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The physiologic coupling of sucking and swallowing coordination provides a unique process for neonatal survival

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Abstract

Aim—Although the coordination of sucking and swallowing is critical for successful oral intake in neonates, the mechanisms that facilitate this coordination are not well understood. This investigation sought to clarify the mechanisms that facilitate this coordination, by comparing sucks that were coordinated with swallows and sucks that were completed in isolation.

Methods—Ten neonates with a median gestational age of 28.2 weeks, ranging from 27.0-35.0 weeks, were recruited from the neonatal nurseries at Nationwide Children's Hospital, Columbus, Ohio, USA. They were evaluated while bottle-feeding at term gestation for differences in characteristics between sucks that were coupled and not coupled with swallows. Suction was evaluated using an intraoral pressure transducer and swallows were identified using a micro-manometry pharyngeal catheter. Linear mixed models were applied to distinguish sucking characteristics.

Results—Suction exhibited an anti-phase relationship with the generation and release of positive pharyngeal pressure during the swallow. Coupled sucks had lower suction generation and release rates ($p<0.0001$), lower suction amplitude ($p=0.004$), longer suction duration ($p<0.0001$) and higher milk ejection pressure ($p<0.0001$).

Conclusion—The coordination of unique sucking and swallowing movement patterns may be achieved by the infant adapting to the sucking kinematics around the lingual patterns that facilitate the pharyngeal swallow.

Keywords

Feeding; Infant; Sucking; Suck-Swallow Ratio; Swallowing

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INTRODUCTION

Successful feeding requires refined integration between the processes of sucking and swallowing (1-3). Although these processes manifest unique kinematic profiles that fulfil distinct functional needs, the successful execution of both relies on the peristaltic movement of one shared organ: the tongue (4,5). Nutritive sucking is characterised by two primary movement patterns. The first movement pattern, nipple expression, occurs as the lingual dorsum elevates in an anterior-posterior peristaltic wave of contraction (4-6). Although this contraction facilitates milk ejection by generating positive intra-nipple pressure (5-7), it is the negative intraoral pressure generated as this wave draws to completion that yields maximum milk flow (6,8). This negative intraoral pressure, termed intraoral suction, is generated as the lingual-mandibular complex descends along an inferior-anterior trajectory in preparation for the next sucking cycle (9,10). Given its effect on bolus extraction, it is no surprise that the integrity of an infant's intraoral suction pressure is associated with their ability to meet nutritional needs (8,11). Infants who are unable to meet nutritional needs, such as those with neurologic immaturity, have been found to generate weaker and less rhythmic suction pressures than their full orally fed counterparts (7,8,11).

Despite its integral role in bolus formation, it is well appreciated that oral feeding demands more than just the generation of high intraoral suction. In order for milk ingestion to occur, the extracted bolus must then be transported from the oral cavity into the pharynx (5,12). The healthy term neonate is able to execute this transition by extending the anterior-posterior wave of lingual contraction from the lingual dorsum, where it was used during expression, to the lingual base to transport the bolus from the oral cavity into the pharynx for the pharyngeal swallow (4,5). While the continuity in lingual patterns between expression and swallowing appears to facilitate a fluent suck-swallow transition, the coordination between the unique lingual patterns of swallowing and suction appears to require higher neuromotor control (1,3). Deficits in the coupling of these two processes have been shown to have detrimental effects on the infant's ability to obtain full oral feeds (1,3).

The purpose of this investigation was to elucidate the kinematic mechanisms that may facilitate the coordination between suction and swallowing through the exploration of two aims. Our first aim was to identify the temporal relationships between the generation of negative intraoral suction and the generation of positive pharyngeal pressure during the pharyngeal swallow. Our second aim was to test the difference in pneumatic attributes between sucks that were coupled with pharyngeal swallows and sucks that occurred in isolation.

SUBJECTS AND METHODS

Subjects and study design

Ten neonates exhibiting mature sucking skills during bottle feeding, as determined by an oral motor kinematic score of at least four (8), were recruited from the neonatal nurseries at Nationwide Children's Hospital, Columbus, Ohio, USA. The research protocol was approved by the Institutional Review board at Nationwide Children's Hospital. Signed informed parental consent was obtained in compliance with the Health Insurance Portability and Accountability Act. Studies were performed in the Nationwide Children's Hospital neonatal intensive care unit with close monitoring by a registered nurse and physician.

