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AI Smart Materials for Enhancing Sucking Ability in Preterm Infants

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In this study, we aimed to develop a dual-channel pressure-sensing electronic pacifier with AI capabilities to detect sucking difficulties in premature infants, enabling early assessment, individualized care plans, and support for parents, ultimately improving neonatal care and enhancing the quality of life for premature infants. LabVIEW software was used to develop a program that measured the characteristics of pressure sensors before and after using the pacifier, including sucking pressure, intensity, and duration. The research yielded several advantages, including the early assessment of sucking ability, individualized care plans, support for parents, and the promotion of oral development. We found that electronic pacifiers can provide individualized feedback and stimulation, helping to improve sucking skills, strength, and coordination in premature infants. Although there is relatively limited research on electronic pacifiers for sucking intervention, these studies provide some evidence of their effectiveness. With the increasing emphasis on the sucking development of premature infants and the continuous advancement of technology, more research on the application value of electronic pacifiers in sucking intervention can be expected in the future.

1. Introduction

Bingham *et al.*[1] conducted a prospective study on non-nutritive sucking (NNS) and feeding skills in premature infants, which provides additional information on the feeding capabilities of preterm infants and emphasizes the need for early interventions. Additionally, Bu'Lock *et al.* utilized ultrasound to study the coordination of sucking, swallowing, and breathing in infants, offering insights into early feeding capabilities in children.[2] Zhang *et al.* explored the use of porous cross-linked polyelectrolyte membranes as invisible bending sensors that may provide a

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more accurate and sensitive method for measuring sucking pressure.[3] Howe *et al.* compared the sucking performances of preterm infants who received oral feeding interventions with those who did not, further demonstrating the potential of electronic pacifiers in intervention.[4] Reynolds *et al.* investigated the impact of oral motor and oral sensory interventions on feeding behavior in preterm infants, contributing to our understanding of the effects of intervention on infant development.[5]

The objective of this study was to develop a silicone electronic pacifier with dual-channel pressure-sensing capabilities, specifically designed to assist the detection of difficulties in sucking ability among premature infants. Using LabVIEW programming, the pressure sensors on the pacifier were utilized to measure various characteristics, including sucking pressure, intensity, and duration. The successful outcomes of this research offer several notable advantages. (1) Early assessment of sucking ability: The accurate information provided by this assessment enables healthcare professionals to make timely adjustments to feeding methods, ensuring that premature infants receive sufficient nutrition. (2) Individualized care plans: The research findings can be used to develop personalized treatment and rehabilitation plans tailored to address the specific sucking difficulties of each premature infant. (3) Parental support: By providing relevant information and suggestions regarding sucking difficulties, parents can better understand and respond to their infants' needs, thus enhancing their ability to provide appropriate support. (4) Promotion of oral and masticatory development: Through the provision of suitable sucking stimulation and support, this research contributes to the development of oral and masticatory skills in premature infants, facilitating their transition to solid foods. Finally, these advantages collectively contribute to the improvement of newborn care, providing enhanced feeding and developmental support and ultimately leading to an enhanced quality of life for premature infants. To address the limitations of previous research and provide a more comprehensive assessment of sucking ability in premature infants, we hypothesize that the utilization of a novel dual-channel pressure-sensing electronic pacifier can accurately detect sucking difficulties and facilitate the development of individualized care plans and support. We also hypothesize that tailored interventions based on the assessment results can effectively enhance the sucking techniques, strength, and coordination of premature infants, ultimately leading to an improved quality of life. This hypothesis underscores the potential of the dual-channel pressure-sensing electronic pacifier to be a groundbreaking tool in the field of neonatal care.

In this study, we employed a dual-channel pressure-sensing silicone electronic pacifier as the research device to measure sucking pressure, intensity, and duration using LabVIEW programming. The study provided insights into the human–machine interaction process and facilitated the development of interactive electronic learning and educational materials. Overall, the importance of implementing intervention measures to support the development and improve the quality of life for premature infants was revealed. Our use of electronic pacifiers can provide individualized feedback and stimulation, which can help improve sucking skills, strength, and coordination in premature infants. The sucking pressure changes, forces, and time were measured by the pacifier with anterior and posterior pressure sensors by the self-developed program under LabVIEW. NNS exhibited three patterns: (1) poor sucking, (2) irregular sucking, and (3) regular sucking. Because the force-sensitive resistor must bear a certain weight to function, the pacifier channel must have a T-shape. Preterm infants who are used to another type of pacifier or those who are about to be discharged are unwilling to suck this T-shape pacifier because the designed pacifier is less flexible than an average pacifier. When this problem occurs, however, it indicates that the infant can be discharged.

In some past studies, the differences between using electronic pacifiers and nonelectronic pacifiers have been compared. For example, Fucile *et al.*(6) and Bu'Lock *et al.*(2) examined the sucking performance of preterm infants using different types of pacifier. Their studies provided valuable information on the effect of different pacifiers on the sucking ability of premature infants. Lau *et al.* compared suck–swallow and swallow–breathe coordinations in preterm infants using a traditional pacifier and an electronic pacifier with a flow-adjusting function.(7) Fucile *et al.* compared the nutritional sucking ability of preterm infants when fed using a traditional feeding bottle and an electronic feeding bottle with a flow-adjusting function.(6) Bu'Lock *et al.* used ultrasound technology to observe differences in the coordinated development of sucking, swallowing, and breathing in preterm infants using conventional and electronic pacifiers.(2) In addition, some scholars have conducted research on the sucking ability of premature infants who have difficulty sucking. Pickler *et al.* developed a sucking intervention program for preterm infants to improve their sucking ability.(8) Howe *et al*. compared the sucking performance of preterm infants with difficulty sucking who received an oral feeding intervention with that of infants who did not.(4) On the other hand, Pickler *et al.* also used a specially designed electronic pacifier to deliver a sucking intervention.(8) The electronic pacifier has specific features that provide individualized feedback and stimulation based on the sucking performance of preterm infants to help them improve their sucking skills and abilities. However, in the study conducted by Howe *et al.*, electronic pacifiers were not used.(4) In this study, we aimed to compare the sucking performance of preterm infants with difficulty sucking who received an oral feeding intervention with that of infants who did not. Early on, preterm infants may have difficulty sucking, weak sucking, or poorly coordinated sucking. This can lead to sucking difficulties and inadequate nutrient intake. However, most premature babies gradually improve their sucking ability as they grow and develop. A professional medical team will usually monitor premature infants' sucking performance and provide appropriate support and interventions to promote their sucking ability and growth. Thus, premature babies may have poor sucking ability, but that does not mean they cannot improve or reach normal levels.

The assistance of an electronic pacifier may be an effective form of assistance. Therefore, the effect of using electronic pacifiers for sucking intervention and improving the sucking ability of premature infants was previously studied. The results provide research evidence and an understanding of the value of electronic pacifiers in the development of sucking in preterm infants. Few studies on evaluating sucking interventions in preterm infants and the effect of electronic pacifiers on improving sucking ability have been conducted. Chen *et al.* developed a smart pacifier to assess NNS patterns in premature infants.(9) They used an electronic pacifier to record and assess the sucking patterns and abilities of premature infants. Pinelli *et al.* explored the use of NNS in high-risk preterm infants, including the use of electronic pacifiers as an intervention tool.(10)

Note that the small number of studies on sucking intervention with electronic pacifiers may be due to the specialization of the field and the challenges inherent in studying preterm infants. However, with increasing emphasis on the care and development of preterm infants, as well as advances in technology, we can expect more research in the future to focus on the effect of electronic pacifiers for sucking intervention and its application value in the care of preterm infants.

