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ORIGINAL ARTICLE

A Ducted, Biomimetic Nipple Improves Aspects of Infant Feeding Physiology and Performance in an Animal Model

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Abstract
Breastfeeding is widely regarded as the optimal form of feeding infants, as it provides both nutritional and physiological benefits. For example, breastfed infants generate greater intraoral suction and have higher amplitude muscle activities compared to bottle-fed infants, with downstream implications for motor function, development, and health. One mechanism that might explain these physiological differences is the structure of the nipple an infant is feeding on. Breasts in most mammals are ducted soft-tissue structures that require suction to be generated for milk to be released, whereas bottle nipples are hollow and allow milk to be acquired by compression of the nipple. We used a validated animal model (pigs) to test how being raised on a novel ducted nipple impacted feeding physiology and performance compared to infants raised on a standard (cisternic) nipple. At the end of infancy, we fed both groups with both nipple types and used high-speed videofluoroscopy synchronized with intraoral pressure measurements to evaluate feeding function. Nipple type did not have a profound impact on sucking or swallowing rates. However, when feeding on a ducted nipple, infant pigs raised on a ducted nipple generated more suction, consumed milk at a faster rate, swallowed larger boluses of milk, and had decreased likelihood of penetration and aspiration than those raised on a cisternic nipple. These data replicate those found when comparing breast- and bottle-fed infants, suggesting that a ducted, biomimetic nipple may provide bottle-fed infants with the physiologic benefits of breastfeeding.

Keywords Feeding · Bioinspiration · Biomimetic · Dysphagia · Aspiration

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Introduction

Breastfeeding and bottle feeding provide different experiences for infants, especially for their growth and development. In addition to the beneficial effects of being fed breastmilk as compared to formula (reviewed in [1]), there are several biomechanical and physiologic benefits to breastfeeding in both infancy and beyond [2–7]. Infants that are breastfed have been argued to have reduced rates of dysphagia, improved muscle function during suckling as well as during mastication in early childhood, reduced malocclusion, and have been implicated to have different respiratory functioning than bottle fed infants [8–14]. One potential causal factor in the observed differences in performance and development could lie in the biomechanical differences that exist between breastfeeding and bottle feeding. As compared with bottle feeding, during breastfeeding, infants generate greater intraoral suction [12, 15], increase cranial muscle activation [9, 12], and experience greater oxygen saturation due to improved coordination of breathing and feeding [16]. Because of the ethical limitations on understanding the neurophysiology and biomechanics of human infant breast vs. bottle feeding, we do not have a full understanding of the differences in these modalities [17].

However, not all infants can be breastfed for a myriad of clinical reasons. For example, many premature infants face difficulties in establishing breastfeeding and infants with other pathophysiologic conditions, such as cleft palate or lip, Down Syndrome, or other neurologic conditions often must be bottle-fed [18]. These conditions can require a suite of interventions to be utilized to facilitate oral feeding, and the decision making process to do this can be complex, and often rely on the use of bottles in addition to other interventions [19, 20]. Furthermore, even when infants are healthy and able to breastfeed, bottle feeding is common in the United States [21]. Only 25% of infants are exclusively breastfed for 6 months, and 60% of mothers stop breastfeeding earlier than planned [22]. However, bottle feeding is often necessary for mothers who must return to work, have less flexible work hours, or have limited maternity leave. These barriers to breastfeeding are reported by low-income women from minority backgrounds, and socioeconomic and racial disparities in breastfeeding are widely reported [23–27]. Furthermore, when parents try to use both breastfeeding and bottle feeding, many infants and their caregivers have difficulty switching successfully between bottle feeding and breastfeeding, making it difficult to continue breastfeeding once bottle feeding is introduced [28].

Substantive structural differences exist between a human breast and commercially available nipples. Breast tissue (of humans and most mammals, including pigs) has narrow lactiferous ducts embedded in connective tissue [29, 30]. In contrast, although many commercial/conventional bottle nipples are touted as being designed to replicate breastfeeding, they all fundamentally differ from breasts, and are hollow inside, like a cistern. Furthermore, there is substantive variation both across and within bottle manufacturers, further complicating differences between breast and bottle feeding [28, 29]. These differences in nipple structure correspond to differences in the ways that infants extract milk during breastfeeding and bottle feeding. During breastfeeding, infants primarily acquire milk by using the tongue to generate intraoral suction [31–33]. In contrast, during bottle feeding, infants generate less intraoral suction and can acquire milk through expression, which occurs when the infants compress the hollow bottle-nipple to obtain milk [34–37]. Expression of milk is possible during bottle feeding because conventional bottle nipples are hollow and compressible. These differences in mechanism for extracting milk may cause the differences in feeding and developmental outcomes that are observed between breastfed and bottle-fed infants. A possible way to reduce the biomechanical differences and subsequent health disparities between breastfeeding and bottle feeding is to change the structure of bottle nipples to better mimic breasts.

We created ducted (biomimetic) bottle nipples and used a validated animal model for infant feeding, pigs [38], to test how a solid, flexible nipple impacts infant feeding function through ontogeny. Animal models are an essential tool for evaluating feeding function in infants, as they allow for increased control over experimental settings and a longitudinal study design. Furthermore, animal models allow for much greater spatial and temporal resolution data to be acquired than in human infants due to ethical considerations associated with radiation exposure during videofluoroscopic swallow studies (VFSS), and allow for a more nuanced assessment of normal as well as pathophysiologic function [17, 38–42]. We raised two groups of infant pigs, one on each nipple type. At the end of infancy, we conducted VFSS, paired with intraoral pressure measurements, while the infant pigs fed on the nipple type that they were raised on, followed by the opposite nipple type. We hypothesized that feeding on the ducted nipple would elicit responses more similar to breastfeeding than feeding from a conventional bottle nipple. Specifically, we predicted that when infant pigs fed on a ducted nipple, they would generate greater intraoral pressure, consume milk more slowly, swallow smaller boluses, and have a reduced rate of milk penetration and aspiration into the airway.

Methods

Animal Housing and Care

We obtained infant pigs (Yorkshire/Landrace) at 48 h of age (Shoup Investments LTD, Wooster, OH, USA). Infants were housed in the NEOMED Comparative Medicine Unit, and were trained to feed on infant milk replacer (Solustart Pig Milk Replacement, Land o'Lakes, Arden Mills, MN, USA). All care and procedures for infants were approved by NEOMED IACUC Protocol # 19-03-222 [42–44].

