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TattooGate: A Systematic Review of Tattoo Pigment Interference with Wearable Photoplethysmographic Sensors

TattooGate: Revisión Sistemática Sobre la Interferencia de Pigmentos de Tatuaje con Sensores Fotopletismográficos Portátiles

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Abstract

Background: Wearable photoplethysmography (PPG) sensors are central to continuous physiological monitoring, but several factors compromise their accuracy. Tattoo pigments represent an under-characterized optical confounder that may impair heart rate (HR) and oxygen saturation (SpO_2) readings. Objective: To systematically review evidence on how tattoo characteristics, pigment composition, color, density, and anatomical location interfere with PPG signal acquisition and wearable-derived health metrics. Methods: Systematic review following PRISMA 2020 across PubMed, Web of Science, and ScienceDirect (2000–2026). Eligible studies examined the effects of tattoos on PPG signals or on the accuracy of wearable optical sensors. The risk of bias in primary studies was assessed using the JBI critical appraisal tools. Seventeen studies were included; a narrative synthesis was conducted given methodological heterogeneity. Results: Evidence was dominated by indirect sources: 10 studies (58.8%) were reviews, 4 (23.5%) experimental, and 3 (17.6%) observational. Only one study directly evaluated tattoo interference on a wearable under controlled conditions, reporting 36% complete signal dropout at rest and a 22.9% mean absolute percentage error for HR. Tattoo pigments attenuate and scatter photons in the dermal sampling volume via Beer-Lambert absorption and particulate scattering, compressing the AC pulsatile component below firmware thresholds. Spectral overlap between the ink and LED wavelengths determines the severity of interference. Conclusions: Tattoos constitute a clinically meaningful PPG confounder; signal dropout, not algorithmic bias, is the dominant failure mode. SpO_2 accuracy in tattooed individuals remains understudied, and direct empirical evidence is scarce, so generalization must be cautious. Future research should standardize tattoo characterization, ensure diverse and adequately powered samples, assess multiple metrics, and develop algorithmic and hardware mitigation.

Keywords: dermal pigmentation, ink absorption, signal dropout, heart rate accuracy, pulse oximetry.

Resumen

Antecedentes: Los sensores fotopletismográficos (PPG) portátiles son centrales para el monitoreo fisiológico continuo, pero varios factores afectan su precisión. Los pigmentos de tatuaje constituyen un confusor óptico poco caracterizado que puede comprometer las lecturas de frecuencia cardiaca (FC) y de saturación de oxígeno (SpO_2). Objetivo: Revisar sistemáticamente cómo las características del tatuaje, su composición, color, densidad y localización, interfieren con la señal PPG. Métodos: Revisión sistemática siguiendo PRISMA 2020 en PubMed, Web of Science y ScienceDirect (2000–2026). Se incluyeron estudios sobre efectos de tatuajes en señales PPG o sensores ópticos portátiles. El riesgo de sesgo de estudios primarios se evaluó con las herramientas JBI. Diecisiete estudios cumplieron los criterios; se aplicó síntesis narrativa por la heterogeneidad. Resultados: La evidencia estuvo dominada por fuentes indirectas: 10 (58,8%) revisiones, 4 (23,5%) experimentales y 3 (17,6%) observacionales. Solo un estudio evaluó directamente la interferencia en condiciones controladas, reportando una pérdida total de señal del 36% en reposo y un error porcentual absoluto medio del 22,9% en FC. Los pigmentos atenúan y dispersan fotones en el volumen dérmico mediante absorción de acuerdo con la ley de Beer-Lambert y dispersión de partículas, lo que reduce el componente AC por debajo del umbral de detección. Conclusiones: Los tatuajes son confusores clínicamente relevantes; la pérdida de señal, no el sesgo algorítmico, es el modo de fallo dominante. La SpO_2 en personas tatuadas está subestudiada y la evidencia directa es escasa, por lo que la generalización debe ser cauta. La investigación futura debe estandarizar la caracterización, utilizar muestras diversas y desarrollar mitigaciones algorítmicas y de hardware.

Palabras clave: pigmentación dérmica, absorción de tinta, pérdida de señal, precisión de frecuencia cardíaca, oximetría de pulso.

Introduction

The rapid proliferation of wearable electronic devices for continuous physiological monitoring has transformed personal health management and telemedicine (Li et al., 2024). Central to these technologies is photoplethysmography (PPG), a non-invasive optical method that detects pulsatile changes in blood volume in peripheral microvascular tissue by illuminating the skin with light-emitting diodes (LEDs) and measuring transmitted or reflected light with a photodetector (Kim & Baek, 2023). PPG captures variations in hemoglobin concentration, yielding cardiovascular parameters such as heart rate (HR) and oxygen saturation (SpO_2) (Heikenfeld et al., 2017; Kim et al., 2016), and can further inform blood pressure, respiratory function, autonomic activity, and heart rate variability (HRV) (Fine et al., 2021). It is routinely employed at peripheral sites such as the fingertip, forehead and earlobe (Elgendi et al., 2019; Kamshilin et al., 2015). However, PPG accuracy is susceptible to motion artifacts, ambient noise, anatomical variation, and individual physiological differences (Ghamari, 2018).

