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The Impact of Varying Nipple Properties on Infant Feeding Physiology and Performance Throughout Ontogeny in a Validated Animal Model

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Abstract

Infant feeding requires successful interactions between infant physiology and the maternal (or bottle) nipple. Within artificial nipples, there is variation in both nipple stiffness and flow rates, as well as variation in infant physiology as they grow and mature. However, we have little understanding into how infants interact with variable nipple properties to generate suction and successfully feed. We designed nipples with two different stiffnesses and hole sizes and measured infant feeding performance through ontogeny using a pig model. We evaluated their response to nipple properties using high-speed X-Ray videofluoroscopy. Nipple properties substantially impacted sucking physiology and performance. Hole size had the most profound impact on the number of sucks infants took per swallow. Pressure generation generally increased with age, especially in nipples where milk acquisition was more difficult. However, most strikingly, in nipples with lower flow rates the relationship between suction generation and milk acquisition was disrupted. In order to design effective interventions for infants with feeding difficulties, we must consider how variation in nipple properties impacts infant physiology in a targeted manner. While reducing flow rate may reduce the frequency an infant aspirates, it may impair systems involved in sensorimotor integration.

Keywords

Infant oral feeding; Animal model; Nipple properties; Feeding physiology

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Conflict of interest The authors declare there are no competing interests.

Ethical Approval All animal care and procedures were approved by NEOMED IACUC #2020-01-248.

Introduction

Infant feeding is a fundamental process across mammals, in which infants use their tongue, palate, lips, and jaws to produce suction and acquire milk [1–3]. The tongue is then used to transport milk posteriorly to the oropharynx, where it accumulates prior to swallowing [2, 4]. Intraoral suction generation is essential to feeding success during both breast and bottle feeding [3, 5]. However, infancy is not a static state, and the anatomy and physiology of an infant changes throughout development [6–9]. It therefore follows that successful feeding through ontogeny relies on changes in mechanisms of intraoral pressure generation, one of the integral components of effective and safe feeding in infants.

However, many infants struggle with feeding, both at birth and through infancy (in humans, typically considered as the first twelve months of life). For example, infants with craniofacial malformations often struggle to generate suction during feeding [10, 11]. Furthermore, infants that are born prematurely (approximately 11% of US births, [12]) often experience a myriad of feeding difficulties [13]. These difficulties are generally associated with generating suction, feeding efficiently [14, 15], and coordinating among behaviors during feeding [7, 16, 17], in addition to other challenges such as high rates of gastroesophageal reflux (GER, [18]). Such feeding difficulties among infants have resulted in the development of several interventions to improve feeding function, often associated with modifying the nipple from which the infant feeds during bottle feeding.

One common intervention is the reduction of milk flow rate by altering the hole size of a nipple on a bottle, which has a positive outcome of reducing the propensity of an infant to aspirate through decreasing milk flow rate [19, 20]. There is extensive variation across commercial nipples in stiffness and material properties [5, 21]. This variation could be clinically important, as variation in nipple stiffness impacts infant function [22, 23]. Thus, there is extensive variation in both the hole size of nipples (one critical component that dictates flow rate) and the stiffness of nipples (which has been demonstrated to impact infant behavior), both of which have implications for feeding performance in infants, especially as there are no manufacturing standards for commercially available nipples [19]. Furthermore, the relationship between suction generation and milk flow is not linear. For example, higher pressure generation may not necessarily equate to larger volumes of milk being transferred to the infant, depending on the properties of the nipple [24]. The extensive amount of variation in nipple properties, and the disjunct between properties and performance makes investigating their relationship challenging, and we have very little insight into how this variation in nipple properties impacts infant feeding physiology.

Here, we aim to systematically evaluate the relationships between intraoral pressure generation and milk acquisition with variation in milk flow rate (nipple hole size) and nipple stiffness, and how these relationships might change through infancy in a validated animal model [25]. Obtaining longitudinal data on infant feeding function can be challenging in human infants for practical and ethical reasons [7, 25, 26]. In contrast, animal models represent an ideal alternative to investigating feeding function, as they can be filmed under fluorographic exposure at much higher spatial and temporal resolutions [25]. Additionally, infant animals can be kept in controlled environments throughout infancy, which minimizes environmental variation. In this experiment we fabricated nipples of two different stiffness and hole sizes and evaluated feeding performance and physiology using an infant pig model [22]. We hypothesized that pressure generation and milk acquisition would be greater with age, and with nipples that were more compliant, or had larger hole size, both of which should decrease the difficulty needed to acquire milk. By testing this hypothesis, we hope to provide insight into the mechanisms by which altering nipple properties impacts feeding performance in infant mammals.

