

Research Article

Agreement Between Wearable-based Vital-sign Monitoring and Standard Bedside Monitoring in Patients After Knee Arthroscopy

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Abstract

Postoperative vital sign monitoring is essential for early detection of inpatient hemodynamic and respiratory complications. Although conventional bedside monitors serve as the clinical gold standard, their fixed design limits patient mobility and continuous ambulatory monitoring, which hinders early rehabilitation after orthopedic surgery. Wearable monitoring devices have shown great potential for postoperative vital sign surveillance due to their mobility and continuous data collection capabilities, yet real-world validation data in orthopedic postoperative patients remain insufficient, and wearable blood pressure measurement accuracy remains controversial. This study aimed to evaluate the agreement between a wearable monitor and a standard bedside monitor for heart rate, respiratory rate, systolic blood pressure, diastolic blood pressure, and peripheral oxygen saturation (SpO₂) in patients undergoing knee arthroscopy. A total of 100 elective knee arthroscopy patients were prospectively enrolled. Paired vital sign data were collected simultaneously via the two devices at four daily time points over two postoperative days. Intra-class correlation coefficient (ICC), Lin's concordance correlation coefficient, Bland-Altman analysis, temporal trend analysis, and clinical acceptability evaluation were performed for statistical assessment. After excluding five missing values, 3995 paired observations were analyzed. The wearable device showed excellent agreement for heart rate (ICC = 0.994, bias = -0.63 bpm, 95% LoA: -2.97 to 1.70 bpm), good agreement for respiratory rate (ICC = 0.940, bias = -0.51 breaths/min, 95% LoA: -2.71 to 1.68 breaths/min), and moderate-to-good agreement for SpO₂ (ICC = 0.872, bias = -0.85%, 95% LoA: -3.50 to 1.80%). Diastolic blood pressure showed moderate agreement (ICC = 0.827, bias = -1.42 mmHg, 95% LoA: -12.90 to 10.06 mmHg), while systolic blood pressure demonstrated the lowest agreement (ICC = 0.811) with a prominent positive systematic bias of 5.63 mmHg. Temporal trends remained stable across postoperative days, with consistent inter-device bias over time. The clinical acceptability rates of heart rate, respiratory rate and SpO₂ exceeded 99.5%, compared with 92.2% for diastolic blood pressure and only 79.6% for systolic blood pressure. In conclusion, the wearable monitor provides reliable heart rate, respiratory rate, and SpO₂ measurements and is suitable for routine postoperative monitoring after knee arthroscopy. However, blood pressure measurements, particularly systolic blood pressure, show notable systematic deviation, and targeted algorithm calibration is needed to improve its blood pressure monitoring performance.

Keywords

Wearable Monitoring, Vital Signs, Bedside Monitor, Measurement Agreement, Knee Arthroscopy, Postoperative Monitoring

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1. Introduction

Postoperative vital-sign surveillance constitutes a cornerstone of inpatient care, enabling early detection of hemodynamic instability, respiratory depression and other postoperative adverse events [1, 2]. Conventional bedside multi-parameter monitors are the clinical gold standard. However, wired or fixed-position hardware restricts patient mobility and continuous ambulatory monitoring, and patients must remain relatively stationary for each measurement reading [3].

With advances in micro-sensor technology, wearable physiological monitors have emerged as a promising alternative for postoperative settings [4]. Wearable devices permit continuous, ambulatory data acquisition without restricting patient activity, which is particularly valuable for postoperative rehabilitation, where early mobilization is emphasized [5]. If measurement performance is clinically acceptable, wearables could reduce nursing workload, facilitate real-time trending, and potentially shorten hospital stays or support step-down ward-based or home-monitoring pathways for surgical patients [6].

Nevertheless, before widespread clinical adoption, rigorous validation against reference-standard bedside monitors is mandatory [7]. Existing validation studies are heterogeneous, often focusing on healthy volunteers or intensive-care cohorts, while real-world postoperative orthopedic-surgical patient data remain limited [8]. Systematic bias and wide limits of agreement have been reported for non-invasive blood-pressure measurement in many consumer-grade wearable systems, raising concerns regarding absolute-value reliability, even when trend tracking appears adequate [9, 10].