One critical yet often overlooked confounder is the presence of dermal tattoos. The increasing prevalence of body tattoos introduces a variable that may compromise the accuracy of optical sensing technologies (Bent et al., 2020). Pigmentation and dermal alterations associated with tattooing can interfere with PPG and pulse oximetry, which are fundamental to many wearable health devices (Lujan et al., 2021). Exogenous tattoo pigments alter the optical path length and absorption characteristics of the dermis (Karimpour et al., 2023; Ray et al., 2021). Depending on spectral absorption, scattering coefficients and particulate density, these inks can distort the PPG waveform, degrading the signal-to-noise ratio, introducing artifacts, and biasing derived metrics such as HR and SpO_2 (Asif et al., 2025; Jiang et al., 2023). Such disruptions can lead to erroneous physiological data with implications for clinical decisions and personalized health interventions (Charlton et al., 2023). Interference depends critically on the wavelengths employed by the sensor. Green light affords a good signal-to-noise ratio but limited penetration, while red and near-infrared light reach deeper layers but are less absorbed by superficial skin (Nelson et al., 2020). Shorter wavelengths are more readily absorbed by melanin and tattoo pigments, while longer wavelengths can mitigate surface artifacts (Lee et al., 2013). This differential interaction, combined with variability in ink composition, color and pigment density, justifies a systematic analysis of how these factors affect sensor performance (Gajda et al., 2023). Furthermore, PPG reliability can be compromised by intrinsic and extrinsic factors (Kim et al., 2022; Sañudo et al., 2019), with specific wavelengths making certain devices more susceptible to interference from tattoo inks (Sviridova et al., 2018).

The main purpose of this review is to systematically investigate how tattoo characteristics, pigment composition, color, density, and anatomical location interfere with PPG signal acquisition and the accuracy of wearable-derived health metrics, and to synthesize the optical principles underpinning these effects in biological tissues (Lee et al., 2021), including conventional inorganic and emerging organic PPG platforms (Chen et al., 2025). The light pigment interaction can significantly attenuate the PPG signal, reducing the signal to noise ratio and potentially yielding inaccurate health metrics (Ajmal et al., 2021). Scarce direct evidence suggests that tattoos reduce PPG accuracy, especially at rest (Navalta et al., 2025). By synthesizing current knowledge and identifying research gaps, the review seeks to inform sensor design and the development of signal-processing strategies to enhance the robustness of wearable devices on tattooed skin.

Methods

Study design and registration

A systematic review design was employed to identify, analyze, and synthesize evidence on the effects of tattoos on PPG signals from wearable sensors. This review was prospectively registered in the Open Science Framework (OSF). The methodology adhered to the PRISMA guidelines to ensure rigor, transparency, and reproducibility throughout all stages of the review. The PRISMA checklist is provided in Supplementary file 1.

Eligibility criteria

Inclusion criteria: studies published between 2000 and 2026 that focused on tattoos and their effects on PPG signals or on wearable optical sensors; studies evaluating PPG signal quality, artifacts or derived metrics (HR, SpO_2) on tattooed skin; articles published in English; and reported comparisons between tattooed and non-tattooed skin or pigment interference assessments.

Exclusion criteria: studies that did not involve PPG or wearable optical sensors, used non-human subjects or non-dermal tissues, or lacked quantitative PPG measurements.

These criteria were applied during the screening and full-text evaluation phases to ensure that only studies directly examining tattoo interference with PPG signals were included. The temporal window was selected to capture the emergence of wearable PPG technology and research on skin modifications, such as tattoos.

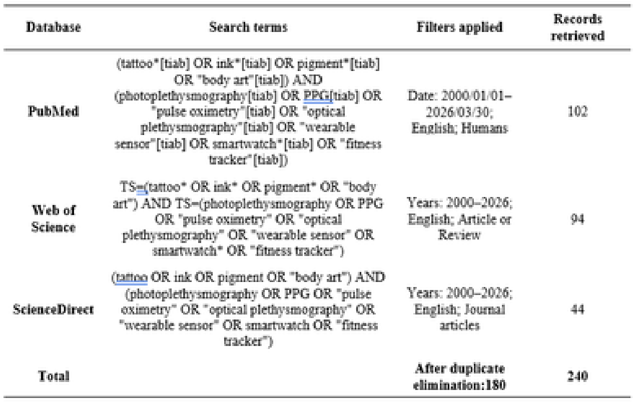
Sources of information and search strategy