Methods

Animal Care

All animal care and procedures were approved by Northeast Ohio Medical University's IACUC committee and followed standard infant pig care practices [7, 27]. We received full term pigs (Yorkshire/Landrace sows, Shoup Investments, LTD, Wooster, OH) 24 h after birth. Animals were housed in the NEOMED Comparative Medicine Unit (CMU). Pigs were trained to drink milk replacer formula (Solustart Pig Milk Replacement, Land o' lakes, Arden Mills, MN) from a bottle throughout the experiment. Using food-safe silicone, nipples were created of Share A hardness ratings of 20 A ('compliant', Cast-a-Mold 20A; Specialty Resin and Chemical) and 55A ('stiff', ReproRubber 55A; Flexbar) with two-hole sizes (cross- sectional areas of 2.0 π mm^2 (large) and 0.5 π mm^2 (small)). A fifth 'training nipple' was created with an intermediate Shore hardness of 40A (Smooth-Sil 940; Smooth-On) with an intermediate hole size cross-sectional area (1.0 π mm^2) so that infants exposed to experimental nipples were less likely to reject them [22].

Data Collection

We recorded pigs at two ages: at seven days old (equivalent to approximately a 1- to 2–month-old human infant), and at 17 days old (approximately equivalent to a 6- to 9-month-old human infant [28, 29]). We collected high-speed videofluoroscopic data (GE 9400C-Arm, 75–85 kV, 4–7 mA) using bilateral x-ray video and cameras (XCIM, XCitex, Cambridge, MA, USA) at 100 frames per second. The pigs fed on a mixture of milk replacer formula and barium in a radiolucent box in front of the fluoroscope. After the first ten seconds of feeding (which occurs at a faster rate than is typical, [30, 31]), we recorded approximately 20 swallows per pig per nipple type in a randomized order, with a washout recording using the intermediate training nipple between. For each suck we measured the total intraoral pressure generated by threading a Millar pressure transducer through the bottle nipple and 1 cm into pig's oral cavity when feeding.

Data Processing

Swallows were identified as the frame where the bolus accumulated in the supraglottal space before passing the epiglottis [27, 32]. Sucks were identified in the feeding sequence by determining the frame where the tongue contacted the hard palate in the lateral x-ray view [7, 14]. We exported raw pressure generation during synchronized data collection from LabChart (Down sampled to 100 Hz to match video filming rate), and separated pressure generation into discrete sucks by loading the suck frames identified in X-Ray Video and the pressure data into a custom MATLAB routine. For each suck, this routine calculated the total pressure generated by subtracting the maximum from the minimum. Bolus size was measured in ImageJ, using the bottle diameter as the scale to convert images from pixels to mm^2 [33, 34].

Variables

Within a sequence of swallows, we measured (1) the timing of sucks and swallows (and the number of sucks per swallow), (2) the area of the bolus in the lateral view prior to swallow initiation, and (3) the amplitude of intraoral pressure generation within each suck and within each swallow (pressure generated within a swallow was calculated by summing the pressure generated within each suck that contributed to a specific swallow). We analyzed the impacts of: (a) nipple hole size, (b) nipple material property (stiff / compliant), and (c) age on sucking and swallowing.

Statistical Analysis

All statistical analyses were performed in R (v 4.2.1). We used linear mixed effects models to evaluate the effect of age, nipple stiffness, hole size, and their interaction on feeding performance, and their interaction using the R package lme4 [35], with individual as a random effect. Where interactions were significant ($p < 0.05$), we performed planned contrast analyses to evaluate the impact of age, stiffness and hole size independently using the R package emmeans [36]. We also calculated effects sizes for each comparison using Cohen’s D [37], and evaluated variation across groups using Levene’s tests for homogeneity of variance. To evaluate the relationship between volume acquisition and suction generation, we used linear models for each nipple type, separated by age.

Results

Sucks Per Swallow and Pressure Generation During Feeding

Nipple properties substantially impacted sucking physiology and performance. Across both ages, pigs produced more sucks per swallow on smaller holed nipples (Fig. 1). Nipple stiffness only impacted sucks per swallow in the large holed nipples in older infants, where infants feeding on compliant nipples produced fewer sucks per swallow than those feeding on stiff nipples (Fig. 1, Table 1, S1). The number of sucks per swallow increased with age within a nipple type for all nipple types (Fig. 1A).