Nipple and Experimental Design

Infants were separated into two groups: One feeding on a standard, cisternic nipple ($N=4$), and one feeding on a ducted nipple ($N=4$). The units of analyses were either sucks or swallows, providing sufficient power to determine differences between groups [43–45]. For both nipples, size and shape were standardized based upon measurements taken from several nursing mothers. We 3-D printed molds that were then used to cast nipples using silicone. We chose a silicone material such that the material properties of the ducted nipples approximated the durometer rating of breast tissue which is 00–10 [46, 47]. We achieved consistent results with silicone rubber of 00–20 (Smooth-On Ecoflex 00–20). To ensure that variation in performance between infant groups was not impacted by nipple stiffness, we measured the amount of force required to compress this ducted nipple by 50%. We repeated this for several cisternic nipples made from materials of different durometer ratings, with a 20 A silicone nipple being most similar to the ducted nipple (Smooth-On Dragon Skin 20 A). We also matched flow rate for the ducted and cisternic nipples both experimentally and using Poiseuille's law. The cisternic nipple had a hole diameter of 1.9 mm, as used previously in the pig model [45, 48], and the ducted nipple was constructed using three 1.6 mm diameter ducts, as many species of mammals have multiple openings at the nipple [49–51, Fig. 1, Fig. S1]. Thus, the only difference in design between nipples was whether one was ducted or cisternic.

Data Collection

Pigs were raised on their assigned nipple for approximately 20 days (equivalent to an ~8 month human infant). During this time, the total volume of milk consumed per feed, and the duration of suckling was recorded for every feed and was averaged for each day. Infant mass was recorded daily.

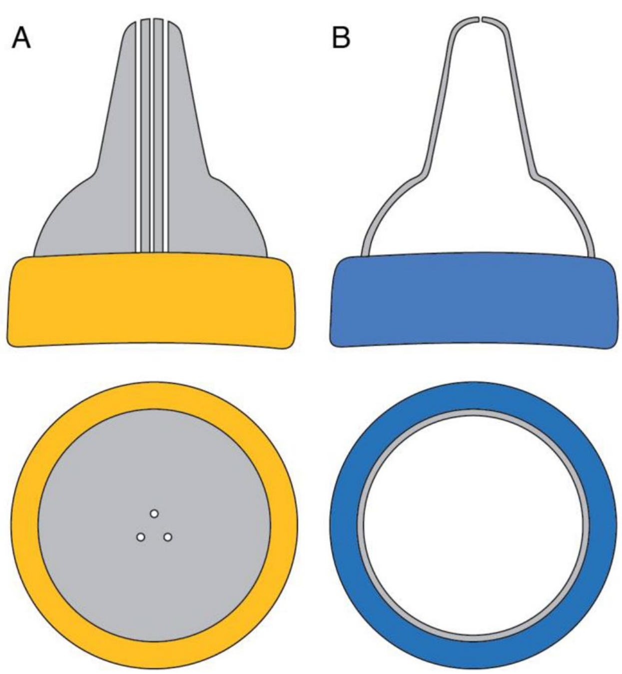

Fig. 1 Lateral view (top) and bottom view (bottom) of the ducted (**A**, gold) and cisternic (**B**, blue) nipples. Grey areas indicate areas where silicone exists, and white indicate areas where milk could fill and flow. Colored areas indicate bottle lid attachments. Note the three central ducts in (**A**) surrounded by silicone

At approximately 20 days of age, we recorded biplanar videofluoroscopy (GE 9400 C-Arm, 71–73 kV, 6.3–7.1 mA) with high-speed cameras (XC1 M, XCitex, Cambridge, MA, USA) at 120 frames per second while pigs fed milk formula with barium (E-Z Paque Barium Sulfate, EZ EM Inc., NY). Pigs were fed first on the nipple they were raised on, and then on the other nipple in order to document feeding with acute exposure to a novel nipple type, typically within the same feeding session. During data collection, pigs were allowed to stand without restraint, with minimal variation in body position across individuals. Bottles were filled to the same volume for each feed and angled so that nipples were always filled with milk. We recorded approximately 20 swallows per pig per condition. X-ray data were synchronized with intraoral pressure generation using a 16 channel Powerlab (16–35, ADInstruments, Colorado Springs, CO, USA) at 10 kHz.

Data Processing

We identified suck timing from X-ray video using standard procedures [43, 52]. We identified a total of 1165 sucks (cisternic pigs on cisternic nipple $N=309$; cisternic pigs on ducted nipple $N=278$; ducted pigs on cisternic nipple $N=307$; ducted pigs on ducted nipple $N=271$). Sucks were identified as beginning on the frame at which the tongue made an anterior seal with the hard palate, and ending the frame before the next suck began [43, 53]. Instantaneous suck rate was calculated as 1 divided by the duration of the suck (providing the frequency of the behavior).

Swallows were identified as beginning on the frame at which the bolus was accumulated in the supraglottic space prior to passing the epiglottis, following standard procedures [43, 44, 54]. In this, we recorded a total of 373 swallows (cisternic pigs on cisternic nipple $N=96$; cisternic pigs on ducted nipple $N=95$; ducted pigs on cisternic nipple $N=88$; ducted pigs on ducted nipple $N=94$). Swallow rate was calculated as 1 divided by the time to the next swallow following standard procedures to calculate the frequency of the behavior [43, 44]. Bolus size was measured by calculating the surface area (in mm^2) of the bolus in the lateral view at the initiation of the swallow using ImageJ [55, 56]. We calculated the volume of milk consumed per second by multiplying bolus size for a given swallow by swallow rate. We determined the frequency of penetration and aspiration using the Infant Mammalian Penetration Aspiration Scale (IMPAS), a scale equivalent to the Penetration Aspiration Scale designed for adults [57, 58].

Intraoral pressure was filtered with a 60 Hz low-pass filter to eliminate baseline electronic noise, downsampled by 83 (to 120 Hz to match framing rate) and exported from Powerlab. Pressure generation data was loaded into a custom MATLAB routine along with data on suck and swallow timing (Version 2021a, Mathworks, Natick, MA). This MATLAB routine calculated the amount of pressure generated per suck and per swallow in mmHg.