Data acquisition and analysis

Intraoral suction was measured using a nipple measurement system previously described by Lau et al (7). A hospital grade standard flow bottle nipple (Abbott Nutrition, Illinois, USA) was adapted to include a polyethylene channel that coursed along the interior nipple chamber and exited flush against the exterior nipple tip. A Mikro-Tip pressure transducer (Millar Inc, Texas, USA) was threaded through this channel and secured at the nipple's distal tip without protrusion into the infant's oral cavity (Figure 1). Pharyngeal swallows were recorded using a Dentsleeve micro-manometry catheter system that was positioned in the pharynx (Mui Scientific, Ontario, Canada). All experimental sessions were sampled at 100 Hz, with sucking and swallowing signals synchronised using the Stationary Solar Gastro Acquisition System version 8.21 (Medical Measurement Systems, New Hampshire, USA).

All infants were provided with a brief catheter acclimatisation period prior to initiation of their feeding assessment. Feeds were conducted at the infant's scheduled feeding time using their prescribed milk type that had been warmed to room temperature. Infants were positioned at a 45° angle and fed with the adapted standard flow nipple that was attached to a Similac Volu-Feed disposable hospital bottle (Abbott Nutrition, Illinois, USA). All efforts were made to maintain constant environmental conditions free of external stimuli or compensatory feeding techniques that may have altered the infant sucking pattern, such as auditory stimulation, tactile stimulation, and external pacing. Feeds were continued until the infant released their latch on the nipple or exhibited signs of cardiopulmonary compromise.

Sucking and swallowing signals were analysed using the AcqKnowledge 4 Analysis Software (BIOPAC Systems Inc, California, USA). Waveforms were zeroed to adjust for baseline drift using the mean baseline value at a time when no sucking or swallowing activity was present. Once the baseline was established, a semi-automated suck-detection algorithm, developed during pilot testing around previously reported intraoral suction thresholds (1,13,14), was applied to identify sucking and swallow events. Sucks were operationally defined as deflections in the intraoral suction signal that were less than or equal to 10 mmHg resting pressure and were consistent in form and shape to surrounding suction signals. Only those sucks that occurred in suck-bursts, as defined by two or more sucks occurring within two seconds of each other, were included in analysis. Swallowing events were defined by an abrupt change in the pharyngeal waveform signal that was at least 4 mmHg above the mean pharyngeal resting pressure. All data points were visually verified for validity with manual modification performed as necessary to remove algorithm placed suck and swallowing events caused by extraneous variables such as infant crying or feeder-induced bottle movement (Figure 2).

Sucks identified using the aforementioned methods were quantified for the following indices of sucking: suction amplitude, suction duration, suction generation duration, suction generation rate and suction release rate (3,15). As the volume of milk extraction per suction event was dependent on both the amplitude of intraoral pressure and how long the rising intraoral pressure was applied (16), milk ejection pressure, measured as the integrated suction generation time, was used to reflect the efficiency of each suck. To examine the effect of the pharyngeal swallow on the sucking attributes, sucks were categorised as coupled and uncoupled and differences in peak pressures were calculated. A suck was identified as coupled if the minimum suction pressure occurred during the pharyngeal swallow. Likewise, sucks were categorised as uncoupled if maximum suction occurred in the absence of a pharyngeal swallow (Figure 2).

Inter-rater reliability was tested between two investigators (KM and MS) using the aforementioned semi-automated approach. Raters were found to be 98% reliable in their identification of negative inflections in the sucking signal that met the previously stated threshold and visual verification criteria. Inter-rater reliability using a two-way mixed consistency average-measures intraclass correlation (ICC) was used to measure the degree of agreement in continuous sucking outcomes between the mutually identified sucking events. The ICC among the mutually identified sucking events was 1.0 (0.99-1.00, $p<0.001$), indicating strong agreement in continuous outcomes between raters.

Linear mixed models were used to examine how the aforementioned suction attributes varied throughout the feed and between coupled and uncoupled sucks. These methods accounted for within subject correlations due to the presence of repeated measures. Statistical analysis was performed using SAS version 9.2 (SAS Institute, Cary, New Carolina, USA), with a p value of < 0.05 considered significant.