No substantial differences in the summed amount of pressure generated per swallow existed among nipple types within the seven-day-old pigs, but at day 17, there were strong effects of both hole size and nipple stiffness. Within stiff nipples at day 17, pressure generation was higher on large holed nipples than on small holed nipples, but conversely, in compliant nipples, pressure per swallow was lower in the large holed nipples than it was in the small holed nipples (Fig. 1). Because of this differential response by age, pressure per swallow was higher within nipple type at day 17 than at day 7 for all nipples other than the large holed, compliant nipple (Fig. 1B). The amount of pressure generated within a single suck (Fig. 1C) similarly differed between days 7 and 17.

Notably, variation in pressure generated during sucking was lower in the small stiff nipple than in the small compliant nipple at both ages (Levene's test: day 7 $t = 45.5$, $p < 0.001$; Day 17 $t = 63.6$, $p < 0.001$). The variance in suck amplitude was also lower in the small stiff nipple than the large stiff nipple at day 17 ($t = 33.4$, $p < 0.001$), although not at day seven. By day 17, variance in pressure generated during sucking was higher in the large stiff nipple (Levene's test $t = 23.1$, $p < 0.001$) and the small compliant nipple (Levene's test $t = 4.9$, $p = 0.03$) than in the large holed compliant nipple.

Milk Volume Per Swallow and Per Suck Across Nipples and Through Infancy

In addition to changes in sucking behaviors, we observed changes in swallowed bolus size and milk obtained per suck depending on nipple type. Bolus volume increased with age within all nipple types (Fig. 2A, Table 2, Table S2). Bolus size was generally higher with larger holes, or with more compliant nipples, although there were no differences in bolus size between the small holed stiff and small holed compliant nipples for either age (Fig. 2A). These patterns were similar when examining the estimated amount of milk obtained per suck. Infant pigs generally obtained more milk per suck on larger holed nipples, and on nipples that were more compliant (Fig. 2, Table 2, Table S2), although we observed no differences between the two small holed nipples at day 7. We only found an age effect for volume per suck for the large holed stiff nipples, in which volumes were actually lower at day 17 than at day 7.

Linking Pressure Generation to Milk Acquisition

The only significant relationship between pressure and volume per suck was for the large holed compliant nipple type, in which there was a positive relationship between suction generation and volume of milk obtained per suck (day 7: $p < 0.001$, $r^2 = 0.14$; day 17: $p < 0.001$, $r^2 = 0.35$). For the other three nipple types (small stiff, small compliant, large stiff), there was no relationship between effort (pressure generation) and volume (suck size, $p > 0.05$, $r^2 < 0.1$, Fig. 3).

Discussion

Overall, we found that modifications to nipple stiffness and flow rate had substantial impacts on infant feeding physiology, especially as infants matured, supporting our hypothesis. Flow rate, but not stiffness had the most profound impact on the number of sucks an infant produced per swallow. We also found that pressure generation generally increased with age, especially in nipples where milk acquisition was more difficult, such as in nipples with higher stiffness or smaller hole sizes. Most strikingly, altering nipple properties decoupled the relationship between suction generation and milk acquisition per suck (wherein the expected relationship would involve an increase in milk acquired per suck with increased intraoral pressure generation).

Nipple Properties Impact Sucking Physiology

Infant pigs feeding on higher flow rate nipples or on nipples with more compliance were able to acquire more milk per suck than lower flow or stiffer nipples at both ages. However, this increased milk acquisition is not necessarily directly related to the amount of pressure generated per suck. Infants feeding on the high flow stiff and the low flow compliant nipples both exhibited higher pressure per suck than when feeding on the high flow compliant nipple, but acquired less milk per suck. Our results suggest that younger infants may require a certain threshold of acquired milk per suck to evoke significant effort, and that only once this threshold is met will effort increase when flow rate is low. However, once flow becomes very high, older infants may modulate their effort to to limit the amount of milk being swallowed and increase swallow safety [33].