Statistical Analyses

All statistical analyses were performed in R (R core team, www.r-project.org, v 4.3.0). We used linear mixed effects models to test for differences in variables of interest, with the nipple an individual was raised on, the nipple an infant was feeding on, and their interaction as fixed effects, and individual infant as a random effect [59]. Variables of interest include: suck rate, swallow rate, pressure generated per suck, bolus volume, milk consumed per second, and sucks per swallow. P values for main effects were obtained using the Anova() function on the model in R. Where interactions between effects were significant, we performed planned contrast analyses as well as Cohen's D [60].

To test for differences in swallow safety, we performed a logistic regression to evaluate differences across all four groups. We combined swallows with no penetration or penetration with clearance as being 'safe', for a total of three levels (safe, penetration without clearance, and aspiration). This follows previous work, gives higher power for detecting differences, and is biologically relevant as swallows that have penetration with clearance are likely functionally not impactful to organismal physiology [56]. Logistic regression analyses calculated odds ratios for moving away from a safe swallow depending on group, and we also calculated p-values using Wald-Chi-Squared Analyses [56, 61].

Results

Ontogenetic Growth

Even though both groups were allowed to feed *ad libitum*, we found that infant pigs who were raised on a ducted nipple were marginally larger than those raised on a cisternic nipple, although differences by the end of infancy (~20 days) were not significant ($F=2.6$, $p=0.13$, cisternic mean = 2.4 ± 0.4 kg, ducted mean = 2.8 ± 0.4 kg, Fig S2A). Similarly, at the end of infancy pigs raised on a ducted nipple tended to consume higher volumes per feed (Fig S2B).

Behavioral Response to Nipple Design

Overall, we found little variation in sucking rate nor swallowing rate depending on what nipple pigs were raised on or feeding on. Pigs raised on the ducted nipple did not differ substantially in suck rate nor swallow rate when feeding on either nipple, and ducted pigs feeding on the ducted nipple did not differ from cisternic pigs feeding on the ducted nipple for suck rate nor swallow rate (Table 1; Fig. 2, Table S1). However, we did find that pigs raised on the cisternic nipple sucked at faster rates when feeding on the cisternic nipple than when feeding on a ducted nipple ($t=5.9$, $p<0.001$, $D=0.67$), and compared to pigs raised on a ducted nipple feeding on a cisternic nipple ($t=8.01$, $p<0.001$, $D=0.75$, Table S1, cisternic pigs feeding on cisternic nipple: 5.99 ± 1.25 Hz, feeding on a ducted nipple: 5.10 ± 1.46 Hz; ducted pigs feeding on a cisternic nipple: 5.00 ± 1.37 Hz, feeding on a ducted nipple: 5.08 ± 1.41 Hz). Cisternic pigs feeding on a cisternic nipple also swallowed at a faster rate than ducted pigs feeding on a cisternic nipple ($t=5.8$, $p<0.$—1, $D=0.8$), although they did not swallow at a statistically significantly faster rate than when feeding on a ducted nipple ($t=3.7$, $p<0.001$, $D=0.45$, Fig. 2, Table S1, cisternic pigs feeding on cisternic nipple: 1.88 ± 0.78 Hz, feeding on a ducted nipple: 1.59 ± 0.46 Hz; ducted pigs feeding on a cisternic nipple: 1.39 ± 0.31 Hz, feeding on a ducted nipple: 1.49 ± 0.46 Hz).

Physiological Response to Nipple Design

In contrast to the limited response in behavioral rates, we found substantive differences in physiology depending on both the nipple an infant pig was raised on and the nipple it fed on. This was especially prominent for pigs raised on a cisternic nipple feeding on a ducted nipple. These pigs generated less suction per suck ($t = -8.8$ $p<0.001$, $D=0.85$),

Table 1 Planned contrast and effect size (Cohen's D) results from statistical analyses (t-statistic, p-value; Cohen's D)

	Nipple effect		Group effect	
	Raised on cist	Raised on duct	Feed on cist	Feed on duct
Suck Rate (Hz)	*-5.8, < 0.001; -0.67*	0.62, 0.54; 0.05	*8.01, < 0.001; 0.75*	0.16, 0.88; 0.02
Swallow Rate (Hz)	-3.7, < 0.001; -0.45	1.2, 0.24; 0.25	**5.9, <0.001; 0.8**	1.2, 0.23; 0.2
Pressure / suck (mmHg)	-5.2, < 0.001; 0.48	-2.3, 0.02; 0.8	-1.7, 0.08; -0.14	**-8.8, < 0.001; -0.85**
Mm2/sec	*-4.1, < 0.001; -0.52*	*3.3, 0.001, 0.65*	1.5, 0.14; 0.19	**-6.0, < 0.001; -1.1**
Bolus size (mm^2)	-2.6, 0.01; -0.33	*-3.9, < 0.001; 0.66*	-2.3, 0.02; -0.32	**-8.9; < 0.001; -1.4**

Italicized values indicate statistically significant differences with medium effects size, bolded values indicate statistically significant differences with large effects sizes

