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A review of biomedical sensing technologies for non-nutritive sucking assessment in preterm infants

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ABSTRACT

Non-nutritive sucking (NNS) is a key indicator of feeding readiness and early orofacial development in preterm infants, with impairment linked to delayed oral-motor coordination and feeding difficulties. This review focuses on sensor-based systems for the quantitative measurement of NNS. Records were retrieved from five databases-IEEE Xplore, PubMed, Scopus, ScienceDirect, and Google Scholar-resulting in 331 initial hits, and after screening against the eligibility criteria, eight studies were retained for synthesis. Two main categories of sensing technologies were identified: pressure-based sensors ($n = 7$) and force-based sensors ($n = 1$). These systems enable objective measurement and signal acquisition and analysis of sucking patterns, including pressure and rhythmic characteristics. However, existing sensing systems lack standardization in device parameters and clinical integration, limiting comparability across studies and broader clinical implementation. Despite these challenges, current technologies demonstrate strong potential as non-invasive biomedical sensing platforms for early functional assessment, supporting future integration into real-time monitoring systems.

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1. INTRODUCTION

Preterm birth continues to pose a major global health challenge, and Indonesia is consistently reported among the nations contributing the largest share of preterm deliveries [1], [2]. This condition requires increased attention from healthcare professionals, including pediatric dentists, to ensure comprehensive early care [3]. Orofacial myofunctional disturbances are frequently observed in this population, most notably an impaired ability to coordinate sucking, swallowing, and breathing, three functions that underlie adequate feeding and normal craniofacial growth [4]. Estimates indicate that between 40% and 70% of infants born preterm display feeding patterns that are immature or atypical [5], [6]. Among the earliest oral functions to emerge is non-nutritive sucking (NNS), a rhythmic sucking pattern that occurs in the absence of nutrient intake and serves as an early marker of feeding readiness [7]-[9]. Coordination among sucking, swallowing, and breathing generally matures over the 32nd to 37th week of gestation [10], [11], and when these functions are impaired, infants tend to face longer hospital stays and a greater likelihood of developmental complications [12]-[17].

Weak or disorganized NNS patterns are commonly seen in preterm infants, signaling oral-motor immaturity and raising the likelihood of subsequent feeding difficulties and developmental delay [6], [18], [19].

Impaired NNS has also been associated with subsequent oral function problems, including speech and masticatory disturbances [20]-[22]. Clinicians have conventionally assessed NNS through subjective means-visual observation, palpation, and qualitative scoring tools such as the neonatal oral-motor assessment scale (NOMAS)-approaches constrained by variability between raters and limited measurement precision [23]-[26]. Although these approaches are useful in routine clinical practice, they cannot objectively capture subtle changes in sucking pressure, rhythm, and coordination [27]. From an engineering perspective, these limitations highlight a fundamental gap: conventional methods cannot convert sucking activity into quantifiable biomedical signals. Sensor-based systems are therefore essential to provide the objective, time-resolved, and quantitative evaluation of NNS performance that clinical observation alone cannot deliver [28].

Advances in sensor technology have enabled objective and quantitative measurement of sucking behavior, including pressure, rhythm, and coordination [29], [30]. Several systems, such as sensorized pacifiers, pacifier-based measurement boxes, and flexible pressure sensors, have demonstrated potential for improving feeding assessment and supporting clinical decision making [31]-[34]. Complementary approaches, including low-cost prototypes designed to measure and stimulate NNS [35] and facial-gesture or video-based methods for quantifying sucking patterns [36], [37], have further broadened the range of available assessment tools. These technologies allow signal acquisition and analysis of NNS parameters that are difficult to evaluate through conventional clinical examination alone. However, existing sensing systems still face several technological limitations, including variation in sensor type, pressure range, sensitivity, sampling rate, calibration method, signal processing approach, and validation protocol [38], [39]. In addition, motion artefacts, sensor placement, sterilization, biocompatibility, usability in neonatal settings, and integration into routine clinical workflows remain important challenges for practical implementation.

A persistent shortcoming of current sensing systems is the absence of standardized device parameters and clinical integration pathways, which restricts comparability between studies and slows broader clinical adoption. Much of the prior literature on NNS has approached the subject from a clinical or therapeutic angle-centering on feeding readiness, oral-motor interventions, and treatment outcomes-while leaving the engineering dimension of sensing technologies largely unexamined. Consequently, an engineering-oriented classification of NNS sensing systems has yet to appear in the literature. This review addresses that gap by concentrating on sensor-based approaches for quantifying NNS, with attention to sensing mechanisms, signal acquisition methods, measurable parameters, and engineering design features. What distinguishes this review is its engineering-based classification of biomedical sensing technologies for NNS assessment, its mapping of technical limitations, and the structured framework it offers to guide future standardization efforts and clinically deployable real-time monitoring for preterm infants. It is anticipated that these findings will support the development of standardized, clinically viable NNS sensing systems and ultimately help improve neonatal feeding outcomes across both resource-constrained and well-resourced healthcare settings.

2. METHOD

This review followed a structured literature review design, with reporting guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework [40].

2.1. Eligibility criteria

To operationalize the review question-what sensor types have been developed to measure NNS in preterm infants-eligibility criteria were structured according to the population, intervention, comparison, outcome, and study design (PICOS) framework [41]. Studies were included if they were published in English, involved preterm infants, and used sensor-based methods to assess NNS. Studies focusing on nutritive sucking, as well as reviews, conference papers, commentaries, and editorials were excluded. Table 1 presents an overview of these eligibility criteria together with the corresponding data items.

Table 1. Eligibility criteria based on PICOS framework

PICOS element	Criteria
Population	Preterm infants; studies on full-term infants were excluded
Intervention	Sensor-based measurement of NNS; studies assessing nutritive sucking were excluded
Comparison	Not applicable
Outcome	Quantitative assessment of NNS
Study design	Original research articles using sensor-based assessment; reviews, conference papers, commentaries, and editorials were excluded

2.2. Search strategy

Studies on sensor-based assessment of NNS in preterm infants were identified by searching five databases: IEEE Xplore, PubMed, Scopus, ScienceDirect, and Google Scholar. Searching concluded in June 2025 and encompassed the ten-year window from June 2015 through June 2025. Free-text terms centered on "sensors," "non-nutritive sucking," and "preterm infants" were combined using Boolean operators to build the search strings. Full details of the syntax applied, the databases searched, the search date, and the yield from each source are given in Table 2.