Altering nipples stiffness and flow rate alters the relationship between suction pressure and milk acquisition. The fact that at both ages, the only nipple that had a positive relationship between suction generation and milk acquisition was the high flow compliant nipple further supports this possibility, as the other nipples may not effectively trigger the sensory system to evoke modifications to motor output. Thus, reducing flow rate by changing nipple hole size may reduce the incidence of aspiration [13, 19, 34], but possibly at the cost of decoupling physiology and performance. Additionally, we saw less variation in sucking physiology and behavior at day seven than we saw at day 17. This could indicate that very young infants have an immature sensory system that limits their ability to respond to variation in nipple properties, suggesting that nipple properties are particularly important to consider when working with this population. The highly variable sucking pressure in the large stiff and small compliant nipples at day 17 is likely due to the lack of a relationship between pressure generation and volume acquisition, whereby infants exhibit irregular suction generation patterns in an attempt to match their physiology to milk flow.

Nipple Properties Have Downstream Impacts on Swallow Physiology

The changes observed in sucking physiology due to variation in nipple properties have downstream impacts on swallow physiology and performance. Infants feeding on stiffer nipples, or with lower flow rates, had reduced bolus volume, which has negative implications for their feeding efficiency [27, 34]. However, fast flowing nipples are not necessarily optimal, as larger boluses are typically associated with an increased risk for aspiration [34, 38]. Furthermore, there is maturation in the coordination between sucking, swallowing, and breathing in infants, suggesting that interventions designed for one age group might not function similarly for others [6, 32, 39, 40]. Thus, a balance must be made between developing nipples that facilitate feeding (either by increasing compliance or flow rate) while still taking into account the physiologic limits of the infant feeding system.

Clinical Implications

Nipple design plays a critical role in establishing successful and safe feeding for bottle-fed infants, and considerations must be made to balance efficiency with swallow safety [33]. While standard practice when working with infants that struggle with feeding is to reduce flow rate (by adjusting nipple hole size or by increasing viscosity), this solution often does not account for the etiology of the feeding difficulty [26, 41]. In order to design effective interventions for infants with feeding difficulties, we must consider how variation in nipple properties impacts infant physiology in a targeted manner. Two aspects of this design include nipple stiffness and flow rate, and our work demonstrates that ignoring those properties can have functional implications not just for performance, but also for infant physiology and development. While reducing flow rate may reduce the frequency an infant aspirates, it may impair systems involved in sensorimotor integration.

Limitations and Conclusions

While infant pigs represent a validated animal model for studies of dysphagia [25], these results may not be directly applicable to human infants. Furthermore, these data come from healthy infants without any indication of a feeding pathophysiology. Infants with dysphagia, such as many of those born prematurely, may respond differently to variation in nipple properties. Additionally, we have only examined one axis of infant feeding physiology through ontogeny, sucking. Yet there is substantial postnatal maturation in swallowing and breathing in infants [6, 7, 42], and how these three components can be impacted by nipple properties remains understudied. However, our data do represent a general model illustrating the importance of considering physiology in concert with performance outcomes when designing interventions for infant feeding [26]. Our observation of increased sucks per swallow with age is also counterintuitive, as efficiency is generally thought to increase with age. This could be because older infants' sensorimotor systems may be better able to handle larger boluses, such that a larger volume of milk is required to initiate the pharyngeal swallow. Additionally, flow rate in bottle-fed infants can be modulated by the caregiver, and we have little insight into how variation in caregiver practices may drive variation in infant physiology and performance. Finally, we demonstrate that both stiffness and flow rate impact performance and physiology, and that in general, infants are more efficient feeders when nipples facilitate milk acquisition. Furthermore, the fact that only the large holed, compliant nipple had any relationship between suction generation and milk acquisition is critical, as disruptions to the sensorimotor system may have long term consequences for neurophysiology and performance.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data Availability

All data used in statistical analyses for this paper are available on figshare at https://doi.org/10.6084/m9.figshare.24526693.

References

1. German RZ, Crompton AW, Hertweck DW, Thexton AJ. Determinants of rhythm and rate in suckling. J Exp Zool. 1997;278:1–8. [PubMed: 9136144]