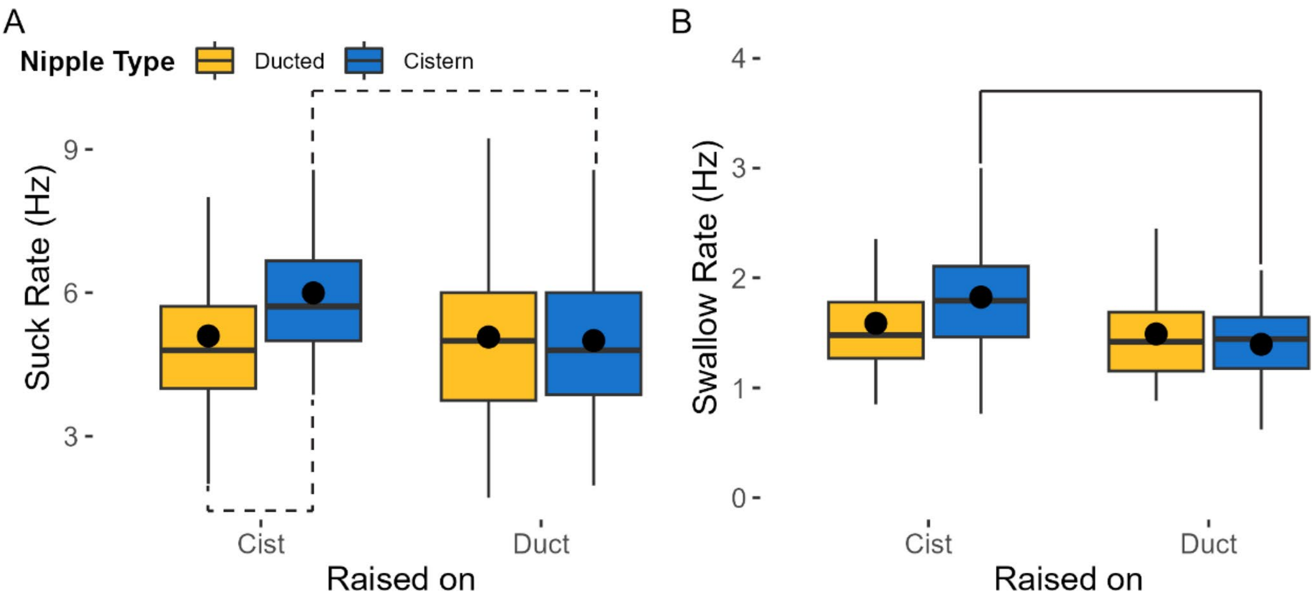

Fig. 2 Rates of sucking (**A**) and swallowing (**B**) in infants raised on a cisternic (left) vs. ducted (right) nipple when feeding on a cisternic (blue) or ducted (gold) nipple (typically within the same feeding session). Dashed lines between groups indicate statistically significant differences with a medium effect size, and solid lines between groups indicate a statistically significant difference with a large effect size

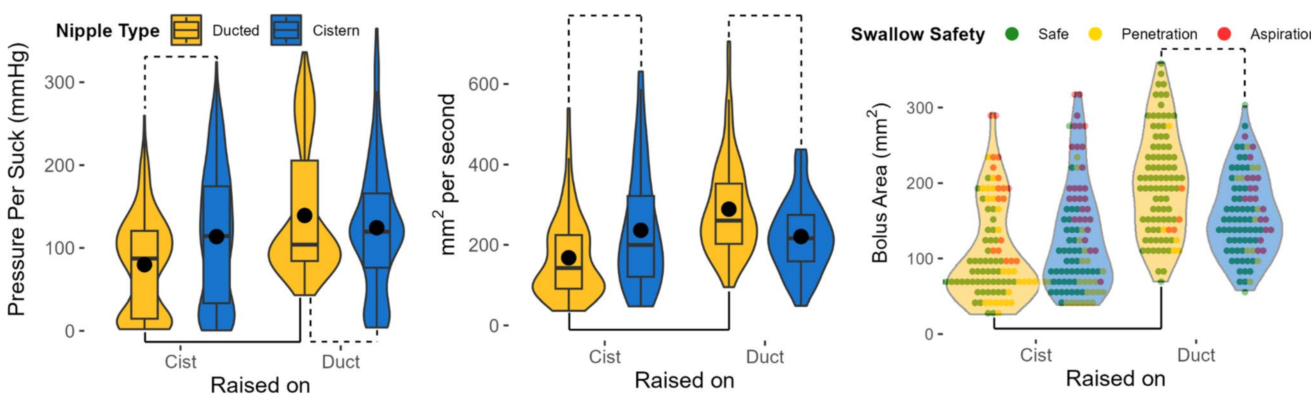

Fig. 3 Pressure generation per suck (top), feeding rate (middle), and bolus area and swallow safety (bottom) of infants raised on a cisternic (left) vs. ducted (right) nipple when feeding on a cisternic (blue) or ducted (gold) nipple (typically within the same feeding session). Dashed lines between groups indicate statistically significant differences with a medium effect size, and solid lines between groups indicate a statistically significant difference with a large effect size. Dots in the bottom panel indicate individual swallows, colored by if they were safe (green), had penetration (yellow) or aspiration (red)

consumed milk more slowly (t = -6.0, $p<0.001$, D = 1.1) and had smaller boluses (t = -8.9, $p<0.001$, D = 1.4) than pigs raised on a ducted nipple feeding on a ducted nipple (Fig. 3; Table 1, Table S1). Pigs raised on a cisternic nipple also acquired less milk per suck and consumed milk more slowly when feeding on a ducted nipple compared to feeding on a cisternic nipple, although with only a medium effect size (Fig. 3; Table 1, Table S1). Infant pigs raised on a ducted nipple feeding on a cisternic nipple had lower pressure generation, slower milk consumption, and smaller boluses than when feeding on a ducted nipple (Table 1, Table S1).

Impact of Nipple Design on Swallow Safety

Using pigs raised on a cisternic nipple feeding on a cisternic nipple as the baseline, we found that the probability of penetration and aspiration was impacted by what nipple an infant was feeding on, and to a lesser extent, what nipple an infant was raised on. Pigs raised on a ducted nipple, and feeding on a ducted nipple were associated with a decrease in the log odds of penetration by 2.18 ($p<0.001$, with the odds of penetration being 0.11) and a decrease in the log odds of aspiration by 2.6 ($p<0.001$, Table 2, with the odds of aspiration being 0.07). Pigs raised on a ducted nipple but feeding on a cisternic nipple were associated with a

Table 2 Results from logistic regression analyses, relative to an infant with a safe swallow raised on a cisternic nipple feeding on a cisternic nipple (log odds ± se, p)

	Raised Cist, Feed duct	Raised Duct, feed Cist	Raised Duct, feed duct
Penetration	0.01 ± 0.35, 0.97	**-1.01 ± 0.42, 0.01**	**-2.18 ± 0.52, < 0.001**
Aspiration	*-0.68 ± 0.37, 0.06*	*-0.69 ± 0.36, 0.05*	**-2.6 ± 0.56, < 0.001**

Bolded values indicate a log odds of increased swallow safety with statistical significance; italicized values indicate a log odds of increased swallow safety with marginal statistical significance

decrease in the log odds of penetration by 1.01 ($p = 0.01$, with the odds of penetration being 0.36) and a decrease in the log odds of aspiration by 0.69 ($p = 0.05$, with the odds of aspiration being 0.50). For pigs feeding on a cisternic nipple, we observed no change in the log odds of penetration when feeding on a duct, but a decrease in the log odds of aspiration by 0.68, with marginal statistical significance ($p = 0.06$, with the odds of aspiration being 0.50).

