inflammatory response peaks in the first six days after surgery. POAF predicts both short- and long-term cardiovascular complications, such as cardiac arrest, thromboembolism, infection, stroke, and the need for reoperation because of internal bleeding [85]. Hypotension and myocardial ischemia may arise from tachyarrhythmias that reduce diastolic filling and cardiac output while increasing myocardial oxygen demand. POAF onset is usually accompanied by fast ventricular rates, making it a symptomatic event. A-fib can cause a 15–25% decrease in cardiac output by disrupting normal atrioventricular synchrony [86].

In the Huawei Heart study, a cohort of 187,912 individuals who were mobile and utilizing a smart device had a continuous PPG measured. A 60-s PPG signal was continually recorded at 10-min intervals for the course of the participants' at least 14-day observation period using a wristband or wristwatch. ECG was only used to evaluate those who had been classified as having "suspected AF." According to the results, 87.0% of the cases had AF, with a positive predictive value of 91.6%. In a prospective study by Reissenberger et al. [87], continuous pulse-wave data were analyzed in short time segments to classify rhythm and estimate cumulative AF duration, showing strong agreement with ECG (intraclass correlation coefficient ~ 0.88) and high specificity for non-AF periods, although accuracy was limited by motion artifacts and signal noise.

Given their increased risk of developing POAF, Hibino et al. [88] observed that using a wearable patch-based monitoring device was a successful detection technique among patients following valve surgery.

A systematic review found that many mHealth solutions demonstrate high sensitivity and specificity for AF detection, particularly in controlled settings, and can facilitate early diagnosis, longitudinal rhythm monitoring, and improved patient engagement [89].

In a large smartphone-based AF screening study ($n = 60,000+$), AF was detected in 1.3% of participants, with a proportion representing newly diagnosed cases. Among individuals with ECG-confirmed AF, oral anticoagulation increased from 56% to 74% following screening, alongside additional adjustments in rate and rhythm control therapy [90].

In order to distinguish between sinus rhythm and AF in 2017, Krivoshei et al. [91] employed only the PPG sensor of the iPhone 4s in conjunction with a custom algorithm in a smartphone app. Following the significant sensitivity and specificity that their technique produced, they proposed that smartwatches might also employ their algorithm.

Compared to an Insertable cardiac monitor (ICM), Wasserlauf et al.'s [92] 2019 study showed that atrial fibrillation sensing watch (AFSW) had a higher sensitivity for determining the existence and duration of AF. These devices are low-cost, noninvasive techniques for managing and monitoring AF.

5.5. Ventricular tachyarrhythmias

Following surgery, isolated premature ventricular complexes (PVC) are frequently seen. PVCs may be connected to other metabolic or electrolyte abnormalities. PVCs can often be easily separated from atrial ectopy with aberrant ventricular conduction using surface ECG or continuous telemetric monitoring [93].

VF and ventricular tachycardia (VT) are examples of sustained ventricular arrhythmias that are rare following surgery. Following heart surgery, reported occurrences vary from 0.41% to 1.4% [94, 95]. Left ventricular dysfunction is linked to complex ventricular arrhythmias [96]. In their case series, Burke et al. [97] demonstrated that smart watches can be used to detect symptomatic arrhythmias, including potentially dangerous VT.

In a study conducted by Chorin et al. [98] on 18 individuals, life-threatening cardiac arrest events were simulated. The PPG algorithm identified seven VT events and six VF events that were produced. VF events and one fast monomorphic VT event (perhaps hypotensive) were identified as "asystole" instead of extremely rapid tachyarrhythmias.

5.6. Respiratory rate

According to reports, as one of the primary vital signs to fluctuate in patients who are deteriorating, the respiration rate is the best indicator of cardiac arrest in general wards [99]. The methods used for RR monitoring now may make it more difficult to identify changes in a patient's state. In many patient care settings, intermittent RR is routinely measured by eye observation. Typically, counts of the chest wall motions are made for a duration of 15 s to one min. This approach has a number of inherent limitations that lessen the clinical utility of these measurements because it is intermittent and some patients have "morphology" (such as obesity or thoracic deformity) that may make it more difficult for caregivers to identify ventilatory-induced movements in the abdomen or chest. Most importantly, this kind of irregular surveillance could result in an incorrect assessment or an underestimate of clinical deterioration or worsening.

The ventilatory components are part of the PPG signal and are thought to modulate the baseline intensity of the PPG signal (Basal Modulation (BM)) as well as the frequency (Frequency Modulation (FM)) and amplitude (Amplitude Modulation (AM)) of the cardiac pulse. Respiratory sinus arrhythmia, a cardiac vagal reflex that causes the HR to rise during inhalation and fall during expiration, is the cause of FM [100–102]. The source of AM is fluctuations in the cardiac stroke volume brought on by the ventilatory influence on venous return, which in spontaneous breathing reduces with exhale and increases with inspiration (conversely in positive ventilation) [101, 102]. The breathing rate is directly reflected in this ventilatory modulation of the PPG signal.