2. Thexton AJ, Crompton AW, Owerkowicz T, German RZ. Correlation between intraoral pressures and tongue movements in the suckling pig. Arch Oral Biol. 2004;49:567–75. [PubMed: 15126138]
3. Elad D, Kozlovsky P, Blum O, Laine AF, Po MJ, Botzer E, et al. Biomechanics of milk extraction during breast-feeding. Proc Natl Acad Sci. 2014;111:5230–5. 10.1073/pnas.1319798111. [PubMed: 24706845]
4. Thexton AJ, Crompton AW, German RZ. Electromyographic activity during the reflex pharyngeal swallow in the pig: Doty and Bosma (1956) revisited. J Appl Physiol. 2007;102:587–600. 10.1152/japplphysiol.00456.2006. [PubMed: 17082375]
5. Geddes DT, Sakalidis VS, Hepworth AR, McClellan HL, Kent JC, Lai CT, et al. Tongue movement and intra-oral vacuum of term infants during breastfeeding and feeding from an experimental teat that released milk under vacuum only. Early Hum Dev. 2012;88:443–9. 10.1016/j.earlhumdev.2011.10.012. [PubMed: 22119233]
6. Gewolb IH, Vice FL. Maturational changes in the rhythms, patterning, and coordination of respiration and swallow during feeding in preterm and term infants. Dev Med Child Neurol. 2006;48:589–94. [PubMed: 16780629]
7. Mayerl CJ, Gould FDH, Bond LE, Stricklen B, Buddington RK, German RZ. Preterm birth disrupts the development of feeding and breathing coordination. J Appl Physiol. 2019;126:1681–86. [PubMed: 31018743]
8. Mayerl CJ, Steer KE, Chava AM, Bond LE, Edmonds CE, Gould FDH, et al. The contractile patterns, anatomy, and physiology of the hyoid musculature change longitudinally through infancy. Proc R Soc B. 2021;288:20210052.
9. Viswanathan S, Jadcherla S. Feeding and swallowing difficulties in neonates: developmental physiology and pathophysiology. Clin Perinatol. 2020;47:223–41. [PubMed: 32439109]
10. Bessell A, Hooper L, Shaw WC, Reilly S, Reid J, Glenny A-M. Feeding interventions for growth and development in infants with cleft lip, cleft palate or cleft lip and palate. Cochrane Database Syst Rev. 2011. 10.1002/14651858.CD003315.pub3.
11. Martin V, Greatrex-White S. An evaluation of factors influencing feeding in babies with a cleft palate with and without a cleft lip. J Child Heal Care. 2014;18:72–83.
12. Kumari S, Barton GP, Goss KN. Increased mitochondrial oxygen consumption in adult survivors of preterm birth. Pediatr Res. 2021;90:1147–52. 10.1038/s41390-021-01387-9. [PubMed: 33619358]
13. Jadcherla S Dysphagia in the high-risk infant: potential factors and mechanisms. Am J Clin Nutr. 2016;103:622S–628S. [PubMed: 26791178]
14. Mayerl CJ, Edmonds CE, Catchpole EA, Myrla AM, Gould FDH, Bond LE, et al. Sucking versus swallowing coordination, integration, and performance in preterm and term infants. J Appl Physiol. 2020;129:1383–92. [PubMed: 33054658]
15. Mayerl CJ, Catchpole EA, Edmonds CE, Gould FDH, McGrattan KE, Bond LE, et al. The effect of preterm birth, recurrent laryngeal nerve lesion, and postnatal maturation on hyoid and thyroid movements, and their coordination in infant feeding. J Biomech. 2020;105:109786. 10.1016/j.jbiomech.2020.109786. [PubMed: 32307182]
16. Edmonds CE, Catchpole EA, Gould FDH, Bond LE, Stricklen BM, German RZ, et al. Preterm birth impacts the timing and excursion of oropharyngeal structures during infant feeding. Integr Org Biol. 2020;2:1–11.
17. Vice FL, Gewolb IH. Respiratory patterns and strategies during feeding in preterm infants. Dev Med Child Neurol. 2008;50:467–72. [PubMed: 18422676]
18. Koo JK, Narvasa A, Bode L, Kim JH. Through thick and thin: the in vitro effects of thickeners on infant feed viscosity. J Pediatr Gastroenterol Nutr. 2019;69:122–8.
19. McGrattan KE, McFarland DH, Dean JC, Hill E, White DR, Martin-Harris B. Effect of single-use, laser-cut, slow-flow nipples on respiration and milk ingestion in preterm infants. Am J Speech-Language Pathol. 2017;26:832–9.
20. Pados BF, Park J, Thoyre SM, Estrem H, Nix WB. Milk flow rates from bottle nipples used after hospital discharge. MCN Am J Matern Nurs. 2016;41:237–43.
21. Nowak AJ, Smith WL, Erenberg A. Imaging evaluation of artificial nipples during bottle feeding. Arch Pediatr Adolesc Med. 1994;148:40–2. [PubMed: 8143007]

22. Adjerid K, Johnson ML, Edmonds CE, Steer KE, Gould FDH, German RZ, et al. The effect of stiffness and hole size on nipple compression in infant suckling. J Exp Zool Pt A. 2023;339:92–100. 10.1002/jez.2657.