Discussion

Nipple properties can have a profound impact on feeding function in infants, and the novel, ducted structure developed here can improve feeding physiology through a variety of mechanisms. These data demonstrate that although nipple design does not appear to have a strong impact on the rate of suckling or swallowing, the physiology controlling those behaviors varied, as infant pigs exhibited increased pressure generation, increased rate of milk consumption, and decreased aspiration when feeding on a ducted nipple, especially if they were raised on a ducted nipple.

Physiologic Implications

Breastfeeding and bottle feeding on commercial nipples fundamentally differ on a variety of physiologic levels. For example, during bottle feeding, infants can acquire milk via a combination of both expression (compressing the nipple and causing milk to flow out) and suction (creating a pressure differential between the nipple and oral cavity to draw milk into the mouth). However, breastfeeding is almost entirely suction-driven [31, 32, 62]. These differences arise from differences in nipple structure, as a ducted nipple has less milk to be expressed when compressed. Our observation that intraoral suction generation increases during feeding on a ducted nipple implies that this design can better replicate breastfeeding, as infants generate more suction during breastfeeding than during bottle feeding when using a conventional cisternic nipple [15]. In fact, several studies have noted that bottle feeding is more similar to drinking from a cup than it is to breastfeeding, and that the neuromotor system functions fundamentally differently during the two behaviors [9, 12]. Several experiments have demonstrated that nipples with suction-only milk release can improve feeding dynamics in infants with feeding difficulties such as those born prematurely [63, 64], however they rely on complex designs that are still fundamentally constructed as cisternic nipples. Our nipple design results in a similar physiologic process (the need to generate suction to acquire milk) but is simpler and mimics the same features of breast tissue (i.e. narrow ducts embedded in a flexible material) that cause milk to be acquired primarily using suction instead of expression.

In addition to differences in suction generation between commercially available bottles and breastfeeding, our data also have implications for understanding how the sensorimotor system powering infant feeding develops [42–44, 65]. Infant pigs raised on a ducted nipple exhibited minimal reductions in feeding performance when exposed to a cisternic nipple at the end of data collection (approximately equivalent to an 8 month old human infant). In contrast, those raised on a cisternic nipple performed much worse when exposed to a ducted nipple at the end of the experiment. This suggests that the structural differences between nipples results in variation in neuromotor output during feeding, and that the increased reliance on compressing a nipple to acquire milk when feeding on a cisternic nipple may be a mechanistic factor for why infants struggle to transition between breast and bottle feeding [66, 67].

In contrast, the reliance on suction to acquire milk in pigs raised on a ducted nipple has little impact on performance when transitioning to a cisternic nipple, as suction can still result in milk acquisition in this feeding modality. These possibilities mirror differences between human breast- and bottle feeding, as the mechanics of milk extraction during breast- and bottle feeding fundamentally differ (i.e. suction vs. expression) [67], as do several kinematic variables associated with tongue and jaw movements that are used to acquire milk (i.e. decreased jaw movements during breastfeeding) [68].

Clinical Implications

Our data in an animal model also has bearings for clinical practice. Infants, and their caretakers, often struggle to transition between breast- and bottle feeding. The challenges associated with transitioning between feeding modalities can result in hospitalization [66], and the early introduction of bottles is thought to result in less effective suckling, breast refusal, and poor infant health outcomes [69, 70]. The use of a ducted, rather than cisternic nipple may ameliorate these challenges, and make the transition from breast and bottle feeding smoother for caregivers. This is especially critical considering the rates of breastfeeding across racial and socioeconomic levels and the use of a ducted nipple may provide access to breastfeeding and switching between bottle and breast for individuals who otherwise would not be able to breastfeed [23–27].

These data also have implications beyond the ability to transition between bottle and breastfeeding for infants. For example, breastfed infants have been demonstrated to show increased self-regulatory abilities than bottle-fed infants [71], and this is thought to be related to childhood obesity, a prevalent problem in the United States [72, 73]. It is possible that the use of a biomimetic nipple may improve self-regulatory ability, especially as it relates to how fluid is extracted, as bottle-fed infants typically show changes in feeding function within a session [74, 75].

Our data also demonstrate that being raised on a ducted nipple, and being fed on a ducted nipple, has implications for the frequency of penetration and/or aspiration during feeding. We found that being raised on a ducted nipple, and feeding on a ducted nipple, decreased the likelihood of aspirating. Aspiration is typically related to the volume of the bolus being swallowed in infants [56, 61], and in general, this was true in our data: infant pigs feeding on a cisternic nipple had higher likelihood of aspirating on a larger bolus than a smaller bolus, and those raised on a cisternic nipple exhibited a similar pattern when feeding on a ducted nipple. However, infants raised on a ducted nipple feeding on a ducted nipple had the largest boluses of any group of infants, yet also aspirated the least. This may relate to differences in tongue position at the initiation of the swallow that leads to a decreased likelihood of aspirating, or could also be related to potentially improved swallow-breathe coordination in this group. This further supports the possibility that a ducted nipple replicates breastfeeding better, as breastfed infants typically have higher blood oxygen saturation than bottle-fed infants, which is thought to arise from decreased ventilatory disruption during breastfeeding [16, 76–81]. Regardless, these data demonstrate that the use of a biomimetic nipple can reduce the likelihood of aspirating, which can lead to a variety of health complications such as aspiration pneumonia, especially in infants experiencing other feeding challenges [82].

Limitations

While these data demonstrate the utility of a ducted nipple for improving infant feeding function, the population we assessed were healthy term infants with no signs of feeding difficulties. How a biomimetic nipple impacts feeding outcomes in infants who have challenges with feeding, such as those born prematurely remains unknown, and in some instances the requirement to generate suction to acquire milk may not improve feeding outcomes, as many populations struggle with the ability to generate suction [41, 83–85]. Additionally, several other factors can vary during infant feeding, such as milk temperature, milk properties (i.e. viscosity), and nipple hole size [45, 48, 86–91], and how a ducted nipple interacts with variation in these variables remains unexplored. Breastfeeding also cannot be fully replicated by bottle feeding, as several other factors, including nutrient composition, antimicrobial functioning, variation in milk flow due to let down, and hormonal signaling cannot be achieved through the use of a biomimetic nipple [65, 92, 93]. Furthermore, while pigs and humans both have a ducted, lactiferous mammary gland, the animal model here may not translate directly to human infants. However, infant pigs are a validated model for infant feeding function [38], and the results presented here have potential to be translated to human infant work. Finally, breastfeeding may be associated with improved speech-language outcomes in children [2], as well as increased likelihood of nasal breathing development [94] but we are unable to assess the potential utility of a biomimetic nipple on speech-language acquisition and skills or breathing development using an animal model. Future work in humans could explore these lines of inquiry.