RESULTS

Patient characteristics

The participant demographics and sucking outcomes are reported as means plus or minus standard errors unless otherwise indicated. Ten infants, comprising of five males and five females, exhibiting mature nutritive sucking skills were included in the investigation. Infants were born at a median gestational age of 28.2 weeks (interquartile range, 27.0-35.0) and evaluated at 44.1 ± 1.4 weeks of postmenstrual age. Infant comorbidities included intrauterine drug exposure (n=2), hypoxic ischaemic encephalopathy (n=2), intraventricular haemorrhage (n=1) and bronchopulmonary dysplasia (n=4) (Table 1). Despite the heterogeneity, at the time of evaluation 70% of infants were meeting full oral nutrition, and 30% of infants were transitioning to full oral feeds.

Nutritive sucking and swallowing temporal relationships

Overall, 64 minutes of feeding were evaluated for attributes of 2,495 sucks and their relationship to 1,355 pharyngeal swallows. The average suck to swallow ratio during suck bursts was 2:1 (1.93 ± 0.037), resulting in a total of 1,167 coupled and 1,328 uncoupled sucks for analysis. Although approximately half (53%) of the analysed sucks were not coupled with a pharyngeal swallow and fewer swallows occurred without being coupled to a suck (13.75%). The majority of these uncoupled swallows occurred during suck burst breaks (92.5%).

In those sucks that were coupled with a swallow, the generation and release of intraoral suction exhibited a closely linked, anti-phase relationship with the generation and release of positive pharyngeal pressure during the swallow. This resulted in oral and pharyngeal pressures being reached within 0.13 seconds of each other (0.13 ± 0.019) (Figure 3). While the generation of maximum intraoral pressure occasionally occurred in complete synchrony with the generation of maximum pharyngeal pressure (3.0%), the majority of sucks reached maximum pressure slightly before (55.7%) or after (41.4%) maximum pharyngeal pressure during the swallow.

Both the suck to swallow ratio and the time from peak suction to peak pharyngeal contraction demonstrated changes throughout the feed. The average suck to swallow ratio decreased by 0.02 sucks for every additional suck burst within the feed (−0.02 ± 0.009, p=0.0413). Likewise, the time difference between peak suction and peak pharyngeal contraction decreased by 0.0018 seconds for every additional suck burst (−0.0018 ± 0.0006, p=0.006) within the feed.

Differences in nutritive sucking kinematic attributes

Nutritive sucking attributes were found to differ between sucks that were coupled with a pharyngeal swallow and those that were uncoupled (Table 2). Sucks that were coupled with a pharyngeal swallow occurred over a longer duration (p<0.0001) and generated lower suction amplitudes (p=0.004) than uncoupled sucks. Despite exerting lower suction amplitudes, coupled sucks generated suction over a longer duration of time, resulting in their exertion of higher milk ejection pressures than uncoupled sucks (p<0.0001). The rate at which the infants generated and released intraoral suction were also different. Coupled sucks generated and released intraoral suction at significantly lower rates than uncoupled sucks (p<0.0001).

Both coupled and uncoupled suction attributes were found to exhibit temporal changes throughout the feed. With every additional suck burst, milk ejection pressure increased by 0.1 mmHg/second (0.1 ± 0.06, p=0.03) and rate of suction release increased by 5.2 mmHg/second (5.2 ± 1.4, p= 0.0003).

To further investigate the potential variables that may have contributed to the observed differences in coupled and uncoupled sucking attributes, coupled sucks were further analysed for differences in attributes between those that followed a coupled suck (1:1 ratio) and those that followed an uncoupled suck (>1:1 ratio) using linear mixed models. Suction duration was the only outcome to exhibit a significant difference between 1:1 and >1:1 coupled sucks. This was characterised by 1:1 coupled sucks exhibiting significantly longer suction durations (0.7± 0.009 seconds) than >1:1 coupled sucks (0.6 ± 0.007 seconds) (p< 0.001).