Knee-arthroscopy represents one of the most common orthopedic surgical procedures, with large volumes of patients receiving short-term inpatient postoperative observation. This patient population is characterized by generally stable perioperative hemodynamics under neuraxial anesthesia, making it a suitable model to test wearable-monitor performance under routine ward conditions. The present study aimed to quantify snapshot measurement agreement under semi-recumbent resting conditions between a wearable vital-sign monitor and standard bedside monitor for heart rate, respiratory rate, systolic blood pressure, diastolic blood pressure and peripheral oxygen saturation (SpO₂) in stable patients following knee arthroscopy. We further explored whether measurement discrepancies varied across these scheduled postoperative time-points and assessed clinical acceptability of wearable-derived resting snapshot values.

2. Materials and Methods

2.1. Study Population

This prospective observational study enrolled 100 adult patients who underwent elective knee-arthroscopy surgery between June 2024 and July 2025. Inclusion criteria included

age ≥ 18 years, receiving knee-arthroscopy under neuraxial anesthesia, expected postoperative inpatient stay ≥ 2 days, and ability to tolerate wearable-sensor placement. Exclusion criteria included severe peripheral-vascular disease limiting non-invasive blood-pressure acquisition, skin injury at wearable-sensor attachment sites, severe cardiopulmonary comorbidities requiring intensive-care-unit-level postoperative care, and inability to cooperate with repeated scheduled measurements. Baseline demographic, anthropometric, surgical-procedure and anesthesia-related variables were retrospectively extracted from electronic medical records. The study was approved by the Ethics Committee of Yan'an University Affiliated Hospital (No. YAS-H01-202406009) and conducted in accordance with the Declaration of Helsinki. This study was registered at the Chinese Clinical Trial Registry (ChiCTR2600122314).

2.2. Measurement Protocol

Two monitoring systems were deployed simultaneously: the standard ward bedside monitor (Group A, reference device: BeneVision N15, Mindray Medical International Ltd., China) and the investigational wearable multi-parameter monitor (Group B, test device: MC10, Hunan Wanmu Qianfan Technology Co., Ltd., China). Paired measurements of heart rate, respiratory rate, systolic blood pressure, diastolic blood pressure, and SpO₂ were collected at four predefined time-points daily (08:00, 10:00, 12:00, 14:00) across two consecutive postoperative days (Postoperative Day 1 and Day 2). Patients maintained a semi-recumbent resting posture throughout each measurement cycle. Missing values due to signal-acquisition failure were documented and excluded from pairwise statistical analyses.

All paired readings from the reference bedside and investigational wearable monitor were captured concurrently by the same trained research observer. At each predefined wall-clock time-point, outputs from both devices were recorded within a 30-second window. Hardware clock synchronization was not performed between the two systems; paired data were matched using scheduled wall-clock snapshot sampling rather than the devices' internal timestamps. Of note, only discrete snapshot measurements at fixed time-points were obtained in this study, and continuous streaming-mode data acquisition was not performed.

2.3. Outcomes

The primary outcome was inter-device measurement agreement between wearable monitor and bedside monitor for five vital-sign parameters. Agreement was comprehensively evaluated using intra-class correlation coefficient (ICC 2, 1), Pearson correlation coefficient, Lin's concordance-correlation co-

efficient (CCC), and Bland-Altman analysis (mean bias defined as Group A – Group B, 95 % limits of agreement, LoA) [11, 12].

The secondary outcomes included:

- 1) Temporal stability of measurement bias: To assess whether device-derived discrepancies changed over the postoperative observation window. Mean values from both monitors and corresponding inter-device biases were calculated for each of the eight scheduled time-points (D1-08:00, D1-10:00, D1-12:00, D1-14:00, D2-08:00, D2-10:00, D2-12:00, D2-14:00). Overall vital-sign levels between postoperative Day 1 and Day 2 were compared.
- 2) Clinical acceptability of wearable measurements: Proportion of paired measurements falling within pre-specified clinical tolerance thresholds: heart rate ± 5 bpm; respiratory rate ± 3 breaths/min; SpO₂ ± 3 %; systolic blood pressure ± 10 mmHg; diastolic blood pressure ± 10 mmHg. Additional metrics included mean absolute error (MAE), root-mean-square error (RMSE), and mean absolute percentage error (MAPE).

2.4. Statistical Analysis

Descriptive statistics for each device-derived vital-sign parameter were calculated as mean $\pm$ standard deviation. Missing data were excluded pairwise.