Conclusions

These data in an animal model demonstrate the utility of a ducted, biomimetic bottle nipple for infant feeding. Infants fed on a ducted nipple exhibited several correlates with breastfeeding, including increased pressure generation when feeding [9, 12, 15]. Being raised on a ducted nipple also resulted in decreased rates of aspiration, especially when feeding on a ducted nipple, which is critical, especially in the context of infants with feeding difficulties who are at risk for health impacts associated with aspiration such as aspiration pneumonia [82]. The use of a ducted nipple may result in an increased ability to switch between bottle and breastfeeding for caretakers who otherwise might only be able to bottle feed. This in turn, would provide bottle-fed infants with the physiologic benefits of breastfeeding.

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Data Availability All data used in statistical analyses are available at https://doi.org/10.6084/m9.figshare.27325524.

Declarations

Ethical Approval All animal use and procedures were approved by NEOMED IACUC #19-03-222.

Competing Interests The authors declare no competing interests.

References

1. Brahm P, Valdés V. The benefits of breastfeeding and associated risks of replacement with baby formulas. Rev Chil Pediatr. 2017;88:7–14.
2. Barbosa C, Vasquez S, Parada MA, Gonzalez JCV, Jackson C, Yanez ND, et al. The relationship of bottle feeding and other sucking behaviors with speech disorder in Patagonian preschoolers. BMC Pediatr. 2009;9:66.
3. Mahurin Smith J. Breastfeeding and language outcomes: a review of the literature. J Commun Disord. 2015;57:29–40.
4. Moges FY, Mengistu Z, Tilahun SW. Determinants of speech and language delay among children aged 12 months to 12 years at Yekatit 12 Hospital, Addis Ababa, Ethiopia: a case–control study. BMC Pediatr. 2024;24:393.
5. Dee DL, Li R, Lee L-C, Grummer-Strawn LM. Associations between Breastfeeding practices and Young Children's Language and Motor Skill Development. Pediatrics. 2007;119:S92–8.
6. Mahurin-Smith J, Ambrose NG. Breastfeeding may protect against persistent stuttering. J Commun Disord. 2013;46:351–60.
7. Novayelinda N, Rahmadhani R, Hasanah O. Does exclusive breastfeeding correlate with infant's early language milestone? Enfermería Clínica. 2019;29:49–51.
8. Pires SC, Giugliani ERJ, Caramez da Silva F. Influence of the duration of breastfeeding on quality of muscle function during mastication in preschoolers: a cohort study. BMC Public Health. 2012;12:934.
9. Inoue N, Sakashita R, Kamegai T. Reduction of masseter muscle activity in bottle-fed babies. Early Hum Dev. 1995;42:185–93.
10. Chen X, Xia B, Ge L. Effects of breast-feeding duration, bottle-feeding duration and non-nutritive sucking habits on the occlusal characteristics of primary dentition. BMC Pediatr. 2015;15:46.
11. Thomaz EBAF, Alves CMC, Gomes e Silva LF, Ribeiro de Almeida CCC, Soares de Britto e Alves MTS, Hilgert JB et al. Breastfeeding Versus Bottle Feeding on Malocclusion in Children: A Meta-Analysis Study. J Hum Lact. 2018;34:768–88.
12. França EC, Sousa CB, Aragão LC, Costa LR. Electromyographic analysis of masseter muscle in newborns during suction in breast, bottle or cup feeding. BMC Pregnancy Childbirth. 2014;14:154.
13. Park EH, Kim J-G, Yang Y-M, Jeon J-G, Yoo J-I, Kim J-K, et al. Association between breastfeeding and childhood breathing patterns: a systematic review and Meta-analysis. Breastfeed Med. 2018;13:240–7.
14. Peres KG, Cascaes AM, Nascimento GG, Victora CG. Effect of breastfeeding on malocclusions: a systematic review and meta-analysis. Acta Paediatr. 2015;104:54–61.
15. 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.
16. Goldfield EC, Richardson MJ, Lee KG, Margetts S. Coordination of sucking, swallowing, and Breathing and Oxygen Saturation during early infant breast-feeding and bottle-feeding. Pediatr Res. 2006;60:450–5.
17. 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.
18. Astuti DD, Rustina Y, Wanda D. Oral feeding skills in premature infants: a concept analysis. Belitung Nurs J. 2022;8:280–6.
19. Harding C, Cockerill H. Managing eating and drinking difficulties (dysphagia) with children who have learning disabilities: what is effective? Clin Child Psychol Psychiatry. 2015;20:395–405.
20. Greene Z, O'Donnell CP, Walshe M. Oral stimulation for promoting oral feeding in preterm infants. Cochrane Database of Systematic Reviews [Internet]. 2023. https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD009720.pub3/full
21. Diaz LE, Yee LM, Feinglass J. Rates of breastfeeding initiation and duration in the United States: data insights from the 2016–2019 pregnancy risk assessment monitoring system. Front Public Health [Internet]. 2023. https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2023.1256432/full
22. CDC. About breastfeeding [Internet]. Breastfeeding. 2024. https://www.cdc.gov/breastfeeding/php/about/index.html
23. Jones KM, Power ML, Queenan JT, Schulkin J. Racial and ethnic disparities in Breastfeeding. Breastfeed Med. 2015;10:186–96.
24. Abbate AM, Saucedo AM, Pike J, Ghartey J, Nutt S, Raghuraman N et al. Impact of household income and Special Supplemental Nutritional Program for Women, Infants, and Children on feeding decisions for infants in the United States. American Journal of Obstetrics and Gynecology. 2023;229:551.e1-551.e6.
25. McKinney CO, Hahn-Holbrook J, Chase-Lansdale PL, Ramey SL, Krohn J, Reed-Vance M, et al. Racial and ethnic differences in Breastfeeding. Pediatrics. 2016;138:e20152388.
26. Merewood A, Bugg K, Burnham L, Krane K, Nickel N, Broom S, et al. Addressing racial inequities in Breastfeeding in the Southern United States. Pediatrics. 2019;143:e20181897.
27. Louis-Jacques A, Deubel TF, Taylor M, Stuebe AM. Racial and ethnic disparities in U.S. breastfeeding and implications for maternal and child health outcomes. Semin Perinatol. 2017;41:299–307.
28. Zimmerman E, Thompson K. Clarifying nipple confusion. J Perinatol. 2015;35:895–9.
29. Jiang L, Hassanipour F. In Vitro Flow visualization in a Lactating Human breast model. Ann Biomed Eng. 2021;49:3563–73.
30. Negin Mortazavi S, Geddes D, Hassanipour F. Lactation in the human breast from a Fluid Dynamics Point of View. J Biomech Eng. 2017;139:011009.
31. 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 USA. 2014;111:5230–5.
32. Geddes DT, Kent JC, Mitoulas LR, Hartmann PE. Tongue movement and intra-oral vacuum in breastfeeding infants. Early Hum Dev. 2008;84:471–7.
33. Sakalidis VS, Geddes DT. Suck-swallow-breathe Dynamics in Breastfed infants. J Hum Lact. 2016;32:201–11.
34. Nowak AJ, Smith WL, Erenberg A. Imaging evaluation of breast-feeding and bottle-feeding systems. J Pediatr. 1995;126:S130–4.
35. Nowak AJ. Imaging evaluation of Artificial nipples during Bottle Feeding. Arch Pediatr Adolesc Med. 1994;148:40.
36. Lagarde MLJ, van Doorn JLM, Weijers G, Erasmus CE, van Alfen N, van den Engel-Hoek L. Tongue movements and teat compression during bottle feeding: a pilot study of a quantitative ultrasound approach. Early Hum Dev. 2021;159:105399.

