Infant Behavior & Development 37 (2014) 435–445

Contents lists available at ScienceDirect

Infant Behavior and Development

Comparison of tongue muscle characteristics of preterm and full term infants during nutritive and nonnutritive sucking

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ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form 3 March 2014
Accepted 26 May 2014

Keywords:
Infant feeding
Tongue force
Preterm infants

ABSTRACT

Background: Independent oral feeding requires coordination of suck, swallow and breathe and the lingual musculature plays a significant role in this coordinative action. However, clinical benchmarks of lingual function fundamental to successful feeding have not been explored.
Aims: The present study tests our model for quantifying infant lingual force and size and compares the muscle measures of interest in two cohorts: healthy full-term infants (FT) ($N = 5$) and healthy preterm infants (PT) ($N = 6$).
Method: Using an instrumented pacifier and bottle nipple, we determined the resultant compressive forces applied to the nipple by the tongue during nutritive (NS) and nonnutritive sucking (NNS). Muscle size was estimated from measures of posterior tongue thickness using ultrasonography.
Results: After controlling for weight and post menstrual age, statistically significant differences were found between FT and PT infants beginning to feed for NNS frequency and NS tongue force. Clinically significant differences were detected for NNS tongue force and posterior tongue thickness. Additionally, PT infants demonstrated a significant difference in mean tongue force between NS and NNS and FT infants did not. FT infants demonstrated a significant difference in mean frequency between NS and NNS and PT infants did not. Linear regression indicated that mean posterior tongue thickness alone predicted 55% of the variance in NS force.
Conclusions: Results demonstrate the feasibility of our approach and suggest that infant tongue muscle characteristics necessary for successful feeding differ between healthy full term infants and preterm infants who are beginning oral feeding.

1. Introduction

Safe and efficient oral feeding is a critical milestone for infants in the Neonatal Intensive Care Unit (Pickler, 2004). The transition from tube feeding to oral feeding is a particular challenge for preterm infants (Bu'Lock, Woolridge, & Baum, 1990)

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http://dx.doi.org/10.1016/j.infbeh.2014.05.010
0163-6383/

and has a direct impact on financial costs as hospital discharge can be delayed if infants demonstrate inability to transition from tube feeding to oral feeding (Lau & Schanler, 2000; Vandenberg, 1990). Underdeveloped oral-motor skills (Lessen, 2011) including reduced muscle tone and tongue strength (Bosma, 1972) are thought to contribute to the preterm infant's oral feeding difficulties.

Independent oral feeding requires coordination of suck, swallow and breathe and the process is commonly described as a sequence of events or phases. The preparatory, or oral phase of the swallow, involves compression and then expression of fluid from the nipple and lingual transport of the fluid (Wolf & Glass, 1992). The tongue seals the oral cavity to produce the positive and negative pressure required for expression and works in conjunction with the lips, jaw, soft palate and hard palate to derive the critical volume of fluid necessary to initiate the swallow (da Costa, van den Engel-Hoek, & Bos, 2008). The fluid is then carried, via the tongue, to the valleculae to initiate the swallow. The pharyngeal phase of the swallow is initiated when the fluid is propelled by the action of the posterior tongue and the contraction of the pharyngeal constrictor muscles. The sensory receptors of the soft palate, pharyngeal walls, faucial arches and the tongue play a significant role in this phase, as the combined inputs activate the ensuing complex motor events. The esophageal, or final phase of the swallow, marks the transfer of fluid from the mouth to the stomach (Wolf & Glass, 1992). In considering the phases of the infant swallow, it becomes clear that the tongue contributes significantly to the necessary coordinative actions that occur during the oral and pharyngeal phases of the swallow (da Costa et al., 2008; Miller & Kang, 2007)

When skeletal muscle, such as the tongue, is not used to its usual capacity neuromuscular changes occur (Burkhead, Sapienza, & Rosenbek, 2007; Lieber, 1992). Using animal models, researchers have documented neuromuscular changes of the rat tongue resulting from artificial rearing practices. In each study, artificially reared pups were fed through gastric cannula while freely engaging in nonnutritive sucking (i.e. pacifier); properties of tongue musculature known to be negatively impacted by disuse were measured and compared to dam-reared pups. Significant differences in muscle were noted in the artificially-reared group and included a change in the contractile properties of the muscle, as well as a reduction in number of muscle fibers (Kinirons, Shall, McClung, & Goldberg, 2003). Subsequent studies have shown that these changes persist into adulthood (Moore, Goldberg, & Shall, 2007). Retarded hypoglossal motoneuron growth in artificially reared versus dam reared rat pups has also been demonstrated suggesting changes in the nervous system driving the muscle (Smith, McClung, & Goldberg, 2006). Researchers speculated that similar changes might also be occurring in the tongue muscle of premature infants artificially fed for extended periods of time. However, it is not clear whether the neuromuscular changes described in animal studies correlate with decreased function.

It is not known how well results of animal studies can be generalized to human infants. In addition, it is currently uncertain whether tongue muscle size indeed decreases in preterm infants and this relative atrophy cannot be examined directly. However, it would be clinically important to better understand the relationship between tongue muscle size and force in the preterm infant tongue since this relationship would certainly impact efficiency of feeding performance. Consequently, we began to explore possible instrumentation techniques for direct measurement of infant lingual properties fundamental to function, susceptible to disuse and currently unexplored relative to infant feeding. To that end, we present a novel and noninvasive approach for studying muscle properties (i.e. muscle force and thickness, as an indicator of size) that support preconditions for safe, efficient suck and swallow. The assessment methods we describe objectively measure tongue muscle attributes critical for successful oral feeding and provide pilot data necessary to determine if further study is warranted and if interventions should be directed at these variables.