23. Zimmerman E, Barlow SM. Pacifier stiffness alters the dynamics of the suck central pattern generator. J Neonatal Nurs. 2008;14:79–86. [PubMed: 19492006]

24. Geddes DT, Chooi K, Nancarrow K, Hepworth AR, Gardner H, Simmer K. Characterisation of sucking dynamics of breastfeeding preterm infants: a cross sectional study. BMC Pregnancy Childbirth. 2017;17:1–11. [PubMed: 28049520]

25. German RZ, Crompton AW, Gould FDH, Thexton AJ. Animal models for dysphagia studies: what have we learnt so far. Dysphagia. 2017;32:73–7. [PubMed: 28132098]

26. Mayerl CJ, Gould FDH, Adjerid K, Edmonds C, German RZ. The pathway from anatomy and physiology to diagnosis: a developmental perspective on swallowing and dysphagia. Dysphagia. 2023;38:33–41. 10.1007/s00455-022-10449-x. [PubMed: 35441265]

27. Mayerl CJ, Myrla AM, Bond LE, Stricklen BM, German RZ, Gould FDH. Premature birth impacts bolus size and shape through nursing in infant pigs. Pediatr Res. 2020;87:656–61. [PubMed: 31645052]

28. Eiby YA, Wright LL, Kalanjati VP, Miller SM, Bjorkman ST, Keates HL, et al. A pig model of the preterm neonate: anthropometric and physiological characteristics. PLoS ONE. 2013;8:e68763. [PubMed: 23874755]

29. Helm JW, German RZ. The epigenetic impact of weaning on craniofacial morphology during growth. J Exp Zool. 1996;276:243–53. [PubMed: 8946727]

30. Gierbolini-Norat EM, Holman SD, Ding P, Bakshi S, German RZ. Variation in the timing and frequency of sucking and swallowing over an entire feeding session in the infant pig *Sus scrofa*. Dysphagia. 2014;29:1–8. 10.1007/s00455-014-9532-y.

31. McGrattan KE, Mcghee HC, Mckelvey KL, Clemmens CS, Hill EG, Detoma A, et al. Capturing infant swallow impairment on videofluoroscopy: timing matters. Pediatr Radiol. 2019;50:199–206. 10.1007/s00247-019-04527-w. [PubMed: 31650190]

32. Mayerl CJ, Gould FDH, Bond LE, Stricklen BM, Buddington RK, German RZ. Preterm birth disrupts the development of feeding and breathing coordination. J Appl Physiol. 2019;126:1681–6. 10.1152/japplphysiol.00101.2019. [PubMed: 31018743]

33. Mayerl CJ, Myrla AM, Gould FDH, Bond LE, Stricklen BM, German RZ. Swallow safety is determined by bolus volume during infant feeding in an animal model. Dysphagia. 2021;36:120–9. 10.1007/s00455-020-10118-x. [PubMed: 32328794]

34. Mayerl CJ, Edmonds CE, Gould FDH, German RZ. Increased viscosity of milk during infant feeding improves swallow safety through modifying sucking in an animal model. J Texture Stud. 2021;52:603–611. 10.1111/jtxs.12599. [PubMed: 33783823]

35. Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixedeffects models using lme4. J Stat Softw. 2015;67:1–48.

36. Lenth R Emmeans: estimated marginal means, aka least-squares means [Internet]. 2018. https://cran.rproject.org/package=emmeans

37. Cohen J A power primer. Psychol Bull. 1992;112:155–9. 10.1037/0033-2909.112.1.155. [PubMed: 19565683]

38. Edmonds CE, German RZ, Bond LE, Mayerl CJ. Oropharyngeal capsaicin exposure improves infant feeding performance in an animal model of superior laryngeal nerve damage. J Neurophysiol. 2022;128:339–49. [PubMed: 35822726]

39. Amaizu N, Shulman R, Schanler R, Lau C. Maturation of oral feeding skills in preterm infants. Acta Paediatr. 2008;97:61–7.

40. Bond LE, Mayerl CJ, Stricklen BM, German RZ, Gould FDH. Changes in the coordination between respiration and swallowing from suckling through weaning. Biol Lett 2020;16:20190942. 10.1098/rsbl.2019.0942. [PubMed: 32264794]

41. Gould FDH, Lammers AR, Mayerl CJ, German RZ. Specific vagus nerve lesion have distinctive physiologic mechanisms of dysphagia. Fontiers Neurol. 2019;10:1301.