DISCUSSION

Intraoral suction is defined as the negative intraoral pressure that is generated as the lingual-mandibular complex descends in an inferior-anterior trajectory in preparation for the next sucking cycle (9,17). Successful feeding requires this lingual-mandibular movement to be seamlessly linked with the lingual movements required for the pharyngeal swallow (1,3,18). Despite the appreciated need for this coordination, we have limited knowledge about how this coordination is obtained. In the current investigation we explored the potential mechanisms that may underlie this coordination by elucidating the temporal and pneumatic relationships between sucking and swallowing in a heterogeneous sample of neonates with mature sucking abilities. We demonstrated that: 1) the generation of positive pharyngeal pressure during the swallow was tightly coupled with the generation of negative intraoral suction; 2) sucks that were coupled with a pharyngeal swallow generated significantly higher milk ejection pressures than sucks that occurred in isolation; 3) sucks that were coupled with a pharyngeal swallow exhibited significantly different suction generation rates, suction durations and suction release rates than uncoupled sucks and 4) coupled sucks following a 1:1 suck to swallow ratio possessed few differences from coupled sucks following a >1:1 suck to swallow ratio.

Although the aforementioned heterogeneity within this preliminary investigation limits our ability to draw larger conclusions regarding the mechanisms that facilitate oral intake in the healthy term infant, the observed associations do draw attention to considerations that warrant future investigation. Past investigations have demonstrated the presence of a tightly linked, anti-phase relationship between sucking and swallowing, where the generation and release of positive pharyngeal pressure was tightly coupled with the generation and release of negative intraoral suction. (1,3,18) These findings were supported by those from the current investigation, where we found that peak oral and pharyngeal pressures were reached within 0.13 seconds of each other. Linking of suction and swallowing is clearly advantageous for feeding efficiency, as it enables the infant to ingest milk generated during the previous suction-expression cycle while initiating the next. Findings by Gewolb et al supported this effect, where investigators demonstrated suck-swallow rhythmicity to be correlated with the infant rate of milk ingestion (19). Findings from the current investigation indicate the infant's method of coordinating sucking and swallowing movement patterns may have provided the infant with additional feeding efficiency benefits. We found that sucks coupled with a pharyngeal swallow generated significantly higher milk ejection pressures than those that were uncoupled. This relationship was not found to be attributed to the preceding suck type, as evident by the similarity in milk ejection pressure between coupled sucks occurring in 1:1 and >1:1 ratios. These findings may indicate that in addition to enabling a faster rate of milk ingestion, suck-swallow coupling may also increase feeding efficiency by providing the infant with a larger volume of bolus extraction. Future investigations on healthy term infants, using precise measures of milk ejection, are necessary to elucidate the potential biomechanical milk ejection benefits the coupling of these lingual patterns may provide.

The observed differences in sucking attributes between coupled and uncoupled sucks were of particular interest in our exploration of the underlying mechanisms that may facilitate this potentially advantageous coupling of sucking and swallowing. We found that sucks that were coupled with a pharyngeal swallow generated intraoral suction at a significantly slower rate, maintained this pressure over a significantly longer period of time and released this pressure with a significantly slower rate than uncoupled sucks. Past investigators have demonstrated that sucking is a highly adaptable motor pattern to internal and external stimuli

(1,8,20). Infants use this adaptability to regulate milk flow from the oral cavity into the pharynx (21,22). These modifications to sucking kinematics are hypothesised to enable greater stability within the physiology of the pharyngeal swallow, a process where functional integrity is of higher hierarchal importance due to its integral role in facilitating safe bolus passage. One of the key movements to facilitate the safe passage of the bolus through the pharynx is the posterior retraction of the tongue (23-25). Clearly, if sucking and swallowing both involve unique movements of the shared lingual structure, refined kinematic and temporal linking between these two processes is integral to oral feeding success. The observed differences in coupled and uncoupled sucking attributes may reflect the manner in which this synchrony is established. It is postulated that the temporal linking of sucking and swallowing may require adaptation of sucking kinematics around those lingual movements that are integral to the success of the pharyngeal swallow. Future investigations identifying the physiologic correlates for the observed oral and pharyngeal pneumatic changes are necessary to elucidate the tongue's potential modulatory role between the processes within the oral cavity and the pharynx.

Neonatal sucking and swallowing movement patterns are governed by highly complex neurologic pathways throughout the pontine and medullary structures. Neurogenesis of these critical structures is completed in early fetal life, enabling primitive sucking and swallowing movements as early as 11-13 weeks of gestation (26). Infant feeding, however, requires these movement patterns to be executed with rhythmic coordination and capable of adapting to accommodate changing bolus properties and feeding conditions. The ability to perform these critical functions is largely dependent on neuronal maturation, a process that extends beyond fetal development, birth and infancy (27).