2. Aims

The purpose of the present study was to compare a cohort of healthy full term infants to a group of healthy preterm infants with respect to infant tongue muscle force during nutritive and nonnutritive sucking. Because our approach to investigating functional properties of infant tongue muscle was novel we included full term infants as a frame of reference for all our measures of interest. Additionally, we were interested in exploring tongue force in the context of both nutritive and nonnutritive sucking since the goals, rhythm, rate and suck–swallow ratio have been shown to differ significantly in healthy term infants (Mizuno & Ueda, 2006; Wolff, 1968; Wolf & Glass, 1992).

Our method for quantifying tongue force was of particular interest as it permits real-time acquisition of tongue induced movement at the nipple interface. Previous investigations of sucking strength have been dependent on measures of sucking pressure yielding derivative knowledge about strength (Lang et al., 2011; Medoff-Cooper, Bilker, & Kaplan, 2001). Here we derived sucking strength from direct measures of tongue force. To the best of our knowledge, this is the first time infant tongue force has been directly measured during nutritive sucking.

An additional aim was to compare mean values of posterior tongue thickness between our two populations of interest. The posterior portion of the tongue was selected for imaging as it is considered to be the aspect of the infant tongue most responsible for moving a bolus to the valleculae to initiate a swallow (Miller & Kang, 2007). Including tongue thickness as an additional muscle measure permitted initial investigation into the relationship between tongue force and muscle thickness in neonatal swallowing; a relationship documented for masseter muscle thickness and bite force magnitude (Raadsheer, van Eijden, van Ginkel, & Prahl-Andersen, 1999), but unexplored in the infant skeletal tongue muscle.

A final aim of the study was to test our model for quantifying infant lingual properties fundamental to function and currently unexplored relative to preterm infant feeding. Our approach includes measurement of actual tongue force during nutritive sucking – which has not been compared between preterm and full term infants. Our approach for investigating

Table 1
Mean (standard deviation) of variables of interest, by population.

	Population	
	Healthy full term ($N=5$)	Preterm ($N=6$)
M:F[a]	4:1	5:1
Gestational Age (weeks)	38.4 (1.4)	31.1 (4.1)
Birth weight (grams)	3276.7 (367.3)	1795.8 (673.8)
PMA[b] Exam (weeks)**	40.2 (1.6)	34.9 (2.5)
Weight at Exam (grams)**	3276.7 (367.3)	1557 (511)

[a] Male to female ration
[b] Post menstrual age at time of exam.
** $p < .01$.

lingual mechanics also permits comparisons of muscle characteristics in nutritive and nonnutritive sucking. Such a comparison is clinically important as research shows that infants who have well-established nonnutritive suck may not necessarily do well with nutritive sucking (Daniels, Devlieger, Casaer, Callens, & Eggermont, 1986). This difference is generally attributed to the additional challenge of suck-swallow-breathe coordination required with the introduction of fluid in nutritive sucking and the interruption in respiration. However, despite interventions targeted at accommodating for this difference (Law-Morstatt, Judd, Snyder, Baier, & Dhanireddy, 2003), a number of preterm infants continue to experience difficulty. We were interested in seeing whether tongue force values differed during nutritive versus non-nutritive sucking between the two groups as a possible explanation.

3. Method

3.1. Participants

To confirm the feasibility of our approach and investigate the muscle characteristics of interest, we performed a pilot study on two groups of infants: healthy, full term infants (FT) defined as 37-40 weeks gestational age with appropriate weight for gestational age and healthy, preterm infants (PT) defined as < 37 weeks gestational age with appropriate weight for gestational age. PT infants had been declared medically stable and ready to begin oral feedings by the attending physician, usually 32-34 weeks postmenstrual age (PMA). Subjects were recruited from a 66-bed level III NICU in the south and the study was approved by the human subjects review board of the institution where the work was carried out. Infants were enrolled if they met the following inclusion criteria: no known genetic or congenital disorders, no chromosomal abnormalities, no major congenital anomalies, no disorders secondary to exposure to toxic substances, negative history of intraventricular hemorrhage greater than Grade II and no anomalies or diseases known to interfere with feeding. Eleven participants (FT = 5; PT = 6) were recruited. Demographic variables of interest for the two groups are presented in Table 1.

3.2. Measures

Our primary measures of interest were nonnutritive and nutritive tongue force and posterior tongue thickness; secondary measures of interest were nonnutritive and nutritive sucking frequency. Similar to other researchers, we tested our model during bottle-feeding as it permits a level of procedural standardization not possible with breast feeding (Bu'Lock et al., 1990).

Muscle force data was collected using a custom fabricated pacifier and flow-through nipple (Cunningham, Capilouto, & Butterfield, 2014). Our novel and noninvasive approach involved nipples instrumented with piezoelectric crystals strategically located so as to enable direct measurement of nipple deformation kinematics in response to forces of the tongue (Fig. 1). Immediately prior to each session, a calibration procedure was performed to measure baseline pressure changes of the bottle system and kinematic changes to the nipple from forces applied (Barlow, Finan, Chu, & Lee, 2008) allowing correlation of exterior force application to the amount of nipple compression and baseline pressure offsets. For the purposes of this paper, muscle force is inferred as the resultant compressive forces applied to the nipple by the tongue during nutritive and nonnutritive sucking.