Table 2. Search strategy and records retrieved from each database

Database	Search date	Search syntax / exact keyword combination	Records retrieved
IEEE Xplore	June 2025	("non-nutritive sucking" OR "NNS") AND ("sensor" OR "pressure sensor" OR "sensorized pacifier") AND ("preterm" OR "neonates" OR "infant")	$n = 9$
PubMed	June 2025	("non-nutritive sucking") AND ("sensor") AND ("preterm" OR "infant")	$n = 3$
Scopus	June 2025	("sensor") AND ("non-nutritive sucking") AND ("premature infant" OR "preterm infant")	$n = 6$
ScienceDirect	June 2025	"sensor" AND "non-nutritive sucking" AND ("premature infant" OR "preterm infant")	$n = 49$
Google Scholar	June 2025	"sensor" AND "non-nutritive sucking" AND ("premature infant" OR "preterm infant")	$n = 264$
Total			$n = 331$

2.3. Study selection

Records generated by the search described in Table 2 were imported into Zotero, where duplicate entries were flagged through the software's built-in detection function and then manually checked for accuracy. Once duplicates had been removed, two authors (SYS and KCN) independently screened titles, abstracts, and full texts against the criteria set out in Table 1. Any disagreement was worked through by discussion, and where consensus could not be reached, a third reviewer (ARS) made the final call. No formal statistic was used to quantify inter-rater agreement, but disagreements between the two primary reviewers were rare and were settled through discussion. The same pair of reviewers (SYS and KCN) also carried out data extraction independently, resolving any discrepancies by discussion and consensus (see analysis framework for details of the extraction criteria). The overall study selection process is presented in Figure 1.

2.4. Analysis framework

To ensure a systematic and engineering-oriented evaluation, the included studies were analyzed based on key technical aspects, including sensing mechanisms, sensor types, measured parameters (e.g., pressure, rhythm, coordination), signal processing methods, and clinical applicability. This framework enables structured comparison and supports the classification of biomedical sensing systems for NNS. Each included study was evaluated against these criteria independently, and findings were summarized in a structured data extraction table to facilitate systematic comparison.

2.5. Quality assessment

Because the included studies primarily evaluated prototype biomedical sensing devices with substantial heterogeneity in sensor architecture, validation procedures, and reported performance metrics, the use of conventional risk-of-bias tools designed for clinical intervention studies was not considered appropriate. Instead, methodological quality was appraised narratively based on engineering-related criteria, including sensor specification, calibration procedure, validation methodology, signal acquisition characteristics, sample size, reproducibility, and reported clinical applicability. This structured appraisal supported the comparative interpretation of the reviewed technologies while acknowledging variations in methodological rigor across studies.

2.6. Data analysis

The characteristics of the included studies were examined through a descriptive comparative analysis. Studies were initially grouped by sensing mechanism-pressure-based versus force-based sensors-and were then compared using the engineering appraisal criteria described in the quality assessment section. Reported technical characteristics, including sensing principles, calibration methods, signal acquisition, validation procedures, and clinical applicability, were synthesized narratively because substantial heterogeneity in device architecture, measurement units, validation methods, and reported outcomes precluded quantitative synthesis or meta-analysis.

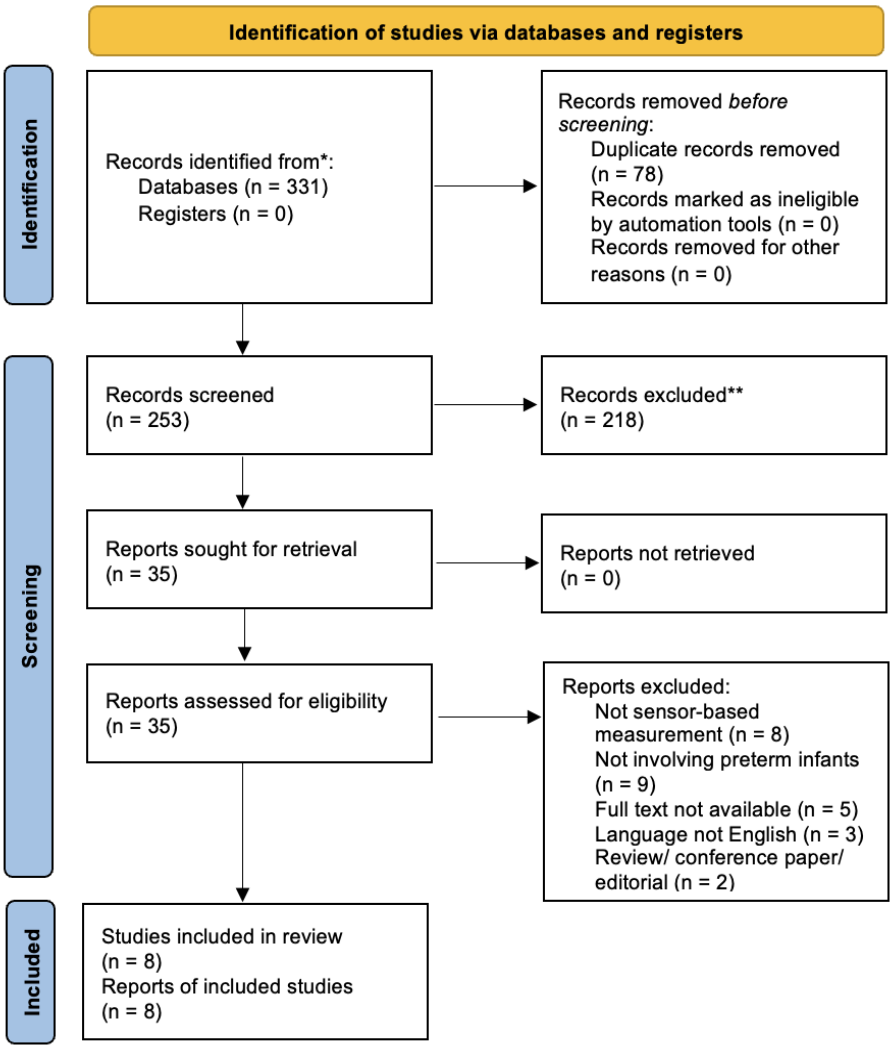


Figure 1. PRISMA flow diagram of study selection

3. RESULTS AND DISCUSSION

3.1. Study selection and characteristics of included studies

Of the 331 records initially identified, eight ultimately satisfied the screening and eligibility requirements. These eight studies span publication years 2015 to 2025 and originate from North America, Europe, and Asia, employing experimental, clinical, and feasibility study designs; the majority focused on preterm infants (<37 weeks of gestation) presenting with feeding or oral-motor difficulties. Table 3 sets out the characteristics of these study populations.

As shown in Table 3, gestational ages across the included preterm cohorts spanned 24 to 45 weeks, with sample sizes varying widely from 4 to 137 participants. While a few studies enrolled both term and preterm infants, the preterm population was the primary focus in most cases. Demographic reporting-particularly of sex distribution and gestational age-varied considerably between studies, which constrained direct comparison across the evidence base.

3.2. Classification and technical characteristics of sensing technologies

Two main categories of sensing technologies were identified: pressure-based sensors ($n = 7$) and force-based sensors ($n = 1$). Pressure-based sensors were the most commonly adopted technology, utilized across various pacifier-integrated and external monitoring systems, whereas the single force-based system detected mechanical deformation at the pacifier surface. Table 4 (in Appendix) summarizes the technical characteristics of each identified sensing system, while Table 5 details the underlying engineering principles, including sensing mechanisms, sensitivity ranges, calibration methods, and signal acquisition specifications.

