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Systematic Review

Wearable devices to monitor recovery after abdominal surgery: scoping review

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Abstract

Background: Wearable devices have been proposed as a novel method for monitoring patients after surgery to track recovery, identify complications early, and improve surgical safety. Previous studies have used a heterogeneous range of devices, methods, and analyses. This review aimed to examine current methods and wearable devices used for monitoring after abdominal surgery and identify knowledge gaps requiring further investigation.

Methods: A scoping review was conducted given the heterogeneous nature of the evidence. *MEDLINE*, *EMBASE*, and *Scopus* databases were systematically searched. Studies of wearable devices for monitoring of adult patients within 30 days after abdominal surgery were eligible for inclusion.

Results: A total of 78 articles from 65 study cohorts, with 5153 patients were included. Thirty-one different wearable devices were used to measure vital signs, physiological measurements, or physical activity. The duration of postoperative wearable device use ranged from 15 h to 3 months after surgery. Studies mostly focused on physical activity metrics (71.8 per cent). Continuous vital sign measurement and physical activity tracking both showed promise for detecting postoperative complications earlier than usual care, but conclusions were limited by poor device precision, adherence, occurrence of false alarms, data transmission problems, and retrospective data analysis. Devices were generally well accepted by patients, with high levels of acceptance, comfort, and safety.

Conclusion: Wearable technology has not yet realized its potential to improve postoperative monitoring. Further work is needed to overcome technical limitations, improve precision, and reduce false alarms. Prospective assessment of efficacy, using an intention-to-treat approach should be the focus of further studies.

Introduction

Recovery after abdominal surgery is a high-risk interval, with up to one-third of patients suffering a major postoperative complication within 30 days of surgery[1]. Delayed recognition of complications and subsequent delays in the escalation of care may lead to further avoidable harm[2,3]. Many studies have identified the 'failure to rescue' patients from complications as a major contributor to perioperative mortality[3–5], highlighting the importance of close postoperative monitoring. Even in patients who do not develop major complications, recovery can be challenging. Modern evidence-based enhanced recovery protocols have been shown to improve recovery, reduce complications, and postoperative duration of hospital of stay, but deviations from these protocols are common and are associated with poorer outcomes[6,7].

Protocol-driven measurements of vital signs by nursing staff are the most common strategy used for postoperative monitoring on surgical wards, often in conjunction with an 'early-warning score' system for escalation[8,9]. However, these traditional recordings rely on intermittent and simplistic measurements of physiological function and may not identify early or intermittent signs of patient deterioration[10,11].

Wearable devices such as 'smart watches' or 'smart patches' have been proposed as a novel method of monitoring patients after surgery to improve safety[12–14]. The activity metrics (such as step count and sleep) and physiological data (such as heart rate and respiratory rate) measured by these devices could be used to continuously monitor patients and track their recovery trajectory. Wearable devices have the potential to predict or detect the occurrence of postoperative complications and may also engage patients as active participants in the recovery process[15]; however, existing studies have used a diverse range of consumer- and research-grade wearable sensor devices and have employed heterogeneous methods of data collection and analysis.

This scoping review aimed to summarize the published literature investigating the use of wearable devices for patients during recovery after abdominal surgery, examine current methods and devices, and identify knowledge gaps requiring further investigation.

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Methods

Trial design

This was a scoping systematic review conducted according to the Joanna Briggs Institute guidance for scoping reviews[16]. This review was reported according to the PRISMA 2020 guidelines and the extension for scoping systematic reviews[17,18] (Appendix S1). Scoping reviews are not eligible for prospective registration on the *PROSPERO* database.

Search strategy

The *MEDLINE* (*Ovid*), *Embase*, and *Scopus* databases were searched from inception to 15 November 2021. Search terms related to surgery were combined with terms related to wearable devices and monitoring using Boolean 'AND' operators. The search strings used are included in Appendix S2.

Study selection

Inclusion criteria

Studies investigating wearable sensor devices in adult patients within 30 days of intra-abdominal surgery (including gastrointestinal, hepatobiliary, urological, gynaecological, and vascular surgery). Wearable sensors were defined as a device worn on the external body surface, unencumbered by wires, for the continuous and non-invasive detection of biosignals (such as movement, heart rate, respiratory rate, and oxygen saturation). There were no limits on sensor type, the specific metrics recorded, or the location of recordings (such as in a hospital or outpatient setting). Studies that used wearable sensors only in theatre or post-anaesthetic recovery units were excluded, as were studies that investigated the use of wearable devices with direct therapeutic intentions (such as electrostimulation).

There were no limits on indication for surgery or surgical approach. Studies conducted in obstetric cohorts (following Caesarean section) were excluded. Both observational and randomized studies were eligible for inclusion.

Studies reporting the use of wearable sensors in pre- or intraoperative settings were only included if they also reported postoperative use of wearable sensor devices.

Exclusion criteria

The exclusion criteria were:

- Paediatric patients (aged under 18 years), or if most of the included patients did not undergo abdominal surgery.
- Case reports, small case series ($n < 10$ patients), conference abstracts, and studies published in languages other than English.
- Study protocols without publication of results.
- Review articles, but the reference lists of all included studies and relevant review articles were manually screened to identify additional eligible papers for inclusion.