The primary agreement analyses:

- 1) Intra-class correlation coefficient (ICC 2, 1, two-way random-effects model for single-measurement reliability);
- 2) Pearson correlation coefficient for linear association;
- 3) Lin's concordance-correlation coefficient (CCC) for systematic and random agreement;
- 4) Bland-Altman analysis: mean bias calculated as Group A – Group B; 95 % limits of agreement (LoA) defined as mean bias $\pm 1.96 \times$ standard deviation of differences.

The secondary analyses:

- 1) Paired-sample t-tests (or Wilcoxon signed-rank test for non-normal differences) to test for mean difference between devices.

2) Temporal-trend analysis: mean values stratified by each of the eight time-points were plotted to visualize postoperative trajectories and inter-device-bias stability over time. Comparison between Day 1 and Day 2 overall means was performed.

3) Clinical-acceptability assessment: pre-defined clinical tolerance thresholds referenced to standard clinical monitoring requirements: heart rate ± 5 bpm; respiratory rate ± 3 breaths/min; SpO₂ ± 3 %; systolic blood pressure ± 10 mmHg; diastolic blood pressure ± 10 mmHg. The proportion of paired differences falling within tolerance thresholds (within-threshold agreement rate), mean absolute error (MAE), root-mean-square error (RMSE), and mean-absolute-percentage error (MAPE) were computed.

Statistical analyses were performed using Python and R; two-tailed $P < 0.05$ was considered statistically significant.

3. Results

3.1. Patient Baseline Characteristics

One-hundred patients were included for analysis. The mean age was 45.38 ± 10.97 years (range 18-59 years). There were 46 % males and 54 % females. The mean BMI was 25.20 ± 4.02 kg/m². Most patients were ASA physical-status Class II (98 %), only 2 % were ASA III. Main anesthesia modalities included combined spinal-epidural (43 %), epidural (41 %), spinal (9 %), and other intraspinal anesthesia (7 %). Mean surgical duration was 80.77 ± 33.79 min and mean anesthesia duration was 124.77 ± 37.29 min. Mean postoperative-length-of-stay was 8.27 ± 3.90 days. 83% of participants had no reported comorbidities, while 8 % had hypertension and 9 % had miscellaneous comorbid conditions. These data were presented in Table 1.

No participants experienced skin irritation, local erythema, or other adverse events associated with wearable-sensor placement, and no subject discontinued participation due to wearable-related discomfort.

Table 1. Demographic and basic operation-related data of the patients.

Variable	Summary
Age, years	45.38 ± 10.97 (range 18-59)
Sex, %	Male 46%, Female 54%
BMI, kg/m ²	25.20 ± 4.02 (Normal 43%, Overweight 35%, Obese 22%)
ASA Class, %	II 98%, III 2%
Anesthesia Type	Combined spinal-epidural 43%, Epidural 41%, Spinal 9%, Intraspinal 7%

Variable	Summary
Surgical Duration, min	80.77 ±33.79
Anesthesia Duration, min	124.77 ±37.29
Postoperative LoS, days	8.27 ±3.90
Comorbidities, %	None 83%, Hypertension 8%, Other 9%

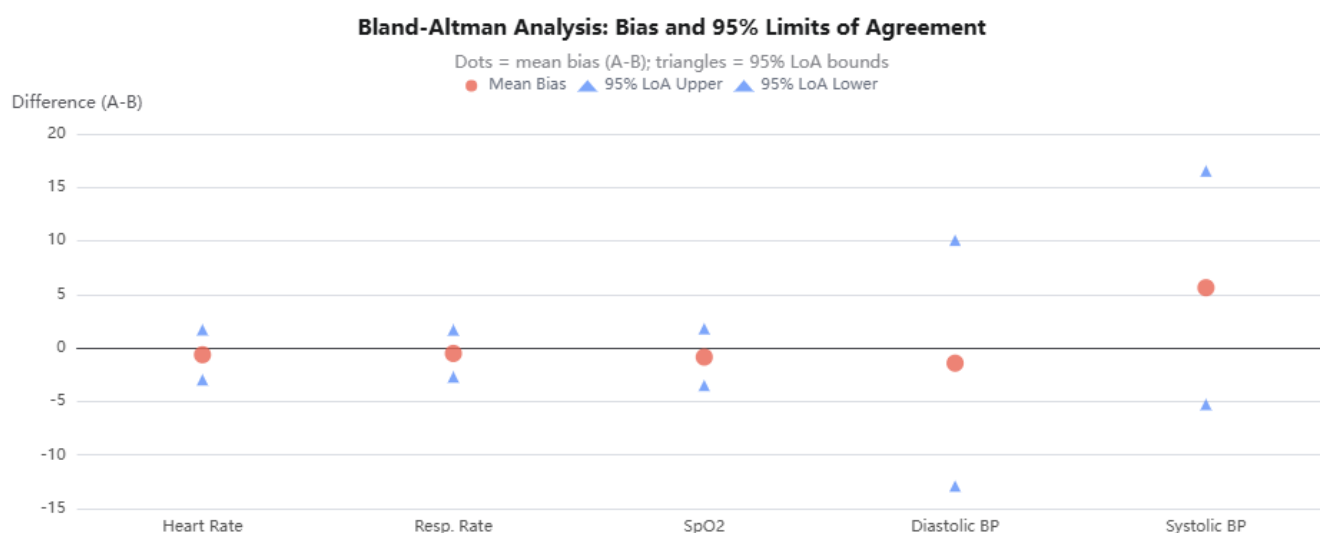
BMI = body-mass index; ASA = American Society of Anesthesiologists physical-status classification; LoS = length of hospital stay.