Table 3. Characteristics of study populations

No.	Author	Device name	Figures	Study population	Sample size (*n*)	GA/PMA (weeks)	Sex	Weight (gram)
1	Wang *et al.* [42]	Wireless oral-feeding monitoring system		Full-term and preterm infants	30 (10 full term; 20 preterm)	Full-term > 37 (38.3 ± 0.9); preterm 34-36 (35.5 ± 0.73)	Full-term: 5M/5F; preterm: 10M/10F	Full-term: 3,700 ± 260; preterm: 2,600 ± 430
2	Cunha *et al.* [31]	Low-cost prototype pressure measurement system		Preterm and term newborns	16 (12 preterm; 4 term)	Preterm: GA median 29.8 (27.6-33.7); PCA at assessment 34.3 ± 1.1; Term: GA median 39.8 (37.6-41.0)	Not reported	Preterm: median 1,420; term: median 3,062
3	Chiu *et al.* [39]	Dual-channel pressure-sensing electronic pacifier (AI smart pacifier)		Preterm infants	22	26–45 (mean: 37.10 ± 3.93)	13M/9F	780-3,635 (mean: 2,365.68 ± 662.6)
4	Wahyuni *et al.* [43]	Sucking pressure measurement device		Preterm infants	120	28–34	62M/58F	ELBW < 1,000 g, VLBW 1,000-1,499 g, LBW 1,500 ≤ 2,500 g
5	Barlow *et al.* [32]	NTrainer system		Extremely preterm infants	117	24–28	59M/58F	Not reported
6	Ebrahimi *et al.* [44]	Compact pediatric portable pacifier		Preterm and term infants	4 (2 preterm, 2 term)	34–40	2M/2F	S1: 2,664 S2: 3,454 S3: 2,187 S4: 3,173
7	Grassi *et al.* [45]	Sensorized pacifier		Preterm and term newborns	9	34–40	5M/4F	Not reported
8	Akbarzadeh *et al.* [33]	Sensitized pacifier / wireless NNS system		Preterm infants	137	29-36	54%M	No sucking ability: 1,200 ± 230 With sucking ability: 1,350 ± 230

Note: ELBW = extremely low birth weight (<1,000 g); VLBW = very low birth weight (1,000–1,499 g); LBW = low birth weight (1,500–2,499 g); GA = gestational age; PCA = post-conceptional age

Pressure-based sensors operate by detecting intraoral pressure changes generated during sucking activity, employing transduction mechanisms that include differential, piezoresistive, barometric, pneumatic, and semiconductor-based approaches. These sensors varied considerably in sensitivity range, calibration strategy, and signal acquisition method, reflecting the diversity of engineering implementations across studies. In contrast, the single force-based sensor detected mechanical deformation caused by tongue and lip pressure against the pacifier surface, offering simpler hardware integration but potentially greater sensitivity to sensor positioning and infant movement. Despite differences in sensor architecture, all systems shared the common goal of capturing sucking dynamics in a non-invasive and clinically feasible manner. Overall, current NNS sensing technologies offer objective and non-invasive assessment with increasing adoption of portable and wireless designs. Nevertheless, heterogeneity in sensor configurations, signal processing methods, and reported outcomes remains a major challenge, underscoring the need for standardization and broader clinical validation.

Table 6 positions the present review within the existing body of literature, comparing its engineering-oriented focus with the clinical and intervention-based emphasis of previous NNS reviews and highlighting the specific engineering gaps this review addresses; this contribution is discussed further under novelty of the present review below.

Table 5. Engineering principles of sensing technologies for NNS assessment

No.	Author	Sensor	Operating principle	Sensitivity/range	Calibration method	Signal acquisition
Group 1: pressure-based sensors ($n = 7$)						
1	Wang *et al.* [42]	Honeywell SSC-SNBN400MD-AA3	Differential pressure via rubber tube to polypropylene bottle/pacifier	Differential pressure (not specified)	Adaptive noise cancellation (ANC); fractal dimension (FD); first derivative (FDI) with dynamic threshold	12-bit ADC; 1024 Hz; wireless Bluetooth v2.0+EDR
2	Cunha *et al.* [31]	Honeywell 26PCAFA6G	Piezoresistive; flexible silicone tube to commercial pacifier mouthpiece	±1 psi	Linear calibration: V = 48.99p + 8.61 mV (cc = 0.99996)	BIOPAC MP100; 16-bit; 10 samples/s
3	Wahyuni *et al.* [43]	JTEKT PMS-5M-2	Semiconductor pressure transducer; detects negative intraoral pressure via air in pacifier	±375 mmHg; min. variation 1.875 mmHg	Spearman's correlation; intraclass correlation coefficient (ICC)	150 Hz; wired; GRAPHTEC GL240
4	Barlow *et al.* [32]	NTrainer pneumatic pressure sensor	Pneumatic; digitized nipple compression pressure during NNS	Threshold 1.6 cmH2O	ALSS baseline correction; automatic peak picker	100 samples/s; 4-pole Butterworth LP 50 Hz
5	Ebrahimi *et al.* [44]	BMP180 (Bosch Sensortec)	Barometric pressure; measures negative intraoral pressure via 0.5 cm hole + rubber tube	300-1100 mbar; 16-bit ADC	FFT-based single-sided PSD; time-domain feature extraction	16 samples/s; micro SD; Li-Po battery
6	Grassi *et al.* [45]	2x LPS331AP (STMicro)	Piezoresistive; dual sensors (teat compression + suction) in 3D-printed acrylic case	26-126 kPa; 4096 LSB/mbar	FD; FDI; ANC	12.5 Hz; I2C interface; LabVIEW + MATLAB
7	Akbarzadeh *et al.* [33]	NXP MP3V5004GP (EP) + MP3V5050V (IP)	Dual piezoresistive; EP via flexible pipe to soft air-chamber nipple; IP via flexible pipe to isolated nipple interior	EP: 0-50 kPa, 54 mV/kPa; IP: 0-50 kPa	20-sample symmetric moving average; sucking incidence detection threshold ≥ 8 units	10-bit ADC; 12.5 kHz down sampled to 25 Hz; Bluetooth + micro SD
Group 2: force-based sensors ($n = 1$)						
8	Chiu *et al.* [39]	2× FSR-400 (interlink electronics)	Force-sensitive resistor; embedded inside food-grade silicone pacifier; detects tongue/lip mechanical deformation	0-1050 gf/cm2; 3V DC	ANOVA (all $p <$ 0.001); decision flowchart for sucking pattern classification	60 Hz; USB; LabVIEW

Table 6. Comparison of previous reviews on NNS and the unique contribution of the present review