Muscle thickness was estimated from measures of posterior tongue thickness from the *m. genioglossus* to the dorsum of the tongue using ultrasonography. Landmarks were identified to confirm consistent transducer placement for each subject and included fascia between the mylohyoid muscle and intrinsic muscles of the tongue and the interface between the soft palate and air in the oral cavity (identified by the hyperechoic line of the soft palate and the hypoechoic air) (Fig. 2). We have demonstrated strong reliability for our procedure using ICC analysis for the intra-trial reliability which yielded low SEM values for the mean tongue thickness measurement for each subject (Capilouto, Frederick, & Challa, 2012).

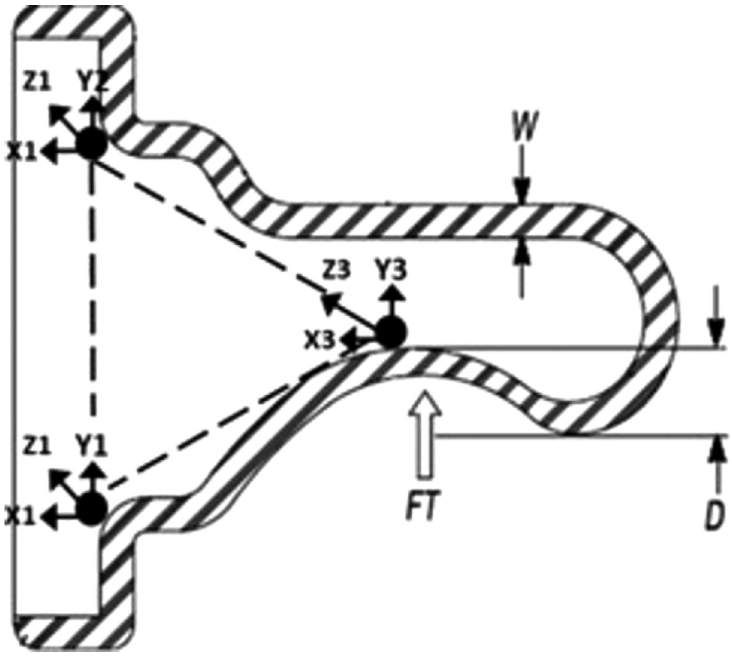

Fig. 1. Diagram of a nipple wall (W) instrumented with piezoelectric crystals (●) to model the amount of 3D deformation (D) caused by a tongue force (FT).

3.3. Procedure

Following consent, measures of interest were collected to coincide with regularly scheduled feedings. One or both parents attended the session. The research procedure was identical to standard medical care except for the use of the instrumented pacifier and bottle. Care was taken to ensure that infants were not disturbed 30 min prior to data collection (Lau & Smith, 2011) as behavioral state and fatigue are known to interfere with feeding performance (Als, 1986). PT infants entered the

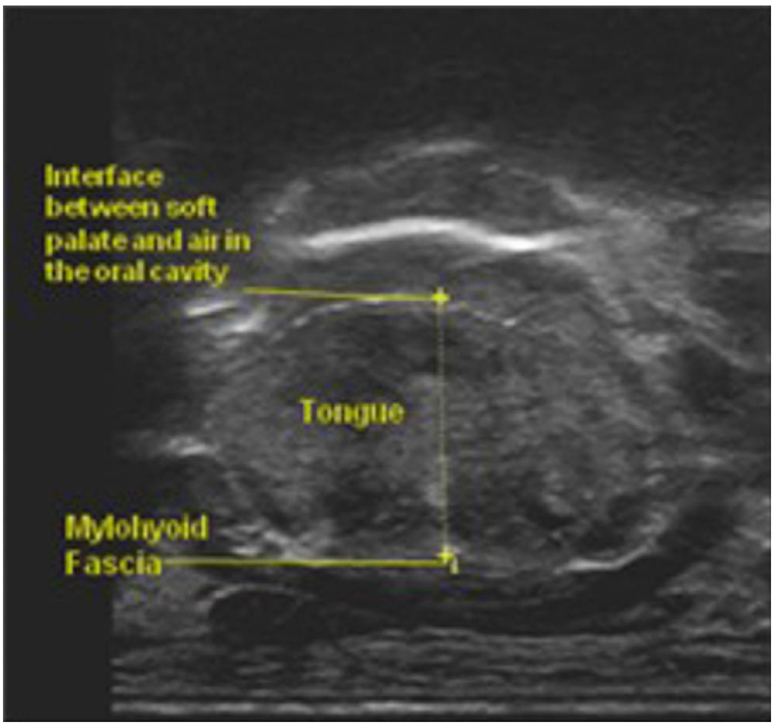

Fig. 2. Ultrasound image with landmarks noted.