A systematic literature search was conducted using three electronic databases: PubMed, Web of Science, and ScienceDirect. The search was limited to studies published between January 1st, 2000, and March 30th, 2026. The complete search strategy is reported in Table 1. The electronic search was supplemented by screening the reference lists of relevant reviews to ensure completeness. Boolean operators were applied, with database-specific adaptations. The core search strategy included terms related to tattoos and photoplethysmography signals from wearable sensors, such as:

("tattoo* OR ink* OR pigment* OR "body art") AND ("photoplethysmography" OR PPG OR "pulse oximetry" OR "optical plethysmography" OR "wearable sensor*" OR smartwatch* OR "fitness tracker*")

Table 1

Search strategy by database.



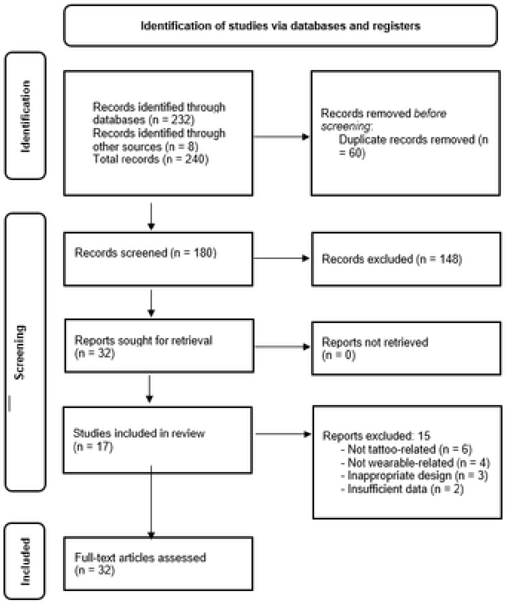
Database	Search terms	Filters applied	Records retrieved
PubMed	(tattoo*[tiab] OR ink*[tiab] OR pigment*[tiab] OR "body art"[tiab]) AND (photoplethysmography[tiab] OR PPG[tiab] OR "pulse oximetry"[tiab] OR "optical plethysmography"[tiab] OR "wearable sensor"[tiab] OR smartwatch*[tiab] OR "fitness tracker"[tiab])	Date: 2000/01/01–2026/03/30; English; Humans	102
Web of Science	TS=(tattoo* OR ink* OR pigment* OR "body art") AND TS=(photoplethysmography OR PPG OR "pulse oximetry" OR "optical plethysmography" OR "wearable sensor" OR smartwatch* OR "fitness tracker")	Years: 2000–2026; English; Article or Review	94
ScienceDirect	(tattoo OR ink OR pigment OR "body art") AND (photoplethysmography OR PPG OR "pulse oximetry" OR "optical plethysmography" OR "wearable sensor" OR smartwatch OR "fitness tracker")	Years: 2000–2026; English; Journal articles	44
Total		**After duplicate elimination:180**	**240**

Study selection process

Records retrieved from the databases were downloaded in CSV and consolidated in Excel to eliminate duplicates. Selection was performed independently by two reviewers across identification, screening, eligibility and final inclusion stages. Disagreements were resolved by discussion or, if needed, by a third reviewer. The PRISMA 2020 flow diagram of the selection process is presented in Figure 1. Data extraction followed a standardized template that captured author and year, study design and aim, sample size, participant characteristics (age, sex, skin tone), tattoo characteristics (composition, color, density, size, age, location), PPG device specifications (wavelength, sensor type), assessed outcomes, comparisons and key findings.

Figure 1

PRISMA 2020 flow diagram of the study selection process.



Risk of bias and data synthesis

Methodological quality of primary studies was assessed using the Joanna Briggs Institute (JBI) critical appraisal tools, with the checklist matched to each design. Cross-sectional, cohort and experimental studies were appraised with the corresponding JBI checklist. Each study was independently assessed by two reviewers; items were rated Yes, No, Unclear or Not applicable, and items not applicable were excluded from the total score. For reporting, the proportion of Yes responses across applicable items was summarized without weighting. Narrative, integrative, and consensus-based reviews were not subjected to formal JBI appraisal due to the absence of an appropriate standardized tool; this limitation is discussed below. Given the substantial heterogeneity across studies and the predominance of indirect evidence, a narrative synthesis approach was used; descriptive statistics summarizing study characteristics are presented in Table 2.