Reference	Focus	Engineering limitation	Present review
Foster *et al.* [4]	NNS intervention	No sensor analysis	Engineering classification of NNS sensors
Pineda *et al.* [46]	NNS development	No sensing mechanism discussion	Comparison of sensor architectures and parameters
Cunningham *et al.* [38]	Objective NNS assessment	Limited engineering evaluation	Analysis of sensor specifications and acquisition systems
Zhao *et al.* [15]	Feeding outcomes	No device or signal analysis	Synthesis of sensing principles and technical limitations
Westemeyer *et al.* [20]	Oral-motor development	No sensor classification	Classification of pressure- and force-based sensors
Existing reviews	Clinical outcomes and interventions	Lack of engineering-oriented synthesis	Comprehensive review of sensing mechanisms, signal acquisition, and future artificial intelligence (AI) / Internet of Things (IoT) integration

3.3. Comparative performance and design trade-offs among sensing devices

The eight reviewed sensing systems demonstrated distinct engineering strategies and performance profiles. Wang *et al.* [42] developed a wireless multi-parameter system that simultaneously monitored sucking, swallowing, and breathing with high detection sensitivity (97.94%, 93.15%, and 97.52%, respectively); its pressure-based transduction contributed to strong measurement stability and calibration accuracy, although the authors noted that application for early detection of choking and apnea episodes warrants further investigation. Cunha *et al.* [31] proposed a low-cost, non-invasive prototype with excellent calibration linearity ($cc = 0.99996$), likewise benefiting from stable pressure-based measurement; however,

the small cohort and the limited representation of term infants constrained how broadly the findings could be applied. Chiu *et al.* [39], the only force-based system in this review, introduced a dual-channel pacifier that objectively classified sucking patterns into three categories using a decision flowchart; its rigid T-shaped design, however, illustrates the common trade-off between mechanical robustness and infant comfort, as it was poorly tolerated by some infants. Wahyuni *et al.* [43] ran a multi-center study involving 120 infants and found that objective and subjective NNS measurements correlated moderately for sucking pressure ($r = 0.58$) and suctions per burst ($r = 0.60$), while the correlation for time between bursts was considerably stronger ($r = 0.74$); the authors argued that objective devices remain important despite being scarce in most perinatology units.

Barlow *et al.* [32] applied frequency-domain analyses and machine learning across four neonatal intensive care units (NICUs), identifying three distinct NNS developmental classes, though the underlying factors contributing to these classes remain unknown. Ebrahimi *et al* [44] proposed a compact, low-cost portable pacifier with battery life exceeding 10 hours, but the extremely small sample size ($n = 4$) limited clinical validation. Grassi *et al.* [45], [47] developed a dual-sensor sensorized pacifier capable of differentiating suction and expression phases simultaneously, though the prototype nature of the device, small sample size ($n = 9$), and absence of wireless communication were acknowledged as key limitations requiring future improvement. Finally, Akbarzadeh *et al.* [33] presented a wireless affordable pacifier (less than $20 per unit) that predicted feeding outcomes with 71% accuracy in 137 preterm infants, though thermal drift artifacts, missing weekly recordings, and limited dataset size constrained the robustness of the prediction model. Collectively, these findings indicate that while smart sensor technologies show considerable promise for objective NNS assessment, challenges remain regarding device accessibility, sample size adequacy, and the need for broader longitudinal clinical validation.

Rather than representing competing technologies, the reviewed sensing systems illustrate different engineering strategies for addressing the same clinical objective. Pressure-based sensors generally provided more stable and quantitative measurements because they directly captured intraoral pressure dynamics within a closed pneumatic environment. In contrast, force-based sensors measured mechanical deformation at the pacifier surface, offering simpler hardware integration but potentially greater sensitivity to sensor positioning and infant movement. Wireless systems improved portability and enabled continuous monitoring, although miniaturization often came at the expense of extensive clinical validation. Collectively, these observations suggest that future NNS sensing devices should not focus solely on improving individual sensor performance, but rather on balancing measurement accuracy, infant comfort, usability, and clinical scalability. This synthesis indicates that engineering optimization alone is unlikely to ensure successful clinical adoption unless accompanied by standardized validation protocols and user-centered device design.

These observed trade-offs- between measurement stability, mechanical design, and device practicality- highlight that no single sensing approach yet satisfies all requirements for reliable, comfortable, and clinically deployable NNS assessment, and should guide subsequent design refinements toward hybrid or adaptive sensor solutions. Beyond identifying these trade-offs, the classification of sensing technologies into pressure-based and force-based categories established in this review offers a practical framework for future sensor development. By clarifying which mechanism aligns with specific design priorities- such as measurement stability versus mechanical robustness- this classification can guide biomedical engineers in selecting or refining sensing approaches suited to their intended clinical application, rather than developing devices in isolation from existing design trade-offs.

3.4. Clinical and engineering considerations for translation into practice

Nearly all of the devices covered in this review are still at the prototype stage, and none has been tested for usability by neonatal nurses or clinicians under routine NICU conditions. None of the included studies reported on device setup time, operator training needs, or how the technology would fit into existing clinical workflows-an omission that stands as a substantial obstacle to wider adoption in practice. Pacifier-based sensing devices come into direct contact with the oral cavity of immunocompromised preterm infants, making biocompatibility and sterilization critical considerations. However, none of the included studies explicitly reported sterilization methods, biocompatibility testing, or compliance with medical device safety standards. Future development of NNS sensing systems must address these concerns, including the selection of food-grade or medical-grade materials, compatibility with standard sterilization procedures such as autoclave or chemical disinfection, and adherence to relevant regulatory frameworks.

Beyond device-specific limitations, several cross-cutting engineering considerations will shape clinical translation. Hardware miniaturization, embedded electronics integration, power-supply management, and sensor calibration-exemplified by the compact designs of Ebrahimi *et al.* [44] and Akbarzadeh *et al.* [33], [48], [49] described above-remain central challenges for reliable, repeatable measurement in neonatal settings. Several systems, including those of Wang *et al.* [42] and Akbarzadeh *et al.* [33], [48], [49] have already demonstrated wireless data transmission, suggesting strong potential for integration with Bluetooth,

Wi-Fi, and IoT protocols to support real-time monitoring within smart healthcare infrastructure. Likewise, the frequency-domain and machine-learning approaches applied by Barlow *et al.* [32] and Akbarzadeh *et al*. [33] point to opportunities for automated, real-time classification of sucking patterns to support clinical decision-making. However, successful clinical translation will additionally depend on satisfying medical device regulatory requirements (such as food and drug administration (FDA) clearance or an equivalent regional pathway), ensuring electrical safety and software reliability, managing risk appropriately, and achieving interoperability with hospital information systems and electronic health records-considerations that none of the included studies addressed. Taken together, the studies reviewed here point to marked heterogeneity in device design, measurement parameters, and reporting practices, which restricts cross-study comparability; standardizing outcome measures and embedding these devices into clinical workflows therefore remain essential for broader implementation of these emerging biomedical sensing platforms.