In conclusion, although there are some limitations in the research of electronic pacifiers as a sucking intervention, the existing research results show that it may have potential in improving the sucking ability of premature infants. Further research should explore the application of more intervention strategies to provide better care and support the development of preterm infants.

Past research has also shown that premature babies often have poor sucking ability. This may be due to premature infants having an underdeveloped nervous system and oral muscles, leading to difficulties with sucking coordination and strength. These sucking difficulties can negatively impact feeding and nutrient intake in preterm infants.

The purpose of sucking interventions with electronic pacifiers is to improve sucking skills, strength, and coordination in preterm infants by providing individualized feedback and stimulation. This intervention uses electronic sensing technology to measure and record sucking-related parameters such as sucking pressure and time. In this way, medical professionals can assess the sucking performance of premature infants and provide tailored treatment and support.

Past research has shown that sucking intervention using an electronic pacifier can improve sucking in preterm infants. This intervention provides immediate feedback and stimulation to help premature babies develop correct sucking patterns and skills. In addition, the electronic pacifier can also measure sucking-related parameters, providing objective data for evaluating and monitoring the sucking progress of premature infants.

However, more research is needed to further understand the effectiveness of electronic pacifiers for sucking interventions and how to maximize their potential. This includes comparing the effects of different types of electronic pacifier and sucking intervention, as well as assessing long-term sucking outcomes and effects on preterm infant development.

In recent years, there has been a great deal of research on treating preterm infants' oral sucking difficulties.(11,12) Several researchers have argued whether training preterm infants to suck pacifiers properly can result in weight gain, reduced hospitalization time, and the improvement of their survival. The researcher primarily focuses on the ability to feed and suck as a starting point.(13) In Barrett and Debelle's study, a case of near-fatal aspiration of a child's dummy is described.(14) Another case describes the almost fatal inhalation of a child's dummy that caused extensive injuries to the mouth and pharynx and acute respiratory embarrassment, necessitating admission to a pediatric intensive care unit. A design fault in the dummy has been discussed, and it has been recommended that the British Standards specification for dummies be changed. Plastic dummies, or infant pacifiers, consist of a teat, a relatively inflexible flange, and a knob or a ring, to permit ease of extraction from the mouth if accidently aspirated.(15) Sucking training that is guided by medical staff has been proven to improve sucking ability, result in infants gaining weight, and reduce the length of stay of newborns.(14) The value of NNS measures as predictors of oral feeding performance in comparison with other putative predictors of feeding skills has been discussed. Regarding the prediction of oral feeding performance, the following factors have been considered: a standardized feeding advancement schedule, the utilization of the Neonatal Oral-Motor Assessment Scale (NOMAS), and an oral feeding advancement schedule. Main outcome measures were the transition time from first to full oral feeding (FOF) and gestational age at FOF. Infants with a more organized sucking pattern attained independent oral feeding three days earlier (16- vs 13-day transition) than infants with more chaotic patterns of suck bursts.(1) It has been reported that pacifiers of a certain design can stimulate the facial nerve and ventilation systems. Specifically, the pressure generated from regular suction stimulates the infant's facial nerve, and swallowing can be identified through the upward movement of the anterior cervical tissues, thus providing information on when infants are hungry and the time for feeding.(2) The time between initial oral feeding and fully independent sucking can vary from a few days to a few months.(16) Preterm infants learn how to use the tongue to press the teat, similar to when sucking through a straw. Subsequently, infants use their hard palate to squeeze out milk into the mouth, a process similar to milking a cow by hand.(3) Studies have confirmed that sucking problems in preterm infants can be solved through training. In one study, preterm infants with and without sucking problems were compared, and it was demonstrated that sucking training reduced the energy consumption rate of the preterm infants and increased their growth rate.(16) In another study, a wireless oral-feeding monitoring system was developed to analyze the sucking patterns of preterm infants.(17) In general, professionally trained medical staff members employ a camera to observe the sucking behaviors of preterm infants with low weight, particularly the duration and times of sucking. However, this method is costly in terms of human resources and time.(18) Preterm infants develop the skills necessary to begin oral feeding as their health stabilizes and as their swallowing and breathing coordinate with oral-motor functioning. Infants use their hard palate to squeeze out milk into the mouth, a process similar to milking a cow by hand.(19–23) Numerous studies on measuring changes in sucking pressure using air pressure sensors have been carried out.(24–26) Different devices can be integrated with pacifiers to measure changes in the sucking pattern of preterm infants,(27) with these differing devices being able to detect various types of data and change.(28,29) A new design for a non-nutritive wireless Bluetooth pacifier pressure suction measuring device has been presented.(30) Past literature shows quantitative data on the number of sucks of preterm infants and the experimental results of suction pressure verification. This dataset has been validated,(7,31) enabling the collection of more information regarding the sucking behaviors of low-weight infants. In the past, the main measurement method used a simple single-gas pressure or the pressure test of the feeding bottle. A single air pressure has also been used as the measurement output metric in the finished product, but it is impossible to accurately know whether or not there is sucking during the measurement. Either the pressure changes between the front and back of the mouth during sucking cannot be obtained by the differential pressure measurement of the baby bottle, or the temperature measurement in the pacifier also yields a single temperature, and the application of the sucking result is not an optimal design. It is impossible to determine the exact position of the tongue. Using the designed pacifier, quantitative data such as sucking pressure, clusters of continuous sucks, and continuous sucking duration can be obtained. Additionally, the pacifier enables researchers to save human-resource-related costs and time and obtain data that can serve as a reference for clinical physicians wanting to provide appropriate rehabilitation for preterm infants. Furthermore, this electric pacifier can be useful in the development of clinical diagnosis guidelines and an evaluation model of sucking training, which will be helpful for clinical physicians. Few studies have been conducted on electric pacifiers, and the proposed pacifier will enable suitable sucking diagnosis in clinical use. In the past, there has been little research on electronic pacifiers using pressure sensing. Therefore, it is necessary to develop a fast and effective electronic auxiliary instrument to provide clinicians with a reference for assessing whether premature infants can be discharged from the hospital. The differences between the electronic dual-channel pressure-sensing pacifier and its parameters and the published research are as follows.

(i) The sensor of the electronic dual-channel pressure-sensing pacifier is placed in the pacifier, and the detection is simple and convenient. There is no need for researchers or nursing staff to adjust the pressure sensor to maintain a certain pressure difference to ensure the credibility of the data.

(ii) The electronic dual-channel pressure-sensing pacifier has dual channels that detect sucking at different positions of the tongue. More information can be obtained than from a single channel. In accordance with the three modes of data provided by clinicians on the degree of premature infants' sucking, in this study, measurement using our dual-channel pacifier yields data on the channel 1 and 2 sucking pressure difference of the three modes, channel 1 and 2 average sucking pressure, the accumulation of sucking clusters, and accumulated sucking time and rest time, which provide clinicians with a greater reference basis.

(iii) Judgment of the three modes of premature infants' sucking tolerance may be different for different clinicians. There is no scientific standard. We here propose two parameters, channel 1 and 2 sucking pressure difference and average sucking pressure judgment, to be used in objective and scientific methods as the basis for assessing the degree of absorption of preterm infants, and to provide clinicians a reference for judging whether or not preterm infants can be discharged from the hospital.