37. Adjerid K, Johnson ML, Edmonds CE, Steer KS, 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.
38. German RZ, Crompton AW, Gould FDH, Thexton AJ. Animal models for Dysphagia studies: what have we Learnt so far. Dysphagia. 2017;32:73–7.
39. Belo LR, Gomes NAC, Coriolano M, de das GW S, de Souza ES, Moura DAA, Asano AG, et al. The Relationship between Limit of Dysphagia and average volume per swallow in patients with Parkinson's Disease. Dysphagia. 2014;29:419–24.
40. Cullins MJ, Connor NP. Differential impact of unilateral stroke on the bihemispheric motor cortex representation of the jaw and tongue muscles in young and aged rats. Front Neurol [Internet]. 2024. https://www.frontiersin.org/journals/neurology/articles/10.3389/fneur.2024.1332916/full
41. 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.
42. 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.
43. 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.
44. 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.
45. Johnson ML, Steer KE, Edmonds CE, Adjerid K, German RZ, Mayerl CJ. Nipple properties affect sensorimotor integration during bottle feeding in an infant pig model. J Experimental Zool Part A: Ecol Integr Physiol. 2023;339:767–76.
46. Briot N, Chagnon G, Connesson N, Payan Y. In vivo measurement of breast tissues stiffness using a light aspiration device. Clin Biomech Elsevier Ltd. 2022;99:105743.
47. Boyd NF, Li Q, Melnichouk O, Huszti E, Martin LJ, Gunasekara A, et al. Evidence that breast tissue stiffness is Associated with risk of breast Cancer. PLoS ONE. 2014;9:e100937.
48. Steer KE, Johnson ML, Edmonds CE, Adjerid K, Bond LE, German RZ et al. The impact of varying nipple properties on infant feeding physiology and performance throughout ontogeny in a validated animal model. Dysphagia. 2023. https://doi.org/10.1007/s00455-023-10630-w
49. Oftedal OT, Dhouailly D. Evo-devo of the mammary gland. J Mammary Gland Biol Neoplasia. 2013;18:105–20.
50. Oftedal OT. The evolution of lactation in mammalian species. In: Ogra PL, Walker WA, Lönnerdal B,Milk, Mucosal Immunity and the Microbiome: Impact on the Neonate: 94th Nestlé Nutrition Institute workshop, Lausanne, September 2019 [Internet], Karger S. AG; 2020. https://www.karger.com/Book/Home/278988
51. Ventrella D, Ashkenazi N, Elmi A, Allegaert K, Aniballi C, DeLise A, et al. Animal models for in vivo Lactation studies: anatomy, physiology and milk compositions in the most used non-clinical species: a contribution from the ConcePTION Project. Animals. 2021;11:714.
52. Mayerl CJ, Adjerid KA, Edmonds CE, Gould FDH, Johnson ML, Steer KE, et al. Regional Variation in contractile patterns and muscle activity in Infant Pig Feeding. Integr Organismal Biology. 2022;4:obac046.
53. Steer KE, Johnson ML, Adjerid K, Bond LE, Howe SP, Khalif A, et al. The function of the Mammal extrinsic Tongue musculature in the transition from Suckling to drinking. Integr Comp Biol. 2023;63:641–52.
54. Mayerl CJ, Steer KE, Chava AM, Bond LE, Edmonds CE, Gould FDH, et al. Anatomical and physiological variation of the hyoid musculature during swallowing in infant pigs. J Exp Biol. 2021;224:jeb243075.
55. Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. Nat Methods. 2012;9:671–5.
56. 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.
57. Holman SD, Campbell-Malone R, Ding P, Gierbolini-Norat EM, Griffioen AM, Inokuchi H, et al. Development, reliability, and validation of an infant mammalian penetration–aspiration scale. Dysphagia. 2013;28:178–87.
58. Rosenbek JC, Robbins JA, Roecker EB, Coyle JL, Wood JL. A penetration-aspiration scale. Dysphagia. 1996;11:93–8.
59. Bates D, Mächler M, Bolker B, Walker S. Fitting Linear Mixed-Effects Models Using lme4. J Stat Soft [Internet]. 2015. http://www.jstatsoft.org/v67/i01/
60. Cohen J. A power primer. Psychol Bull. 1992;112:155–9.
61. 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.
62. Cannon AM, Sakalidis VS, Lai CT, Perrella SL, Geddes DT. Vacuum characteristics of the sucking cycle and relationships with milk removal from the breast in term infants. Early Hum Dev. 2016;96:1–6.
63. Geddes D, Kok C, Nancarrow K, Hepworth A, Simmer K. Preterm Infant Feeding: a mechanistic comparison between a Vacuum Triggered Novel Teat and Breastfeeding. Nutrients. 2018;10:376.
64. Perrella SL, Nancarrow K, Trevenen M, Murray K, Geddes DT, Simmer KN. Ho JJ editor 2019 Effect of vacuum–release teat versus standard teat use on feeding milestones and breastfeeding outcomes in very preterm infants: a randomized controlled trial. PLoS ONE 14 e0214091.
65. Mayerl CJ, German RZ. Evolution, diversification and function of the maternal–infant dyad in mammalian feeding. Philosophical Trans Royal Soc B: Biol Sci. 2023;378:20220554.
66. Praborini A, Purnamasari H, Munandar A, Wulandari RA. Hospitalization for Nipple confusion: a method to restore healthy breastfeeding. Clin Lactation. 2016;7:69–76.
67. Moral A, Bolibar I, Seguranyes G, Ustrell JM, Sebastiá G, Martínez-Barba C, et al. Mechanics of sucking: comparison between bottle feeding and breastfeeding. BMC Pediatr. 2010;10:6.
68. Aizawa M, Mizuno K, Tamura M. Neonatal sucking behavior: comparison of perioral movement during breast-feeding and bottle feeding. Pediatr Int. 2010;52:104–8.
69. Newman J, Wilmott B. Breast rejection: a little-appreciated cause of Lactation failure. Can Fam Physician. 1990;36:449–53.
70. Neifert M, Lawrence R, Seacat J. Nipple confusion: toward a formal definition. J Pediatr. 1995;126:S125–9.
71. Li R, Fein SB, Grummer-Strawn LM. Do infants Fed from bottles lack self-regulation of milk intake compared with directly breastfed infants? Pediatrics. 2010;125:e1386–93.
72. Thompson AL. Developmental origins of obesity: early feeding environments, infant growth, and the intestinal microbiome. Am J Hum Biology. 2012;24:350–60.
73. Dewey KG. Is Breastfeeding Protective against Child Obesity? J Hum Lact. 2003;19:9–18.
74. Pollitt E, Consolazio B, Goodkin F. Changes in nutritive sucking during a feed in two-day-and thirty-day-old infants. Early Hum Dev. 1981;5:201–10.
75. McGrattan KE, McGhee HC, McKelvey KL, Clemmens CS, Hill EG, DeToma A, et al. Capturing infant swallow impairment on videofluoroscopy: timing matters. Pediatr Radiol. 2020;50:199–206.