A

B

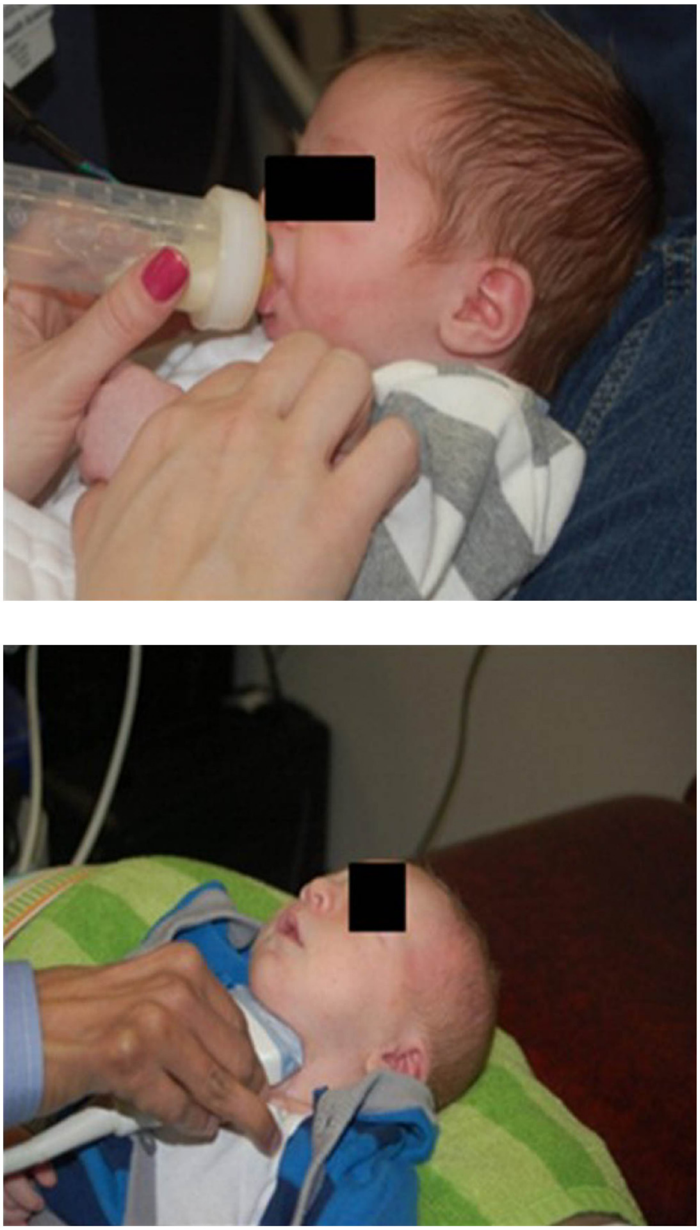

Fig. 3. Infant position for data collection during nutritive and nonnutritive sucking (A) and infant position for ultrasound imaging (B).

protocol when they were declared medically stable and ready to begin oral feeding by their attending neonatologist (usually 32–34 weeks PMA). Data collection for the PT infants occurred within 24–36 h of evidence of sustained bottle feeding, i.e. taking 1–2 feedings per day (Scheel, Schanler, & Lau, 2005). FT infants entered the protocol within 24–36 h of delivery. However, if data collection was not possible within this time frame, FT infants returned for testing no longer than 14 days post birth. The experimental sessions were identical for both cohorts.

The experimental session began by having the infant suck on the examiner's gloved finger (about 30–60 s) to increase alert state and ready the infant for feeding (White-Traut, Berbaum, Lessen, McFarlin, & Cardenas, 2005). This was followed by nonnutritive suck (NNS) on the instrumented pacifier while in their typical feeding position (held by mother) (Fig. 3A). NNS data were collected for approximately 1–3 min so as not to fatigue the infant. Following NNS, the infant engaged in nutritive suck (NS) on the instrumented bottle nipple for about 5–10 min, again while in their typical feeding position (held by mother). All feeding sessions were monitored according to the guidelines specified by the Unit's critical pathway for feeding. Calibrated force measurements were temporally synced with nipple cavity pressure throughout the collection sessions. The peak force observed throughout each respective session was determined and suck cycle frequencies were calculated from

Table 2
Mean (standard deviation) of measures of interest, by population.

	Population	
	Healthy full term ($N = 5$)	Preterm ($N = 6$)
NNS sucking frequency (Hz)[a] **	2.02 (0.05)	1.18 (.41)
NNS tongue force (N)[b] ˆ	4.899 (1.09)	2.517 (1.04)
NS sucking frequency (Hz)	1.068 (0.183)	0.9757 (0.264)
NS tongue force (N)*	4.819 (0.667)	1.283 (.987)
Mean tongue thickness (mm)[c] ˆ	15.5 (1.05)	12.1 (.95)

[a] Hertz (cycles per second).
[b] Newtons.
[c] Millimeters.
ˆ $p < .10$.
** $p < .01$.
* $p < .05$.

the duration between peak pressures and averaged throughout each session. The location of data collection (NICU versus well-baby nursery) did not permit collection of force data, blinded. However, following collection of all measures for the study sample, the last author calculated mean force/frequency for each and was blinded to group assignment.