Data extraction and analysis

Records from the database search were exported and deduplicated in EndNote X9 (Clarivate, Philadelphia, Pennsylvania, USA) using the methods of Bramer *et al.*[19]. Two independent reviewers then used the Rayyan web application to screen the titles and abstracts for full-text review[20]. Discrepancies were settled by discussion between the reviewers as required. Authors were contacted by e-mail to clarify when it was unclear whether the study should be included.

Two investigators assessed and extracted relevant data from included full-text articles. Data and narrative summaries were extracted for each study with a pro forma developed specifically for the purposes of this review (Appendix S3).

It was expected that included papers would be too heterogeneous in their methods and inclusion criteria to perform a meaningful quantitative analysis. Therefore, this scoping review did not undertake any statistical analysis other than simple descriptive statistics used to report percentages or averages. A descriptive review of the included articles is presented.

Results

A total of 7138 records were screened, and 78 articles representing 65 study cohorts with a total of 5153 patients were included (*Fig. 1* and Appendix S4). Studies were predominantly conducted in Europe ($n = 33$, 42.3 per cent) and North America ($n = 28$, 35.9 per cent), with a minority from Asia ($n = 14$, 17.9 per cent) and Australia/New Zealand ($n = 3$, 3.8 per cent). More than half the included studies were published in 2020 or 2021 (*Fig. 2a*).

Most included articles were prospective observational studies ($n = 54$, 69.2 per cent); only 20 randomized studies were identified (25.6 per cent) (*Table 1*). Only six articles (7.7 per cent) were from multicentre studies; the majority were single-centre investigations. Studies mostly recruited mixed cohorts of patients undergoing abdominal surgery, and were predominantly conducted in elective patients, with only four studies including acute presentations.

Wearable devices used

A total of 31 different wearable devices were used by the included studies to measure vital signs or other physiological measurements (*Table 2*), or physical activity metrics (*Table 3*). Most devices were commercial- or research-grade ($n = 22$, 71.0 per cent); only a minority were medical-grade wearable sensors with US Food and Drug Administration or CE mark approvals ($n = 9$, 29.0 per cent). Several studies used wearable sensors as one component of a larger mHealth or eHealth programme for postoperative monitoring[21–28].

Most studies ($n = 56$, 71.8 per cent) reported on postoperative physical activity, predominantly measured as daily step counts (*Fig. 2b*). Respiratory rates and heart rates were the most measured vital signs and were reported by 19 (24.4 per cent) and 17 (21.8 per cent) studies respectively. Accelerometry data from these sensors were obtained from a range of body locations, including wrist, waist/hip, thigh, and ankle (*Tables 2* and *3*).

The duration of postoperative recordings was variable and ranged from 15 h to 3 months after surgery. Forty-five studies (57.7 per cent) used wearable sensors only during hospitalization, 6 studies (7.7 per cent) only at home, and 27 studies (34.6 per cent) had both hospital- and home-based recordings. In 36 studies (46.2 per cent), preoperative recordings were also used.

Patient recruitment and exclusion were often described poorly; 29 studies (37.2 per cent) reported the total number of patients screened, and 40 (51.3 per cent) reported the number of eligible patients, the number approached, and the number of eligible patients who declined to participate. Of the study cohorts who reported sufficient data, the mean rate of eligible patients who declined to participate was 30.2 ± 22.9 per cent (range 0–81.5 per cent). Patient characteristics were variably described; age and sex in 77 studies (98.7 per cent) each, ethnicity or race in 22 (28.2 per cent), BMI in 53 (67.9 per cent), and ASA score or other co-morbidity measures in 47 (60.3 per cent).