In previous studies, electronic and nonelectronic pacifiers have been compared to evaluate their impact on the sucking ability of premature infants. In another study, researchers examined the effects of different pacifier types on sucking performance in premature infants, providing valuable insights into the effectiveness of various pacifiers.(2,6) Additionally, Lau *et at*. compared the coordination of suck–swallow and swallow–breathe actions in premature infants using a traditional pacifier and an electronic pacifier with flow-adjusting functionality.(7) Fucile *et al.* investigated the liquid sucking ability of premature infants when fed with a traditional feeding bottle versus an electronic feeding bottle with flow control.(6) Bu'Lock *et al.* utilized ultrasound technology to observe the coordinated development of sucking, swallowing, and breathing in premature infants using conventional and electronic pacifiers.(2) These studies shed light on the differences in the coordination of sucking, swallowing, and breathing, as well as the impact of electronic and nonelectronic pacifiers on nutritive sucking ability in premature infants. This research contributes to our understanding of the effects of different nipple types on premature infants and offers practical recommendations for guiding feeding management for such infants. Furthermore, interventions to improve the sucking ability of premature infants with sucking difficulties should also be explored. Another group of researchers developed a sucking intervention program to enhance sucking skills in preterm infants.(8) Howe *et al.* compared the sucking performances of preterm infants with difficulty sucking who did and did not receive oral feeding intervention.(4) Pickler *et al.* also utilized a specially designed electronic pacifier to deliver sucking intervention and provide individualized feedback and stimulation based on the sucking performance of preterm infants.(8) The results of these studies demonstrated that sucking intervention using an electronic pacifier improved sucking ability and promoted sucking development in preterm infants with sucking difficulties. These findings suggest that the use of an electronic pacifier is an effective intervention for enhancing feeding ability and development in preterm infants with sucking difficulties.

Note that the number of studies on sucking interventions with electronic pacifiers is limited, likely due to the specialized nature of the field and the challenges associated with studying preterm infants. However, as the focus on the care and development of preterm infants increases and technology advances, it is anticipated that future research will be directed toward further exploration of the effectiveness and application value of electronic pacifiers for sucking interventions for preterm infants. In conclusion, although there are some limitations in the research on electronic pacifiers as a sucking intervention, the existing evidence indicates their potential in improving the sucking ability of premature infants. Further research should be conducted to explore additional intervention strategies to provide better care and support for the development of preterm infants.

In short, we address the following issues in this study. (1) Premature infants are often afflicted with inadequate sucking ability because of an underdeveloped nervous system and oral muscles, leading to difficulties in sucking coordination and strength, which in turn affects their feeding and nutrient intake. (2) Currently, there are various challenges in assessing the sucking ability of premature infants, such as a lack of accurate assessment methods and tools, which may result in an insufficient understanding of their sucking difficulties. (3) Because of the potential variations in sucking difficulty among premature infants, individualized treatment and rehabilitation programs tailored to each infant's specific condition are needed to address their sucking challenges and promote their development. (4) Parents require relevant information and advice to better understand and respond to their infant's sucking difficulties, enabling them to provide appropriate support. (5) The early assessment and intervention of sucking ability are crucial to ensure adequate nutrition for premature infants and require accurate assessment tools and corresponding intervention measures. To address these issues, we propose the following objectives. (1) Develop accurate assessment tools for sucking ability by utilizing existing technologies and AI tools, such as pressure sensors and other instruments to measure sucking pressure, intensity, and duration, among other sucking-related features. (2) Using accurate assessment results of sucking ability, formulate individualized treatment and rehabilitation plans. This may include treatment targeting specific sucking difficulties, such as providing specific sucking stimulation and support to help premature infants improve their sucking techniques and abilities. (3) Provide relevant information and advice to parents, enabling them to better understand and respond to their premature infant's sucking difficulties. This can be achieved by educating parents about the development of sucking in premature infants and providing techniques and strategies to support their infant's sucking ability in a home environment. (4) Emphasize the early assessment and intervention of sucking ability, ensuring timely support and treatment for premature infants during their developmental process. This requires healthcare professionals to closely monitor the sucking performance of premature infants and provide appropriate intervention measures based on the assessment results. (5) Foster continuous research and technological innovation to further explore the value of applying electronic pacifiers and other technologies in sucking interventions. Through ongoing research and technological innovation, improvements can be made to sucking assessment tools and intervention methods, providing more effective support and treatment options. Therefore, to address the sucking difficulties in premature infants, we aim to develop accurate assessment tools, formulate individualized treatment and rehabilitation plans, and provide corresponding support to parents. Additionally, we should emphasize the importance of early intervention and continuous research and technological innovation as they will contribute to improving the sucking ability of premature infants and providing better care and developmental support. Thus, we propose the research project entitled "AI Smart Materials for Enhancing Sucking Ability in Preterm Infants."

Our study is significantly different from previous research because we use our electronic dual-channel pressure-sensing pacifier. Previous studies primarily focused on observing and evaluating surface-level characteristics of sucking behavior and lacked in-depth analyses of key features such as sucking pressure, intensity, and duration. Additionally, personalized treatment and rehabilitation plans were often not provided in previous research, limiting the selection of tailored interventions for the specific sucking difficulties of each premature infant. In this study, we aim to address these limitations by developing a dual-channel pressure-sensing electronic pacifier that accurately measures key sucking features.

Finally, the impacts of different types of pacifier on the sucking ability of premature infants have been compared in previous studies and valuable insights have been obtained. However, those studies often focused on observing and evaluating surface-level characteristics of sucking behavior and lacked in-depth analyses of key features such as sucking pressure, intensity, and duration. Additionally, previous research often ignored personalized treatment and rehabilitation plans, which limited the selection of tailored interventions for the specific sucking difficulties of each premature infant. Moreover, there was a lack of support and guidance for parents, leaving them without the relevant information and advice they needed. We aim to address these limitations by developing a dual-channel pressure-sensing electronic pacifier that accurately measures key sucking features. The precise assessment results will be used to develop personalized treatment and rehabilitation plans that target the specific sucking difficulties of each premature infant. Furthermore, relevant information and advice will be provided to appropriately support and guide parents to help them better understand and respond to their premature infant's sucking difficulties. In summary, the objective of this study is to complement the shortcomings of previous studies by providing a comprehensive and personalized assessment of sucking ability and intervention measures, along with support and guidance for parents. Through these efforts, we aim to improve the sucking ability of premature infants and provide better care and developmental support. Our dual-channel pressure-sensing electronic pacifier offers personalized feedback and stimulation to assist premature infants in improving their sucking skills, strength, and coordination. Lastly, we emphasize the importance of early assessment and intervention to ensure timely support and treatment during the developmental process of premature infants.

