Research Square

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Development and bench evaluation of a smart support surface integrating multimodal sensing and localized low-flow oxygen delivery to support pressure injury prevention

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Abstract

Background

Pressure injury risk reflects sustained tissue deformation together with impaired tissue tolerance and adverse skin-support microclimate. Continuous monitoring can characterize interface conditions over time. We developed an investigational smart bedding surface that combines distributed pressure, temperature, and relative-humidity sensing with controlled low-flow oxygen delivery. This study evaluated short-duration technical performance and formative simulated-use feasibility; it did not test clinical safety or pressure injury prevention effectiveness.

Results

At nominal reference loads of 40, 80, and 120 mmHg, mean pressure readings were 41.2 ± 1.5, 78.9 ± 2.1, and 118.4 ± 2.8 mmHg, respectively. The absolute difference between each measured mean and its reference value was 1.1–1.6 mmHg, and coefficients of variation were 2.4%-3.6%. The source summary reported mean temperature and relative-humidity errors of 0.3°C and 2.1% RH, respectively. During 6-, 12-, and 24-h operation, mean oxygen flow was 0.98–1.01 L/min against a 1.0-L/min target; surface temperature increased by 0.3–0.5°C and relative humidity by 1.8%-2.4%. Reported 24-h changes were + 1.9% for pressure, + 2.3% for relative humidity, and + 0.20°C for temperature. In formative simulated-use tasks, mean setup, daily-check, and cleaning times were 6.5, 2.1, and 4.3 min, respectively; cable routing was the main observed operational issue.

Conclusions

The available bench data support the engineering feasibility of integrating multimodal interface sensing and low-flow oxygen delivery in one bedding platform. They do not establish clinical efficacy, comprehensive safety, metrological agreement across use conditions, or readiness for patient use. Replicated testing against traceable reference instruments, verification of oxygen distribution and oxygen-related hazards, formal usability engineering, durability testing, and staged clinical evaluation are required.

Introduction

Pressure injuries (PIs) remain an important patient-safety problem in hospitals and long-term care, particularly among people with limited mobility [1, 2]. A global systematic review identified a substantial burden among hospitalized adults, and the international DecubICUs study documented a high prevalence in intensive care [2, 3]. Other intensive-care studies have characterized injuries acquired during admission, including those associated with medical devices [4, 5]. Hospital-acquired PIs are also associated with prolonged care and considerable excess cost [6, 7].

Contemporary models describe PI development as an interaction among sustained mechanical loading, tissue deformation, ischemia-reperfusion, impaired lymphatic clearance, and individual tissue tolerance [8, 9]. A single interface-pressure threshold cannot capture this combination of factors [9]. The 2019 international guideline recommends a multimodal approach that includes risk assessment, regular skin assessment, repositioning, pressure redistribution, and management of heat and moisture at the skin-support interface [1]. An engineering review identified staffing and caregiver constraints as barriers to regular repositioning [10]. An integrative review of wearable sensors also highlighted staff training needs and uncertainty about clinical effectiveness [11].

Wireless sensor systems have demonstrated continuous measurement of pressure and temperature, with some systems also measuring skin hydration [12, 13]. These systems can record changes in interface conditions over time [12, 13]. For this prototype, interpretation of sensor output requires characterization of measurement performance, including bias and stability [14]. Use-related risks also need assessment in relation to intended users, tasks, and environments [15]. Pressure magnitude should be interpreted together with exposure duration and pressure relief rather than treated as an isolated value [16].

Microclimate is a relevant component of tissue tolerance [9, 17]. Increased skin temperature can alter skin structure and function [18]. Excessive moisture can damage skin and increase friction at supporting interfaces [9, 19]. A prospective intensive-care study also reported associations between sacral skin microclimate and assessed PI risk [20]. Oxygen availability is physiologically relevant to wound repair [21]. The cited consensus document on topical oxygen concerns treatment of existing wounds [22]. Extrapolating those findings to PI prevention through an oxygen-delivering bedding interface would require direct safety and outcome evidence.