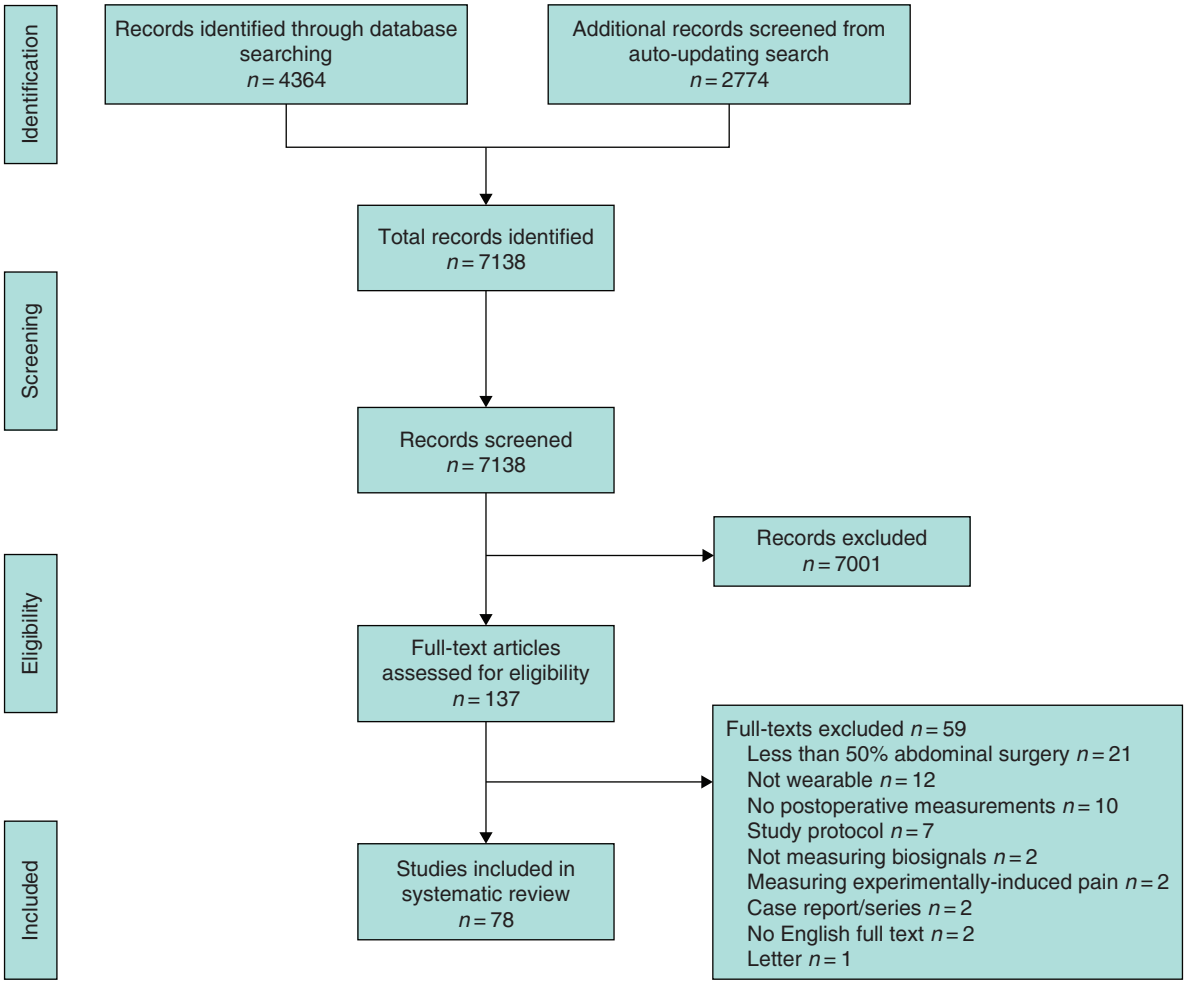

Fig. 1 PRISMA diagram

The reporting of adherence with the wearable device, rates of missing data, device failure, and strategies used to account for missing data were also poor. Adherence with the wearable device was only reported by 32 papers (41.0 per cent). Of those that did report adherence, this ranged from 49.2–100 per cent, though was defined variably between studies and could not be pooled. Two studies showed higher compliance with wrist-worn sensors during home-based recordings compared with in-hospital[26,29], however, others showed no difference[30]. Several studies reported higher compliance with wearable use compared with other elements of an mHealth programme such as symptom reporting[27,31]. The rate of missing or unusable data or device failure or loss was only reported by 39 studies (50.0 per cent) and ranged from 3.0–51.4 per cent. Poor signal quality, data transmission, and connection problems were all reported to contribute to missing data by several studies[24,32–34].

Physiological monitoring

Most studies on wearables to monitor postoperative physiology utilized in-hospital continuous vital sign monitoring. Pilot and feasibility trials implementing continuous vital sign monitoring systems suggested that this resulted in a shorter duration of hospital stay and fewer unplanned ICU admissions[35,36]. A continuous temperature monitoring device (iThermonitor) showed feasibility to identify fevers 4 h earlier and with a higher peak temperature than routine nurse measurements[37]. One small study implemented outpatient continuous vital sign monitoring following oesophagectomy; this showed no changes in clinical management but established the feasibility of home-based monitoring[38].

Inspection of vital sign recordings from wearable sensors showed that they can detect selected postoperative complications, particularly postoperative atrial fibrillation[39]. Abnormal respiratory patterns and cyclical airway obstruction were common in patients receiving postoperative opioid analgesia[40]. Other studies showed episodes of hypotension and hypoxia are common in postoperative patients and often unrecognized by routine measurements[41–43]. Two studies recorded gastrointestinal electrical activity from the abdominal surface and reported that this had the potential to predict postoperative ileus and diet readiness[44,45].

Several clinical validation studies compared the accuracy of wearable sensors with routine nursing measurements[33,34,46,47], bedside monitors[48–50], or other sensors[51]. Across the range of devices investigated, accuracy was generally acceptable with small errors in mean difference. However, the precision was poor with broad limits of agreement often outside clinically acceptable differences (*Table 4*). Several studies noted a 'digit bias' in nursing measurements of respiratory rate[46,47,52]. This implausible prevalence of respiratory rates of 16, 18, and 20 has