Following data collection, infants and their mothers were left in privacy to complete feeding via breast or bottle. Following feeding, infants were placed in supine on a plinth, with neck in slight hyperextension to access the sub-mental area under the chin (Fig. 3B). Warmed ultrasound transducer gel was placed on a linear 12L-RS probe or a 12L hockey stick transducer and positioned transversely. Ultrasound images were collected by a pediatric diagnostic radiologist using the LOGIQ-e portable ultrasound machine (G.E. Healthcare, Milwaukee, WI). Optimization of the image was achieved using presets that include depth, gain, focus, harmonics, frequency, scan area, and edge enhance. The linear transducer was placed submentally at the base of the tongue and moved anteriorly until the posterior 1/3 of the tongue was in clear view. Landmarks were identified to confirm consistent transducer placement for each subject (Capilouto et al., 2012) and images collected. Following acquisition, US images were evaluated by for obliqueness and the distance between the aforementioned landmarks was measured using the electronic calipers on the ultrasound machine(Capilouto et al., 2012) and images were stored (software v R5.2, R6). A minimum of three images were collected for each infant. The mean of the three measures was calculated and used for analysis. Due to the exploratory nature of the study, statistical significance level was set at .05 with clinical significance set at .10. PASW Statistics 18.0 was used for all analyses.

4. Results

These pilot data were analyzed using univariate analyses of variance. Preliminary analyses indicated a significant difference in postmenstrual age (PMA) at exam ($p = .002$) and weight at exam ($p = .001$) between the preterm group and the full term group. Consequently, these variables were treated as covariates in the remaining statistical analyses. Variables of interest for the two cohorts included mean nonnutritive sucking force and frequency, mean nutritive sucking force and frequency and mean tongue thickness. Forces were calculated from the peaks of the sinusoidal force-time traces, and frequency was calculated as number of peaks/time.

4.1. *Nonnutritive sucking*

No adverse events were noted or recorded during NNS for either cohort (e.g. changes in HR or RR; apnea or bradycardia). Results indicated a clinically significant difference in mean tongue force during NNS between the two groups, after controlling for age and weight at exam ($p = .10$); mean NNS tongue force for FT infants was greater compared to PT infants (Fig. 4A). After controlling for weight and PMA, a statistically significant difference in NNS frequency was detected between the two groups ($p = .006$); mean NNS frequency for PT infants was significantly less than that of FT infants (Fig. 4B).

4.2. *Nutritive sucking*

As reported for NNS, no adverse events were noted or recorded during NS for either cohort. Univariate analysis indicated a statistically significant difference in NS tongue force between cohorts ($p = .014$); PT infants demonstrated significantly lower mean peak force as compared to FT infants (Fig. 4A). No statistically significant or clinically significant difference in NS frequency between the two groups ($p = .41$) was seen (Fig. 4B).

4.3. *Comparisons within cohorts*

Paired-sample t-tests were used to compare force and frequency measures within cohorts (Table 2). For FT infants, results indicated no significant difference in mean tongue force between NNS and NS ($p = .774$); full term infants used comparable tongue force for both activities. In contrast, mean frequency between the two actions was significantly different; mean frequency for NNS was twice that of NS ($p = .001$). For the PT group, results were exactly the opposite. For example, PT infants demonstrated a significant difference in mean tongue force between NS and NNS sucking; NNS tongue force was almost double that of NS tongue force ($p = .005$). However, in contrast to term infants, preterm infants did not demonstrate a significant difference in mean frequency between NNS and NS sucking ($p = .291$).

4.4. *Tongue size*

No adverse events were noted or recorded during collection of ultrasound data. Testing infants post feeding proved beneficial as most remained in a drowsy state during the entire procedure. Univariate analysis indicated a clinically significant difference in mean posterior tongue thickness for the two groups, ($p = .08$). PT infants were found to have smaller mean tongue thickness as compared to FT infants, after adjusting for age and weight at exam (Fig. 5).