2. Material and Methods

2.1 Design processes of the pacifier

The dual-channel force-and-pressure-sensing electronic pacifier is designed with several specific features and components to ensure the safety and effectiveness of its use by infants. The following key points are considered in its design. (a) Safety: The pacifier incorporates mechanisms to ensure the safety of infants during use. One important feature is the insulation that covers the silicone teat, which prevents any contact between the skin and the electronic circuit. This insulation effectively prevents any potential harm or discomfort due to direct contact with the circuit. (b) Compliance with Standards: The design of the pacifier complies with relevant standards, such as IEC 60601-1-2. This standard ensures the safety and compatibility of medical electrical equipment with electromagnetic environments. Adhering to this standard guarantees that the pacifier meets the necessary requirements for safe and reliable use. (c) Measurement and Data Collection: The pacifier is designed to collect various types of data related to the infant's sucking ability. These data play a crucial role in quantifying and evaluating the oral sucking capability of preterm infants. Parameters such as sucking pressure, clusters of continuous sucks, and the total duration of continuous sucks are collected and analyzed using specialized sensors and data acquisition systems. (d) Design for Premature Infants: The pacifier's mold design includes specific features to make it suitable for premature infants. The shape of the pacifier closely resembles traditional pacifiers or soothers commonly used by preterm infants. Additionally, the smooth shape at the bottom of the pacifier ensures proper tongue contact, facilitating a natural sucking motion. This design consideration was aimed at providing a comfortable and effective sucking experience for premature infants. (e) Simplified Silicone Molding Process: The silicone molding process involves using a high-quality certified-food-grade silicone material and an extruding machine to fill the mold. The molding process takes approximately 15–20 min and requires a specific temperature range (167–186 ℃) and pressure (750 kg/cm^2). (f) Design Parameters: Specific temperature ranges, pressures, and other design parameters are carefully selected and controlled to ensure the optimal performance and safety of the pacifier. These parameters are determined on the basis of the results of extensive research and analysis to provide the best possible user experience for infants. (g) Technological Innovations: The dual-channel force-and-pressure-sensing electronic pacifier incorporates several technological and engineering innovations. The integration of dual-channel force-sensitive resistors allows for the accurate measurement and analysis of the infant's sucking ability. This unique feature enables us to use the pacifier to quantify and classify the oral sucking capability of preterm infants, providing valuable insights for medical professionals and caregivers. In short, the design of the dual-channel pressure-sensing electronic pacifier combines safety, compliance with standards, data collection capabilities, tailored design for premature infants, a simplified silicone molding process, optimized design parameters, and technological innovations. These features collectively contribute to a reliable and effective tool for assessing and supporting the oral sucking ability of preterm infants.

The main purpose of this study is to design a novel dual-channel force-and-pressure-sensing electronic pacifier as a means to quantify and classify the oral sucking ability of preterm infants. After quantitative measurement and data analysis, the classification of sucking ability can be achieved. Our developed pacifier was equipped with dual-channel force-sensitive resistors. The resistors have a 3 V direct current circuit; this current is safe for the human body (measured output current: 0.15–35 μA; voltage: 0.3–1.15 V). Relevant data were obtained using two FSR-400 sensing resistors (Interlink Electronics) and analyzed using a personal computer. The pacifier's silicone teat is covered by an insulator to ensure that the circuit does not come into contact with the skin. The pacifier fulfills the requirements of IEC 60601-1-2. In preterm infants, the early stages of coordination development are normally longer than the later stages. The severity of diseases that occur during the transitional period tends to affect infants' suck–swallow ability. The following data were collected from a 5 min synchronization of the electric dual-channel pacifier: sucking pressure, clusters of continuous sucks, and the total duration of continuous sucks. The output of the electronic pacifier was displayed and analyzed using the LabVIEW programming environment. The sucking ability was categorized to evaluate the quantitative data of sucking ability of preterm newborns during hospitalization. The shape of the designed pacifier is similar to that of the pacifiers or soothers used by most preterm infants, with a smooth shape at the bottom to ensure that the tongue can touch the teat. After discussing our design with clinical physicians, we commissioned a mold manufacturer to develop a mold of the designed pacifier. The pacifier is made of high-quality certified-food-grade silicone. A manufacturer then produced the silicone pacifier with the pressure-sensing function using an extruding machine to push the raw material (Shore 30A) into the mold. The mold has three layers. The upper die is filled with raw material, and the middle and bottom dies are used for molding. The upper die (filled with food-grade silicone) and middle and bottom dies are squeezed together to form the pacifier. The molding pressure is 750 kg/cm^2, the temperature is in the range between 167 and 186 ℃, and the entire process is completed within 15–20 min. Careful attention must be paid to molding. The cycle time of silicone heating molding is perfect when the amount of silicone filling is not excessive. Release agents are not allowed in the mold. Finished silicone rubber products must be sterilized and disinfected, preserved, and verified by the silicone rubber softness test.

After the pacifier has been cured, a test was conducted to measure its voltage range; the result was 0.3–1.15 V. The pressures that could be detected by the force-sensitive resistors were 0–1050 gf/cm^2 following weight conversion. The design processes of the developed pacifier in this study are shown in Fig. 1. The prototype structure of the dual-channel pressure-sensing electric pacifier is shown in Fig. 2.

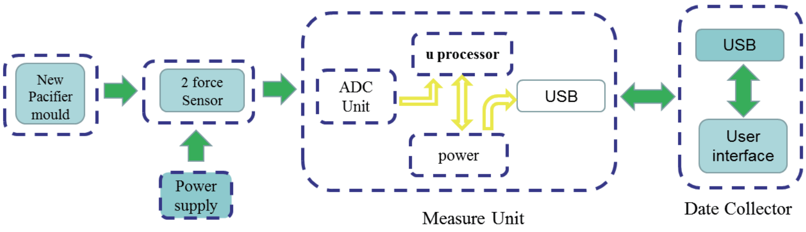

Fig. 1. (Color online) Design processes of the dual-channel pressure-sensitive electronic pacifier.

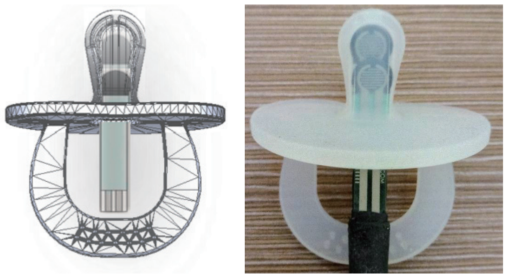

Fig. 2. (Color online) Dual-channel force pressure-sensing prototype.

2.2 Research limitations

During hospitalization in the preterm infant insured ward, the designed prototype dual-channel pacifier (channel 1 and 2 positions are near the throat and gum, respectively) was adopted to investigate the changes in the NNS pattern, tongue pressure, and position of preterm infants in the neonatal intensive care unit. The synchronized use of the pacifier (simultaneous use of the electronic pacifier was performed to measure the sucking ability of premature infants) was performed for 5 min prior to feeding to obtain data regarding the sucking process. Preterm infants need to be carefully cared for. Whether or not they can participate in this study was carefully evaluated by doctors. During this process, the following preterm infants were excluded from participation in this study: (1) preterm infants with congenital malformations, (2) preterm infants who rely on a respirator to maintain life, and (3) preterm infants for whom consent for participation could not be obtained from parents or family members.

Data recording was paused or delayed if the preterm infant moved restlessly, cried, held their breath, became sick, or were undergoing any treatment. Sucking training was performed by a physical therapist using the developed pacifier. The training helped the infants improve their sucking ability. Because infants differ from each other in multiple aspects (e.g., age, weight, development progress, and training progress), the outcomes of pacifier use were determined by observing the teat-sucking movements. In Fig. 3, the sucking movement when using the developed pacifier is shown.

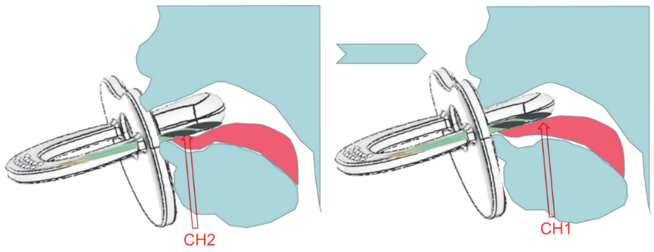

Fig. 3. (Color online) The sucking movement progresses from the second channel (CH2) to the first channel (CH1).