Results

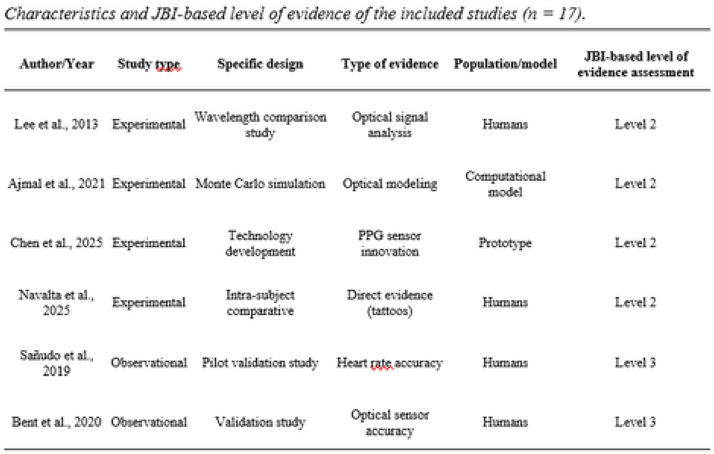
Review findings

Seventeen unique studies were included. Of these, 10 (58.8%) were narrative, integrative, or systematic reviews on PPG principles, wearable sensor technologies, and known sources of inaccuracy; 4 (23.5%) were experimental, including optical simulations and controlled human experiments; and 3 (17.6%) were observational validation designs. Only one study (Navalta et al., 2025) directly evaluated tattoo interference on a wearable using a controlled intra-subject design, while the remaining 16 studies (94.1%) provided indirect mechanistic or validation evidence.

This distribution shows that the current evidence base is heavily weighted toward indirect, lower-level evidence. Although experimental and observational studies together account for 41.2% of the included literature, most do not isolate tattoo-related effects, limiting direct applicability. The convergence of optical modeling and validation studies supports the plausibility of tattoo interference; however, the scarcity of direct empirical research substantially constrains inference and highlights a critical gap in controlled human studies.

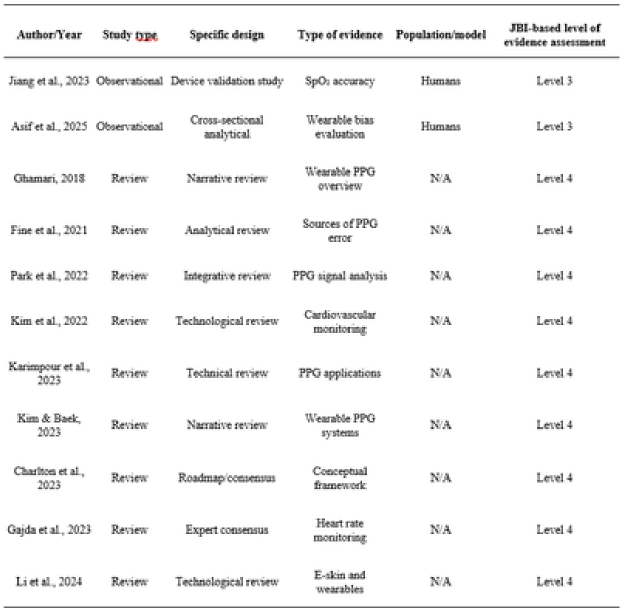
Table 2

Characteristics and JBI-based level of evidence of the included studies (n = 17).



Characteristics and JBI-based level of evidence of the included studies (n = 17).

Author/Year	Study type	Specific design	Type of evidence	Population/model	JBI-based level of evidence assessment
Lee et al., 2013	Experimental	Wavelength comparison study	Optical signal analysis	Humans	Level 2
Ajmal et al., 2021	Experimental	Monte Carlo simulation	Optical modeling	Computational model	Level 2
Chen et al., 2025	Experimental	Technology development	PPG sensor innovation	Prototype	Level 2
Navalta et al., 2025	Experimental	Intra-subject comparative	Direct evidence (tattoos)	Humans	Level 2
Sañudo et al., 2019	Observational	Pilot validation study	Heart rate accuracy	Humans	Level 3
Bent et al., 2020	Observational	Validation study	Optical sensor accuracy	Humans	Level 3



Author/Year	Study type	Specific design	Type of evidence	Population/model	JBI-based level of evidence assessment
Jiang et al., 2023	Observational	Device validation study	SpO_2 accuracy	Humans	Level 3
Asif et al., 2025	Observational	Cross-sectional analytical	Wearable bias evaluation	Humans	Level 3
Ghamari, 2018	Review	Narrative review	Wearable PPG overview	N/A	Level 4
Fine et al., 2021	Review	Analytical review	Sources of PPG error	N/A	Level 4
Park et al., 2022	Review	Integrative review	PPG signal analysis	N/A	Level 4
Kim et al., 2022	Review	Technological review	Cardiovascular monitoring	N/A	Level 4
Karimpour et al., 2023	Review	Technical review	PPG applications	N/A	Level 4
Kim & Baek, 2023	Review	Narrative review	Wearable PPG systems	N/A	Level 4
Charlton et al., 2023	Review	Roadmap/consensus	Conceptual framework	N/A	Level 4
Gajda et al., 2023	Review	Expert consensus	Heart rate monitoring	N/A	Level 4
Li et al., 2024	Review	Technological review	E-skin and wearables	N/A	Level 4