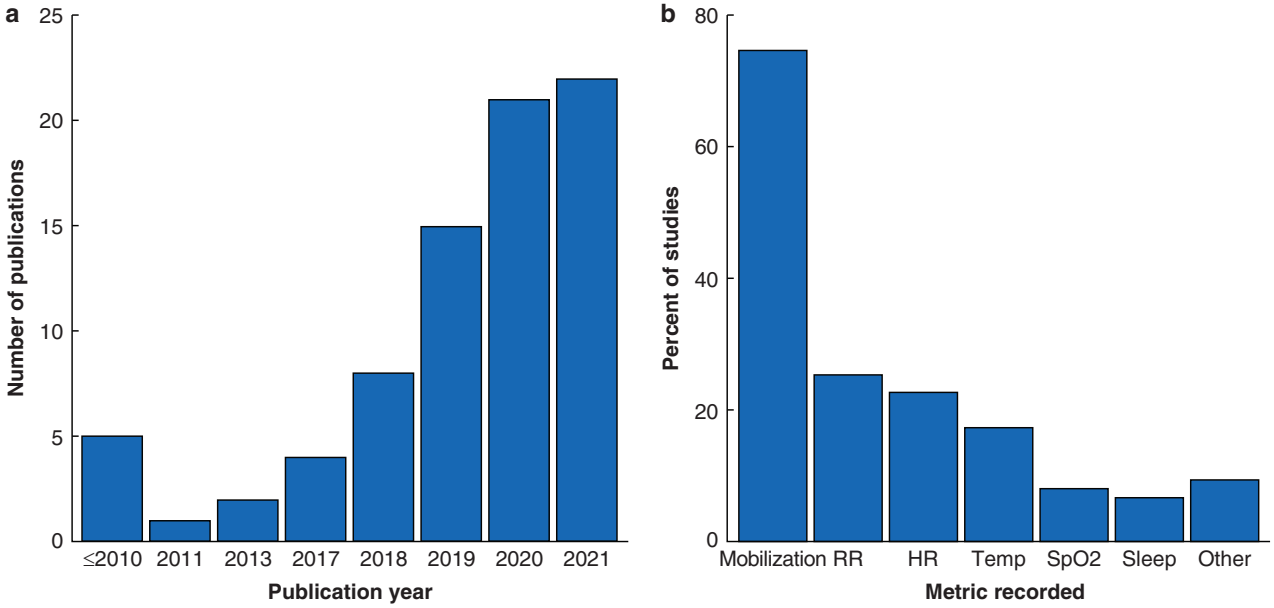

Fig. 2 a Number of included articles published per year. b Percentage of studies investigating various metrics using wearable sensors
RR, respiratory rate; HR, heart rate; Temp, temperature; SpO2, oxygen saturation.

Table 1 Summary characteristics of included studies and patient cohorts

	Studies, $n = 78$	Cohorts, $n = 65$
Specialty		
Mixed cohort	39 (50.0%)	29 (44.6%)
Colorectal	13 (16.7%)	11 (16.9%)
Oesophagogastric	8 (10.3%)	7 (10.8%)
Hepatopancreaticobiliary	7 (9.0%)	7 (10.8%)
Gynaecology	6 (7.7%)	6 (9.2%)
Bariatric	3 (3.8%)	3 (4.6%)
Urology	2 (2.6%)	2 (3.1%)
Study design		
Randomized trial	20 (25.6%)	18 (27.7%)
Non-randomized trial	4 (5.1%)	4 (6.2%)
Observational cohort	52 (69.2%)	42 (66.2%)
Number of centres		
Single	72 (92.3%)	61 (93.8%)
Multiple	6 (7.7%)	4 (6.2%)
Surgical urgency		
Elective only	65 (83.3%)	53 (81.5%)
Acute and elective	4 (5.1%)	3 (4.6%)
Not stated	9 (11.5%)	9 (13.8%)
Funding*		
Academic	54 (69.2%)	43 (66.2%)
Philanthropic	4 (5.1%)	3 (4.6%)
Industry	9 (11.5%)	8 (12.3%)
Unfunded	5 (6.4%)	4 (6.2%)
Not stated	14 (17.9%)	13 (20.0%)
Conflicts of interest*		
None	42 (53.8%)	34 (52.3%)
Wearable related	11 (14.1%)	10 (15.4%)
Not wearable related	14 (17.9%)	10 (15.4%)
Not stated	13 (16.7%)	12 (18.5%)

*Does not add up to 100% due to articles with multiple funding sources or conflicts of interest.

been previously reported[53], suggesting that routine nursing measurements may not be an appropriate gold-standard comparison for device validation.

Patient-reported evaluations of continuous vital sign monitoring generally reported high levels of acceptance, comfort, and safety[34–38,54,55]. However, in a randomized trial on the SensiumVitals patch, 24 per cent of patients chose to discontinue monitoring early[35], usually due to adverse skin effects. Several studies reported a patient preference to go home with wearable monitoring[55], potentially facilitating earlier discharge from the hospital[38]. Patients emphasized the importance of not losing opportunities for human contact with clinical staff, and concerns about devices not capturing other important aspects of the patient experience such as pain[33,54,56,57].

Nurses and other clinicians often recognized the potential of wearable devices for continuous vital signs monitoring, but also expressed concerns regarding the number of false-positive alerts (when the wearable device triggered an alert for abnormal vital signs that were normal on manual review of the patient), increasing workload, and overload of data[33,55,57].

Physical activity

Many papers investigated changes in physical activity perioperatively, showing reduced step counts after surgery, with a long return to baseline that may take weeks to months[21,25–27,29–31,58–68]. The recovery trajectory in physical activity differed depending on type of operation[64], use of laparoscopy[69–71], need for ICU admission[64], as well as overall performance status[72]. Romain *et al.* showed that postoperative step counts were correlated with preoperative steps[61]. Kovar *et al.* showed step counts on postoperative day three could predict activity levels at 1 month after surgery[68].