3.5. Novelty of the present review

The novelty of the present review can be further understood in the context of existing literature. Earlier reviews addressing NNS in preterm infants have largely centered on clinical and intervention-related questions-for instance, how NNS stimulation influences feeding outcomes, oral-motor development, and physiological stability. These works are undoubtedly useful, yet none has examined NNS specifically through an engineering or signal-measurement lens. What sets the present review apart is its classification of sensing technologies by engineering characteristics-sensing mechanisms, signal acquisition methods, and measurable parameters-covering ground that clinically oriented reviews have left untouched. In this sense, the present work complements rather than duplicates prior literature, linking the clinical and engineering sides of NNS research.

3.6. Limitations and directions for future research

Several limitations of this review warrant acknowledgment. To begin, the sample sizes across included studies were generally modest, spanning only 4 to 137 participants, which raises questions about how well these findings would generalize to wider clinical populations. Beyond that, the lack of standardized protocols governing device design, signal processing, and outcome measurement makes direct comparison and replication of results difficult across the evidence base. None of the eight included studies performed longitudinal validation of their sensor systems either, so the long-term reliability and clinical value of these technologies remain unconfirmed. A further limitation is that this review omitted a formal quality assessment or risk-of-bias evaluation; this choice reflects the review's exploratory, engineering-oriented scope, which favored technical characterization of sensing mechanisms over grading clinical evidence-though it does mean the relative strength of evidence across the reported technologies could not be weighed. Looking ahead, future work in this area should pursue larger and more diverse study populations, work toward standardized assessment protocols, undertake longitudinal studies to establish the clinical effectiveness of NNS sensing technologies in preterm infants, and adopt structured quality-appraisal tools-such as Joanna Briggs Institute (JBI) checklists suited to each study design-going forward.

4. CONCLUSION

This review offers a wide-ranging, engineering-grounded classification of the sensing technologies used to objectively assess NNS in preterm infants. Both pressure- and force-based sensing approaches now permit accurate, quantitative, non-invasive evaluation of sucking behavior, marking a clear improvement over conventional subjective clinical assessment. Even so, pronounced heterogeneity in sensor architecture, signal acquisition, validation approaches, and reporting conventions continues to hinder reproducibility, comparability across studies, and translation into clinical practice. Moving forward, research in this space should prioritize standardized evaluation frameworks, multicenter clinical validation, and device development centered on end-user needs, so as to widen adoption within neonatal care. Multimodal sensing, AI-assisted signal analysis, and IoT-enabled monitoring all hold promise, yet the evidence supporting them remains confined largely to prototype-stage devices. Bringing these technologies into routine clinical use will therefore hinge on rigorous technical validation, standardized performance benchmarking, and demonstrated clinical utility under real-world neonatal conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Not applicable to this article, as this study did not generate or analyze any new datasets.

REFERENCES

[1] X. Zeng, W. Jiang, X. He, and J. Zhang, "Preterm Birth: Epidemiology, Risk Factors, Pathogenesis, and Prevention," in *Oxford Research Encyclopedia of Global Public Health*, Oxford University PressNew York, NY, 2024. doi: 10.1093/acrefore/9780190632366.013.515.

[2] Y. Rahmawati, J. Prasetyo, and R. Wardani, "Factors Related to Conservative Preterm Therapy on BPJS Claim Achievement in Waluyo Jati Hospital Probolinggo Regency," *Asian Journal of Health Research*, vol. 2, no. 3, pp. 19–24, 2023, doi: 10.55561/ajhr.v2i3.126.

[3] J. A. Park, H. L. Jun, M. Lee, H. J. Choi, I. Jung, and C. M. Kang, "Early dental visit affects dental treatment in Korean preschool children born preterm: a nationwide population-based study," *Scientific Reports*, vol. 14, no. 1, 2024, doi: 10.1038/s41598-024-74809-3.

[4] J. P. Foster, K. Psaila, and T. Patterson, "Non-nutritive sucking for increasing physiologic stability and nutrition in preterm infants," *Cochrane Database of Systematic Reviews*, vol. 2016, no. 10, 2016, doi: 10.1002/14651858.CD001071.pub3.

[5] G. J. Capilouto and T. J. Cunningham, "Objective assessment of a preterm infant's nutritive sucking from initiation of feeding through hospitalization and discharge.," *Neonatal intensive care : the journal of perinatology-neonatology*, vol. 29, no. 1, pp. 40–45, 2016.

[6] N. Khalessi, S. Nazi, M. Shariat, M. Saboteh, and Z. Farahani, "The effects of pre-feeding oral stimulations and non-nutritive sucking on physical growth and independent oral feeding of preterm infants," *Iranian Journal of Neonatology*, vol. 6, no. 4, pp. 25–29, 2015.

[7] B. G. S. de M. Sales, R. M. M. M. Furlan, C. A. V. Ramos, N. S. Fracaroli, E. B. de Las Casas, and A. R. Motta, "Characterization of parameters for the analysis of objective measures of non-nutritive sucking of newborns," *CoDAS*, vol. 36, no. 4, 2024, doi: 10.1590/2317-1782/20242023149en.

[8] C. L. C. Batista, V. P. Rodrigues, V. S. Ribeiro, and M. D. S. B. Nascimento, "Nutritive and non-nutritive sucking patterns associated with pacifier use and bottle-feeding in full-term infants," *Early Human Development*, vol. 132, pp. 18–23, 2019, doi: 10.1016/j.earlhumdev.2019.03.007.

[9] S. Fucile, E. Wener, and K. Dow, "Enhancing breastfeeding establishment in preterm infants: A randomized clinical trial of two non-nutritive sucking approaches," *Early Human Development*, vol. 156, p. 105347, 2021, doi: 10.1016/j.earlhumdev.2021.105347.

[10] L. Li, L. Liu, F. Chen, and L. Huang, "Clinical effects of oral motor intervention combined with non-nutritive sucking on oral feeding in preterm infants with dysphagia," *Jornal de Pediatria*, vol. 98, no. 6, pp. 635–640, 2022, doi: 10.1016/j.jped.2022.02.005.

[11] A. Alidad, M. Tarameshlu, L. Ghelichi, and H. Haghani, "The effect of non-nutritive sucking combined with oral motor stimulation and oral support on feeding performance in premature infants: A single-blind randomized-clinical trial," *Journal of Pediatric Rehabilitation Medicine*, vol. 14, no. 3, pp. 379–387, 2021, doi: 10.3233/PRM-190651.

[12] A. Vijay, R. K. Balasubramanium, R. Krishnamurthy, U. Chilwan, N. Kamath, and K. Bhat, "Profiling non-nutritive sucking skills in full-term and preterm neonates," *Egyptian Journal of Otolaryngology*, vol. 39, no. 1, 2023, doi: 10.1186/s43163-023-00550-9.