We developed a smart bedding surface prototype, termed Bedding Surface Oxygen Therapy (BSOT) in the development program, that combines localized low-flow oxygen delivery with embedded pressure, temperature, and relative-humidity sensing. To avoid implying proven treatment efficacy, this report uses the functional description “smart bedding surface with low-flow oxygen delivery” when discussing the tested prototype. The aim was to evaluate short-duration technical performance and formative simulated-use feasibility before any patient-facing study. The prespecified scope did not include PI incidence, skin outcomes, tissue oxygenation, or clinical effectiveness.

Methods

Study design and reporting scope

This engineering design-verification study combined bench testing with a formative simulated-use evaluation and was conducted at Universitas Negeri Jakarta (UNJ), East Jakarta, Indonesia, from July to September 2026. The study addressed four questions: (1) whether the pressure-sensing subsystem produced stable responses across three nominal loads; (2) whether the temperature and relative-

humidity sensors tracked controlled reference conditions; (3) whether the oxygen-delivery subsystem maintained the target inlet flow during continuous operation without large concurrent changes in surface temperature or relative humidity; and (4) whether basic setup, daily-check, and cleaning tasks could be completed in simulated nursing workflows. This phase focused on technical performance and formative usability and was not designed to assess clinical effectiveness.

Intended use and prototype architecture

The Bedding Surface Oxygen Therapy (BSOT) prototype was developed as an investigational support-surface platform for potential use alongside established pressure injury (PI) prevention practices in people exposed to prolonged bed rest. Its proposed use was adjunctive to repositioning, skin inspection, pressure redistribution, continence care, nutrition management, and clinical judgment [1]. The present study evaluated engineering performance and formative simulated use; it did not establish clinical effectiveness.

The prototype integrated four functional components: a multilayer bedding interface; distributed pressure, temperature, and relative-humidity sensors; an oxygen-delivery layer; and an edge-processing unit for signal acquisition, aggregation, and device-status monitoring. Breathability, durability, and compatibility with routine cleaning were design considerations during material selection. Sensors were embedded beneath the user-contact layer to limit surface protrusion. Oxygen-delivery channels were incorporated within the bedding structure to convey gas toward the intended interface region.

During the reported continuous-operation tests, the oxygen subsystem was operated at a target inlet flow of 1.0 L/min. This inlet setting represented the supplied gas flow and did not establish the oxygen concentration or spatial distribution at the skin–support interface. Local oxygen exposure and tissue oxygenation were not quantified in the reported evaluation. The reported tests did not establish the performance of fault detection, alarms, or automatic shutdown. Accordingly, these functions are not presented as verified safety capabilities. Further verification is required to establish fault-detection thresholds, alarm behavior, shutdown response times, and reset procedures under defined normal and fault conditions.

Bench-test setting and reference instruments

Bench testing was conducted at Universitas Negeri Jakarta (UNJ), East Jakarta, Indonesia, from July to September 2026. The evaluation examined pressure-sensor responses at selected nominal reference pressures, temperature and relative-humidity responses under selected reference conditions, and oxygen-flow behavior relative to a target inlet setting of 1.0 L/min. Before each run, the prototype and reference instruments were allowed to stabilize and sensors were zeroed or conditioned according to the study protocol.

Pressure-sensor verification

Pressure responses were examined at nominal reference pressures of 40, 80, and 120 mmHg. Responses were summarized as the measured mean and standard deviation (SD). Signed bias relative to the nominal reference was calculated by subtracting the nominal reference pressure from the measured mean [14]. Absolute bias was the magnitude of this difference. The coefficient of variation (CV) was calculated as 100 times the SD divided by the measured mean.

Absolute bias of the mean was distinguished from mean absolute error (MAE), which requires observation-level absolute differences. The present summaries characterize responses at three nominal pressure levels and do not establish full-range linearity, hysteresis, creep, dynamic response, or performance across all sensor locations.

Temperature and relative-humidity verification

Temperature and relative-humidity sensing was examined over reference-condition ranges of 32–36°C and 40–75% RH, respectively. These ranges describe the conditions examined and should not be interpreted as the full measurement ranges of the sensors. Quantitative evaluation of agreement requires condition-specific paired sensor and reference measurements with explicitly defined error statistics [14].

Oxygen-flow and continuous-operation testing

The oxygen-delivery subsystem was operated at a target inlet flow of 1.0 L/min. Flow summaries were reported at durations of 6, 12, and 24 h, together with surface temperature and relative humidity. Flow was described using the mean, SD, and CV. Surface measurements were compared with baseline values.