The data of preterm infants born at Taichung Veterans General Hospital in Taiwan were collected. After obtaining the parent Institutional Review Board (IRB) consent, a total of 22 infants participated in the experiment, and the non-nutritive pacifier sucking test was begun by the rehabilitation and nursing staff. The data of 224 sessions of the actual sucking measurements were recorded for each infant. Data regarding 5 min NNS were also obtained. The demographic data of the 22 preterm infants, 13 boys and 9 girls, aged from 26 to 45 weeks, with weights from 780 to 3635 g are listed in Table 1.

Palmer has defined the following three nourishment-ingesting sucking of infants on the basis of the sucking patterns frequency: immature sucking pattern, transitional sucking pattern, and mature sucking pattern.(32)

The following four parameters were proposed in this study: the absolute standard difference between two channels, σ_D; the average of the pressures measured at channels 1 and 2, which is higher than the threshold pressure, P_T; the sucking frequency of preterm infants, G; and the ratio of the total duration of continuous sucks between the two channels, S%. The sample rate is set to be 60 Hz in this study. The mean (μ) and standard deviation (σ) of the average of the pressures $P_{ch}(k)$ measured at channels 1 and 2 are calculated as follows.

Assume that the 5 min sucking signal from channel 1 is

$$P_{ch1}(k), k = 1, 2, 3, \cdots, 18000$$

and that from channel 2 is

$$P_{ch2}(k), k = 1, 2, 3, \cdots, 18000.$$

Then, the average of the pressures $P_{ch}(k)$ measured at channels 1 and 2 is defined as

$$P_{ch}(k) = \frac{P_{ch1}(k) + P_{ch2}(k)}{2}. \quad (1)$$

Table 1
Demographic data of preterm infants.

Variable	Min	Max	Mean	Standard deviation
Gestational age (weeks)	26	45	37.10	3.93
Birthweight (g)	780	3635	2365.68	662.6
APGAR score (1 min)	1	7	5.21	2.04
APGAR score (5 min)	2	9	7.57	1.83

$n = 22$.

The mean (μ) and standard deviation (σ) of $P_{ch}(k)$ are calculated as

$$\mu = \frac{1}{18000}\sum_{k=1}^{18000} P_{ch}(k), \tag{2}$$

$$\sigma = \sqrt{\frac{1}{18000}\sum_{k=1}^{18000}\left(P_{ch}(k)-\mu\right)^2}. \tag{3}$$

The amplitude threshold T is defined as $T = \mu + \sigma$.

The first parameter σ_D is calculated as Eq. (4). Generally, a smaller σ_D may indicate better sucking or nonsucking ability. The pressure difference between two channels, $D(k)$, is $D(k) = |P_{ch1}(k) - P_{ch2}(k)|$. The mean value of $D(k)$ is $\mu_D = \frac{1}{18000}\sum_{k=1}^{18000} D(k)$. Then,

$$\sigma_D = \sqrt{\frac{1}{18000}\sum_{k=1}^{18000}\left(D(k)-\mu_D\right)^2}. \tag{4}$$

The second parameter P_T is defined as Eq. (5). If $P_{ch}(k) > T$, then $P(k) = P_{ch}(k)$; otherwise, $P(k) = 0$.

$$P_T = \sum_{k=1}^{18000} P(k) \tag{5}$$

The third parameter G is defined as follows.

If $\begin{cases} P_{ch1}(k) \geq T & 1 \leq k \leq k+j \leq 18000 \\ P_{ch1}(k+j) < T & 1 \leq j \leq 60 \end{cases}$, then let $S(k) = 1$; otherwise, $S(k) = 0$.

Let $G_{ch1} = \sum_{k=1}^{18000} S(k)$. Similarly,

$$\text{if} \begin{cases} P_{ch2}(k) \geq T & 1 \leq k \leq k+j \leq 18000 \\ P_{ch2}(k+j) < T & 1 \leq j \leq 60 \end{cases}, \text{ then } S(k) = 1; \text{ otherwise, } S(k) = 0.$$

Let $G_{ch2} = \sum_{k=1}^{18000} S(k)$.

Thus, G can be calculated as

$$G = \frac{G_{ch1} + G_{ch2}}{2}. \tag{6}$$

A sucking cluster is determined as follows. The sensor records data when the sucking pressure is higher than the set valve pressure (T), and stops when the sucking pressure is lower than T for more than 1 s. The same steps are repeated within 5 min from the start of the first recording to define a different sucking cluster. The average of the cluster data of CH1 and CH2 is the standard for defining the sucking ability of preterm infants.

The fourth parameter $S\%$ indicates the data consistency between channels 1 and 2 and is used to evaluate the validity of the sucking data.

If $P_{ch1}(k) < T$, $1 \leq k \leq 18000$, then let $\gamma_1(k) = 1$; otherwise, $\gamma_1(k) = 0$

The sucking time for channel 1 can be calculated as

$$S_1(n) = \frac{18000 - \sum_{k=1}^{18000} \gamma_1(k)}{60}.$$

Similarly,

if $P_{ch2}(k) < T$, $1 \leq k \leq 18000$, then let $\gamma_2(k) = 1$; otherwise, $\gamma_2(k) = 0$.

The sucking time for channel 2 can be calculated as

$$S_2(n) = \frac{18000 - \sum_{k=1}^{18000} \gamma_2(k)}{60}.$$

Therefore, the ratio of the total duration of continuous sucks between the two channels can be calculated as

$$S\% = \begin{cases} \dfrac{S_2(n)}{S_1(n)} \times 100\%, \text{ if } S_1(n) > S_2(n) \\ \dfrac{S_1(n)}{S_2(n)} \times 100\%. \text{ if } S_2(n) > S_1(n) \end{cases} \tag{7}$$

2.3 Analysis, evaluation, and classification of sucking

$$D(k) = \left|P_{ch1}(k) - P_{ch2}(k)\right|, \ \mu_D = \frac{1}{18000}\sum_{k=1}^{18000} D(k) \text{ and}$$

$$P_{ch}(k) = \frac{P_{ch1}(k) + P_{ch2}(k)}{2}, \ \mu = \frac{1}{18000}\sum_{k=1}^{18000} P_{ch}(k)$$

Irregular sucking, the parameter of 94 person-times in the stage, is an average of 36.03 μ_D. (Note that "person-time" refers to the number of times an individual performs a specific activity within a given period. Therefore, "94 person-times" means that there were a total of 94 instances of sucking movements occurring during that stage.) The standard deviation σ is 18.44. Then, $\alpha = 36.03 - 18.44 = 17.59$.

The average parameter value for μ is 108.09, with a standard deviation of 31.06. We can calculate β as $\beta = 108.09 - 31.06$, which equals 139.15. Both α and β are important data for assessing the level of absorption (refer to Fig. 4 for the 5-min read data flow chart, which classifies the pressure measured using the sucking pacifier).

Step 1: Among all 224 instances, we classify the data as poor sucking.

Step 2: Next, we compare the average μ_D to $\alpha = 17.59$. Among the 129 instances with negative data, we identify those with an average μ greater than $\beta = 139.15$, and classify them as regular sucking.

Step 3: Since the average μ is less than $\beta = 139.15$, we classify the remaining instances as irregular sucking.

According to the data shown in Fig. 5, both CH1 and CH2 exhibit low sucking pressures, along with a low standard difference in sucking pressure. The ratio between G and $S\%$ is also small. In the second stage, infants display irregular sucking patterns, characterized by irregular sucking pressure in both CH1 and CH2, along with a high standard difference. The ratio between G and $S\%$ is moderately irregular. However, in the third stage, infants exhibit a regular sucking pattern, with both CH1 and CH2 showing high sucking pressures. The standard difference is low, and both the sucking frequency and pressure are higher than the threshold T. The ratio between G and $S\%$ is high. Note that poor sucking patterns are observed during the initial 30 s among infants in the third stage. The outcome of this research can be utilized to evaluate the most effective tools for assessing the sucking ability of preterm newborns.