Multiple studies showed that greater postoperative physical activity was correlated with shorter length of stay[28,58,73–75], and a reduced risk of readmission following discharge[15,73,76,77]. Higher postoperative step counts were associated with a lower risk of complications[30,72–74,78–81], faster gastrointestinal recovery[73], and lower long-term skeletal muscle loss[82]. Patients with postoperative delirium had similar mobilization in the early postoperative interval and had lower physical activity at 1 month after surgery[83]. Of these studies aiming to predict postoperative outcomes with postoperative physical activity

Table 2 Wearable devices tracking vital signs and other physiology

Name	Company	Number of studies	Location	Grade	US Food and Drug Administration	CE mark	Metrics
HealthPatch MD/Vital Patch	VitalConnect (California, USA)	8	Chest	Clinical	Yes	Yes	ECG, heart rate, heart rate variability, respiratory rate, skin temperature, accelerometery
SensiumVitals Patch	Sensium (UK)	7	Chest	Clinical	Yes	Yes	Heart rate, respiratory rate, axillary temperature
ViSi Mobile	Sotera Wireless (California, USA)	6	Wrist and chest	Clinical	Yes	Yes	Continuous non-invasive blood pressure, oxygen saturation, heart rate, pulse rate, respiratory rate, skin temperature, ECG, posture, fall detection
G-Tech Patch	G-Tech Medical (California, USA)	2	Abdomen	Research	No	No	Cutaneous electrical signals from the gastrointestinal tract
Orient Speck	Centre for Speckled Computing, University of Edinbugh (UK)	2	Chest/ Abdomen	Research	No	No	Respiratory rate
Aingeal	Renew Health (Ireland)*	1	Chest	Clinical	Yes	Yes	Respiratory rate, ECG, skin temperature, accelerometery
HealthDot	Phillips (The Netherlands)	1	Chest	Clinical	No	Yes	Heart rate, respiratory rate, body posture, activity
iThermonitor	Raiing Medical Company (China)	1	Axilla	Clinical	Yes	Yes	Axillary temperature
Radius- 7	Masimo (California, USA)	1	Arm	Clinical	Yes	Yes	Oxygen saturation, pulse rate, perfusion index, pleth variability index, total haemoglobin, methaemoglobin, carboxyhaemoglobin, oxygen content, oxygen reserve index, acoustic respiration rate

*Formerly called Intelesens.

Table 3 Wearable devices tracking activity metrics

Name	Company	Number of studies	Location	Grade	US Food and Drug Administration	CE mark
Fitbit (various models*)	Fitbit (California, USA)	18	Wrist	Consumer	No	No
Vivofit (various models†)	Garmin (Switzerland)	8	Wrist	Consumer	No	No
UP MOVE	Jawbone (California, USA)†	4	Wrist	Consumer	No	No
ActiGraph (GT3X+ or GT9X)	Actigraph (Florida, USA)	4	Hip/Waist	Clinical	Yes	Yes
Active tracer AC-301	GMS Co. (Tokyo, Japan)	3	Ankle	Research	No	No
E-care Fit	NEWEL (France)	2	Wrist	Research	No	No
Lifecorder	Suzuken Co. (Japan)	2	Waist	Research	No	No
acitvPAL3 micro	PAL Technologies (UK)	1	Thigh	Research	No	No
Active style Pro HJA-750C	Omron Healthcare (Japan)	1	Hip/Waist	Consumer	No	No
Actiwatch 64	Mini Mitter/Respironics, (Oregon, USA)	1	Wrist	Clinical/ Research	No	Yes
Apple Watch	Apple (California, USA)	1	Wrist	Consumer	No	No
Lifegram LA11M-BS	LG Electronics (South Korea)	1	Wrist	Consumer	No	No
Mini-Motion Logger Actigraph	Ambulatory Monitoring (New York, USA)	1	Wrist	Research	No	No
MTN/220 accelerometer	ACOS Co. (Japan)	1	Hip/Waist	Research	No	No
New Lifestyles NL-2000i	New Lifestyles (Michigan, USA)	1	Hip/Waist	Consumer	No	No
OMRON Walking Style Pro 2.0	OMRON Medizintechnik (Germany)	1	Hip/Waist	Consumer	No	No
PAM AM101 accelerometer	PAM (The Netherlands)	1	Hip/Waist	Consumer	No	No
Polar Loop Activity Tracker	Polar Electro Oy (Finland)	1	Wrist	Consumer	No	No
Portable Sleep Monitor (PSM100A)	Chengdu Sealand Technology Co. (China)	1	Chest	Research	No	No
Positional Activity Logger	Gorman ProMed (Victoria, Australia)‡	1	Thigh	Research	No	No
Samsung Gear	Samsung Group (South Korea)	1	Wrist	Consumer	No	No
Tractivity ankle pedometer	Kineteks Corporation (Canada)‡	1	Ankle	Consumer/ Research	No	No

*Alta HR, Inspire HR, Zip, Charge, Charge 2, Flex, Versa. †Vivofit, Vivofit 2, Vivofit 3. ‡No longer active.

measurements, only four accounted for patients' baseline preoperative physical activity levels[76,80,81,83]. No studies analysed physical activity data in 'real time' to monitor recovery or identify complications.