The reported oxygen assessment characterized supplied flow and concurrent surface conditions. Oxygen concentration at the skin–support interface, spatial uniformity, leakage, local accumulation, and tissue oxygenation were not quantified in the reported results. Accordingly, inlet-flow stability cannot establish local oxygen exposure or a physiological effect.

Twenty-four-hour sensor stability

Sensor behavior over 24 h was considered an exploratory assessment. Instrumental drift concerns changes attributable to the measurement system rather than changes in the measured quantity or recognized influence quantities [14]. The reported endpoint differences alone do not establish this attribution, and numerical drift estimates are therefore not presented.

Scope of performance interpretation

Performance was interpreted descriptively under the conditions examined. Formal pass/fail conclusions are not presented. The evaluation does not establish compliance with predefined acceptance limits,

comprehensive device safety, or clinical effectiveness.

Formative simulated-use evaluation

A formative simulated-use evaluation examined initial setup, daily checking, and routine cleaning in a simulated nursing workflow. Nursing professionals performed the tasks, and completion times and observed handling issues were summarized descriptively. The exercise was intended to identify practical workflow concerns and did not constitute summative human-factors validation [15].

Routine-cleaning observations concerned task execution in the simulated workflow. This study does not establish disinfection efficacy, material compatibility over repeated cycles, or reprocessing durability.

Safety and risk-management scope

The reported evaluation did not establish comprehensive device safety. In particular, it does not demonstrate verification of oxygen-enrichment control, ignition or flammability behavior, electrical safety, electromagnetic compatibility, ingress protection, biocompatibility, mechanical or tubing/cable hazards, repeated-disinfection durability, or performance under foreseeable misuse. Fault detection, alarms, and automatic shutdown are not described as verified safety capabilities. Additional documented risk assessment and verification are required before readiness for patient use can be established.

Data analysis

Bench outcomes were summarized descriptively. Pressure bias and CV were calculated as specified above, and oxygen-flow CV used the same SD-to-mean calculation. Derived pressure statistics were calculated from the reported summary values and rounded to one decimal place. Task completion was described using means, ranges, and recorded observations. No clinical hypothesis testing was performed. Confidence intervals, observation-level MAE, root-mean-square error, and agreement limits were not reconstructed from the available aggregate summaries.

Ethics approval and consent

The protocol for the simulated-use and participant-involved activities was reviewed and approved by the Ethics Committee of STIKep PPNI Jawa Barat (approval no. III/137/KEPK/STIKep/PPNI/Jabar/IV/2025). Written informed consent was obtained from the participants.

Results

Prototype operation during completed tests

The reported bench evaluation described integrated operation of the sensing, oxygen-delivery, and processing components. Operational reliability, expressed as failure rate or uptime, was not established by the reported summaries.

Pressure response

Measured mean pressure was 41.2 mmHg at a nominal reference of 40 mmHg, 78.9 mmHg at 80 mmHg, and 118.4 mmHg at 120 mmHg (Table 1). Corresponding signed biases were + 1.2, − 1.1, and − 1.6 mmHg, with absolute biases of 1.2, 1.1, and 1.6 mmHg. SD increased from 1.5 to 2.8 mmHg. CV ranged from 2.4% to 3.6%. These results describe responses at the three nominal pressures and do not establish overall sensor accuracy or performance under dynamic loading.

Figure 1 illustrates the spatial pressure response during a simulated-loading test. Anatomically specific localization and spatial accuracy cannot be inferred without the loading geometry, sensor layout, orientation, processing method, and verified pressure scale.

Microclimate-sensor response

Across the reported reference ranges of 32–36°C and 40%-75% RH, the source summary listed mean errors of 0.3°C and 2.1% RH, respectively (Table 2). A further value of 0.4°C for temperature and 2.8% RH for relative humidity was reported without a central measurement or an unambiguous statistical definition. Condition-level agreement, repeatability, and maximum error cannot be assessed until the underlying observations and definitions are supplied.

