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# A silver nanowire-based flexible pressure sensor to measure the non-nutritive sucking power of neonates

Jean G. de Oliveira, Tausif Muhammad and Sohee Kim\* 

## Abstract

Preterm infants are prone to have higher risks of morbidity, disability and developmental delay compared to term infants. The primitive reflexes, inborn behaviors found in early life development, are shown to be a good tool to assess the integrity of the central nervous system of infants and to predict potential malfunctions. Among these reflexes, the non-nutritive sucking reflex plays an important role in indicating congenital abnormalities in brain development and feeding readiness, especially for premature infants. Conventionally, pediatricians evaluate the oral sucking power qualitatively based on their experiences, by using a gloved finger put inside the infant's mouth. Thus, more quantitative solutions to assess the sucking power of preterm infants are necessary to support healthcare professionals in their evaluation procedures. Here, we developed a silver nanowire (AgNW)-based flexible pressure sensor to measure the non-nutritive sucking power of infants. The flexible sensor was fabricated using silver nanowires deposited on polydimethylsiloxane (PDMS) in a sandwich-like structure. The sensor based on the principle of strain gauge was attached to a ring-shaped connecting module, and then to a pacifier. The negative sucking pressure exerted by the infant deformed the sensor membrane, causing its electrical resistance to change without any contact between the infant's mouth and the sensing element. The fabricated sensor was characterized and optimized to achieve both the suitable sensitivity and stability. Thanks to the excellent long-term electro-mechanical stability and high sensitivity, the developed sensor is expected to provide the means to quantitatively assess the non-nutritive sucking of infants, with a portable, low-cost, non-invasive and light-weight solution.

**Keywords:** Premature infant, Non-nutritive sucking, Pressure sensor, Flexible sensor, Silver nanowires

## Introduction

The World Health Organization (WHO) defines preterm birth as any birth before 37 completed weeks of gestation, or fewer than 259 days since the first day of the woman's last menstrual period [1]. This definition can be sub-divided based on gestational age (GA), as moderate or late preterm (32 to 37 completed weeks of gestation); very preterm (28 to 32 weeks of gestation); extremely preterm (less than 28 completed weeks of gestation). In addition, the WHO estimates that 15 million preterm

babies are born yearly, in which 7% of those die due to preterm birth complications and lack of adequate newborn care. Also, in most countries, the premature birth rate is increasing [2, 3].

Primitive reflexes, a group of inborn behaviors found in normal early development, are one of the most frequently used tools to assess the integrity of the central nervous system of infants [4]. Among these primitive reflexes, the sucking reflex, a reflexive oromotor behavior, is described as the most precocious and complex behavior of the newborn, and it is a potential predictor of neurodevelopmental outcomes during early infancy [5]. This sucking reflex can be divided into non-nutritive sucking (NNS) and nutritive sucking (NS). The first is defined as the sucking

\*Correspondence: soheekim@dgist.ac.kr

Department of Robotics Engineering, Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu 42988, Republic of Korea

on a dry nipple or pacifier, induced by placing a nipple in the infant's mouth without the presence of liquid [6], while the latter can be defined as the sucking when a nutrient such as milk is involved, accompanied by ingestion from a bottle or breast.

Premature birth can affect the NNS reflexive behavior in the neonatal period, causing weak muscle strength below the necessary level for a successful sucking reflex [7]. Besides, a poor NNS may indicate the central nervous system problems or cerebral injuries. The rhythmic properties of NNS can be used as an objective clinical indicator for congenital abnormalities, and there are evidences that this reflex is linked to childhood language, childhood motor abilities, IQ, and overall neurodevelopment [8]. NNS is a prerequisite skill for oral feeding, but its success does not necessarily translate into oral feeding success when measured at a single time point, since oral feeding is a much more complicated ability, requiring precise timing of sucking, swallowing, and breathing. On the other hand, regular measurements of NNS over a certain time period can indicate improvement towards a more stable sucking pattern, which is related to feeding success. Therefore, NNS has a potential usage in routine measurements over time, being a possible predictor of feeding ability success [7]. Also, since oral feeding readiness is one of the primary pre-requisites to discharge a neonate from the neonatal intensive care unit (NICU), early intervention of NNS practice leads to a decrease in the length of hospital stay [9].

The common clinical procedure to assess the oral sucking power is based on placing a gloved finger inside the infant's mouth to elicit the NNS reflex, which is qualitative and subjective [8, 10]. It has necessitated the development of more quantitative means to assess the sucking reflex. Previously, Lau and Kusnierczyk, based on the gloved finger technique used in hospitals, developed a finger device using a sensor transducer on the fingertip, connected to a processing module through a silicone tube [11]. Grassi et al. proposed a pacifier that contained a catheter connected to a pressure sensor in its interior, and this catheter invaded the infant's oral cavity by approximately 2 mm. In [12], a device to evaluate both nutritive and non-nutritive sucking was developed. In this device, the pacifier mouthpiece did not have any electrical connections inside, and the measurement was made remotely via a silicone tube, one side connected to the pacifier and the other side to a commercial pressure transducer. In [13], a compact and portable device was developed to measure NNS. In this work, a compact device to fit in the pacifier was designed, a wireless system was implemented to eliminate wires and tubes, and a small rechargeable battery was used. The system design focused on reducing the size and weight, but the