[13] C. Lau, "Breastfeeding Challenges and the Preterm Mother-Infant Dyad: A Conceptual Model," *Breastfeeding Medicine*, vol. 13, no. 1, pp. 8–17, 2018, doi: 10.1089/bfm.2016.0206.
[14] A. J. Hughes, S. A. Redsell, and C. Glazebrook, "Motor development interventions for preterm infants: A systematic review and meta-analysis," *Pediatrics*, vol. 138, no. 4, 2016, doi: 10.1542/peds.2016-0147.
[15] S. Zhao *et al.*, "Effects of implementing non-nutritive sucking on oral feeding progression and outcomes in preterm infants: A systematic review and meta-analysis," *PLoS ONE*, vol. 19, no. 4 April, p. e0302267, 2024, doi: 10.1371/journal.pone.0302267.
[16] C. Lau, "Development of suck and swallow mechanisms in infants," *Annals of Nutrition and Metabolism*, vol. 66, no. Suppl. 5, pp. 7–14, 2015, doi: 10.1159/000381361.
[17] F. Asadollahpour, F. Yadegari, F. Soleimani, and N. Khalesi, "The effects of non-nutritive sucking and pre-feeding oral stimulation on time to achieve independent oral feeding for preterm infants," *Iranian Journal of Pediatrics*, vol. 25, no. 3, 2015, doi: 10.5812/ijp.25(3)2015.809.
[18] R. Pineda, D. Prince, J. Reynolds, M. Grabill, and J. Smith, "Preterm infant feeding performance at term equivalent age differs from that of full-term infants," *Journal of Perinatology*, vol. 40, no. 4, pp. 646–654, 2020, doi: 10.1038/s41372-020-0616-2.
[19] L. K. Wahyuni *et al.*, "Non-nutritive sucking milestones of preterm infants in Indonesia: a descriptive study," *Paediatrica Indonesiana(Paediatrica Indonesiana)*, vol. 62, no. 5, pp. 311–317, 2022, doi: 10.14238/pi62.5.2022.311-7.
[20] R. Westemeyer, M. Hines, A. Martens, and E. Zimmerman, "The association between infant non-nutritive suck and oral motor development," *Infant Behavior and Development*, vol. 77, p. 101993, 2024, doi: 10.1016/j.infbeh.2024.101993.
[21] Ş. Dur and D. Gözen, "Nonnutritive Sucking Before Oral Feeding of Preterm Infants in Turkey: A Randomized Controlled Study," *Journal of Pediatric Nursing*, vol. 58, pp. e37–e43, 2021, doi: 10.1016/j.pedn.2020.12.008.
[22] M. Ostadi, F. jokar, A. M. Armanian, M. Namnabati, Y. Kazemi, and M. Poorjavad, "The effects of swallowing exercise and non-nutritive sucking exercise on oral feeding readiness in preterm infants: A randomized controlled trial," *International Journal of Pediatric Otorhinolaryngology*, vol. 142, p. 110602, 2021, doi: 10.1016/j.ijporl.2020.110602.
[23] F. C. B. Neiva *et al.*, "Non-nutritive sucking evaluation in preterm newborns and the start of oral feeding: A multicenter study," *Clinics*, vol. 69, no. 6, pp. 393–397, 2014, doi: 10.6061/clinics/2014(06)05.
[24] P. M. Bingham, T. Ashikaga, and S. Abbasi, "Prospective study of non-nutritive sucking and feeding skills in premature infants," *Archives of Disease in Childhood: Fetal and Neonatal Edition*, vol. 95, no. 3, pp. F194–F200, 2010, doi: 10.1136/adc.2009.164186.
[25] C. Ibrahim, P. Chavez, D. Smith, J. Craig, and R. Pineda, "Oral motor interventions used to support the development of oral feeding skills in preterm infants: An integrative review," *Early Human Development*, vol. 198, p. 106125, 2024, doi: 10.1016/j.earlhumdev.2024.106125.
[26] C. M. Moreira, R. P. Cavalcante-Silva, M. Miyaki, and C. I. Fujinaga, "Effects of nonnutritive sucking stimulation with gloved finger on feeding transition in very low birth weight premature infants," *Revista CEFAC*, vol. 16, no. 4, pp. 1187–1193, Aug. 2014, doi: 10.1590/1982-0216201424212.
[27] R. M. Westemeyer, A. Martens, H. Phillips, M. Hatfield, and E. Zimmerman, "Non-Nutritive Suck Parameters Measurements Using a Custom Pressure Transducer System," *Journal of Visualized Experiments* , vol. 2024, no. 206, 2024, doi: 10.3791/66273.
[28] M. D. Nascimento, D. da S. Gonçalves, G. de P. Bolzan, F. P. H. da Silveira, A. R. M. Weinmann, and M. V. de Moraes, "Reliability of the S-FLEX® device to measure non-nutritive sucking pressure in newborns," *Audiology - Communication Research*, vol. 24, 2019, doi: 10.1590/2317-6431-2019-2191.
[29] M. Pereira, O. Postolache, and P. Girão, "A smart measurement and stimulation system to analyze and promote non-nutritive sucking of premature babies," *Measurement Science Review*, vol. 11, no. 6, pp. 173–180, 2011, doi: 10.2478/v10048-011-0033-y.
[30] J. G. de Oliveira, T. Muhammad, and S. Kim, "A silver nanowire-based flexible pressure sensor to measure the non-nutritive sucking power of neonates," *Micro and Nano Systems Letters*, vol. 8, no. 1, 2020, doi: 10.1186/s40486-020-00121-0.
[31] M. Cunha *et al.*, "A promising and low-cost prototype to evaluate the motor pattern of nutritive and nonnutritive suction in newborns," *Journal of Pediatric and Neonatal Individualized Medicine*, vol. 8, no. 2, 2019, doi: 10.7363/080220.
[32] S. M. Barlow *et al.*, "Spectral features of non-nutritive suck dynamics in extremely preterm infants," *Pediatric Medicine*, vol. 6, p. 23, 2023, doi: 10.21037/pm-21-91.
[33] S. Akbarzadeh *et al.*, "Predicting Feeding Conditions of Premature Infants Through Non-Nutritive Sucking Skills Using a Sensitized Pacifier," *IEEE Transactions on Biomedical Engineering*, vol. 69, no. 7, pp. 2370–2378, 2022, doi: 10.1109/TBME.2022.3144094.
[34] J. D. Pereira, V. M. R. Viegas, O. A. Postolache, and P. S. Girao, "A Flexible and Low-Cost Solution to Measure and Stimulate NNS Skills of Premature Babies," *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC). IEEE*, pp. 1–5, May 17, 2021. doi: 10.1109/I2MTC50364.2021.9460092.
[35] J. M. Pereira, V. Viegas, O. Postolache, and P. S. Girão, "A dual measurement and stimulating system to monitor and promote NNS," *Journal of Physics: Conference Series*, vol. 1379, no. 1, p. 12034, 2019, doi: 10.1088/1742-6596/1379/1/012034.
[36] X. Huang, A. Martens, E. Zimmerman, and S. Ostadabbas, "Infant Contact-less Non-Nutritive Sucking Pattern Quantification via Facial Gesture Analysis," 2019, *arXiv*. doi: 10.48550/ARXIV.1906.01821.
[37] S. Zhu *et al.*, "Subtle signals: Video-based detection of infant non-nutritive sucking as a neurodevelopmental cue," *Computer Vision and Image Understanding*, vol. 247, p. 104081, 2024, doi: 10.1016/j.cviu.2024.104081.
[38] T. Cunningham, D. Mullineaux, E. Tamilia, C. Papadelis, P. Giannone, and G. Capilouto, "Quantifying Neonatal Sucking Performance: Promise of New Methods," *Seminars in Speech and Language*, vol. 38, no. 2, pp. 147–158, 2017, doi: 10.1055/s-0037-1599112.
[39] C. C. Chiu, H. H. Chen, T. M. Wang, and I. T. Shih, "AI Smart Materials for Enhancing Sucking Ability in Preterm Infants," *Sensors and Materials*, vol. 36, no. 3, pp. 919–943, 2024, doi: 10.18494/SAM4540.
[40] J. Tetzlaff, M. Page, and D. Moher, "PNS154 the Prisma 2020 Statement: Development of and Key Changes in an Updated Guideline for Reporting Systematic Reviews and Meta-Analyses," *Value in Health*, vol. 23, pp. S312–S313, 2020, doi: 10.1016/j.jval.2020.04.1154.
[41] C. Schardt, M. B. Adams, T. Owens, S. Keitz, and P. Fontelo, "Utilization of the PICO framework to improve searching PubMed for clinical questions," *BMC Medical Informatics and Decision Making*, vol. 7, no. 1, 2007, doi: 10.1186/1472-6947-7-16.
[42] Y. L. Wang *et al.*, "Development of a wireless oral-feeding monitoring system for preterm infants," *IEEE Journal of Biomedical and Health Informatics*, vol. 19, no. 3, pp. 866–873, 2015, doi: 10.1109/JBHI.2014.2335742.
[43] L. K. Wahyuni *et al.*, "A comparison of objective and subjective measurements of non-nutritive sucking in preterm infants," *Paediatrica Indonesiana*, vol. 62, no. 4, pp. 274–81, 2022, doi: 10.14238/pi62.4.2022.274-81.
[44] Z. Ebrahimi, H. Moradi, and S. J. Ashtiani, "A Compact Pediatric Portable Pacifier to Assess Non-Nutritive Sucking of Premature Infants," *IEEE Sensors Journal*, vol. 20, no. 2, pp. 1028–1034, 2020, doi: 10.1109/JSEN.2019.2943869.
[45] A. Grassi, F. Cecchi, G. Sgherri, A. Guzzetta, L. Gagliardi, and C. Laschi, "Sensorized pacifier to evaluate non-nutritive sucking in newborns," *Medical Engineering and Physics*, vol. 38, no. 4, pp. 398–402, 2016, doi: 10.1016/j.medengphy.2015.12.013.