Given their tight-linked association with neuromotor integrity and its non-invasive ease of assessment, nutritive sucking characteristics have long been used in the clinical and research arena as a surrogate measure of neurologic and feeding function. Infants with reduced neurologic integrity resulting from premature birth or acquired cerebral insult exhibit weaker, less rhythmic suction pressures and take longer to achieve full oral feeds (7,8,11,28). Findings from the current investigation, and investigations in the past (19,29,30), indicate that while neonatal sucking attributes are clearly a reflection of these central neurologic functions, they may more strongly reflect the integrity within the interdependent oral feeding processes within the pharynx, oesophagus and the lungs. Successful bottle feeding requires infants to strike a delicate balance between the employment of a highly efficient sucking pattern that maximises milk ingestion and a low-efficiency sucking pattern that maximises cardiopulmonary function. The healthy term infant is able to achieve this balance at birth by coupling sucks and swallows in a rhythmic 1:1 suck to swallow ratio (3). In contrast, infants suffering from impairments in respiratory function demonstrate a reduced ability to strike this balance, as they employ what appears to be a compensatory shift towards the use of less efficient, respiratory sparing, sucking physiology (19). These interrelationships highlight the caution that must be exerted in the clinical interpretation and management of manifestations of infant feeding deficits as isolated impairments that are confined to the oral, pharyngeal or the oesophageal domain. Although the use of a 1:1 suck to swallow ratio may enable the healthy term infant to meet both its cardiopulmonary and nutritional needs, forcing an infant to attain such a pattern through clinical feeding manipulations may pose detrimental consequences to those whose underlying impairment lies in downstream aerodigestive function.

While the current investigation has introduced a number of coordinative dynamics that warrant further investigation, the ability to draw larger conclusions with direct clinical translation is limited by a number of factors. The most significant of these factors is the heterogeneity of the sample that was studied. While all of these infants demonstrated mature sucking abilities, they suffered from a variety of comorbidities that may have influenced suck-swallow relationships and feeding outcomes. Future investigations employing larger samples of healthy term infants are necessary to determine such concepts and elucidate the true underlying mechanisms that facilitate oral feeding success.

CONCLUSION

In the current investigation we elucidated characteristics of coordination between sucking and swallowing processes in a group of infants with mature sucking abilities. We found sucking and swallowing exhibited tightly linked, temporal relationships that were associated with changes in intraoral suction pressure. Although future investigations are necessary to explore how the stability of these suck-swallow relationships are altered with varying levels of maturational, neurologic and respiratory functions, the observed association between these physiologically distinct events highlights the interdependence between the oral and pharyngeal sucking and swallowing domains. While nutritive sucking may be directly used to assess characteristics of lingual-mandibular motion, the way that these movements are executed may be a greater reflection of an infant's downstream aerodigestive function.

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Key Notes

- Suck-swallow coordination is critical for successful oral intake in neonates, but the actual mechanisms needed to be clarified.
- This American study found that sucks that occurred in coordination with pharyngeal swallows had significantly different characteristics to those that occurred in isolation.
- Infants may achieve coordination between the unique sucking and swallowing movement patterns by adapting sucking kinematics to facilitate the lingual movements required for the pharyngeal swallow.