Several studies investigated trends in activity to predict outcomes. Iida *et al.* investigated the impact of different recovery trajectories following hepatectomy, classifying patients into 'steady increase', 'bell curve', and 'flat' categories[78,79]. Patients

Table 4 Accuracy and precision of wearable devices reported in clinical validation studies

Device	Study	Reference standard	Patients	Pairs of measurements	Mean difference (reference – device)	95% Limits of agreement
Heart rate (b.p.m.)						
HealthPatch	Breteler 2018[49]	Bedside monitor	25	3986	−1.2	−5.7 to 3.2
	Breteler 2020[48]	Bedside monitor	25	29 619	1.3	−4.1 to 6.9
	Weenk 2017[33]	Nursing measurements	10	86	−1.52	−9.51 to 12.55
	Weenk 2019[56]	Nursing measurements	30	NS	−1.00	−11.11 to 13.11
SensiumVitals	Breteler 2020[48]	Bedside monitor	25	16 917	1.0	−14.6 to 16.7
	Downey 2019[46]	Nursing measurements	51	1135	−1.85	−23.92 to 20.22
ViSi Mobile	Weenk 2017[33]	Nursing measurements	10	86	−0.20	−11.06 to 10.66
	Weenk 2019[56]	Nursing measurements	30	NS	0.69	−17.48 to 18.86
Masimo	Breteler 2020[48]	Bedside monitor	25	34 992	−0.4	−11.9 to 11.0
Aingeal	Cheng 2021[34]	Nursing measurements	35	NS	1.12	−24.03 to 26.27
Healthdot	Van der Stam 2021[50]	Bedside monitor	25	237 928	−0.23	−7.43 to 6.97
Respiratory rate (/min)						
HealthPatch	Breteler 2018[49]	Bedside monitor	25	4001	−2.4	−10.8 to 5.9
	Breteler 2020[48]	Bedside monitor	25	29 135	4.4	−5.8 to 14.7
	Weenk 2017[33]	Nursing measurements	10	86	−0.64	−10.32 to 9.04
	Weenk 2019[56]	Nursing measurements	30	NS	−1.94	−8.92 to 5.04
SensiumVitals	Breteler 2020[48]	Bedside monitor	25	17 595	−0.8	−8.5 to 6.9
	Downey 2019[46]	Nursing Measurements	51	1134	2.93	−8.19 to 14.05
ViSi Mobile	Weenk 2017[33]	Nursing measurements	10	86	1.19	−5.53 to 7.91
	Weenk 2019[56]	Nursing measurements	30	NS	0.84	−5.88 to 7.56
Masimo	Breteler 2020[48]	Bedside monitor	25	33 032	0.2	−6.6 to 6.3
Aingeal	Cheng 2021[34]	Nursing measurements	35	NS	1.04	−6.88 to 8.96
Healthdot	Van der Stam 2021[50]	Bedside monitor	21	263 742	0.28	−5.19 to 5.74
Temperature (°C)						
HealthPatch	Weenk 2019[56]	Nursing measurements	30	NS	2.76	1.02 to 4.50
ViSi Mobile	Weenk 2019[56]	Nursing measurements	30	NS	2.96	0.75 to 5.17
Aingeal	Cheng 2021[34]	Nursing measurements	35	NS	−1.45	−5.67 to 2.76
SensiumVitals	Downey 2019[46]	Nursing measurements	51	1132	0.82	−1.13 to 2.78
iThermonitor	Liu 2020[37]	Nursing measurements	526	3621	−0.03	−0.73 to 0.63
Oxygen saturation (%)						
ViSi Mobile	Weenk 2019[56]	Nursing measurements	30	NS	0.94	−4.25 to 6.13
Systolic blood pressure (mmHg)						
ViSi Mobile	Weenk 2019[56]	Nursing measurements	30	NS	5.42	−22.5 to 33.4

NS, not stated.

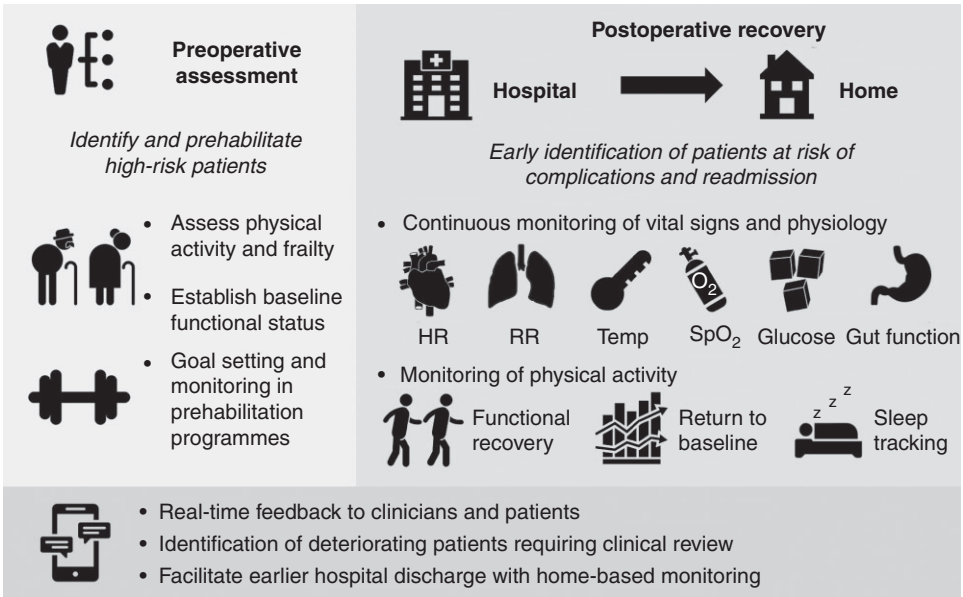

Fig. 3 Potential preoperative and postoperative uses of wearable technology for patients undergoing major abdominal surgery

RR, respiratory rate; HR, heart rate; Temp, temperature; SpO2, oxygen saturation.

with a 'steady increase' had a low risk of complications. Wound infections, pleural effusions, and ascites were more common in the bell curve group, and postoperative pneumonia was observed only in patients with a flat recovery profile[79]. Robinson *et al.* showed that a decrease in step count of more than 50 per cent over 2 days consecutively after surgery had a 79 per cent sensitivity and 90 per cent specificity for hospital readmission.