3.2. Overall Inter-device Agreement

Of theoretically 800 paired records per vital-sign variable, five diastolic blood pressure records were missing due to signal loss, yielding $n = 796$ for diastolic blood pressure, $n = 799$ for respiratory rate, and $n = 800$ for heart rate, systolic blood pressure and SpO₂.

Table 2 shows the results of inter-device agreement. Heart-rate agreement was excellent, with an ICC of 0.994, a Pearson correlation coefficient of 0.995, and a Lin's CCC of 0.994. The mean bias was -0.63 bpm, and the 95 % limits of agreement ranged from -2.97 bpm to 1.70 bpm (Figure 1). Respiratory-rate agreement was good. The ICC was 0.940, the Pearson r was 0.950, and the Lin's CCC was 0.940. The mean bias reached -0.51 breaths/min, with 95 % limits of agreement

from -2.71 breaths/min to 1.68 breaths/min (Figure 1). SpO₂ showed moderate-to-good agreement. It had an ICC of 0.872, a Pearson r of 0.910, and a Lin's CCC of 0.872. The mean bias was -0.85 %, and the 95 % limits of agreement were -3.50 % to 1.80 % (Figure 1). Diastolic blood pressure demonstrated moderate agreement, presenting an ICC of 0.827, a Pearson r of 0.847, and a Lin's CCC of 0.827. The mean bias was -1.42 mmHg, and the corresponding 95 % limits of agreement spanned -12.90 mmHg to 10.06 mmHg (Figure 1). Systolic blood pressure yielded the lowest agreement metrics among all parameters. Its ICC was 0.811, Pearson r was 0.897, and Lin's CCC was 0.811. A substantial positive mean bias of $+5.63$ mmHg was observed, indicating that values from the bedside monitor were higher than those from the wearable device; the 95 % limits of agreement for systolic blood pressure ranged from -5.28 mmHg to 16.53 mmHg (Figure 1).



Paired-sample testing revealed statistically significant mean differences for all five parameters (all $P < 0.001$, Table 2).

Figure 1. Summary of Bland-Altman analysis for five vital sign parameters. Red circles represent the mean bias (calculated as reference bedside monitor measurements minus wearable monitor measurements, $A-B$). Blue triangles denote the upper and lower bounds of the 95% limits of agreement (95% LoA). The horizontal solid line indicates zero bias. HR, heart rate; Resp. Rate, respiratory rate; SpO₂, peripheral oxygen saturation; Diastolic BP, diastolic blood pressure; Systolic BP, systolic blood pressure.

Table 2. Overall device agreement of the groups.