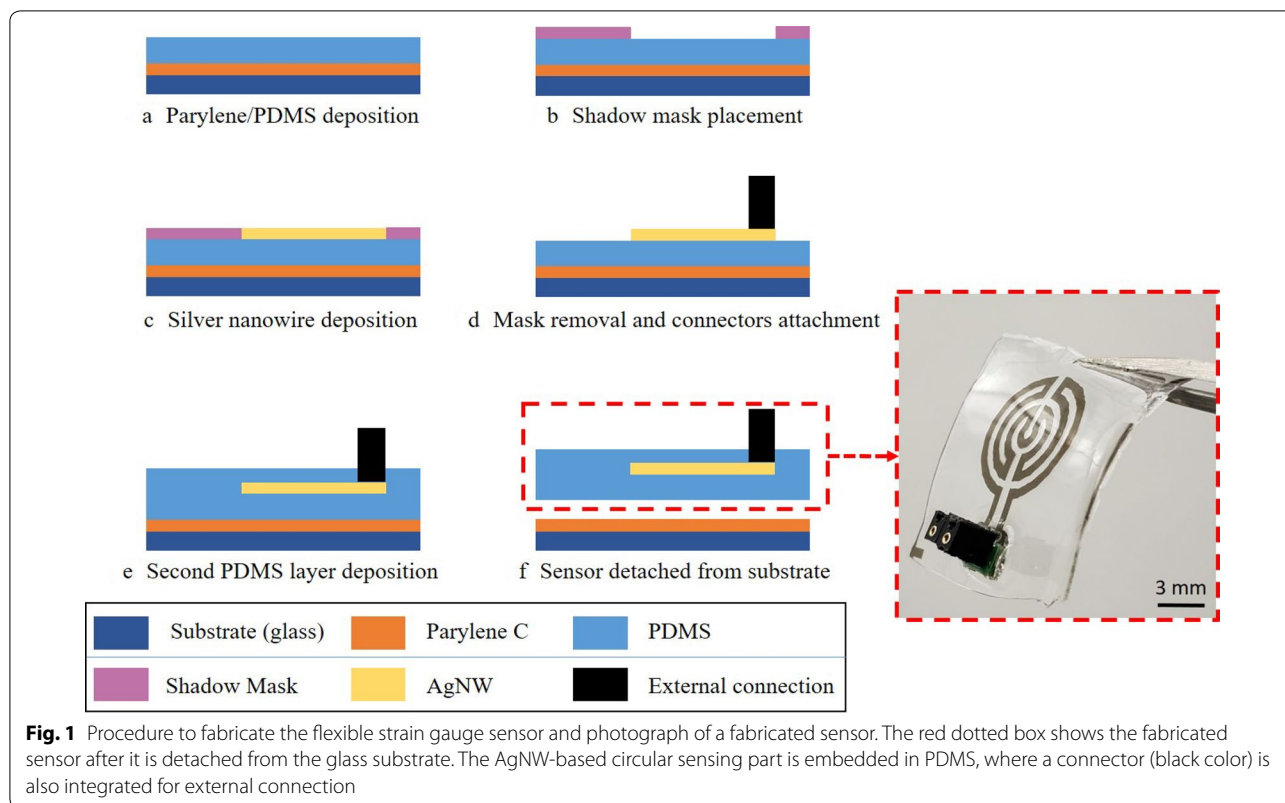
resolution of the pressure sensor was 1 kPa, which limits the measurements from infants with very weak sucking power [7, 11, 12, 14]. A company called *Innara Health* developed the NTrainer [15], an FDA approved device for both assessment of NNS parameters and therapy through patterned and frequency-modulated oral stimulation with therapeutic pulses to train the infant's NNS skills. Lastly, in [8], a contact-less method of quantifying NNS was developed by using video-based analysis of facial gesture. Most of the previous studies, however, were designed to include sensors, tubes or electronic components inside the pacifier mouthpiece, raising potential safety and hygiene issues. Some of these studies used commercially available pressure sensors designed for a much wider range of pressure, such as barometric sensors used in smartphones [10, 13]. Although the common pressure range of NNS can be covered, they perform with low accuracy or resolution below the levels necessary to measure the sucking power of weaker infants. Additionally, as mentioned in [8], sensorized devices alter the pacifier stiffness by contacting it, thereby distorting the natural sucking behavior.

In this study, we reported the development of a new sensing device to measure infant's NNS pressure. The sensor was designed to work based on the strain gauge principle, and fabricated based on silver nanowires deposited on polydimethylsiloxane (PDMS) in a sandwich-like structure. The developed sensor was demonstrated to be adequate to measure NNS, in a non-invasive and non-contact manner. The sensor was not put inside the infant's mouth nor in contact with the artificial nipple, unlike the previous studies. The detected pressure range and frequency of NNS were in the ranges reported in literature [7, 11, 12, 14, 16–18]. In addition, the sensor showed an excellent sensitivity, stability, and resolution high enough to measure NNS from even very preterm and extremely preterm infants, in a range of pressure as low as 150 Pa [7, 19].