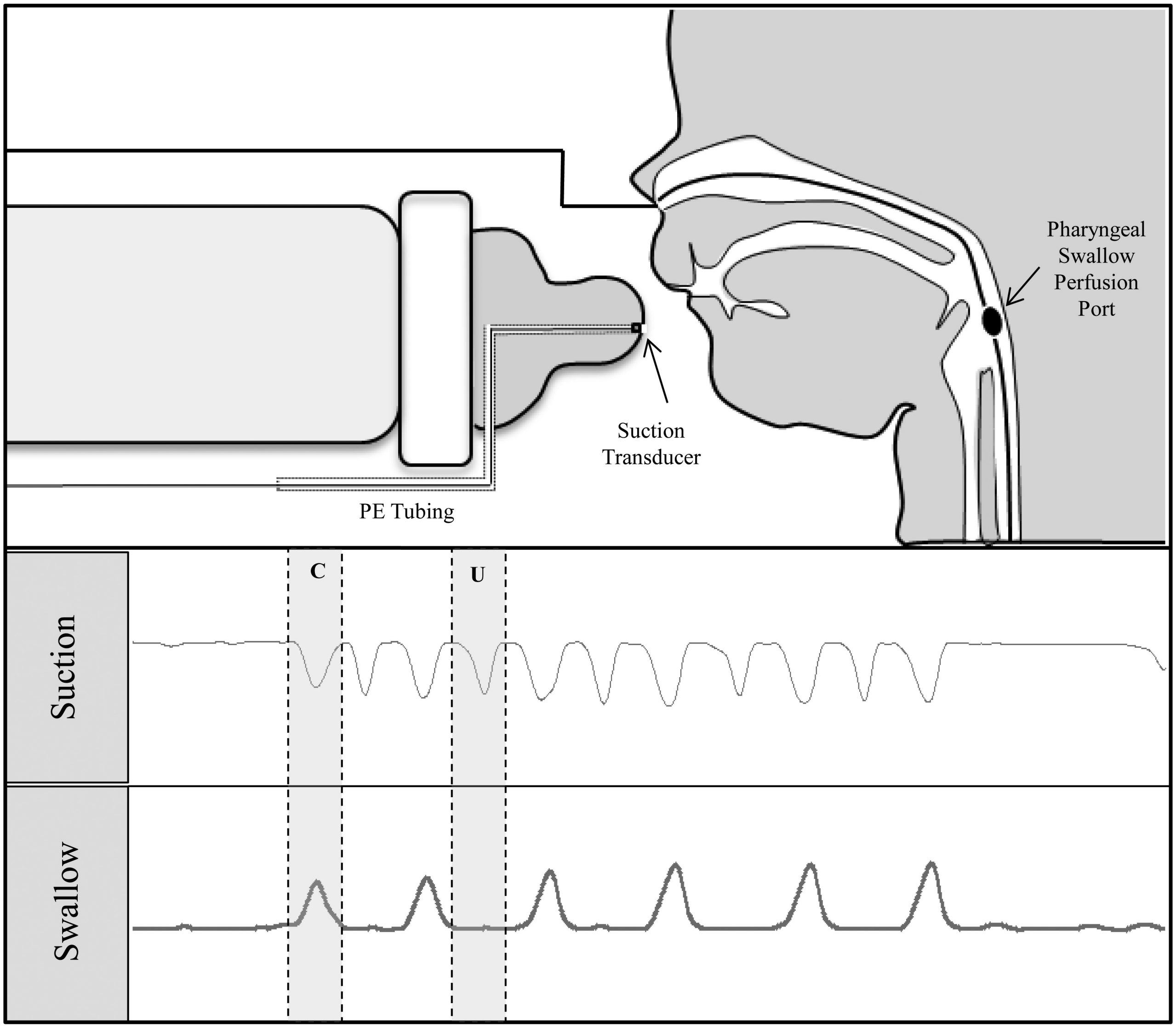

Figure 1.

Sucking and swallowing data acquisition method. Intraoral suction was measured with a pressure transducer threaded through a polyethylene channel that exited flush against the nipple tip. Pharyngeal swallows were measured with a micro-manometry catheter system with a sensor positioned in the pharynx. Sucking and swallowing signals were synchronized and digitally recorded on the MMS data acquisition system at 100 hertz to enable the detection and quantification of coupled (C) and uncoupled (U) sucking attributes.