Oxygen-flow stability and surface conditions

Mean flow was 0.99 ± 0.04 L/min at 6 h, 1.01 ± 0.05 L/min at 12 h, and 0.98 ± 0.05 L/min at 24 h (Table 3), corresponding to mean deviations of -1%, + 1%, and − 2% from the 1.0-L/min target. CV ranged from 4.0% to 5.1%. Surface temperature increased by 0.3–0.5°C and surface relative humidity by 1.8%-2.4% from baseline. These findings describe source-flow and surface-condition summaries only; they do not demonstrate the oxygen concentration or dose reaching skin, spatial distribution, or oxygen-related safety.

Twenty-four-hour relative sensor change

After 24 h, the reported relative change from each initial sensor reading was + 1.9% for pressure, + 0.6% for temperature, and + 2.3% for relative humidity (Table 4). Without absolute baselines, constant reference inputs, and replicate measurements, no conclusion about metrological drift or long-term stability can be made.

Formative simulated-use observations

Mean task times were 6.5 min for initial setup, 2.1 min for the daily check, and 4.3 min for routine cleaning (Table 5). Recorded ranges were 5–8, 1–3, and 3–6 min, respectively. Cable routing was the only specifically reported operational inconvenience. The number of participants and scenarios, task-success rates, assistance, use errors, and severity-classification method were not supplied; the findings therefore support only preliminary formative feedback.

Table 1
Pressure-sensor response under three nominal loads

Load level	Reference (mmHg)	Measured mean ± SD (mmHg)	Signed bias (mmHg)	Absolute bias (mmHg)	CV (%)
Low	40	41.2 ± 1.5	+ 1.2	1.2	3.6
Moderate	80	78.9 ± 2.1	-1.1	1.1	2.7
High	120	118.4 ± 2.8	-1.6	1.6	2.4

SD, standard deviation; CV, coefficient of variation. Signed bias = measured mean - reference. Absolute bias = |measured mean – reference.

Table 2
Reported microclimate-sensor verification summary

Parameter	Reported reference range	Unresolved source value*	Reported mean error
Temperature	32–36°C	± 0.4°C	0.3°C
Relative humidity	40%-75% RH	± 2.8% RH	2.1% RH

Table 3
Oxygen-flow stability during continuous operation

Duration	Target flow (L/min)	Mean flow ± SD (L/min)	CV (%)	Surface ΔT (°C)	Surface ΔRH (%)
6 h	1.0	0.99 ± 0.04	4.0	+ 0.3	+ 1.8
12 h	1.0	1.01 ± 0.05	5.0	+ 0.4	+ 2.1
24 h	1.0	0.98 ± 0.05	5.1	+ 0.5	+ 2.4

SD, standard deviation; CV, coefficient of variation; ΔT, change from baseline surface temperature; ΔRH, change from baseline surface relative humidity.

Table 4
Twenty-four-hour relative changes in sensor readings

Sensor	Constant reference input	Baseline reading	24-h reading	Absolute change	Relative change
Pressure	80.00 mmHg	80.00 mmHg	81.52 mmHg	+ 1.52 mmHg	+ 1.9%
Temperature	34.00°C	34.00°C	34.20°C	+ 0.20°C	Not reported as %
Relative humidity	60.00% RH	60.00% RH	61.38% RH	+ 1.38% RH	+ 2.3%

Table 5
Formative simulated-use task times and observations

Task	Mean time (min)	Range (min)	Reported observation
Initial setup	6.5	5–8	No critical issue reported
Daily check	2.1	1–3	Minor cable-routing inconvenience
Routine cleaning	4.3	3–6	Reported as compatible with protocol

Participant number, scenario number, task-success criteria, assistance, use errors, and issue-severity definitions were not reported and must be added.

Discussion

Principal findings

This study provides an early engineering description of a bedding prototype that integrates pressure and microclimate sensing with low-flow oxygen delivery. The available summaries show close mean pressure response at three nominal loads, source-flow means near the 1.0-L/min target over 24 h, and small concurrent changes in surface temperature and relative humidity. Formative task times also suggest that basic setup, checking, and cleaning can be completed within minutes. These observations justify further engineering work, but the current evidence is not sufficient to label the system accurate, safe, clinically useful, or effective for PI prevention.

Interpretation of the sensing results

The combination of pressure, temperature, and relative-humidity measurements is relevant because PI risk involves mechanical loading and tissue tolerance, including microclimate [8, 9, 18, 20]. Continuous pressure measurements may help identify changing load patterns [12, 13], while microclimate data may contextualize tissue tolerance [9, 20]. However, three nominal static loads cannot characterize performance across sensor locations, curved body-support interfaces, shear, motion, repeated loading, bedding layers, or long-duration creep. A monitoring approach should also account for exposure duration and pressure relief rather than reducing risk to a single instantaneous threshold [16].