76. Meier P. Bottle- and breast-feeding: effects on transcutaneous oxygen pressure and temperature in preterm infants. Nurs Res. 1988;37:36–41.
77. Meier P, Anderson GC. Responses of small Preterm infants to bottle- and breast-feeding. MCN: Am J Maternal/Child Nurs. 1987;12:97.
78. Meier P, Pugh EJ. Breast-feeding behavior of small Preterm infants. MCN: Am J Maternal/Child Nurs. 1985;10:396.
79. Chen C-H, Wang T-M, Chang H-M, Chi C-S. The effect of breast- and bottle-feeding on Oxygen Saturation and Body temperature in Preterm infants. J Hum Lact. 2000;16:21–7.
80. Miller MJ, Difiore JM. A comparison of swallowing during apnea and periodic breathing in premature infants. Pediatr Res. 1995;37:796–9.
81. Sakalidis VS, McClellan HL, Hepworth AR, Kent JC, Hartmann PE, Geddes DT, et al. Oxygen Saturation and suck-swallow-breathe coordination of term infants during breastfeeding and feeding from a teat releasing milk only with Vacuum. Int J Pediatr. 2012;2012:e130769.
82. Jadcherla S. Dysphagia in the high-risk infant: potential factors and mechanisms1–3. Am J Clin Nutr. 2016;103:S622–8.
83. 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.
84. Amaizu N, Shulman R, Schanler R, Lau C. Maturation of oral feeding skills in preterm infants: maturation of oral feeding skills. Acta Paediatr. 2007;97:61–7.
85. Lau C, Alagugurusamy R, Schanler R, Smith E, Shulman R. Characterization of the developmental stages of sucking in preterm infants during bottle feeding. Acta Paediatr. 2000;89:846–52.
86. Almeida MB, de Almeida M, de Moreira JAG, Novak MEL. Adequacy of human milk viscosity to respond to infants with dysphagia: experimental study. J Appl Oral Sci. 2011;19:554–9.
87. Sunarić S, Jovanović T, Spasić A, Denić M, Kocić G. Comparative analysis of the physicochemical parameters of breast milk, starter infant formulas and commercial cow milks in Serbia. Acta Facultatis Medicae Naissensis. 2016;33:101–8.
88. Howe S, Steer K, Johnson M, Adjerid K, Edmonds C, German R et al. Exploring the interaction of viscosity and nipple design on feeding performance in an infant pig model. J. Texture Stud. 2023. https://doi.org/10.1111/jtxs.12797.
89. 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;52:603–11.
90. Stuart S, Motz JM. Viscosity in infant Dysphagia Management: comparison of viscosity of thickened liquids used in Assessment and Thickened liquids used in treatment. Dysphagia. 2009;24:412–22.
91. Bolivar-Prados M, Hayakawa Y, Tomsen N, Arreola V, Nascimento W, Riera S, et al. Shear-Viscosity-Dependent Effect of a gum-based Thickening product on the safety of swallowing in older patients with severe Oropharyngeal Dysphagia. Nutrients. 2023;15:3279.
92. Hinde K, German JB. Food in an evolutionary context: insights from mother's milk. J Sci Food Agric. 2012;92:2219–23.
93. Martin P, Cebo C, Miranda G. Milk proteins: introduction and historical aspects. In: McSweeney PLH, Fox PF, editors. Advanced dairy chemistry: Volume 1A: proteins: basic aspects, 4th edn. Boston, MA: Springer US; 2013. https://link.springer.com/10.1007/978-1-4614-4714-6
94. Limeira AB, Aguiar CM, de Lima Bezerra NS, Câmara AC. Association between breastfeeding and the development of breathing patterns in children. Eur J Pediatr. 2013;172:519–24.