Wearable sensor technologies for physiological monitoring

Wearable physiological monitoring devices broadly employ optical and electrical sensing. Optical sensors of which PPG dominates consumer wearables infer cardiovascular and respiratory parameters from light absorption or reflection, while electrical sensors (electrocardiography, ECG) measure myocardial electrical activity through skin electrodes. ECG provides beat-to-beat resolution and serves as the gold standard for HR and HRV (Gajda et al., 2023) but requires direct electrode contact and is sensitive to impedance and motion. PPG operates without direct electrical contact, allows continuous pulse-wave morphology analysis and can be miniaturized into form factors unsuitable for ECG, making it the dominant approach in consumer wearables despite its higher susceptibility to skin-related optical confounders (Kim & Baek, 2023; Lee et al., 2021).

Modern PPG implementations vary in LED wavelength, photodetector design, placement and signal processing. Reflectance PPG (wrist-worn) emits light perpendicular to the skin and collects backscattered photons. Transmission PPG (finger or ear clips) emits light through an extremity for greater optical depth and SpO_2 accuracy. Emerging platforms include organic PPG sensors (Chen et al., 2025), contactless PPG imaging and flexible epidermal electronics that conform to the skin to reduce motion artifacts (Li et al., 2024).

Physiological parameters derived from PPG

HR is derived from the fundamental frequency of the PPG waveform via peak detection or spectral analysis. Under optimal conditions, wrist-based PPG agrees with ECG within approximately 5 bpm at rest, accuracy degrades during vigorous exercise due to motion artifact (Sañudo et al., 2019; Gajda et al., 2023). HRV reflects variation in interbeat intervals and is widely used as a noninvasive marker of autonomic modulation (Fine et al., 2021; Kim et al., 2022). PPG-derived HRV (pulse rate variability) is acceptable as a surrogate under controlled, low-motion conditions but degrades when signal quality is compromised, including by tattoo pigments (Karimpour et al., 2023). SpO_2 is estimated from the ratio of AC-to-DC PPG amplitudes at two wavelengths (red ~660 nm and near-infrared ~940 nm). Any factor that selectively attenuates one channel—such as a spectrally selective tattoo ink—biases the ratio and the SpO_2 estimate (Jiang et al., 2023; Asif et al., 2025). Regulatory guidance accepts an RMS accuracy of $\leq 3\%$ SpO_2 between 70–100%; evidence suggests that skin tone and, by extension, spectrally confounding tattoos can push consumer-grade devices beyond this threshold (Bent et al., 2020).

Known factors affecting PPG accuracy

Multiple confounders are recognized in the PPG literature (see Figure 2). Motion artifacts dominate during vigorous activity (Ghamari, 2018). Low skin perfusion reduces AC pulsatile amplitude, decreasing the signal-to-noise ratio. Melanin absorbs green and red photons proportionally to its concentration, introducing calibration bias in devices not adequately validated across skin tones (Asif et al., 2025; Ajmal et al., 2021). Anatomical variables (subcutaneous fat, hair follicle density, vascular architecture), ambient light, device fit and contact pressure further affect signal quality. Tattooing adds a permanent, localized and optically characterizable modification that is in principle more tractable to systematic investigation than many other confounders.

Figure 2

Tattoo pigment interference with PPG sensors: mechanisms, ink composition and wavelength sensitivity.

Source: prepared by the authors.

Tattoo ink composition and optical properties

Tattoo inks are complex mixtures of pigment particles in a carrier fluid. Pigments comprise organic azo compounds, polycyclic aromatic structures or inorganic metal oxides depending on the desired hue (Ray et al., 2021). Black inks the most prevalent worldwide are mostly carbon black, with broadband absorption from UV to near-infrared. Red inks contain azo pigments with absorption peaks between 500 and 560 nm, overlapping the green LEDs used by most wrist-worn HR sensors. Blue inks (phthalocyanine pigments) absorb in the red-to-orange band (600–700 nm), coinciding with the red LED used for SpO_2. Green inks absorb in the red and near-infrared, while white inks (titanium dioxide) show low absorption but high scattering (Ajmal et al., 2021; Park et al., 2022). Following deposition into the papillary and upper reticular dermis (1.0–2.5 mm), particles are phagocytosed by macrophages and keratinocytes, creating a stable, optically dense layer that persists for years (Karimpour et al., 2023; Ray et al., 2021). As tattoos age, macrophage redistribution and UV photodegradation reduce superficial pigment concentration, potentially altering absorption and scattering over time, a consideration relevant to the null finding regarding tattoo age reported by Navalta et al. (2025).