Several interventions to increase postoperative physical activity were studied, often with limited success[84–91]. One randomized trial investigating a targeted step count intervention showed no difference in duration of hospital stay and increased fatigue scores in patients with a wearable fitness tracker[92]. In comparison, a non-randomized trial showed a lower risk of pneumonia and shorter duration of hospital stay in a self-selected group of patients[93]. Feedback from wearable devices had mixed effects; some studies reported increased activity[74,94], whereas others reported no effect[63,95].

Five studies reported on postoperative sleep metrics derived from accelerometer data in combination with or separate from other physiological information (such as electrocardiogram signals)[59,96–99]. Sleep was generally poor during hospital stays[96,97], predominantly driven by night-time awakenings, correlated with patient-reported symptoms[59,98], and better sleep quality was associated with shorter duration of hospital stay[99].

Discussion

Wearable technology has the potential to revolutionize postoperative monitoring and recovery after abdominal surgery (*Fig. 3*), but this possibility has not yet been realized. This scoping review identified a heterogeneous range of wearable sensors that have been studied in patients undergoing major abdominal surgery. Most studies were non-randomized and focused on the feasibility of using wearables to monitor physical activity or vital signs. Sensors were generally commercially available products and were not designed specifically for postoperative monitoring. Data were predominantly stored on the wearable device without wireless transmission, and rates of device failure and data loss were poorly reported. Adherence with the device was also infrequently described, and analysis was predominantly conducted retrospectively with a 'per-protocol' analysis rather than in real-time. Several studies suggested that measurements from wearable sensors were associated with clinical outcomes, including complications, duration of hospital stay, and readmission; however, while promising, the overall efficacy of these devices for early detection of complications compared with existing standards of care remains unclear.

Continuous vital sign and physiological monitoring

Wearable devices have the potential to improve surgical safety by identifying high-risk deteriorating patients for early intervention and 'rescue' from complications[10,100]. Vital sign changes are the fundamental components behind early-warning score systems that have been introduced worldwide to recognize deteriorating patients[8]; however, intermittent vital sign measurement often misses significant postoperative hypotension, hypoxemia, and apnoea[41,101,102], with potential clinical consequences. Continuous monitoring of vital signs and early-warning score data in real-time may allow for earlier detection of vital sign changes, recognition of early signs of complications, and a faster time to intervention[103–105]. Using wearable devices is clearly preferable to traditional wired bedside monitors; however, technical challenges of accuracy, precision, and data transfer remain incompletely solved. Furthermore, it remains unclear whether earlier detection translates to meaningful clinical benefits. Pilot and feasibility randomized trials have shown promise in reducing unplanned ICU admission and duration of hospital stay[35,36]; however, these findings need to be replicated in adequately powered efficacy trials across a range of hospital settings.

Multiple sensors are available for continuous vital sign measurement, and these are rapidly advancing[106]. Patch-based sensors with electrodes for sensing heart rate and respiratory rate such as SenisumVitals, HealthDot, and Vital Patch offer a non-obstructive solution for monitoring with favourable acceptability to patients[34,38,47,50,56]. More complex systems such as the ViSi Mobile device include the use of finger plethomyosgraphy sensors with a wider range of metrics but may be more intrusive due to wired connections between components[56]. Although the accuracy of these devices was generally acceptable, precision was highly variable and often outside clinically acceptable limits. Addressing this will require further technical advancements in sensor design, signal processing, and validation against appropriate gold standards[107], especially given the 'digit bias' evident in nursing measurements of respiratory rate, which are not consistent with true respiratory rates[108,109].

Respiratory rate is crucial in identifying deteriorating patients[110], and the accurate non-invasive measurement of this metric is paramount to the clinical applicability of wearable devices. In this review, respiration was measured by various techniques, including impedance pneumography, derivation from respiratory sinus arrhythmia changes in electrocardiogram signals, and accelerometers[47]. The relative accuracy and precision of these methods need further investigation. Furthermore, the assessment of respiratory function may be more complicated than measuring respiratory rate alone. Previous work has shown respiratory rate changes do not correlate with changes in either tidal volume or minute ventilation[111]. For other vital signs, it remains unclear whether skin temperature measurements from patch-based sensors can capture changes in core temperature, relevant for identifying fevers or other postoperative complications[47].