Vital Sign	Group A	Group B	Pearson r	ICC (2, 1)	CCC	Bias (A-B)	95% LoA	Paired t p
Heart Rate	74.24±11.99	74.87±11.99	0.995	0.994	0.994	-0.63	[-2.97, 1.70]	<0.001
Respiratory Rate	15.02±3.53	15.53±3.54	0.950	0.940	0.940	-0.51	[-2.71, 1.68]	<0.001
SpO ₂	94.24±3.26	95.09±2.92	0.910	0.872	0.872	-0.85	[-3.50, 1.80]	<0.001
Diastolic BP	64.49±11.01	65.91±9.31	0.847	0.827	0.827	-1.42	[-12.90, 10.06]	<0.001
Systolic BP	122.21±12.34	116.58±12.11	0.897	0.811	0.811	+5.63	[-5.28, 16.53]	<0.001

Values for Group A and Group B are reported as mean ± standard deviation. Bias was calculated as Group A – Group B. LoA = 95 % limits of agreement from Bland-Altman analysis. ICC (2, 1) = two-way random-effects intra-class correlation coefficient for single-measurement reliability. CCC = Lin's concordance-correlation coefficient. The p-values were derived from paired-samples t-tests. BP = blood pressure.

3.3. Postoperative Two-day Temporal-trend Outcomes

All five vital-sign parameters remained physiologically stable throughout the two-day postoperative observation period, with no statistically-significant overall difference between Postoperative Day 1 and Day 2 (all $P > 0.05$, Figure 2). Inter-device mean biases remained nearly constant across all

eight sequential measurement time-points (Figure 2). Paired time-series curves for bedside and wearable readings ran largely parallel, indicating that measurement discrepancies represented consistent systematic device-level differences rather than time-dependent or patient-state-dependent drift (Figure 2). Systolic blood pressure persistently displayed the largest inter-device offset of approximately 5-6 mmHg at every measured time-point (Figure 2).