The present data should therefore be framed as response checks rather than full metrological validation. Condition-level observations, traceable reference instruments, independent repetitions, agreement analyses, spatial characterization, hysteresis, and dynamic tests are needed. The ambiguous microclimate table is a particularly important reporting defect because readers cannot distinguish accuracy, variability, and maximum error without the underlying test points.

Interpretation of low-flow oxygen delivery

The oxygen-delivery subsystem is a distinctive element of the concept and requires particular caution. Oxygen is biologically relevant to wound physiology [21], and topical oxygen has been studied as a treatment for existing wounds [22]. These sources do not establish that low-flow oxygen delivered through bedding prevents tissue injury in intact skin [21, 22]. The present study measured source flow and changes in surface temperature and relative humidity; it did not quantify oxygen concentration at the skin-support interface, tissue oxygenation, perfusion, cellular response, or PI outcomes.

Future verification should map oxygen concentration and spatial uniformity under representative loads and linens, characterize leakage and local accumulation, establish dose control, and determine whether delivered oxygen materially changes interface or tissue oxygenation. Oxygen enrichment increases fire hazards, and oxygen equipment requires attention to leakage, ignition sources, and material compatibility [23]. For this prototype, risk analysis should therefore address enrichment beneath the bedding, ignition and flammability, static and electrical sources, compatibility of materials and cleaning agents, tubing occlusion or disconnection, and foreseeable misuse. Until those hazards are tested and controlled, the prototype should remain investigational and should not be used with patients.

Workflow and human factors

The formative simulated-use component focused on recurring nursing tasks. The observed cable-routing inconvenience identifies a design issue for further assessment; the reported observations do not establish its frequency or severity. Task duration alone does not establish safe and effective use [15]. Human-factors evaluation should address intended users and environments, critical tasks, use-related hazards, training, task performance, assistance, observed use errors, and close calls [15]. Iterative redesign should be followed by validation with representative users and use scenarios [15].

Clinical and engineering implications

The platform’s potential value lies in integrating sensing and an active output within one support-surface architecture. That integration could support future closed-loop or decision-supported prevention, and may introduce interactions requiring investigation: sensor error could affect interpretation, oxygen delivery could alter microclimate, and tubing or electronics could change the mechanical properties of the bedding. The next development stage should therefore evaluate the system as an integrated device rather than treating each subsystem independently.

A staged program is warranted. First, complete design inputs, risk management, traceable bench verification, oxygen-distribution and fire-safety work, electrical and environmental safety testing, cleaning durability, and formative usability. Second, perform short supervised studies of operational safety and interface physiology under ethics and institutional device governance. Third, only after predefined safety and feasibility criteria are met, evaluate patient-centered outcomes using recognized PI definitions and an appropriate comparator. Clinical studies should preserve standard prevention care in both groups [1].

Limitations

This study has important limitations. The number of prototypes, independent runs, replicates, and simulated-use participants was not reported in the available manuscript. Hardware and reference-instrument specifications were incomplete, acceptance criteria were not stated, and raw data were unavailable for agreement or uncertainty analysis. Static bench conditions cannot reproduce body contours, shear, movement, incontinence, linens, variations in perfusion, or repeated repositioning. The microclimate summary is ambiguous, and the 24-h values cannot be interpreted as drift without stable reference inputs. Source flow was measured, but actual oxygen exposure at the interface was not. Safety testing was incomplete, and the formative workflow exercise was not a summative usability validation. No clinical, physiological, or patient-reported outcome was measured. These limitations substantially restrict generalizability and require resolution before clinical claims are made.

Conclusions

The smart bedding surface prototype demonstrated short-duration integration of pressure and microclimate sensing with low-flow oxygen delivery, and the available summaries support continued engineering development. The results should be interpreted as proof of technical feasibility only. They do not establish comprehensive safety, clinical effectiveness, or readiness for patient use. Reproducible reporting, replicated verification against traceable references, direct measurement of interface oxygen exposure, safety and durability testing, formal usability engineering, and staged clinical evaluation are required.