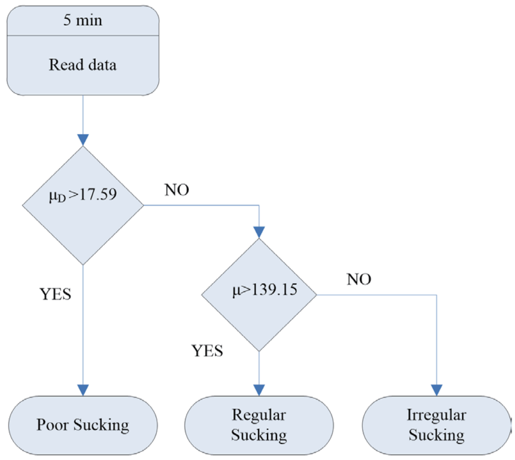

Fig. 4. (Color online) Flow chart of classification.

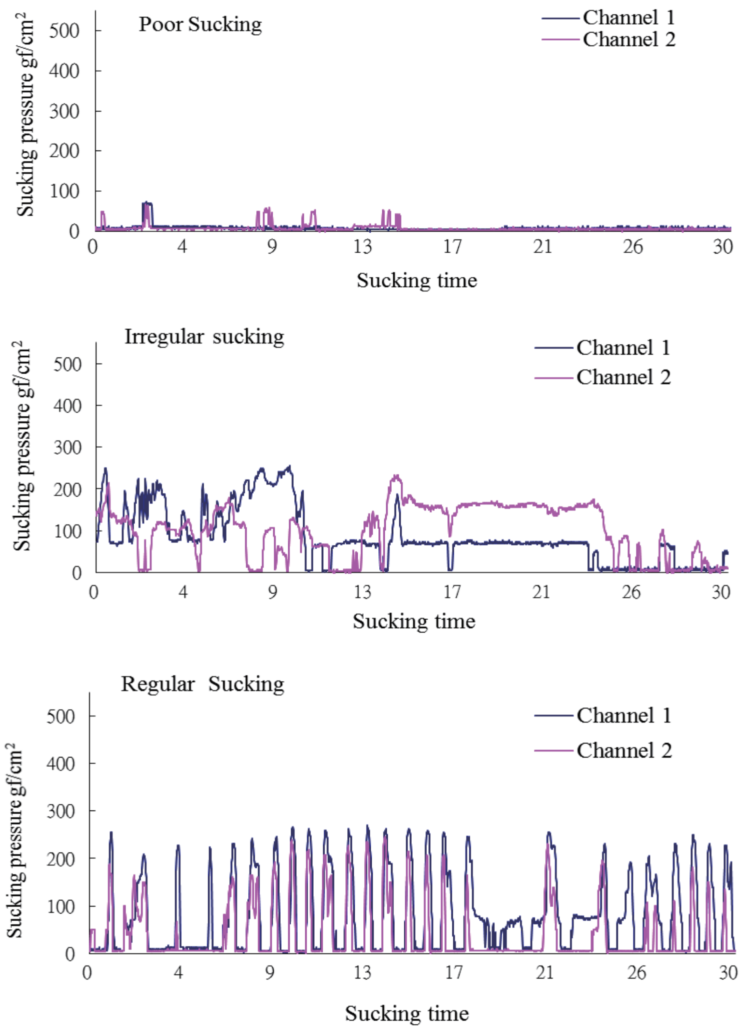

Fig. 5. (Color online) Sucking behavior patterns of premature infants on a pacifier. (Note: Figure 5 shows the sucking behavior of premature infants on a pacifier. It illustrates the different patterns of sucking, including poor sucking, irregular sucking, and regular sucking. These patterns are compared and analyzed in this study.)

3. Results and Discussion

3.1 Evaluating pacifier effectiveness in identifying sucking stages: importance of sensitivity and specificity

Here, we provide a concise explanation of why the sensitivity and specificity of the pacifier are crucial for evaluating the effectiveness of the pacifier and its ability to identify different sucking stages. These metrics serve as important indicators of the pacifier's accuracy in distinguishing between different sucking patterns. Sensitivity measures the pacifier's ability to correctly identify individuals in a specific sucking stage, whereas specificity measures its ability to correctly identify individuals not in that stage. By assessing sensitivity and specificity, we can evaluate the pacifier's performance in accurately classifying sucking stages and determine its effectiveness in clinical applications.

3.2 Dual-channel force pressure-sensing pacifier: enhancing healthcare for preterm infants

When discussing the practical applications and relevance of the dual-channel force pressure-sensing pacifier, we emphasize its significant contribution to improving healthcare for preterm infants. This advanced technology provides a valuable tool for assessing and monitoring the sucking ability of these infants, offering crucial insights for healthcare professionals. By accurately quantifying sucking parameters and identifying different sucking stages, the pacifier can aid in developing individualized care plans and improving feeding outcomes for preterm infants. Its application in clinical settings can enhance early intervention strategies and promote better healthcare outcomes for this vulnerable population.

3.3 Assessing infant maturity with the dual-channel force pressure-sensing pacifier

Maternal maturity refers to the pacifier's ability to detect and evaluate the sucking reflex in infants, which serves as an indicator of their developmental maturity. By monitoring and evaluating the sucking patterns of preterm infants, healthcare professionals can gain insights into their oral motor skills and overall development. Understanding this point will help readers better comprehend the pacifier's role in assessing infant maturity and its potential for guiding appropriate care interventions.

3.4 Dual-channel force pressure-sensing pacifier: improving efficiency and outcomes in preterm infant care

When discussing how the designed pacifier can save costs and time for healthcare professionals, we emphasize the benefits and outcomes of using the pacifier in preterm infant care. By providing accurate and objective measurements of sucking parameters, the pacifier reduces the need for subjective assessments and manual data collection. This not only saves valuable time for healthcare professionals but also improves the accuracy and efficiency of evaluations. Additionally, the use of the pacifier can enable more tailored and effective interventions, ultimately enhancing overall care and outcomes for preterm infants.

In this study, we aimed to design a prototype of a dual-channel pressure-sensing silicone pacifier and evaluate its feasibility for clinical application in collaboration with the Pediatric Intensive Care Unit (PICU) at Taichung Veterans General Hospital. With the assistance of medical staff and rehabilitation therapists, we assessed the sucking behavior of each infant and collected samples representing consistent sucking ability. The discriminant used in LabVIEW software design included four classifications: the difference in sucking pressure between stages 1 and 2, the average sucking pressure of stages 1 and 2, the total cumulative sucking time, and the cumulative sucking time. Statistical analysis was performed using ANOVA in this study. The statistical significance was observed as all four parameters yielded p-values less than 0.001. After calculating parameter 1, the results for the first stage were 11.95 ± 8.92 (g*f/cm^2), those for the second stage were 36.03 ± 18.44 (g*f/cm^2), and those for the third stage were 42.75 ± 15.89 (g*f/cm^2). The calculated values of parameter 2 were 57.70 (g*f/cm^2) for the first stage, 108.09 (g*f/cm^2) for the second stage, and 199.93 (g*f/cm^2) for the third stage. Parameters 3 and 4 correspond to the display plexus and total sucking time, respectively.