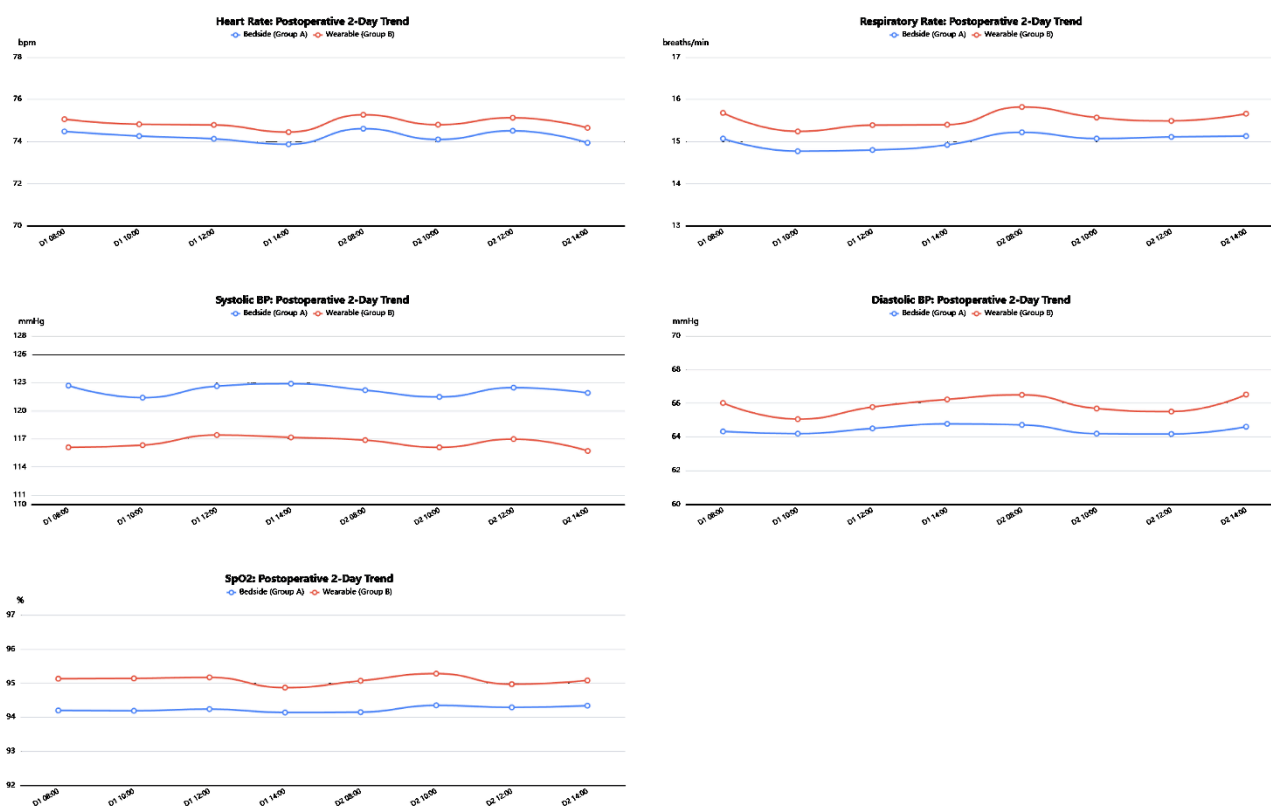


Figure 2. Temporal trends of vital signs over the first two postoperative days. Blue lines indicate measurements obtained from the reference bedside monitor (Group A), and red lines represent measurements acquired by the wearable monitor (Group B). Subplots display sequential changes in heart rate, respiratory rate, systolic blood pressure, diastolic blood pressure, and peripheral oxygen saturation. bpm, beats per minute; breaths/min, breaths per minute; mmHg, millimeters of mercury.

3.4. Clinical Acceptability

Table 3 presents the clinical acceptability of the measurements. The within-threshold agreement for heart rate was 99.9 %, with a mean absolute error (MAE) of 0.99 bpm. The within-threshold agreement for respiratory rate was 99.5 %, and its MAE was 0.91 breaths/min. SpO₂ achieved a

within-threshold agreement of 100.0 % alongside an MAE of 1.22 %. Diastolic blood pressure reached a within-threshold agreement of 92.2 %, with an MAE of 5.02 mmHg. Systolic blood pressure exhibited the poorest clinical performance; only 79.6 % of paired differences fell within the predefined ± 10 mmHg clinical tolerance window, corresponding to an MAE of 6.91 mmHg.

Table 3. Clinical acceptability assessment of the groups.

Vital Sign	Clinical Tolerance	Within-Threshold Rate	MAE	Max Abs Error	RMSE	MAPE
SpO ₂	$\pm 3\%$	100.0%	1.22	3	1.60	1.30%
Heart Rate	± 5 bpm	99.9%	0.99	7	1.35	1.38%
Respiratory Rate	± 3 breaths/min	99.5%	0.91	7	1.23	6.42%
Diastolic BP	± 10 mmHg	92.2%	5.02	14	6.02	8.19%
Systolic BP	± 10 mmHg	79.6%	6.91	18	7.91	5.65%

Clinical tolerance thresholds were predefined according to standard clinical postoperative monitoring requirements. Within-threshold rate denotes the percentage of paired measurement differences falling within the predefined tolerance range. MAE, mean absolute error; Max Abs Error, maximum absolute error; RMSE, root-mean-square error; MAPE, mean absolute percentage error. BP, blood pressure.

4. Discussion

This prospective study compared wearable-monitor performance against a standard bedside monitor in postoperative knee-arthroscopy patients under real-ward clinical conditions. Our results demonstrate that heart rate, respiratory rate and SpO₂ obtained from the wearable device achieve excellent-to-good measurement agreement and high clinical acceptability for resting snapshot measurements, supporting its feasibility for routine postoperative trend monitoring of these three parameters. By contrast, blood-pressure measurement, particularly systolic blood pressure, exhibited notable systematic bias and wider limits of agreement, limiting direct clinical use of absolute blood pressure values without correction or cross-checking.

Heart rate and SpO₂ measurements are optically derived via photoplethysmography in many wearable systems, and previous validation studies have commonly reported strong agreement for these two variables in stable postoperative patients, consistent with our findings [13, 14]. Respiratory rate estimation from wearable sensors, although indirectly derived, also showed satisfactory reliability in our stable postoperative cohort, which is promising for postoperative respiratory-depression risk screening [15]. It should be noted that these favorable performances may partly reflect our study population's relatively stable physiological status. The performance may degrade under conditions of motion-artefact, hypoperfusion or arrhythmia, which were infrequently observed in the present

dataset [16, 17].

Blood pressure assessment remains the principal challenge for current wearable-monitoring technology. In our study, we observed a consistent positive bias: bedside-monitor systolic blood-pressure readings were on average 5.63 mmHg higher than values output by the wearable device, and merely 79.6 % of paired systolic blood-pressure measurements met predefined clinical tolerance criteria. This observation is consistent with prior validation studies, which report that cuff-free wearable blood-pressure estimation algorithms are vulnerable to patient-specific vascular characteristics, peripheral perfusion, and body position. These factors can produce fixed-pattern systematic deviations even when correlation coefficients remain acceptable [7, 18, 19]. In the present work, systolic blood-pressure offset remained stable across all postoperative time-points, demonstrating temporally consistent measurement discrepancies under our study conditions. Nevertheless, since the cuff-free blood-pressure estimation algorithm and hardware specifications of the investigated wearable are proprietary, we cannot empirically determine which of these candidate factors gave rise to the observed systematic bias. Plausible mechanistic contributors may include pulse-wave-analysis-related artefacts, sensor-skin interface effects, or inter-individual differences in vascular properties, yet we lack access to device-level technical details to verify any of these hypotheses. We can therefore only characterize the magnitude and temporal stability of bias under ward-based resting conditions, rather than draw firm conclusions about its root cause. Importantly, statistical significance identified via paired testing