[46] R. Pineda, K. Dewey, A. Jacobsen, and J. Smith, "Non-Nutritive Sucking in the Preterm Infant," *American Journal of Perinatology*, vol. 36, no. 03, pp. 268–276, Aug. 2018, doi: 10.1055/s-0038-1667289.
[47] A. Grassi, F. Cecchi, A. Guzzetta, and C. Laschi, "Sensorized pacifier to quantify the rhythmicity of non-nutritive sucking: A preliminary study on newborns," *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan, Italy*, 2015, pp. 7398-7401, doi: 10.1109/EMBC.2015.7320101.
[48] S. Akbarzadeh, T. Lyu, Z. Mei and W. Chen, "A New Wireless Sensorized Pacifier for Evaluating Infants' Feeding Skills During the Non-nutritive Sucking," *2018 International Symposium in Sensing and Instrumentation in IoT Era (ISSI), Shanghai, China*, 2018, pp. 1-4, doi: 10.1109/ISSI.2018.8538048.
[49] S. Akbarzadeh *et al*., "Evaluation of Apgar Scores and Non-Nutritive Sucking Skills in Infants Using a Novel Sensitized Non-Nutritive Sucking System," *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Montreal, QC, Canada*, 2020, pp. 4282-4285, doi: 10.1109/EMBC44109.2020.9176146.

APPENDIX

Table 4. Summary of sensing technologies for assessing non-nutritive sucking in preterm infants

No	Sensor specification	Sensing mechanism	Measured parameters	Signal processing method
1	Honeywell SSC-SNBN400MD-AA3; 12-bit ADC; sampling rate 1024 Hz; Bluetooth v2.0+ EDR	Differential pressure sensor (Honeywell SSC-SNBN400MD-AA3) connected via rubber tube to polypropylene bottle/pacifier. Also includes microphone (swallowing sound) and surface EMG (breathing)	– Sucking pressure (mmHg) – Swallowing frequency (events/min) – Breathing frequency (events/min) – Sucking–swallowing–breathing coordination ratio – Continuous vs. intermittent sucking phase	Preamplifier + bandpass filter (0.5 – 500 Hz for sucking pressure); high-pass filter (160 Hz) for swallowing sound; ANC to remove ECG artifact from breathing EMG. FD for swallowing/breathing feature extraction. FDI with dynamic threshold for event detection. 12-bit ADC at 1024 Hz sampling rate. Wireless Bluetooth transmission
2	Honeywell 26PCAFA6G; piezoresistive; ± 1 psi range; 16-bit ADC (BIOPAC MP 100); 10 samples/s; gain 200×2.5	Piezoresistive pressure sensor (Honeywell 26PCAFA6G, ±1 psi range) connected via flexible silicone tube to commercial pacifier mouthpiece. Sensor placed remotely no electrical components inside pacifier. Two-stage instrumentation amplifier (gain 200×2.5)	– Sucking pressure (mmHg) – Sucking amplitude (mmHg) – Burst duration (s) – Number of bursts/min – Number of sucks/burst – Inter-burst pause duration (s) – Sucking frequency (Hz) – Minimum and maximum pressure	Signal amplified and filtered; digitized by BIOPAC A/D converter (MP 100, 16-bit, 10 samples/s). Data stored and analyzed in AcqKnowledge 3.8 software. Low-pass filtering to minimize noise. Linear calibration: $V_0 = 48.99\,p + 8.61\,mV$ ($cc = 0.99996$). Manual burst identification; nonparametric Mann-Whitney U test for group comparison
3	2× FSR-400 (interlink electronics); force-sensitive resistor; 0–1050 gf/cm² range; 3V DC; 60 Hz sampling rate; USB; LabVIEW	Two force-sensitive resistors (FSR-400, interlink electronics) embedded inside food-grade silicone pacifier Channel 1 (near throat) and Channel 2 (near gum). DC circuit 3V; output current 0.15–35 µA; output voltage 0.3–1.15 V. Detectable pressure range: 0–1050 gf/cm²	– Sucking pressure CH1 & CH2 (gf/cm²) – Pressure difference between channels (σD) – Average sucking pressure above threshold (PT) – Sucking frequency (G, Hz) – Total duration of continuous sucks (S%) – Number of sucks per cluster – Sucking pattern classification (poor / irregular / regular)	60 Hz sampling rate; 5-min recording window (18,000 data points/channel). Four derived parameters: σD (inter-channel pressure SD), PT (cumulative pressure above threshold $T = \mu + \sigma$), G (sucking frequency via cluster detection), S% (sucking time ratio between channels). LabVIEW software for data acquisition and classification. Decision flowchart: poor → $\sigma D < 17.59$; regular → $\mu > 139.15$; irregular → others. ANOVA for statistical analysis (all $p < 0.001$)
4	JTEKT PMS-5M-2 (50K); semiconductor transducer; ± 375 mmHg range; min. variation 1.875 mmHg; 150 Hz; wired; GRAPHTEC GL240	PMS-5M-2 (50 K) semiconductor pressure transducer connected to pacifier. Detects pressure changes when infant lips/tongue press against air in pacifier; negative intraoral pressure transmitted to transducer at 150 Hz	– Sucking pressure (mmHg) – Number of suctions per burst – Time between bursts (s)	Signal A/D-converted, recorded and analyzed in Microsoft Excel for Mac v16. Detection range ± 375 mmHg. Minimum detectable variation: 0.5% (1.875 mmHg). Frequency at 150 Hz. Spearman's correlation test for objective vs. subjective comparison. ICC for correlation level classification