42. Gewolb IH, Vice FL, Schweitzer-Kenney EL, Taciak VL, Bosma JF. Developmental patterns of rhythmic suck and swallow in preterm infants. Dev Med Child Neurol. 2001;43:22–7. [PubMed: 11201418]

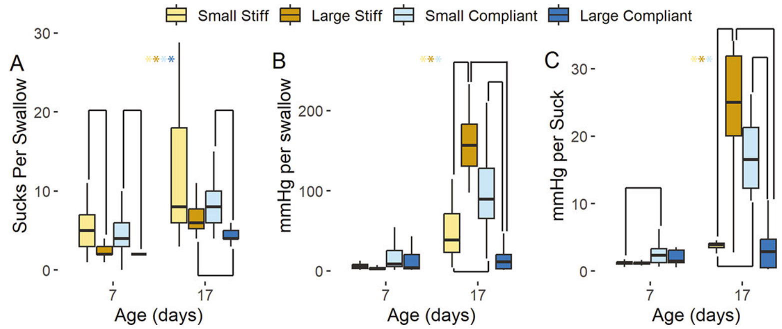

Fig. 1.

Age and hole size both resulted in increased sucks per swallow (**A**), whereas, in general, pressure generation per swallow **B** and suck **C** increased with age, with variable effects of nipple properties. Colored plots indicate median (horizontal line) ± interquartile range. Lines between box plots within an age indicate statistically sig differences with large effect sizes. Asterisks indicate statistically significant differences with large effect sizes across ages within nipple type across ages, with color indicating nipple type

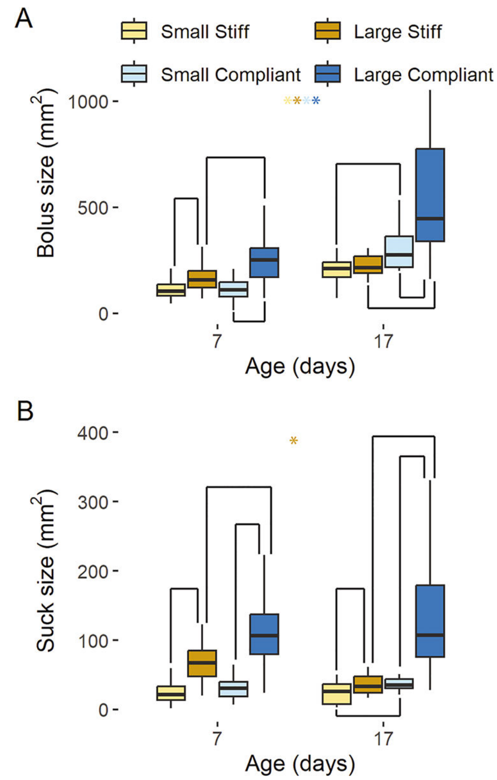

Fig. 2.
Bolus size **A** and suck volume **B** were larger when feeding on larger holed and more compliant nipples. Colored plots indicate median (horizontal line) ± interquartile range. Lines indicate statistically significant differences with large effect sizes within an age. Asterisks indicate statistically significant differences with large effect sizes across ages within nipple type across ages, with color indicating nipple type

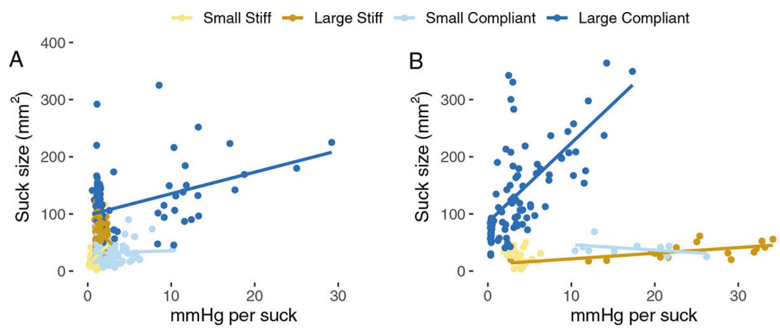

Fig. 3.