## Methods

### Sensor fabrication

Figure 1 shows the fabrication steps of the strain gauge sensor. First, a 1- $\mu\text{m}$  thick parylene layer, as a sacrificial layer, was deposited on a glass substrate using a parylene coating system (OBTPB200, Obang Technology). Over the parylene layer, as shown in Fig. 1a, PDMS (184 A and B, Dow Corning) with a weight ratio of 10:1 was spun, and cured at 120 °C for an hour. The PDMS thickness was controlled by the rotation speed of the spin coater. The top surface of PDMS was then treated with O<sub>2</sub> plasma to enhance the adhesion and evaporate any remaining solvent from the surface. Then, a patterned shadow mask, fabricated by engraving the designed pattern on



an acrylic-based low-adhesive film by using a cutting plotter (Craft ROBO CE5000-40-CRP, Graphtec INC.), was attached on the treated PDMS surface, as illustrated in Fig. 1b. A methanol solution containing 1% of dispersed silver nanowires (AgNWs) was deposited over the attached mask by spray coating, with a spraying distance of 16 cm from the substrate, as shown in Fig. 1c. The choice for a low-adhesive film for the mask allowed it to be removed without peeling off the PDMS from the substrate. After removing the mask, the sample was placed on a hot plate at 190 °C for 10 min to enhance the electrical conductivity of AgNWs. For the external connection, a printed circuit board (PCB) with female pin headers attached was placed on the patterned AgNW terminals, and fixed using conductive epoxy (Fig. 1d). Finally, as illustrated in Fig. 1e, an encapsulating PDMS layer, with the same thickness of the first one, was spun over and then cured at 120 °C for an hour. Due to the weak adhesion between parylene and PDMS, the sensor could be easily peeled off from the substrate (Fig. 1f). Four sensors were fabricated per batch.

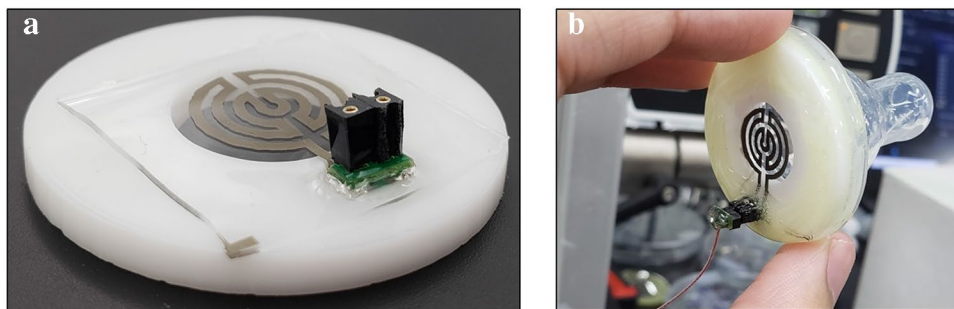
The AgNW pattern was designed to accommodate a long conductive line in a limited area, to increase the sensitivity, but keeping a certain level of radial symmetry, as a uniform pressure application will deform the membrane in a centrosymmetric fashion. After separated

from the substrate, the sensor was attached to a connecting module, as shown in Fig. 2a, which was a 4 mm-thick acrylic ring with an inner diameter of 14 mm and an outer diameter of 35 mm, fabricated using a laser cutting system (VLS4.60, Universal Laser System). This module served as an interface between the sensor and the artificial nipple, as illustrated in Fig. 2b. Moreover, the inner diameter of the connecting module was an important parameter for tuning the sensor performance.

### Sensor evaluation setup

To evaluate the sensor characteristics, a customized evaluation setup was built. The sensitivity of the fabricated pressure sensor was characterized by detecting the changes in resistance due to the deformation when pressure was applied to the sensor. The sensor was also characterized in terms of working pressure range, sensitivity, reliability, response delay time, recovery time, hysteresis and resolution.

The setup included a syringe, where the syringe's piston was controlled by a z-axis motorized stage (ESM303, MARK-10), to apply negative gauge pressure inside the cylinder and consequently to the sensor. The pressure applied in the system was directly measured by a pressure data logger (KP321, Kimo Instruments). The changes in resistance caused by the applied



**Fig. 2** **a** Strain gauge sensor placed on the connecting module and **b** fully assembled sensor with a commercial pacifier. The sensing region of the sensor is located in the central hole of the acrylic connecting module, where it can freely deform, while the external connection part of the sensor, made of a PCB (green color) and a female pin header (black color), are firmly placed on the rigid surface of the connecting module

pressure were then measured using an LCR meter (E4980A, KEYSIGHT). For noise reduction and better device handling in future clinical applications, a customized wire was manufactured using thermocouple wires. Both the resistance and the pressure obtained during the experiment were transferred to a computer, where the data were further processed and correlated. Figure 3 shows the entire setup and its working principle.