Table 4. Summary of sensing technologies for assessing non-nutritive sucking in preterm infants (*Continued*)

No	Sensor specification	Sensing mechanism	Measured parameters	Signal processing method
5	NTrainer System; pneumatic pressure sensor; cmH_2O unit; threshold 1.6 cmH_2O; 100 samples/s; 4-pole Butterworth LP 50 Hz; NeoNNS (Python)	Digitized nipple compression pressure dynamics during NNS. NTrainer delivers pulsatile orocutaneous stimulation (FM 2.8–1.6 Hz bursts). NeoNNS records 3-minute suck sessions; most active 2-minute window extracted for analysis	– NNS compression pressure (cmH_2O) – Peak frequency-Welch PSD (Hz) – PSD amplitude – Area under the curve (AUC) – Yule-Walker peak frequency (Hz)	Low-pass Butterworth filter (4-pole, 50 Hz) → down sampled to 100 Hz. Asymmetric least-squares smoothing (ALSS) baseline correction. Automatic peak picker (threshold: 1.6 cmH_2O). Frequency domain: FFT, Welch PSD (90% overlapped segments, 50% flattop window), Yule-Walker PSD (autoregressive model, order 8, high-pass $fc = 0.4$ Hz). ML longitudinal k-means cluster analysis; linear mixed modeling (LMM) in R and SAS 9.4
6	BMP180 (Bosch Sensortec); barometric pressure; 300–1100 mbar; 16-bit ADC; 16 samples/s; micro SD; Li-Po battery; PCB 21×24 mm²	BMP180 digital barometric pressure sensor (Bosch Sensortec®) measures negative intraoral pressure via 0.5 cm hole + rubber tube from pacifier nipple to sensor. Range: 300–1100 mbar, internal 16-bit ADC. Sampled at 16 samples/second. Powered by 3.7 V 100 mAh Li-Po battery; data stored on micro SD card via SPI interface	– Suck cycle duration (s) – Sucking burst duration (s) – Pause duration (s) – Suck frequency (Hz) – Sucks per minute – Bursts per minute – Sucks per burst – Minimum suck peak amplitude (mbar) – PSD bandwidth (Hz) – PSD amplitude (mbar²/Hz)	FFT-based single-sided power spectral density (PSD) from 60-second NNS signal. NNS signal bandwidth mainly below 4 Hz with dominant component ~2 Hz. Data processed on computer/smartphone. Time-domain: suck cycle, burst, pause durations and counts extracted. Frequency-domain: PSD amplitude and bandwidth per subject. Results compared across gestational ages (34–40 weeks).
7	2× LPS331AP (STMicro); piezoresistive; 26–126 kPa; 4096 LSB/mbar; 12.5 Hz; I²C; NI-845; LabVIEW + MATLAB	Two miniaturized digital piezoresistive sensors (LPS331AP, STMicro, 3×3×1 mm, 26–126 kPa, 4096 LSB/mbar) in commercial latex teat via 3D-printed acrylic case. Sensor 1 (expression): teat compression via hole in rigid case. Sensor 2 (suction): negative intraoral pressure via catheter (Ø 6 Fr, ~2 mm into oral cavity). Dual signals acquired via I²C interface	– Sucking pressure (mmHg) – Swallowing frequency (events/min) – Breathing frequency (events/min)	Preamplifier + bandpass filter (0.5–500 Hz); high-pass filter (160 Hz) for swallowing; ANC to remove ECG artifact from breathing EMG. FD for feature extraction. FDI with dynamic threshold for event detection. 12-bit ADC at 1024 Hz. Wireless Bluetooth transmission
8	NXP MP3V5004GP (EP) + MP3V5050V (IP); piezoresistive; 0–50 kPa; 54 mV/kPa; 10-bit ADC; 25 Hz; Bluetooth + micro SD; wireless charging	Two NXP piezoresistive sensors: MP3V5004GP (EP, 0–50 kPa) and MP3V5050V (IP, 0–50 kPa), sensitivity 54 mV/kPa. EP sensor connected via flexible pipe to soft air-chamber inside nipple. IP sensor connected via flexible pipe to isolated nipple interior. Sensors on PCB inside 3D-printed body. ADC: 10-bit at 125 kHz, downsampled to 25 Hz; data via Bluetooth + micro SD. Battery: single-cell Li-ion >10 h; wireless charging coil embedded	– Intraoral pressure — IP (kPa) – Expression pressure — EP (kPa) – Sucking frequency (Hz) – Mean sucking duration (s) – EP mean amplitude – IP mean amplitude – EP early amplitude (first 100 ms) – IP early amplitude (first 100 ms) – EP–IP correlation (Pearson)	Thermal drift correction: 20-second symmetric moving average subtracted from raw signals. Sucking incidence detection: threshold = 8 units on 1-second absolute EP fluctuation; minimum duration ≥ 0.5 s. Six NNS features/week (weeks 32–38). Feature matrix (42 features/infant) + medical records concatenated. Logistic regression with 5-fold cross-validation (Python, scikit-learn v0.23.2). Overall accuracy: 71%. ROC curve analysis performed

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