Nipple properties disrupted the relationship between suction generation and milk acquisition for all nipples except the large holed compliant nipple at both young **A** and older **B** ages

Table 1

Results from planned contrast analyses and effects size analyses for sucks per swallow, pressure generation per swallow, and pressure generation per suck (t value, p value, Cohen's D)

Comparison type		Sucks per swallow (t, p; d)	mmHg per swallow (t, p; d)	mmHg per suck (t, p; d)
Age	Young small stiff vs old small stiff	**− 9.2, < 0.001; − 1.2**	**− 9.8, < 0.001;− 2.9**	**− 3.5, 0.005; − 3.5**
Age	Young small compliant vs old small compliant	**− 5.7, < 0.001;−1.2**	**− 14.9, < 0.001;− 3.7**	**− 12.7, < 0.001; − 6.3**
Age	Young large stiff vs old large stiff	**− 6.2, < 0.001; − 2.7**	**− 34.6, < 0.001; − 7.8**	**− 25.2, < 0.001; − 6.8**
Age	Young large compliant vs old large compliant	**− 5.4, < 0.001; − 2.1**	− 0.8, 0.42; − 0.12	0.58, 0.56; 0.06
Hole size	Young small stiff vs young large stiff	**7.7, < 0.001; 1.15**	1.1, 0.28; 0.71	− 0.22, 0.83; − 0.18
Hole size	Young small compliant vs young large compliant	**6.7, < 0.001; 1.1**	1.1, 0.29; 0.14	− 2.9, 0.004; − 0.34
Stiffness	Young small stiff vs young small compliant	− 2.5, 0.014; 0.29	4.1, 0.001; − 0.79	**2.9, 0.003; − 1.1**
Stiffness	Young large stiff vs young large compliant	− 1.2, 0.2142; 0.45	4.4, < 0.001; − 0.78	5.7, < 0.001; − 0.69
Stiffness	Old small stiff vs old small compliant	− 3.2, 0.001; 0.46	**8.84, < 0.001; − 1.4**	**10.3, < 0.001; − 4.5**
Hole size	Old small stiff vs old large stiff	4.8, < 0.001; 0.71	**− 20.7, < 0.001; − 2.7**	**− 18.8, < 0.001; − 3.6**
Hole size	Old small compliant vs old large compliant	**6.4, < 0.001; 2.5**	**14.8, < 0.001; 3.7**	**11.7, < 0.001; 3.4**
Stiffness	Old large stiff vs old large compliant	**− 3.9, < 0.001; 1.8**	**− 31.3, < 0.001; 5.9**	**− 22.5, < 0.001; 4.2**

Bolded values indicate statistically significant results with large effects sizes. Young: 7 days; Old: 17 days

Table 2

Results from planned contrast analyses and effects size analyses for bolus size per swallow and aliquot size per suck (t value, p value, Cohen's D)

Comparison type		Bolus size (t, p; d)	Suck size (*t*, *p*; *d*)
Age	Young small stiff vs old small stiff	− **3.3, 0.001; − 1.6**	0.6, 0.55; 0.31
Age	Young small compliant vs old small compliant	− **6.7, < 0.001; − 3.1**	− 0.5, 0.64; − 0.43
Age	Young large stiff vs old large stiff	− **1.8, 0.05; − 1.0**	**2.6, 0.01; 1.34**
Age	Young large compliant vs old large compliant	− **17.1, < 0.001; − 1.4**	− 3.7, 0.0002; − 0.34
Hole size	Young small stiff vs young large stiff	− **3.0, 0.002; − 0.98**	− **5.9, < 0.001; − 1.7**
Hole size	Young small compliant vs young large compliant	− **8.9, < 0.001; − 1.57**	− **12.3, < 0.001; − 1.99**
Hole size	Old small stiff vs old large stiff	− 0.8, 0.42; − 0.44	− **0.96, 0.34; − 0.96**
Hole size	Old small compliant vs old large compliant	− **8.3, < 0.001; − 0.95**	− **6.37, < 0.001; − 1.2**
Stiffness	Young small stiff vs young small compliant	0.7, 0.94; − 0.02	0.75, 0.45; − 0.26
Stiffness	Young large stiff vs young large compliant	**5.7, < 0.001; − 0.98**	**7.05, < 0.001; − 1.1**
Stiffness	Old small stiff vs old small compliant	**3.2, 0.001; − 1.24**	**1.1, 0.29; − 1.3**
Stiffness	Old large stiff vs old large compliant	**10.5, < 0.001; − 1.27**	**8.41, < 0.001; − 1.3**

Bolded values indicate statistically significant results with large effects sizes