The clinical changes in the sucking pattern of preterm infants were examined and identified to fall into one of the following three stages. In the first stage, the infant does not suck (poor sucking); in the second stage, the infant starts to suck but the sucking is unsatisfactory (irregular sucking); and in the third stage, the infant can independently suck (regular sucking). Quantitative daily measurements indicate that our electronic pacifiers can be used for accurate analysis and classification. The sucking frequency of the infants in the third stage was the most constant, followed by those in the second and then the first stage. The sucking frequency of the infants in the third stage steadily increased over time; the frequency in the second stage was uneven, and the frequency in the first stage was excessively low because most of the infants could not suck.

Table 2 illustrates the characteristics of poor sucking in channels 1 and 2 during a 5-min period for preterm infants. It is observed that these infants exhibit a lack of response, a low number of sucks, decreased suction pressure, a small number of sucking plexuses, an extended duration of continuous rest, and a short overall duration of constant sucking. These findings indicate the necessity for doctor and caregiver intervention to train preterm infants at this stage.

Table 2
Classification of sucking in premature in infants.

Item	Difference between two channels ABS (g*f/cm^2)	Average sucking pressure (g*f/cm^2)	Number of continuous sucks per cluster	Total duration of continuous sucks /s	p	Sensitivity
Poor Sucking	11.95 ± 8.92	57.70 ± 29.70	16.28 ± 7.50	30.43 ± 28.12	<0.001	84.04
Irregular Sucking	36.03 ± 18.44	108.09 ± 31.06	27.69 ± 10.56	28.06 ± 24.20	<0.001	84.62
Regular Sucking	42.75 ± 15.89	199.93 ± 34.32	36.74 ± 9.94	67.18 ± 18.83	<0.001	97.22

n = 224.

Additionally, the measurement results of NNS among preterm infants in the first, second, and third stages are presented, revealing significant differences across all variables between the different stages.

The characteristics of irregular sucking in premature infants are as follows: Comparing the data of channels 1 and 2, it can be found that premature infants suck too many times (indicating poor sucking). In addition, the longer continuous sucking time shows that there are differences in the sucking ability of premature infants at this stage.

For regular sucking, comparing the durations of channels 1 and 2, we found that the number of sucks increased significantly in premature infants as they matured, with an average sucking pressure of 199.93 (g*f/cm^2).

Table 3 shows statistical sensitivity and specificity as classification metrics.

(1) All 224 instances meeting the criterion $\mu_D < \alpha = 17.59$ are classified as belonging to the poor sucking category. A contingency table can be constructed to present the corresponding test outcomes. Note that within the instances categorized as poor sucking, positive test results are observed. Out of the 79 instances, 15 are negative, while 16 show positive results in stages other than poor sucking. Additionally, 114 instances are negative. Consequently, the following results can be derived: sensitivity = 79/94 = 84.04%, specificity = 114/130 = 87.70%, and accuracy = 193/224 = 86.16% (as depicted in Table 4).

(2) A total of 129 subjects exhibit negative data meeting the criterion $\mu_D > \alpha$ =17.59 and $\mu > \beta$ = 139.15. These data are indicative of regular sucking and can be organized in a contingency table. Within the infants categorized as regular sucking, 35 tested positive and 1 tested negative. Additionally, 12 infants not in the regular sucking stage tested positive, while none tested negative. As indicated in Table 3, there are 93 instances. Consequently, the following results can be derived: sensitivity = 35/36 = 97.22%, specificity = 81/93 = 87.1%, and accuracy = 116/129 = 89.92% (as shown in Table 4).

(3) When $\mu < \beta = 139.15$, it is judged to indicate irregular sucking, and such test results can be listed in a contingency table. Among the infants in the irregular sucking stage, 66 tested positive. There were 12 infants who tested negative. Among infants not in the irregular

Table 3
Clinical statistics.

Item	Poor (%)	Irregular (%)	Regular (%)	Total accuracy (%)
Sensitivity	84.04	84.62	97.22	
Specificity	87.70	68.63	87.10	80.35
Accuracy	86.16	78.29	89.92	

Table 4
Sensitivity and specificity.

Contingency	Poor		Regular		Irregular	
	T	F	T	F	T	F
P	79	16	35	12	66	16
N	15	114	1	81	12	35
sessions	94	130	36	93	78	51

sucking stage, 16 were positive and 35 were negative. The following results were obtained: sensitivity = 66/78 = 84.62%, specificity = 35/51 = 68.63%, and accuracy = 101/129 = 78.29%. The overall accuracy was (79 + 35 + 66)/224 = 80.35% (shown in Table 4).

The force pressure-sensing pacifier designed in this study is considerably different from air-pressure-based pacifiers. Few studies have been reported on pressure-sensing pacifiers. After several years of design and clinical experimentation, we have made a significant contribution by developing an electric pacifier with dual channels. Our research fills a gap in the field of pressure-sensing pacifiers and opens up new possibilities for infant care. Unlike pacifiers with only one channel, the proposed pacifier provides sufficient space for the tongue to move. Additionally, the two channels inside the pacifier enable researchers to obtain specific data by separately detecting sucking at different positions; the information that can be obtained includes changes in the number of sucks and sucking pressure. The pacifier thus makes a considerable contribution to clinical research. Future research on the designed pacifier can be conducted from multiple aspects including model and multichannel development, direction expansion for pressure sensing, the use of software algorithm analysis, circuit diversification, and incorporation with a smartphone application. The test pacifier utilized in this study will exhibit resistance to maternal maturity. However, gathering sputum reflex data during the maturity stage proves challenging, despite its importance prior to infant discharge.

The designed pacifier enables researchers to save human-resource-related costs and time and to obtain data that can serve as a reference for clinical physicians wanting to provide appropriate rehabilitation for preterm infants. Moreover, the utilization of this electric pacifier enables the timely diagnosis of the sucking state. Additionally, it facilitates the development of an evaluation model for sucking training, which proves beneficial for clinical physicians.

3.5 Clinical contribution and discussion

In clinical research, the practical applications and impact of using a dual-channel pacifier can be significant. The force pressure-sensing pacifier designed in this study differs considerably from traditional air-pressure-based pacifiers, and its unique features enable valuable insights to be gained for improving preterm infant care. By incorporating dual channels, the pacifier allows for the separate detection of sucking at different positions, providing specific data that can be used to enhance preterm infant care. Researchers can obtain information such as changes in the number of sucks and sucking pressure, which can contribute significantly to clinical research. The data obtained from different sucking positions can be utilized to improve preterm infant care in various ways. For example, it can help in the assessment of the effectiveness of feeding interventions and the evaluation of the impact of different feeding techniques on oral motor development. Specific data can also aid in individualizing care plans based on an infant's unique sucking patterns and needs.

In future research on the designed pacifier, multiple aspects can be explored, including model and multichannel development, expanding the directions for pressure sensing, utilizing software algorithm analysis, circuit diversification, and incorporating smartphone applications. These advancements will further enhance the pacifier's functionality and contribute to broadening its clinical application. Note that the designed pacifier have limitations. Its T-shape design, necessary to accommodate the force-sensitive resistor, may be less flexible and hence may not be preferred by preterm infants accustomed to other pacifier types or infants nearing discharge. However, conversely, this reluctance to suck on the T-shape pacifier may indicate readiness for discharge.

Overall, the dual-channel force pressure-sensing pacifier offers practical applications and benefits in clinical research and provides specific data that can be utilized to improve preterm infant care and guide individualized interventions.

The design of a force pressure-sensing pacifier with dual channels represents a significant advancement from that of traditional air-pressure-based pacifiers. This innovative design addresses several limitations and offers various clinical benefits.