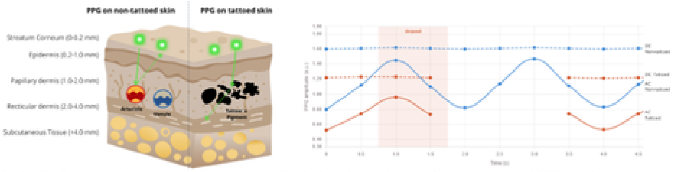
Mechanisms of PPG signal interference

Two pathways disrupt the PPG signal. First, ink particles attenuate photons on both forward and return trajectories through a modified Beer-Lambert process; the effective attenuation coefficient of densely pigmented skin can be three to ten times higher than that of non-tattooed skin of equivalent melanin content, compressing the dynamic range for AC pulsatile detection (Ajmal et al., 2021; Lee et al., 2013). Second, particulate scattering broadens the photon path distribution and reduces signal coherence, adding stochastic noise that algorithms cannot distinguish from physiological pulsations (Park et al., 2022; Karimpour et al., 2023).

At the algorithmic level, commercial firmware uses peak-detection and adaptive filtering that assume a clean, high-amplitude AC component. When AC amplitude falls below device thresholds, three failure modes can emerge: complete signal dropout (zero or null HR, observed in 36% of tattooed participants by Navalta et al., 2025), substitution of plausible but erroneous values driven by noise harmonics, and selective beat-detection failure that creates artifactual long inter-beat intervals and inflates HRV metrics such as RMSSD (Fine et al., 2021; Kim et al., 2022). Figure 3 illustrates these effects.

Figure 3

PPG signal acquisition in non-tattooed versus tattooed skin



Note: Left: schematic cross-section of skin illustrating the optical path of green light (530 nm) in non-tattooed and tattooed tissue. Right: representative PPG waveforms comparing non-tattooed and tattooed skin across AC and DC components over a 4.5 s window; the shaded region (0–1.75 s) denotes a complete signal dropout, occurring when the AC amplitude falls below the firmware detection threshold. Source: prepared by the authors.

Discussion

This systematic review synthesizes the available evidence on tattoo pigment interference with PPG-based wearable sensors, integrating experimental data, optical modeling and validation studies in a mechanistic framework. Across studies, dermal tattoos serve as a clinically and technically meaningful confounder, with effects mediated by spectral overlap between ink absorption bands and sensor LED wavelengths, pigment density and depth within the optical sampling volume, and the sensitivity of device algorithms to reductions in AC amplitude.

The most direct experimental evidence comes from Navalta et al. (2025), whose intra-subject paired design provides the clearest quantification to date of tattoo-related HR inaccuracy. The finding that 36% of tattooed participants experienced complete signal dropout at rest, with a mean absolute percentage error of 22.9% that improved substantially during exercise, is mechanistically interpretable: exercise-induced vasodilation augments the pulsatile AC component, partially compensating for tattoo-induced attenuation. This pattern suggests that the primary failure mode is insufficient signal amplitude rather than systematic algorithmic bias, and that interventions raising the effective AC amplitude (higher LED power, improved skin conformance, longer wavelengths) could mitigate the problem. However, this body of direct empirical evidence rests on a single small-sample study, so any generalization of the "TattooGate" effect must be approached with caution until independent replications across diverse populations and devices become available. The observation that skin tone, but not tattoo-specific characteristics (age, color, intensity), was the only significant predictor of HR accuracy in Navalta et al. (2025) warrants careful interpretation. From a statistical standpoint, the small sample (n = 25) and the limited precision of tattoo characterization (subjective ratings, self-reported age) reduce the power to detect tattoo-specific moderation. From a mechanistic standpoint, darker skin tones and dark pigments share overlapping spectral absorption profiles, making their effects difficult to disentangle. The null result for tattoo characteristics should not be read as evidence of absence, but as a call for larger, standardized, imaging-based studies.

A critical gap is the near-complete absence of SpO_2-specific studies in tattooed individuals. The SpO_2 algorithm is particularly vulnerable to spectrally selective interference because it relies on the ratio of signals at two discrete wavelengths; selective attenuation of one channel by a color-matched ink predictably shifts the ratio (Jiang et al., 2023; Asif et al., 2025). Blue and purple inks absorbing near 660 nm would theoretically produce the most severe SpO_2 errors; near-infrared-absorbing inks (carbon-based blacks) would affect both channels. Given recent regulatory and clinical attention to pulse-oximetry inaccuracies in darker skin tones, the parallel question of tattoo-induced SpO_2 bias warrants urgent empirical investigation.

The interaction between tattoo pigments and skin tone constitutes a compounding vulnerability that has not been systematically examined. Both variables degrade PPG signal quality through partially overlapping mechanisms and disproportionately affect populations historically under-represented in device validation (Bent et al., 2020; Asif et al., 2025). The tattooed individual with darker skin represents a worst-case optical scenario; no published study has specifically characterized this intersection. Health equity considerations demand that this gap be addressed in future validation work as wearable health monitoring expands across diverse clinical and community settings.