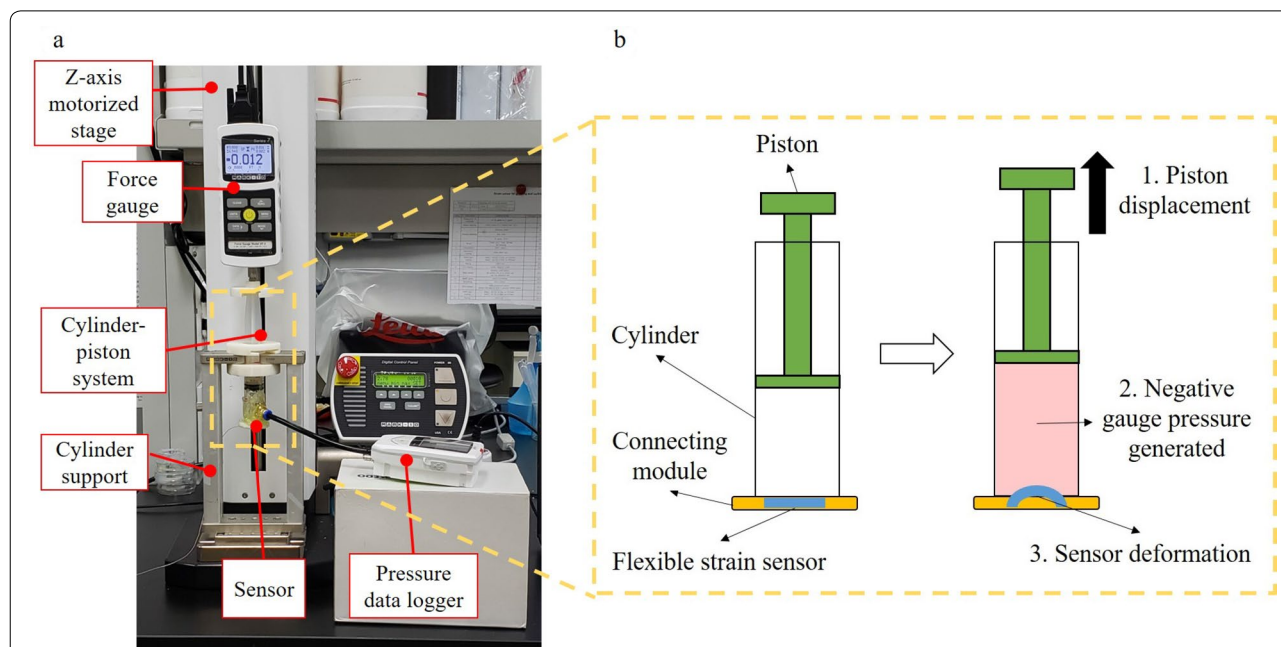
**Results and discussion**

**Parametric study**

First, the effects of the thickness of the sensor membrane and the inner diameter of the connecting module on the sensitivity were investigated. Defining the sensitivity as

$$S = \Delta(\Delta R/R_0)/\Delta P, \tag{1}$$

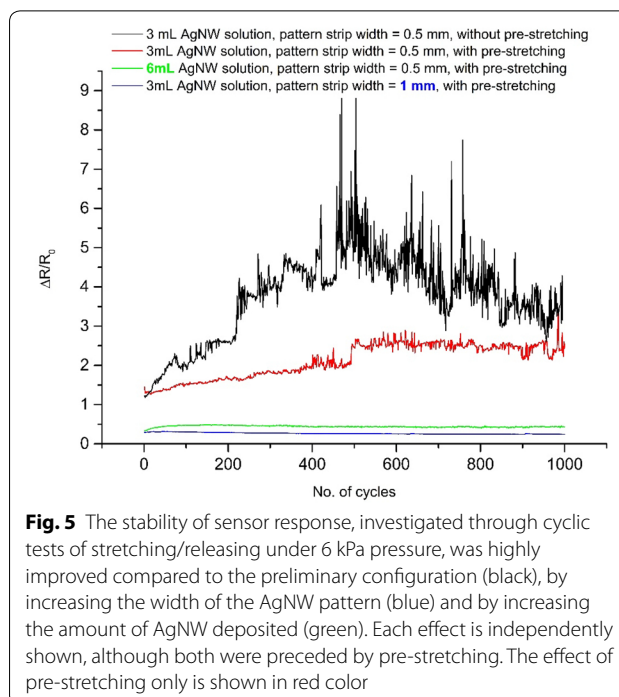
where  $\Delta R/R_0 = (R - R_0)/R_0$ , with R and  $R_0$  representing the resistance with and without gauge pressure applied, respectively, and P is the applied gauge pressure, the sensitivity curves with different configurations were



**Fig. 3** **a** Customized evaluation setup to characterize the pressure sensing device and **b** working principle of the setup to measure the pressure and the change in resistance of the sensor. When the piston is displaced by the Z-axis motorized stage, the negative gauge pressure generated inside the cylinder is measured by a pressure data logger, and the change in resistance of the sensor due to deformation is measured by an LCR meter

obtained. Using connecting modules with different inner diameters and a fixed PDMS thickness of 375  $\mu\text{m}$ , the sensitivity curves are shown in Fig. 4a. It can be seen that the larger the diameter, the larger the change in resistance for the same applied pressure. Similarly, using a connecting module with an inner diameter of 12 mm, the sensitivity curves for different PDMS thicknesses are shown in Fig. 4b, presenting a lower sensitivity for a thicker PDMS layer. All results, however, presented large standard deviations, particularly at higher pressure levels.