Abbreviations

BSOT
Bedding Surface Oxygen Therapy (development-program name)
CV
coefficient of variation
PI
pressure injury
RH
relative humidity
SD
standard deviation.

Declarations

Ethics approval and consent to participate

The protocol for the simulated-use evaluation involving human participants was approved by the Ethics Committee of STIKep PPNI Jawa Barat (approval no. III/137/KEPK/STIKep/PPNI/Jabar/IV/2025). Written informed consent was obtained from all participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

T: Conceptualization, Methodology, Formal analysis, Investigation, Resources (prototype development), Writing – original draft. YCC: Conceptualization, Validation, Supervision, Writing – review and editing. LL: Methodology, Formal analysis, Writing – review and editing. TQ: Methodology, Resources (prototype development). AM: Validation, Investigation. ID: Validation, Supervision, Writing – review and editing. All authors read and approved the final manuscript.

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Authors' information

Not applicable.

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Figures

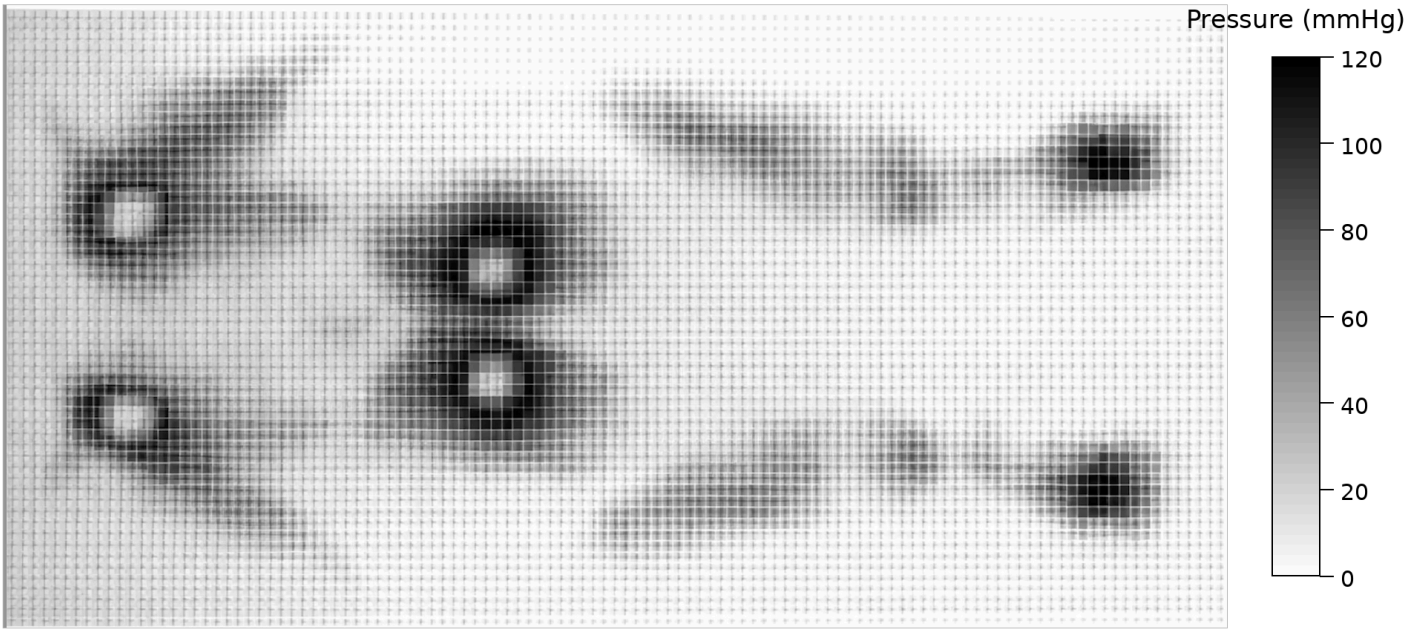


Figure 1

Representative pressure-distribution map generated by the BSOT prototype under simulated loading.

The grayscale map shows the spatial distribution of interface-pressure readings recorded by the embedded pressure-sensor array. Darker regions indicate higher recorded pressure, and the accompanying scale is expressed in mmHg. The map is presented as an engineering visualization of sensor response; no anatomical orientation is implied.