From a sensor-design perspective, the TattooGate phenomenon points to several engineering opportunities. Multi-wavelength sensors that monitor signal quality independently per LED channel could flag spectrally anomalous attenuation patterns (Charlton et al., 2023; Lee et al., 2021); adaptive gain control able to operate at lower AC amplitudes without amplifying noise; and wavelength-specific calibration accounting for known ink absorption spectra represent software-level mitigations not requiring hardware changes. Emerging organic and flexible PPG sensors with tunable spectral sensitivity and improved skin conformance (Chen et al., 2025) offer a longer-term hardware path to address both tattoo- and skin-tone–related limitations.

Strengths and limitations

This review was prospectively registered and adhered to PRISMA 2020, providing a transparent and reproducible synthesis. The narrative approach was appropriate given the substantial methodological heterogeneity, which precluded a quantitative meta-analysis. The primary limitation is the sparsity and heterogeneity of the underlying evidence: most included studies are small, methodologically variable, and focused mainly on HR rather than the full range of PPG-derived metrics. The dominance of secondary literature (10 of 17 studies were reviews) introduces a potential indirectness bias because some of the inferences depend on prior aggregations of evidence rather than primary observations. Furthermore, narrative, integrative, and consensus-based reviews were not subjected to a formal critical-appraisal tool tailored to their design (e.g., AMSTAR 2); this is a methodological limitation, and future updates should incorporate AMSTAR 2 for the systematic-review subset and downgrade certainty when the underlying evidence rests on overlapping secondary sources. Publication bias toward positive findings cannot be excluded.

Directions for future research

Future studies should prioritize: (1) standardized quantitative tattoo characterization using calibrated digital imaging and spectrophotometric methods to measure ink color, density and coverage fraction; (2) larger, adequately powered samples with diverse skin tones and tattoo types to detect moderating effects; (3) systematic evaluation of SpO_2 accuracy alongside HR across clinically relevant tattoo colors; (4) longitudinal assessment of how interference evolves as pigment ages and redistributes; (5) controlled wavelength-specific experiments comparing green, red and near infrared performance across matched tattoo colors to map the spectral interference landscape; and (6) development and validation of algorithm and hardware-level mitigation strategies in tattooed populations.

Conclusions

Tattoo pigments represent a clinically meaningful and mechanistically well-characterized source of PPG signal interference in wearable optical sensors. The degree of interference is determined by the spectral overlap between ink absorption and sensor LED wavelengths, by pigment density and depth within the dermal optical sampling volume, by individual skin tone, and by the algorithms' sensitivity to reduced AC amplitude. Current evidence, although limited in scope and methodological rigor, consistently indicates that dark and colored tattoos at PPG sensor sites reduce HR accuracy, particularly at rest, and that complete signal dropout is the dominant failure mode. SpO_2 accuracy in tattooed individuals remains critically understudied. Because the strongest empirical anchor of the TattooGate effect comes from a single direct study, the present conclusions should be considered preliminary and require independent replication. Future research using standardized tattoo characterization, diverse populations, and multi-metric outcomes is urgently needed to quantify the full clinical impact of TattooGate and to guide the development of more inclusive, resilient wearable sensor technologies.

Statement on the use of artificial intelligence

During the literature search phase of this systematic review, the authors used Anthropic's Claude (large language model assistant) to support the identification and shortlisting of candidate sources from the queried databases. The tool was not used to draft scientific conclusions, perform critical appraisal, or generate quantitative data. All records retrieved were independently re-examined by the authors against the prespecified inclusion and exclusion criteria; final eligibility, data extraction, and risk-of-bias assessment were performed manually by two reviewers and verified for accuracy, plagiarism, and bias before being incorporated into the manuscript. No automatic text generation by AI was retained in the final manuscript without human revision.