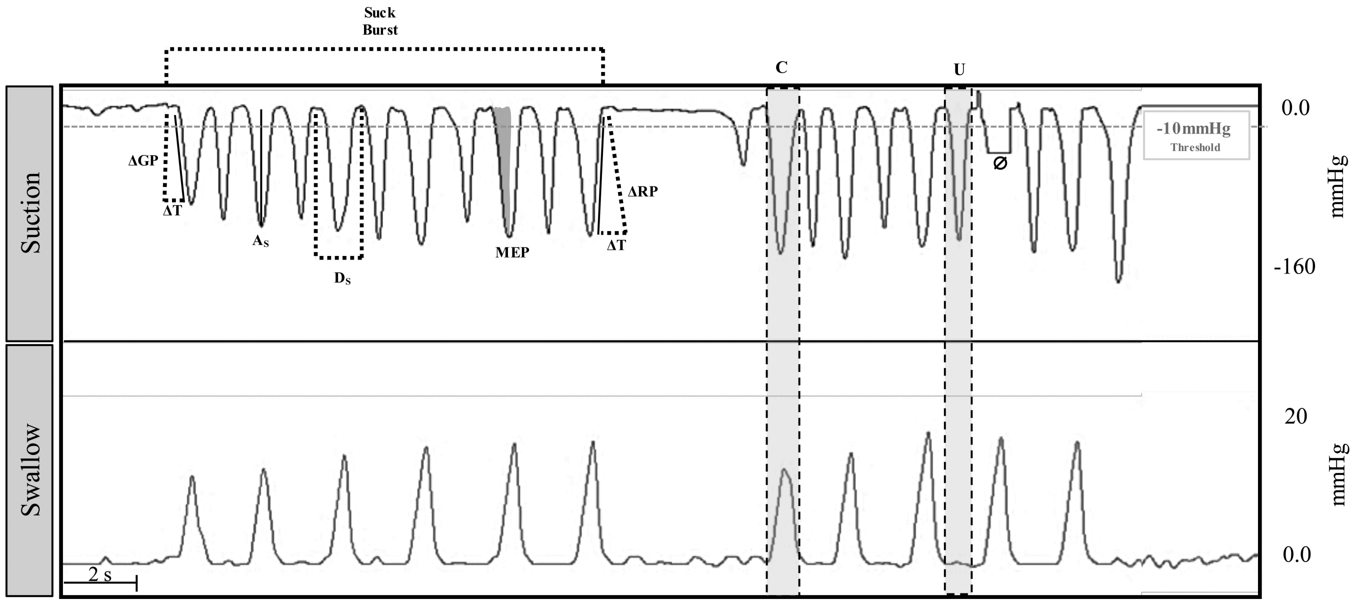

Figure 2.

Sucking analysis method. Semi-automatic suck-detection algorithm requiring the intraoral suction signal to generate ≤ −10 mmHg change in pressure and occur in a suck-burst, as defined by ≥ 2 sucks in ≤ 2 seconds of each other. Manual verification of sucks meeting these criteria was performed to ensure identified sucks were consistent in form and shape to surrounding sucks and not a result of equipment artifact (Ø). Demarcated coupled sucks initiating during pharyngeal contraction (C) and those uncoupled (U) sucks occurring in the absence of pharyngeal contraction were quantified for sucking amplitude (A_S), suck duration (D_S), suction generation rate (**Δ**SG/**Δ**T), suction generation duration (GD_S), suction release rate (**Δ**SR/**Δ**T), and milk ejection pressure (MEP).