Assessment and optimization of the patient experience will be essential for the implementation of continuous vital signs monitoring in clinical practice[112]. Although the devices were generally well accepted by the patients in these studies, it should be noted that on average up to one-third of eligible patients declined to participate or withdrew during the study, and the reasons for this remain largely unexplored. The use and implementation of wearable devices in vulnerable patients (those with cognitive impairment, communication difficulties, delirium, or low health literacy) should be explored as this setting poses unique challenges and opportunities for continuous monitoring. Optimal strategies for data processing and presentation to clinicians also remain unclear, as a high rate of false-positive alarms was identified as a barrier to clinical implementation of wearable sensors among nursing staff[33,55,57]. Optimization of device precision and methods for artefact filtering is essential to prevent alarm fatigue when data are presented in real-time to clinical staff. Averaging data over longer periods has been proposed as a solution to reduce the number of false alarms[49], but this should be balanced against maintaining granularity of data to ensure that clinically

significant episodes are detected. Prediction of patient deterioration using advanced data analytics may offer another solution to this problem and more accurately identify deteriorating patients[113]. Future studies should directly assess the impact of continuous monitoring on clinician workload, particularly for nursing staff.

Other potential avenues for wearable technology in postoperative patients include recording of gastrointestinal activity (with acoustic or electrical signals)[44,45,114,115], continuous glucose monitoring for subclinical insulin resistance driven by the surgical stress response[116,117], sensing of postoperative pain[118,119], or other novel biomarkers of autonomic tone[120]. Continuous oximetry using wearable patches also remains an avenue of further development; however, care must be taken during sensor design to ensure compatibility with different skin tones and prevent the reinforcement of existing healthcare inequities[121].

Postoperative physical activity monitoring

Early postoperative mobilization is a core tenant of enhanced recovery after surgery (ERAS) guidelines for all abdominal surgical specialties, and it therefore is a potential avenue for intervention to accelerate patient recovery through the utilization of digital technologies[112]. Wearables were used by several studies in this review to measure physical activity after surgery, either passively, or as part of other interventions aiming to increase mobilization.

Numerous studies showed that patients who mobilized less (both before and after surgery) were at a higher risk of complications, readmissions, and other adverse outcomes[58,66]; however, to what extent these findings represent the baseline frailty of patients rather than a potentially modifiable mediator of perioperative risk remains unclear. Notably, a recent randomized trial conducted within an established ERAS programme found that mobilization targets did not reduce patient complications, but increased levels of fatigue[92].

Normalizing a patient's postoperative physical activity relative to their baseline may be a more appropriate method for risk assessment[76,80], and the characterization of mobilization 'patterns' as suggested by Iida *et al.* may offer more detailed insights into the prediction of specific postoperative complications[78,79]. The ability of physical activity to predict complications in 'real time', as opposed to retrospectively, also remains unclear, and requires further targeted investigation. Targeted feedback of physical activity data from wearable devices has the potential to change behaviour and decision-making for both patients and clinicians and optimal methods to help guide this should be explored[122,123].

There are also several technical challenges with applying wearable activity trackers to monitor postoperative recovery that remain unsolved. Movement in postoperative patients may be characterized by shorter steps that are less purposeful, and concerns regarding the reliability of sensors in these populations have been raised, given few commercial activity monitors have been validated in hospitalized or postoperative patients[124,125]. A more sophisticated approach than measuring 'step counts' may be required for more accurate assessment of postoperative physical activity. Furthermore, concerns have been expressed regarding the reliability of wrist-based measurements of activity[126], and this may vary with the location of device placement (such as wrist, ankle, or hip)[127].

Limitations of this review

There are several limitations to this scoping review, including its focus on abdominal surgery, without considering other specialties; however, this was carried out as the principles of recovery for abdominal surgery are relatively homogenous across procedures. This review did not assess specialty-specific outcomes such as joint movement after orthopaedic surgery, although the applications of this technology have been described elsewhere[128]. Second, mobile applications, and environmental sensors also have potential roles in tracking postoperative recovery[129–131], either in the hospital or after discharge, though evaluating these approaches was beyond the scope of this review. Finally, we were unable to perform a quantitative analysis due to the heterogeneous methods, devices, and populations included in the review.

Future research

Ongoing work in this field should be guided by the IDEAL framework[132], clearly reported[133], and initially developed/explored (stage 2a and 2b trials) to develop optimal devices and methods for postoperative monitoring, before moving to an adequately powered stage 3 randomized trial.

Technical advances in accuracy and reliability of wearable devices for physiological monitoring are needed, with consideration of appropriate gold-standard comparisons, and optimization of filtering and alarm thresholds[107]. Future clinical studies should clearly report adherence with wearable device use, reasons for refusal to participate, and aim to assess device acceptance by patients and nursing staff. Technical performance metrics, including the rates of missing data and device failure, should also be reported. Other authors have called for standardization in the quantification and analysis of data from wearable sensors[134], and this remains an area requiring consensus.

'Failure to rescue' is an important concept in postoperative monitoring[10] but is difficult to apply as a primary outcome given the relatively rare occurrence of postoperative mortality. Proxy measures, including the time of detection of complications compared with standard observations, the overall number, and burden of postoperative complications, rate of unplanned ICU admission, or duration of hospital stay could be considered by future studies investigating wearable devices.

Patient-reported outcome and experience measures should be assessed as part of overall postoperative recovery, in addition to adherence to enhanced recovery protocols and postoperative mobilization. Additionally, home-based continuous vital sign monitoring and 'unsupervised' use of devices also remains an area requiring further study[38].

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Supplementary material

Supplementary material is available at *BJS Open* online

Data availability

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

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