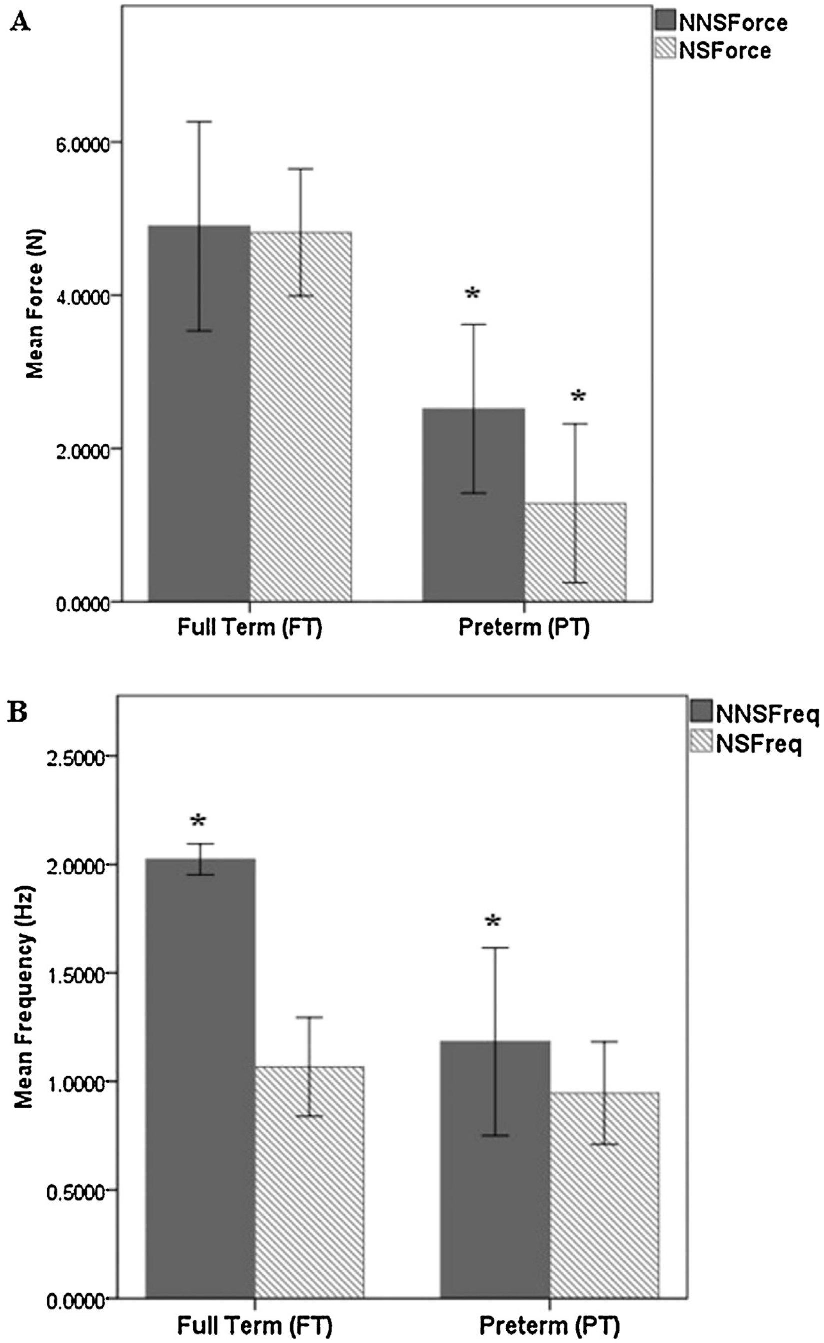

Fig. 4. Tongue force (A) and sucking frequency (B) for nutritive (NS; gray bars) and non-nutritive sucking (NNS; stripped bars) of full term (FT) and preterm (PT) infants. Values are means ± SD, *indicates significant difference from FT, $p < 0.05$.

4.5. Relating tongue force and size

To investigate factors that might influence tongue force during NS, we conducted one post hoc linear regression. NS force was the dependent variable of interest and PMA and muscle thickness (estimated from measures of posterior tongue thickness from the *m. genioglossus* to the dorsum of the tongue) served as the predictor variables. We employed a backward elimination model due to the likelihood of continued collinearity among our predictor variables. Results indicated two significant models, $p = .021$, adjusted $R^2 = .526$ and $p = .006$, adjusted $R^2 = .547$, respectively. In the first model, mean tongue thickness and PMA together explained approximately 53% of the variance in NS force, and in the second model, mean posterior tongue thickness alone predicted approximately 55% of the variance in NS force (Fig. 6). These results suggest that posterior tongue thickness may be a more significant predictor of NS force than postmenstrual age.

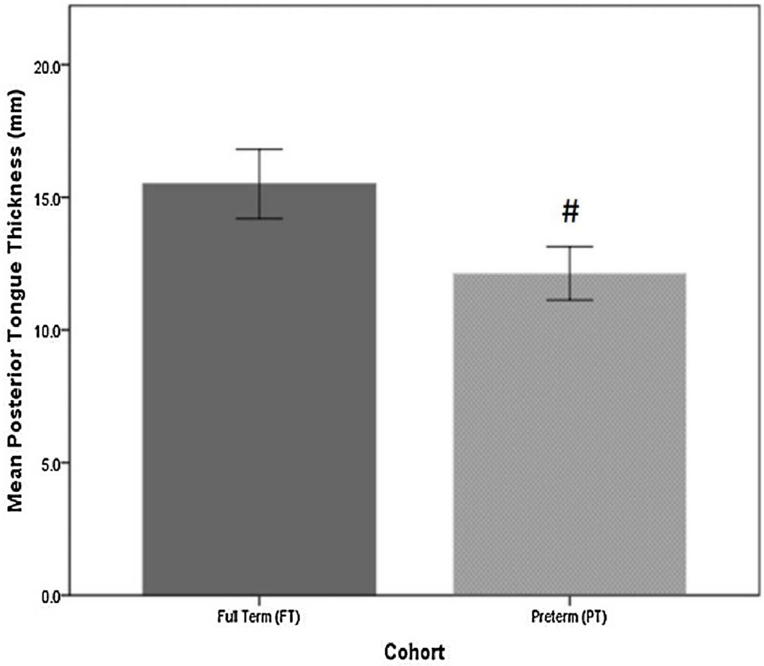

Fig. 5. Mean posterior tongue thickness as measured by ultrasound for full term (FT, gray bar) and preterm (PT, dotted bar) infants at time after feeding. Values are means ± SE, # indicates clinically significant difference, $p < 0.10$.

5. Discussion

The primary aims of this study were to assess the feasibility of our approach for direct measurement of infant lingual properties during NS and NNS and to compare these measures in healthy full term and healthy preterm infants. Our novel and noninvasive approach for quantifying lingual mechanics during sucking may be useful as a clinical method for determining readiness to begin oral feeding as well as facilitate clinical decision-making relative to the progression of oral feeding.