L'her and colleagues examined the recordings of 201 ICU patients (SAPS II 51.7 ± 34.6) during the study's retrospective review phase. Most of these patients were admitted because they had respiratory failure and required invasive mechanical ventilation. 95.5% of patients had access to PPG-RR determination; it was comparable to the reference and showed a strong correlation with reference values ($R = 0.952$; $p < 0.0001$) [103].

Gehring et al. [104] found a > 0.96 connection between the PPG wristband and home sleep apnea tests, as well as accurate resting HR and breathing rate readings.

According to root mean square accuracy, PPG measurements were within 1 b[r]pm of reference measurements, indicating good accuracy.

5.7. Blood pressure

Monitoring blood pressure in ambulatory post-cardiac surgery patients is crucial for assessing their cardiovascular health and detecting any potential complications. After discharge, they

Table 1
Practical applications of wearable devices in healthcare

| Domain | Practical application | Clinical impact |
|---------------------------|---|--|
| Early mobilization | Step-count tracking | Reduced length of stay, improved functional recovery |
| Heart rate monitoring | Continuous HR tracking via PPG/ECG | Early detection of tachycardia, improved hemodynamic monitoring |
| Arrhythmia detection | Identification of atrial fibrillation (20–55% incidence post-surgery) | Timely intervention, reduced risk of stroke and complications |
| Respiratory monitoring | PPG-derived respiratory rate tracking | Early detection of respiratory deterioration |
| Remote monitoring | Post-discharge surveillance of vitals and activity | Enables early discharge, reduces readmissions, improves continuity of care |
| Complication detection | Detection of changes with mobility in HR, SpO ₂ | Identifies complications earlier than routine clinical observation |
| Rehabilitation support | Activity feedback and goal-setting | Enhances adherence to cardiac rehab programs |
| Data-driven decisions | Continuous data collection integrated into care plans | Personalized treatment and risk stratification |
| Limitations | Motion artifacts, battery life, sensor accuracy | May affect reliability and require clinical validation |
| Data and privacy concerns | Continuous collection of sensitive health data | Requires secure systems and regulatory compliance |

may be advised to continue monitoring their blood pressure regularly at home using a digital blood pressure monitor.

Blood pressure monitoring devices can provide continuous monitoring of blood pressure throughout the day and may be particularly useful for post-cardiac surgery patients who prefer a more integrated approach to monitoring their cardiovascular health. Telemonitoring platforms allow healthcare providers to remotely monitor patients' blood pressure readings and receive alerts for any abnormal values. This approach enables timely intervention and management of hypertension or hypotension in post-cardiac surgery patients, even when they are at home.

6. Practical Implications

In cardiac surgery, the practical implications of using wearable devices are increasingly significant, particularly in enhancing postoperative monitoring and recovery pathways such as ERAS. Wearables enable continuous, noninvasive tracking of key physiological parameters—including HR, rhythm, RR, oxygen saturation, and physical activity—both in-hospital and after discharge, reducing reliance on intermittent manual observations. Clinically, step-count data provide an objective measure of early mobilization, where achieving approximately 1000 steps on the first postoperative day has been associated with shorter hospital stays and lower complication risk, supporting more personalized rehabilitation targets. Continuous heart rhythm monitoring through wearable ECG or PPG can facilitate early detection of arrhythmias such as POAF, which occurs in up to 20–55% of cardiac surgery patients, allowing prompt intervention and potentially preventing serious complications like stroke or hemodynamic instability. Remote monitoring capabilities also enable earlier discharge with ongoing surveillance, improving bed utilization and reducing healthcare costs while maintaining patient safety. However, practical deployment requires addressing limitations such as reduced accuracy during motion or arrhythmias, battery life constraints, data integration into clinical workflows, and ensuring data privacy and regulatory compliance. Overall, wearable devices offer a pragmatic approach to bridging

inpatient and outpatient care in cardiac surgery, supporting early mobilization, timely complication detection, and more efficient, patient-centered recovery management (Table 1).

Edney et al. [2], in their systematic review, concluded that wearable devices are acceptable and feasible to use in acute care. The use of WATs by acute cardiac patients may increase patient participation in exercise and identify more sedentary patients who are at a greater risk of increased length of stay and hospital readmission.

7. Conclusions

Wearable devices hold significant promise as an adjunct to conventional monitoring in postoperative cardiac surgery care. By enabling early mobilization, continuous physiologic assessment, and remote surveillance, they can enhance recovery pathways, reduce complications, and potentially shorten hospital stays. However, challenges related to accuracy, data security, regulatory standards, and large-scale validation remain. Further high-quality clinical studies are needed to establish their safety, reliability, and cost-effectiveness before widespread integration into ERAS protocols.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Abisho Russal Starlet: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Anshuman Darbari:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Shubham Singh Rawat:** Validation, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. **Ishan Jhalani:** Validation, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization.

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How to Cite: Starlet, A. R., Darbari, A., Rawat, S. S., & Jhalani, I. (2026). Role of Wearable Devices in the Current Era of Healthcare. *Smart Wearable Technology*. <https://doi.org/10.47852/bonviewSWT62029375>