Moreover, the stability of the sensor was investigated through cyclic tests of stretching/releasing under 6 kPa pressure. The preliminary experiments showed the stability of sensor responses was poor, with a big increase in  $\Delta R/R_0$  over cycles. To improve the stability of the sensor, a pre-stretch of 14.5 kPa was performed prior to the cyclic test. The degree of pre-stretch was intentionally set to be higher than the actual range of stretch, to create initial cracks in the nanowire network that will help prevent the formation of new microcracks when stretches of lower degree are applied. The pre-stretching considerably improved the stability, although a certain level of increase in relative resistance change still existed, as shown in Fig. 5. To improve the stability further, more alternative electrical pathways should be retained in the nanowire network when under deformation, therefore reducing the degree of degradation in resistance over cycles [20]. Possible approaches to retain more pathways are increasing the density of AgNWs or increasing the width of AgNW pattern strips, as described in [20]. Figure 5 shows the  $\Delta R/R_0$  stability over 1000 cycles under 6 kPa pressure for the sensor without and with pre-stretching, as well as the effects of combining the pre-stretching with increased

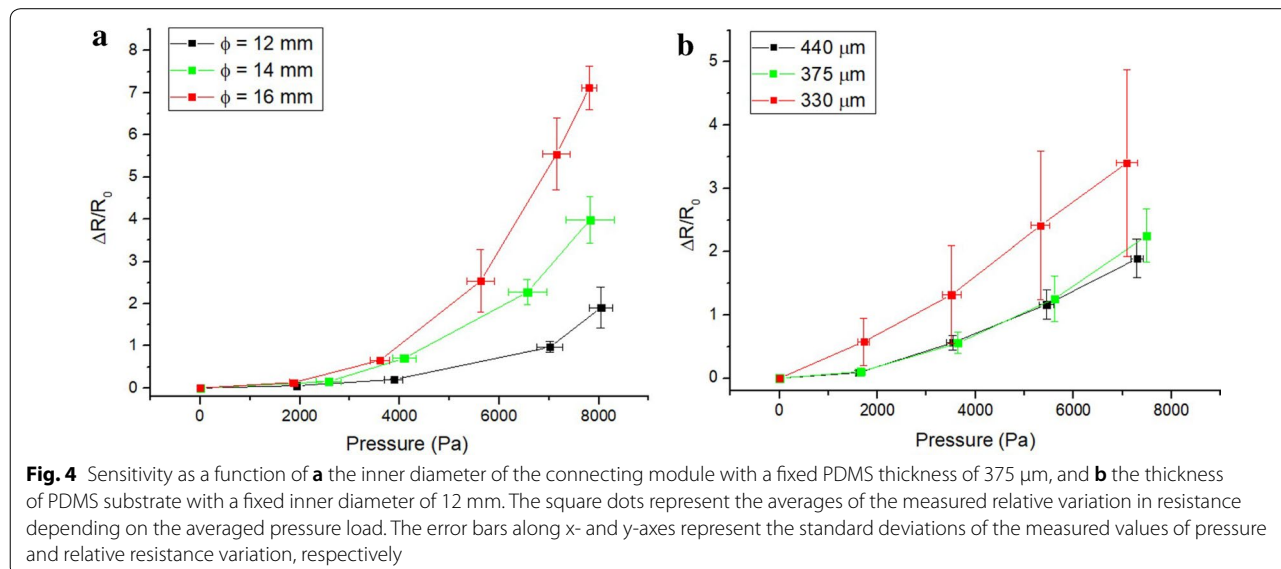


**Fig. 5** The stability of sensor response, investigated through cyclic tests of stretching/releasing under 6 kPa pressure, was highly improved compared to the preliminary configuration (black), by increasing the width of the AgNW pattern (blue) and by increasing the amount of AgNW deposited (green). Each effect is independently shown, although both were preceded by pre-stretching. The effect of pre-stretching only is shown in red color

pattern strip width or increased amount of AgNW deposited. Both approaches showed significant improvements in the stability of sensor response, although they compromised the sensitivity.

**Results of device characterization**

The sensor configuration was finally optimized based on the results of the parametric study, assuring both the stability and the sensitivity. The resultant dimensions of



**Fig. 4** Sensitivity as a function of **a** the inner diameter of the connecting module with a fixed PDMS thickness of 375  $\mu\text{m}$ , and **b** the thickness of PDMS substrate with a fixed inner diameter of 12 mm. The square dots represent the averages of the measured relative variation in resistance depending on the averaged pressure load. The error bars along x- and y-axes represent the standard deviations of the measured values of pressure and relative resistance variation, respectively

the sensor as well as the SEM image of the sensor's cross-sectional view are shown in Fig. 6. The sensor weighed 0.4 g without the connecting module, and 3 g with it. The resultant thickness of the sensor was 440  $\mu\text{m}$ .

The sensitivity curve was obtained by characterizing four sensors, in which 12 to 16 measurements were performed for 6 different levels of pressure per sensor. Figure 7a shows the relative change in resistance as a function of applied pressure, in which two distinct regions were identified, resulting in sensitivities of  $0.06 \text{ kPa}^{-1}$  and  $0.63 \text{ kPa}^{-1}$  for the pressure ranges of 0 kPa to 3.5 kPa and 3.5 kPa to 6.8 kPa, respectively. The stability of the sensor was evaluated through approximately 1000 cycles of loading/unloading under pressure loads of 3.5 kPa and 5.1 kPa. The relative variation in resistance in response to the cyclic test showed a stable behavior, as exhibited in Fig. 7b. This was possible thanks to the robust interface between the sensor and the external connection part, which allows the interface region to remain undeformed during the deformation of the sensor. In addition, the AgNW sandwiched between two PDMS layers prevents the delamination of nanowires.