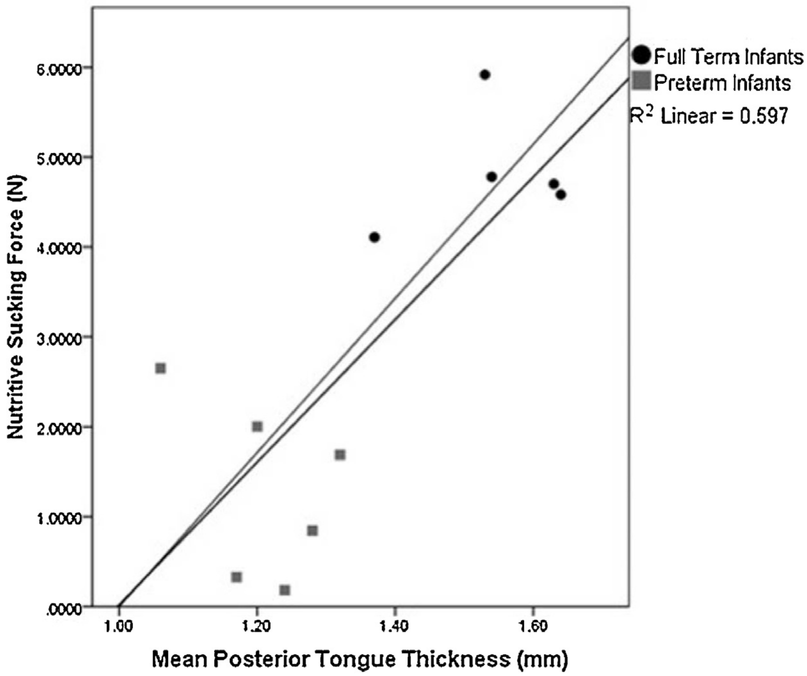

Fig. 6. Nutritive sucking force as a function of posterior tongue thickness for full term infants (circles) and preterm infants (squares).

Results from this initial clinical trial demonstrate the feasibility of our approach. Results suggest that infant tongue muscle characteristics necessary for successful feeding differ between healthy FT infants and PT infants who are beginning oral feeding.

For our initial pilot, we chose to focus on tongue muscle force since the strength of the suck is considered the bottle feeding variable most frequently associated with oral-motor skill acquisition and development (Medoff-Cooper, McGrath, & Shults, 2002). Not surprisingly, we found that FT infants had significantly greater tongue force during NS as compared to our group of PT infants, just beginning to bottle feed. These results could stem directly from our PT infants' limited experience with oral feeding as compared to the FT infants. However, the relative contributions of experience and maturation remain unclear. For example, Medoff-Cooper et al. (2002) compared the sucking strength of FT and PT infants using the Kron Nutritive Sucking Apparatus. FT infants were tested on the second day of life and PT infants were tested at 40 weeks PCA as part of a visit for follow-up from discharge home. Similar to the present study, they reported that extremely early born infants (24–29 weeks gestation) had significantly lower mean maximum pressure as compared to PT infants born 30–32 weeks gestation and FT infants. Authors concluded that despite the fact that infants were at the same post conceptual age at the time of testing, the comparatively weaker sucking pressures for the earliest born infants might be attributable to a combination of experience with feeding and developmental immaturity.

In the present study, we collected tongue force data related to both NNS and NS since the patterns of sucking for each has been shown to be distinctive in full term infants (Mizuno & Ueda, 2003). Interestingly, FT infants demonstrated equivalent tongue force levels for both NNS and NS. In contrast, PT infants demonstrated almost twice the tongue force during NNS as compared to NS. The role of NNS in the development of NS has been studied extensively with contradictory results. A Cochrane review published in 2005 found that NNS resulted in a significant decrease in length of stay for preterm infants. However, the impact of NNS on other important clinical variables, such as weight gain and age at full oral feeds, was inconsistent (Pinelli & Symington, 2005).

The findings here support those studies that suggest the mechanisms (Pickler & Reyna, 2004) and lingual configurations (Miller & Kang, 2007) involved during NNS differ from those needed for NS and so NNS may not necessarily aid in the development of NS. It has been shown that preterm infants may engage eagerly in nonnutritive sucking and at the same time have difficulty with nutritive sucking (da Costa et al., 2008). The explanation for the difference has been that nutritive sucking has the added requirement of coordinating sucking and swallowing with breathing. Though that is certainly true, these pilot data suggest that during the early stages of transition to oral feeding, PT infants may lack the degree of tongue muscle force necessary to extract sufficient fluid and propel the bolus to the posterior pharyngeal wall to initiate a swallow (Bu'Lock et al., 1990). An insufficient degree of tongue force production could in fact lead to a disruption in the timing of force and negatively impact coordination with swallowing and breathing, though further study is warranted to confirm this idea.

The influence of experience on the development of sucking suggests that a degree of motor learning is involved. Perhaps the principles of practice specificity and context specificity as relates to motor learning (Schmidt & Lee, 1999) have applicability. Both would suggest that experience with actual feeding may serve to improve the adequacy of tongue force levels for nutritive sucking in preterm infants as opposed to simply practice with NNS. Additionally, there is the need to correlate quantitative measures of sucking, such as the ones presented here and in other studies, with actual feeding performance-data we are currently pursuing in our lab.