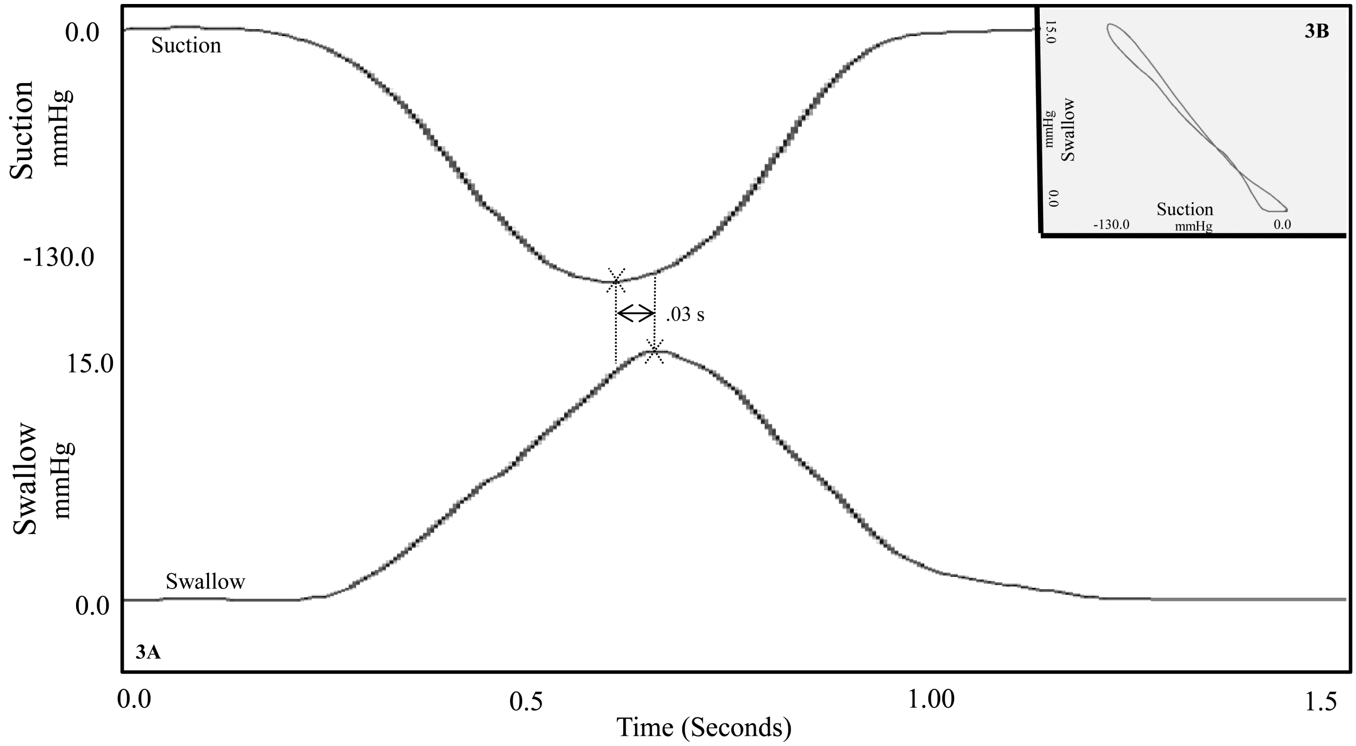

Figure 3.

A. Coupling of sucking and swallowing. Generation of intraoral suction demonstrating an anti-phase relationship with the generation of positive pharyngeal pressure during the swallow. B. X-Y Plot showing the relationship between increasing and decreasing negative intraoral pressure and increasing and decreasing positive pharyngeal pressure.

Table 1

Subject Demographics, Comorbidities, and Characteristics at Evaluation

Demographics and Birth History						*Comorbidities*						*Characteristics at Evaluation*			
Subject	**Sex**	**GA (weeks)**	**Birth Weight (grams)**	**Apgar 1 Minute**	**Apgar 5 Minute**	**RDS**	**IDM**	**IUDE**	**HIE**	**IVH**	**BPD**	**PMA at Evaluation (weeks)**	**Respiratory Status**	**Feeding Method**	**Length of Hospital Stay (days)**
1	M	27	1048	8	8	X					X	41.71	Room Air	Full Oral	106
2	F	35	1758	2	8			X				43.00	Room Air	Full Oral	12
3	M	28	835	1	6	X				X	X	40.14	Nasal Cannula	Transition	104
4	F	39	4590	2	6	X	X		X			44.14	Nasal Cannula	Transition	87
5	M	25.7	709	8	9	X					X	48.99	Nasal Cannula	Transition	217
6	F	39	3716	2	3	X			X			50.40	Room Air	Full oral	66
7	F	35	2400	NA	NA							37.40	Room Air	Transition	48
8	M	28.43	1369	5	7	X						38.86	Room Air	Full Oral	126
9	F	26.14	825	5	8	X						48.17	Room Air	Full Oral	132
10	M	27.71	1025	2	6	X		X			X	47.71	Nasal Cannula	Full Oral	143

Abbreviations for demographics, comorbidities, and characteristics at evaluation are as follows: *Gestational Age (GA), Respiratory Distress Syndrome (RDS), Infant of a diabetic mother (IDM), Intrauterine Drug Exposure (IUDE), Hypoxic Ischemic Encephalopathy (HIE), Intraventricular Hemorrhage (IVH), Bronchopulmonary Dysplasia (BPD), Postmenstrual Age (PMA)*

Table 2

Comparison of coupled and uncoupled sucking attributes

	Coupled	Uncoupled	P
Suction Amplitude (mmHg)	76.5 ± 4.1	80.5 ± 4.1	0.004
Suction Duration (s)	0.6 ± 0.006	0.5 ± 0.006	<0.0001
Suction Generation Duration (s)	0.35 ± 0.005	0.30 ± 0.005	<0.0001
Suction Generation Rate (mmHg/s)	230.1 ± 11.2	340.0 ± 11.0	<0.0001
Suction Release Rate (mmHg/s)	306.9 ± 14.4	417.8 ± 14.2	<0.0001
Milk Ejection Pressure (mmHg·s)	13.8 ± 0.6	9.6 ± 0.6	<0.0001

Values are expressed as means ± SE

Pressures reported as absolute value of suction

Significance is based on mixed model with repeated measures