Firstly, the dual-channel configuration provides ample space for the tongue to move during sucking, allowing for a more natural and unrestricted feeding experience for preterm infants. This improvement overcomes the limitations of pacifiers with only one channel, which may restrict tongue movement and hinder proper oral motor development. Secondly, the two channels inside the pacifier enable researchers to gather specific data by separately detecting sucking at different positions. This feature allows for the measurement of changes in the number of sucks and sucking pressure, providing valuable insights into an infant's feeding pattern and oral motor function. This level of detailed information contributes significantly to clinical research in the field.

In short, the dual-channel force pressure-sensing pacifier represents a significant advancement in the field as it addresses the limitations of traditional pacifiers and provides valuable clinical benefits in assessing feeding patterns and supporting oral motor development in preterm infants.

3.6 Future outlook and suggestions

1. The new pacifier may contain some steam after cleaning, which will affect the accuracy of measurements. To avoid this problem, it should be used after thorough drying.
2. By employing the wireless transmission sucking method, a remote database can be established. A database of learning and education types and emotion classification of premature infants should be established.
3. Different hospitals should collect more data of premature babies to improve accuracy.

4. Conclusions

We successfully developed a dual-channel pressure-sensing electronic pacifier to address the difficulties in sucking ability among premature infants. By utilizing LabVIEW software and pressure sensors, the pacifier accurately measures key characteristics such as sucking pressure, intensity, and duration. However, further research is required to validate the effectiveness and explore the long-term effects of using electronic pacifiers on the sucking ability of preterm infants. In summary, the introduction of a dual-channel pressure-sensing electronic pacifier offers significant insights into the sucking capacity of premature infants. This technological advancement holds the potential to revolutionize neonatal care by facilitating precise assessment, personalized care planning, and improved parental comprehension. Ongoing research and further advancements in electronic pacifiers will continue to enhance their efficacy and broaden their application in the care of preterm infants, ultimately fostering their optimal development and overall well-being.

The primary objective of this study was to develop a dual-channel pressure-sensing electronic pacifier for the purpose of detecting difficulties in sucking ability among premature infants. By utilizing LabVIEW software, the pressure sensors on the pacifier were effectively employed to measure key characteristics such as sucking pressure, intensity, and duration. The successful outcomes of this research have yielded several notable advantages that contribute to the improvement of newborn care. Specifically, the early assessment of sucking ability provides accurate information that enables healthcare professionals to make necessary adjustments to feeding methods and frequencies, ensuring the provision of sufficient nutrition.

Moreover, the research findings facilitate the development of individualized care plans that address the specific sucking difficulties experienced by each premature infant, thereby enabling tailored treatment and rehabilitation. Additionally, the research outcomes offer valuable information and suggestions to parents, enhancing their understanding and ability to effectively respond to their infants' needs. Lastly, the results of this study contribute to the promotion of oral and masticatory development in premature infants, facilitating their successful transition to solid foods.

In the 5-min experiment using the designed pacifier, we measured the sucking pressures at channels 1 and 2, the difference in sucking pressure between the two channels, clusters of continuous sucks, the duration of continuous sucks, and rest time following a continuous suck. The measurements were performed to determine the outcomes of using the designed pacifier in sucking training. A small difference between the pressures measured at the two channels indicates effective suction.

Because of the specialization of the field and the challenge of working with preterm infants, there is little research on electronic pacifiers used in sucking interventions and improving sucking ability in preterm infants. However, the results of some studies support their effectiveness in sucking interventions. These findings suggest that the use of electronic pacifiers that provide individualized feedback and stimulation can help improve sucking skills, strength, and coordination in preterm infants.

With the emphasis on the development of sucking in premature infants and the continuous advancement of technology, we can expect more research on sucking intervention with electronic pacifiers in the future, which will allow us to further understand its application value in the care of premature infants.

The results of this study showed that the use of the electronic pacifier enabled us to quantify and classify a baby's sucking ability and collect data on NNS, leading to an understanding of the changes and patterns in sucking. Further exploration of the long-term effects of electronic pacifiers on the sucking ability of preterm infants and how to optimize intervention strategies to provide better care and support the development of preterm infants may be possible topics of future research.

However, despite the limited research on electronic pacifiers for sucking interventions, there is already some research evidence supporting their effectiveness in the care of preterm infants. These findings help improve our understanding of the sucking ability of preterm infants and provide the basis for developing more effective intervention strategies.

Overall, sucking intervention with electronic pacifiers can be an effective method to improve sucking ability in preterm infants. The application of this intervention helps premature infants better meet their feeding and nutritional needs and promotes their development and growth. However, further research is needed to better understand the optimal use of electronic pacifiers for sucking interventions and their long-term effects on the long-term development of preterm infants.

Further research on the design and function of the electronic pacifier is needed to improve its performance and applicability. For example, adding other sensing technologies or features to more fully assess and support the sucking ability of preterm infants can be explored. In addition, further research and evaluation are needed on the safety and comfort of electronic pacifiers, as well as their acceptance and feasibility of use by parents and healthcare professionals.

Overall, electronic pacifiers have potential as a sucking intervention tool in improving sucking ability in preterm infants. The application of this technology can provide individualized support and treatment for premature infants, promote the development of their sucking ability, and improve the effect of feeding. With the continuous advancement of technology and more research investment, we expect further improvement and optimization of the use of electronic pacifiers to better meet the sucking needs of premature babies and improve their chances of growth and development.

In addition, the application of electronic pacifiers is not limited to sucking intervention. They can also be used as a tool to monitor and assess the sucking ability of premature infants and provide valuable data for evaluation and treatment planning by medical professionals. Through the use of electronic pacifiers, the medical team can more accurately understand the premature baby's sucking ability and the development of sucking technique, strength, and coordination.

Furthermore, for premature infants, sucking is not only a physical process, but also closely related to emotion and development. Therefore, the design and application of electronic pacifiers should also take into account their impact on the emotion and development of premature infants. By providing individualized stimulation and feedback, electronic pacifiers can help premature babies establish good sucking experience, enhance their emotional connection with their mothers or caregivers, and promote their physical and mental development.

However, it should be pointed out that the electronic pacifier is merely a tool for sucking intervention, and it should be used in combination with other comprehensive treatment and care methods. Direction and supervision by a medical professional are essential. Every premature baby has unique circumstances and needs. Therefore, individual evaluation and appropriate intervention planning should be carried out when using electronic pacifiers.

Overall, electronic pacifiers have the potential to improve the sucking ability of preterm infants and play an important role in preterm infant care. With further research and practice, we can better understand how it works and how it is applied. The ultimate purpose is to promote the healthy growth and development of premature infants.

The difference in sucking ability between premature infants using electronic and nonelectronic pacifiers has been examined in previous studies. In this study, we aimed to design and evaluate a dual-channel pressure-sensing electronic pacifier to detect difficulties in sucking ability among premature infants. With the assistance of medical staff and rehabilitation therapists, we collected data on sucking pressure, intensity, and duration using the designed pacifier. Our research outcomes demonstrated the effectiveness of the electronic pacifier in quantifying and classifying sucking abilities, providing valuable information for healthcare professionals to adjust feeding methods and frequencies and develop individualized care plans. Additionally, our results contribute to the promotion of oral and masticatory development in premature infants, facilitating their successful transition to solid foods. The advantages of our study lie in the accurate assessment of sucking ability, individualized care planning, enhanced understanding and response from parents, and the improved overall quality of life for premature infants.

Our developed dual-channel pressure-sensing electronic pacifier contributes to the field by offering a practical tool for healthcare professionals to comprehensively assess and support the development of the sucking ability of premature infants. Our research outcomes contribute to the advancement of care practices and provide insights into the optimization of feeding strategies for this vulnerable population.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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