Results of this pilot investigation revealed a significant difference in NNS frequency between FT and PT infants with comparable frequencies for NS. Moreover, preterm infants failed to demonstrate a change in sucking rate between NNS and NS. Studies document a frequency shift from nonnutritive sucking to nutritive sucking of 2:1 in healthy FT infants(da Costa et al., 2008). A lack of this typical rate change is considered to be an indication of dysfunctional suck-swallow (Palmer, Crawley, & Blanco, 1993). This rate shift to a slower movement is attributed to the addition of fluid and the need to swallow (Pickler & Reyna, 2004). Pickler and Reyna (2004) reported that a stable sucking rhythm is not usually established until about 34 weeks gestation. Since the mean age for our preterm group was close to 35 weeks PMA the lack of rate shift was surprising. One possible explanation is that PT infants failed to distinguish the difference between the NNS and NS conditions (i.e. the addition of fluid) in ways demonstrated by typical FT infants (da Costa et al., 2008). Consequently, they failed to adapt their sucking behavior to match the changed environment. Given their limited experience with NS at the time data was collected, this is certainly plausible.

The PT infants in our study demonstrated smaller tongue thickness as compared to FT infants suggesting that reduced tongue thickness was present, in conjunction with reduced tongue force for PT infants, even after controlling for weight and age. To consider factors that could influence tongue thickness and ultimately NS tongue force, we conducted a post hoc linear regression. Results indicated that posterior tongue thickness explained as much of the variance in NS tongue force as PMA and thickness combined. Miller and Kang (2007) used ultrasound imaging to investigate the lingual-hyoid mechanics in NNS and NS for one preterm infant. They reported that the posterior region of the tongue demonstrated greater displacement than the anterior regions, especially and most notably during NS (Miller & Kang, 2007), providing support for our findings. If this finding is supported by larger group studies, it would imply that increasing tongue size could be a valid oral-motor intervention.

Preliminary results are promising though the study has a number of limitations. The sample was small, but adequate to achieve sufficient power to detect differences. Additionally, only one feeding observation was made for each infant. In addition, PT infants were in the early stages of transitioning from gavage to bottle feeding which may have influenced the results. To be clinically useful, multiple observations are needed to address the ways in which NNS and NS lingual biomechanics change as a result of CNS maturation and increased practice with feeding. Also, due to the preliminary nature of the study and the emphasis on feasibility, test-retest reliability for the force and frequency measures was not conducted. Moreover, the two-week window permitted for FT infants may not provide a valid comparison, despite the fact that the differences in age and weight between cohorts at the time of data collection was controlled for statistically. The study was also limited with respect to important physiological measures. Heart rate, respiratory rate and oxygen saturation were being monitored during data collection but were not available for incorporation with the current analyses. Physiologic and behavioral correlates are critical parameters for relating quantitative measures of lingual dynamics to actual feeding performance and are being considered in ongoing clinical trials. Lastly, as stated previously, we tested our model during bottle-feeding as it permitted a level of procedural standardization not possible with breast feeding. Consequently, the implications of these results for breast-feeding would be purely speculative. We are currently exploring possible methods for collecting tongue force measures and derivatives during breastfeeding.

6. Conclusions

Our method for modeling lingual biomechanics during nutritive and nonnutritive sucking offers advantages over other previously published methods (Hayashi, Hoashi, & Nara, 1997; Kron & Litt, 1971; Lang et al., 2011) as it permits noninvasive real time acquisition of tongue induced movement at the nipple. Although not pursued in the present study, other pertinent measures of lingual dynamics can be explored in future research using our approach; including the relative contributions of the anterior and posterior tongue at the nipple interface as well as the influence of the timing of tongue force production and coordination with swallowing and breathing. We have discovered a means to integrate measurements of both kinematics and kinetics throughout the entire suck-swallow-cycle which may offer additional insight of the role of lingual dynamics in infant feeding.

It is widely accepted that with maturation, PT infants will acquire the necessary lingual mechanics necessary for safe and efficient feeding. However, if these findings are supported by larger longitudinal studies, it will be important to consider benchmark values of critical lingual dynamics that correspond to safe, efficient feeding, as well as interventions that systematically build the strength of tongue muscle more rapidly, as one would any other skeletal muscle. Lessen (2011) has presented pilot data suggesting that resistance exercises to build tongue strength prior to initiating oral feeding quickens the transition from gavage to oral feeding and reduces overall hospital length of stay (Lessen, 2011). However, the impact of interventions like the one proposed by Lessen hold that early NNS impacts the development of NS, a position that is not universally held. We are exploring interventions for increasing tongue strength in ways theoretically aligned with state dependent learning (Schmidt & Lee, 1999) such as functional resistance exercises delivered through nipples of progressive compliance.

As we extend our protocol to more vulnerable term and preterm populations, we may find that certain infants continue to have reduced tongue muscle force with maturation, which contributes to more long term problems with feeding. In summary, we believe being born early may leave certain preterm infants vulnerable to the effects of tongue muscle disuse which may alter the initial functional lingual properties required for safe, efficient oral feeding.

Conflict of interest statement

The first, second and last authors have received a patent for the instrumentation used in this work and have assigned rights to CCB Research Group, LLC. Provisional patents were applied for after data were collected and analyzed.

Acknowledgements

Collection of pilot data were made possible with a grant from the Kentucky Science and Engineering Foundation (KSEF) under Grant/Award Agreement #148-502-10-260 with the Kentucky Science and Technology Corporation. KSEF had no role in study design, collection, analyses and/or interpretation of data, writing of the manuscript or the decision to submit the manuscript. The authors thank the participants of this pilot investigation and clinical pediatric radiologist Dr. Harigovenda Challa for his expertise in developing the methodology for collection/measurement of ultrasound data.

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