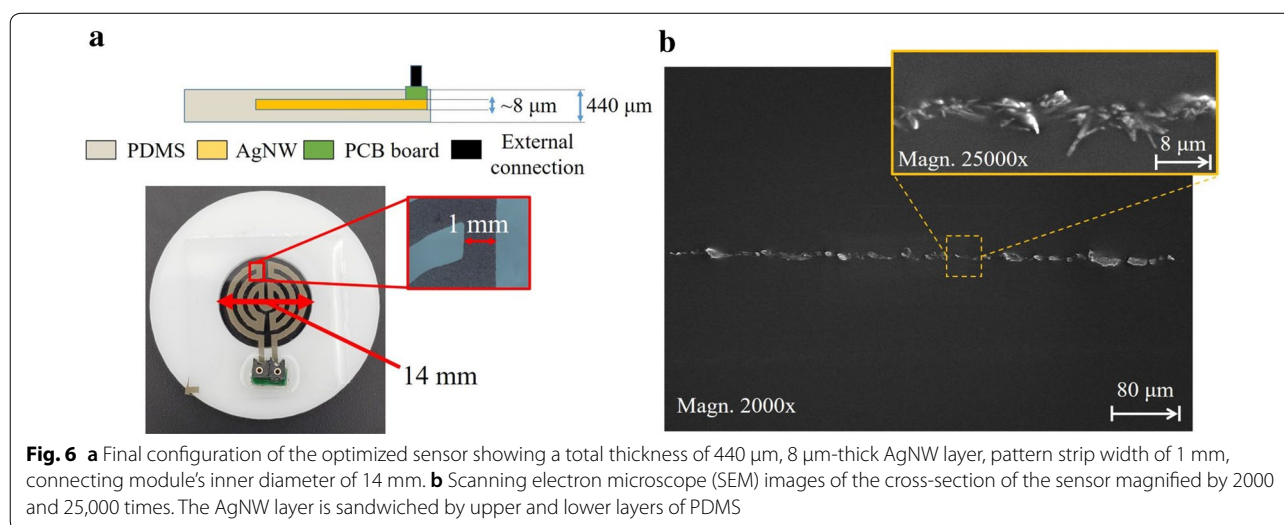
The response delay time of the sensor was analyzed under an input of approximately 6 kPa, with a rising time of 0.25 s, as an attempt to reproduce the infant's non-nutritive sucking speed, conservatively assuming a maximum sucking frequency of 2 Hz [7, 12, 16, 17], and not considering any pause between sucks. Under this condition, the time that the resistance took to reach the peak was 0.434 s, as shown in Fig. 7c. Subtracting this value from the rising time, the sensor's delay time was found to be 0.184 s. One thing to note is that this experiment was limited by the temporal resolution of the LCR meter used, which was 0.217 s.