does not equate to clinical relevance. Mean biases for heart rate, respiratory rate, and SpO₂ were numerically trivial and unlikely to change clinical decision-making. In contrast, the magnitude of systolic blood-pressure bias carries potential clinical implications when judging hypertension or hypotension [20].

Temporal-trend analysis is an important strength of this study. Inter-device bias did not fluctuate across postoperative Day 1 and Day 2 or across morning-to-afternoon sampling time-points. This pattern suggests that observed discrepancies originate primarily from hardware-algorithm characteristics intrinsic to the two monitoring devices rather than evolving postoperative patient physiology [8, 21]. Consequently, if appropriate calibration offsets could be established, wearable blood-pressure readings might still provide useful trending information, though absolute values should be interpreted cautiously [22].

Limitations

First, measurements were acquired under scheduled resting conditions. We cannot evaluate performance during patient mobilization, sleep or periods of acute physiological deterioration. Second, this study enrolled predominantly ASA-II orthopedic patients recovering uneventfully after knee arthroscopy. The results cannot be generalized to critically-ill, hemodynamically-unstable or arrhythmia-heavy populations. Third, only one specific wearable-monitor model was investigated. The outcomes are not directly transferable to other wearable-monitor products with different sensing and algorithm designs. Fourth, the blood-pressure estimation algorithm and hardware specifications of the tested wearable monitor are commercially proprietary. Without access to its full technical details, mechanistic drivers for the observed systolic blood-pressure systematic bias cannot be determined.

Implications and future perspectives

For clinical practice, under semi-recumbent resting conditions, the investigated wearable device can provide reliable snapshot readings for tracking heart rate, respiratory rate and SpO₂ in stable postoperative knee-arthroscopy patients. These results do not validate its performance during patient mobilization or unsupervised continuous ambulatory monitoring. For blood-pressure evaluation, wearable outputs should be regarded as trend-oriented rather than gold-standard absolute readings. A cuff-based bedside measurement should be retained whenever blood-pressure-driven clinical decisions are required. Future work should focus on improving wearable blood-pressure-estimation algorithms, incorporating individualized calibration strategies, and validating performance under conditions of patient activity and physiological perturbation. Larger multi-center studies covering diverse surgical-patient populations are also warranted to confirm generalizability.

5. Conclusion

In stable, semi-recumbent resting patients following knee

arthroscopy, the wearable vital-sign monitor shows excellent-to-good agreement with bedside reference measurements for heart rate, respiratory rate and SpO₂ for discrete snapshot readings and is suitable for postoperative trend monitoring based on scheduled resting measurements. Blood pressure measurement presents substantial systematic bias and limited clinical acceptability even under resting conditions, requiring further algorithm optimization before unassisted clinical application for blood-pressure-related decision-making.

Abbreviations

ASA	American Society of Anesthesiologists Physical-status Classification
BMI	Body Mass Index
BP	Blood Pressure
bpm	Beats Per Minute
CCC	Lin's Concordance Correlation Coefficient
HR	Heart Rate
ICC	Intra-class Correlation Coefficient
LoA	Limits of Agreement
LoS	Length of Hospital Stay
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
RMSE	Root-Mean-Square Error
SpO ₂	Peripheral Oxygen Saturation

Author Contributions

Min Wang: Conceptualization, Investigation, Methodology, Writing – original draft

Pan Zhang: Data curation, Formal Analysis, Investigation

Wenhui Ma: Investigation, Resources, Validation

Jing Hu-Yan: Project administration, Supervision

Erfei Zhang: Conceptualization, Funding acquisition, Writing – review & editing

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Data Availability Statement

The original data can be accessed by contacting the corresponding author.

Conflicts of Interest

The authors declare no conflict of interests.

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