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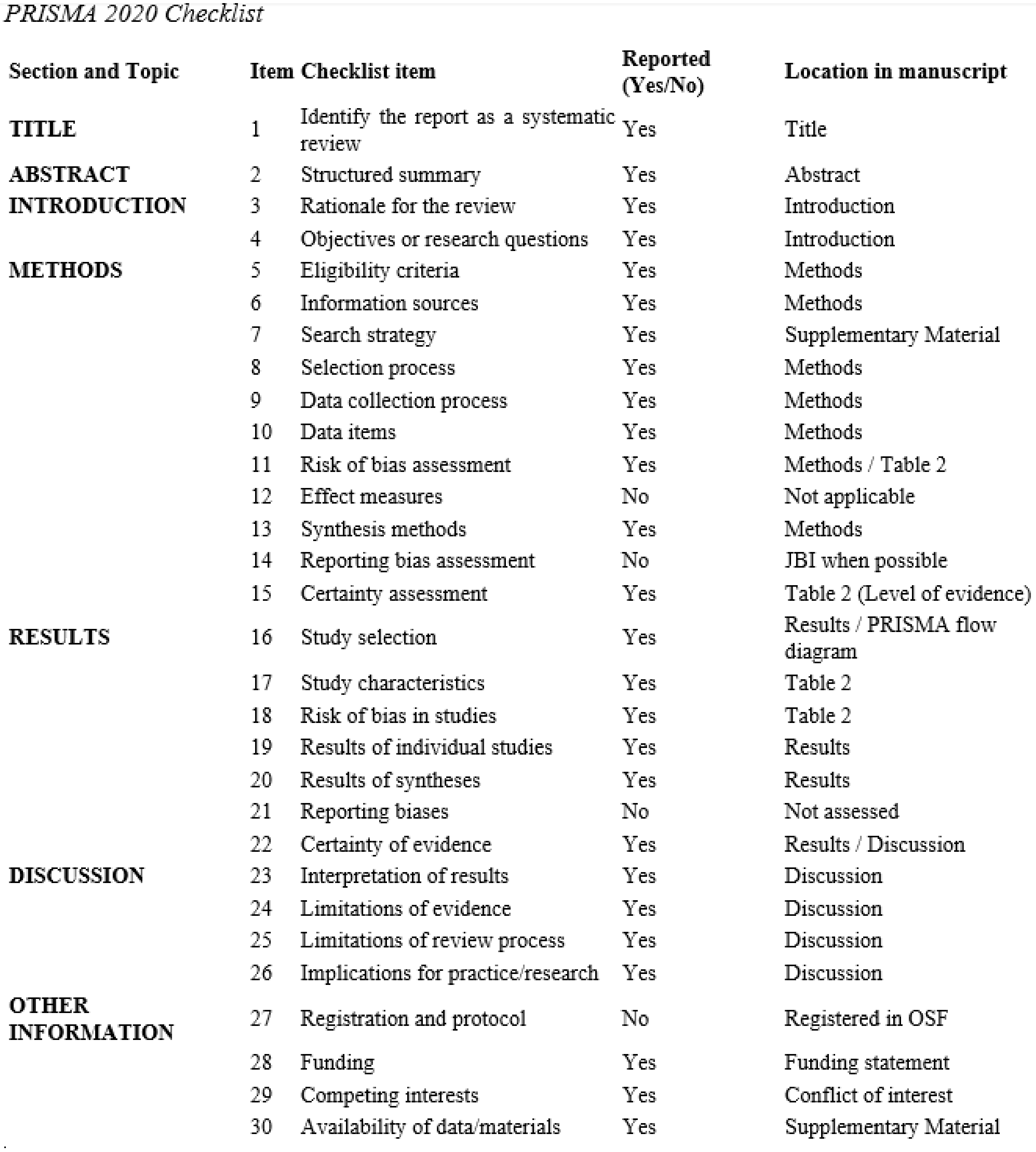

PRISMA 2020 Checklist

Section and Topic	Item	Checklist item	Reported (Yes/No)	Location in manuscript
TITLE	1	Identify the report as a systematic review	Yes	Title
ABSTRACT	2	Structured summary	Yes	Abstract
INTRODUCTION	3	Rationale for the review	Yes	Introduction
	4	Objectives or research questions	Yes	Introduction
METHODS	5	Eligibility criteria	Yes	Methods
	6	Information sources	Yes	Methods
	7	Search strategy	Yes	Supplementary Material
	8	Selection process	Yes	Methods
	9	Data collection process	Yes	Methods
	10	Data items	Yes	Methods
	11	Risk of bias assessment	Yes	Methods / Table 2
	12	Effect measures	No	Not applicable
	13	Synthesis methods	Yes	Methods
	14	Reporting bias assessment	No	JBI when possible
	15	Certainty assessment	Yes	Table 2 (Level of evidence)
RESULTS	16	Study selection	Yes	Results / PRISMA flow diagram
	17	Study characteristics	Yes	Table 2
	18	Risk of bias in studies	Yes	Table 2
	19	Results of individual studies	Yes	Results
	20	Results of syntheses	Yes	Results
	21	Reporting biases	No	Not assessed
	22	Certainty of evidence	Yes	Results / Discussion
DISCUSSION	23	Interpretation of results	Yes	Discussion
	24	Limitations of evidence	Yes	Discussion
	25	Limitations of review process	Yes	Discussion
	26	Implications for practice/research	Yes	Discussion
OTHER INFORMATION	27	Registration and protocol	No	Registered in OSF
	28	Funding	Yes	Funding statement
	29	Competing interests	Yes	Conflict of interest
	30	Availability of data/materials	Yes	Supplementary Material