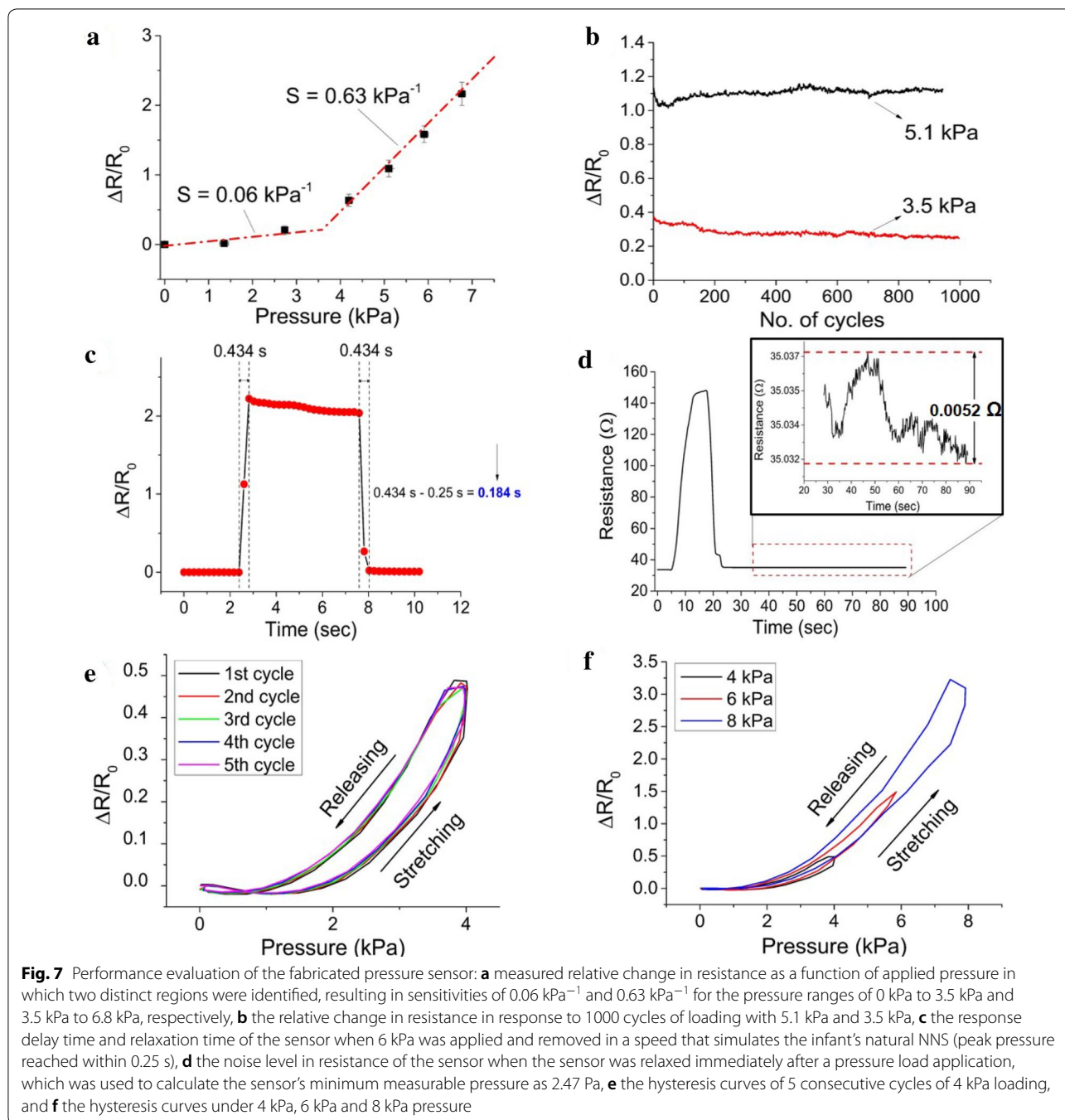
Adapting the method in [21], the pressure resolution was calculated by estimating the noise level ( $R_{\text{noise}}$ ). As shown in Fig. 7d, the noise level was  $0.0052 \Omega$ . The sensor's pressure resolution ( $P_{\text{res}}$ ) can, therefore, be calculated by  $P_{\text{res}} = R_{\text{noise}}/R_0 \times S$ , which resulted in a minimum measurable pressure of 2.47 Pa. Additionally, the average accuracy in measurement was calculated to be 220.8 Pa, by comparing 45 measurements under three different applied pressure levels, using the fabricated sensor and the pressure data logger as reference. The hysteresis for the sensor is presented in Fig. 7e for 5 cycles of 4 kPa pressure, showing a repeatable behavior over cycles. Similarly, in Fig. 7f, the hysteresis curve was obtained for three different loads of pressure, 4 kPa, 6 kPa and 8 kPa.

## Conclusion

We designed and fabricated a flexible pressure sensor based on the strain gauge principle to measure the non-nutritive sucking power of preterm infants, in which both the sensitivity and the stability in sensor responses were achieved. The developed device is simple and cheap to fabricate, easy to customize, very compact and light weight, and most noticeably, completely non-invasive. Using the developed sensor, no parts would be put inside the infant's mouth or in contact with the pacifier during the sensing of NNS power, which is fundamental to assure the infant's safety and to preserve the natural sucking behavior.

The sensor, based on silver nanowires and PDMS, was characterized for a pressure range up to 6.8 kPa, and exhibited sensitivities of  $0.06 \text{ kPa}^{-1}$  and  $0.63 \text{ kPa}^{-1}$  for the pressure ranges of 0 kPa to 3.5 kPa and 3.5 kPa to 6.8 kPa, respectively. Additionally, the pressure sensor





showed excellent electro-mechanical stability under repeated cyclic loads, good transient response for the intended application, as well as the capability of measuring pressure as low as  $2.47 \text{ Pa}$ . These features are expected to be sufficient to detect the NNS pattern of all types of preterm infants. As reported by previous works, the sensor is expected to properly measure

the NNS of preterm infants at all ages, including the extremely premature ones.

In the future, a wireless communication module will be implemented to facilitate the use of the sensor in clinical environments. Furthermore, experiments will be conducted in order to validate the developed sensor in clinical settings.

### Abbreviations

AgNW: Silver nanowire; PDMS: Polydimethylsiloxane; WHO: World Health Organization; GA: Gestational age; NNS: Non-nutritive sucking; NS: Nutritive sucking; NICU: Neonatal intensive care unit; PCB: Printed circuit board; SEM: Scanning electron microscope.

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### Authors' contributions

JGO fabricated the devices and conducted all experiments. JGO and TM built the customized setup for sensor characterization. JGO and SK performed analysis of results and drafted the manuscript. All authors read and approved the final manuscript.

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### Availability of data and materials

All data generated or analyzed during this study are included in this published article.

### Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### References

1. March of Dimes, PMNCH, Save the Children, WHO (2012) Born Too Soon: The Global Action Report on Preterm Birth. World Health Organization, Geneva.
2. Liu L, Oza S, Hogan D, Chu Y, Perin J, Zhu J, Lawn JE, Cousens S, Mathers C, Black RE (2016) Global, regional, and national causes of under-5 mortality in 2000–2015: an updated systematic analysis with implications for the Sustainable Development Goals. *Lancet* 388:3027–3035. [https://doi.org/10.1016/S0140-6736\(16\)31593-8](https://doi.org/10.1016/S0140-6736(16)31593-8)
3. Blencowe H, Cousens S, Oestergaard MZ, Chou D, Moller AB, Narwal R, Adler A, Vera Garcia C, Rohde S, Say L, Lawn JE (2012) National, regional, and worldwide estimates of preterm birth rates in the year 2010 with time trends since 1990 for selected countries: a systematic analysis and implications. *Lancet* 379:2162–2172. [https://doi.org/10.1016/S0140-6736\(12\)60820-4](https://doi.org/10.1016/S0140-6736(12)60820-4)
4. Zafeiriou DI (2004) Primitive reflexes and postural reactions in the neurodevelopmental examination. *Pediatr Neurol* 31:1–8. <https://doi.org/10.1016/j.pediatrneurol.2004.01.012>
5. Capilouto GJ, Cunningham TJ, Mullineaux DR, Tamilia E, Papadelis C, Giannone PJ (2017) Quantifying neonatal sucking performance: promise of new methods. *Semin Speech Lang* 38:147–158. <https://doi.org/10.1055/s-0037-1599112>
6. Pickler RH, Reyna BA (2004) Effects of non-nutritive sucking on nutritive sucking, breathing, and behavior during bottle feedings of preterm infants. *Adv Neonatal Care* 4:226–234. <https://doi.org/10.1016/j.adnc.2004.05.005>
7. Pineda R, Dewey K, Jacobsen A, Smith J (2019) Non-Nutritive Sucking in the Preterm Infant. *Am J Perinatol* 36:268–276. <https://doi.org/10.1055/s-0038-1667289>
8. Huang X, Martens A, Zimmerman E, Ostadabbas S (2019) Infant Contactless Non-Nutritive Sucking Pattern Quantification via Facial Gesture Analysis. <https://arxiv.org/abs/1906.01821>. Accessed 16 Jun 2020
9. Grassi A, Sgherri G, Chorna O, Marchi V, Gagliardi L, Cecchi F, Laschi C, Guzzetta A (2018) Early intervention to improve sucking in preterm newborns. *Adv Neonatal Care*. <https://doi.org/10.1097/anc.0000000000000543cccc>
10. Grassi A, Cecchi F, Sgherri G, Guzzetta A, Gagliardi L, Laschi C (2016) Sensorized pacifier to evaluate non-nutritive sucking in newborns. *Med Eng Phys* 38:398–402. <https://doi.org/10.1016/j.medengphy.2015.12.013>
11. Lau C, Kusnierczyk I (2001) Quantitative evaluation of infant's nonnutritive and nutritive sucking. *Dysphagia* 16:58–67. <https://doi.org/10.1007/s004550000043>
12. Cunha M, Barreiros J, Pereira JD, Viegas V, Banha C, Diniz A, Pereira M, Barroso R, Carreiro H (2019) A promising and low-cost prototype to evaluate the motor pattern of nutritive and non-nutritive suction in newborns. *J Pediatr Neonatal Individ Med* 8:e080220. <https://doi.org/10.7363/080220>
13. Ebrahimi Z, Moradi H, Ashtiani SJ (2019) A compact pediatric portable pacifier to assess non-nutritive sucking of premature infants. *IEEE Sens J* 20:1. <https://doi.org/10.1109/2943869>
14. Pereira M, Postolache O, Girão P (2011) A smart measurement and stimulation system to analyze and promote non-nutritive sucking of premature babies. *Meas Sci Rev* 11:173–180. <https://doi.org/10.2478/v10048-011-0033-y>
15. Innarahealth, The NTrainer System. [innarahealth.com/ntrainer](http://innarahealth.com/ntrainer). Accessed 01 May 2020
16. Hafström M, Kjellmer I (2000) Non-nutritive sucking in the healthy preterm infant. *Early Hum Dev* 60:13–24. [https://doi.org/10.1016/S0378-3782\(00\)00091-8](https://doi.org/10.1016/S0378-3782(00)00091-8)
17. Lundqvist C, Hafström M (1999) Non-nutritive sucking in full-term and preterm infants studied at term conceptual age. *Acta Paediatr Int J Paediatr* 88:1287–1299. <https://doi.org/10.1080/080352599750030455>
18. Hack M, Estabrook MM, Robertson SS (1985) Development of sucking rhythm in preterm infants. *Early Hum Dev* 11:133–140. [https://doi.org/10.1016/0378-3782\(85\)90100-8](https://doi.org/10.1016/0378-3782(85)90100-8)
19. Liao C, Rosner AO, Maron JL, Song D, Barlow SM (2019) Automatic nonnutritive suck waveform discrimination and feature extraction in preterm infants. *Comput Math Methods Med* 2019:4–7. <https://doi.org/10.1155/7496591>
20. Park M, Kim W, Hwang B, Han SM (2019) Effect of varying the density of Ag nanowire networks on their reliability during bending fatigue. *Scr Mater* 161:70–73. <https://doi.org/10.1016/j.scriptamat.2018.10.017>
21. Deng C, Pan L, Zhang D, Li C, Nasir H (2017) A super stretchable and sensitive strain sensor based on a carbon nanocoil network fabricated by a simple peeling-off approach. *Nanoscale* 9:16404–16411. <https://doi.org/10.1039/c7nr05486f>

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