Differing structural properties of foods affect the development of mandibular control and muscle coordination in infants and young children

Meg Simione\textsuperscript{a,} Chrystel Loret\textsuperscript{b,} Benjamin Le Révérend\textsuperscript{b,} Brian Richburg\textsuperscript{c,} Mirna Del Valle\textsuperscript{b,} Marc Adler\textsuperscript{d,} Mireille Moser\textsuperscript{b,} Jordan R. Green\textsuperscript{c,}\textsuperscript{*}

\textsuperscript{a} Department of Pediatrics, MassGeneral Hospital for Children, United States
\textsuperscript{b} Nestlé Research Center, Switzerland
\textsuperscript{c} Nestlé Nutrition, Switzerland
\textsuperscript{d} Speech and Feeding Disorders Lab, MGH Institute of Health Professions, United States

\section*{A R T I C L E   I N F O}

\textbf{Keywords:}
Mastication
Development
Electromyography
Kinematics
Food structure

\section*{A B S T R A C T}

The development of chewing is an essential motor skill that is continually refined throughout early childhood. From a motor control perspective, the advancement of textures is dependent upon the fit between a child’s oral anatomic and motor system and food properties. The purpose of this exploratory study is to identify age-related changes in chewing motor coordination and control and to determine if these changes are associated with the differing structural properties of solid foods, as well as to explore the role of explanatory variables such as the emergence of teeth and bite force. The masticatory muscle coordination (i.e., coupling of synergistic and antagonistic muscle pairs) and control (i.e., speed, displacement, chewing rate, duration, and number of chews) of fifty children were assessed cross-sectionally at five ages: 9-, 12-, 18-, 24-, and 36-months using electromyography (EMG) and 3D optical motion capture while children ate three foods that had differing structural properties. The results of this study found that children made gains in their chewing motor control (decreased duration of chewing sequences and lateral jaw displacement) and coordination (improved jaw muscle coupling) throughout this period. The structural differences in foods also affected chewing performance at all ages. These preliminary findings suggest that some solid textures are better adapted for immature mandibular control than others and that the development of chewing is a protracted process that may be impacted by the emergence of teeth and changes to bite force.

\section*{1. Introduction}

The development of chewing is an essential motor skill that is continually refined throughout early childhood. By the end of their first year, most children have begun to eat solid foods. The introduction of solids has numerous benefits to the developing child including increasing satiety, promoting growth and nutrition, healthy dietary habits [1,2], and the health of teeth and mandibular bones and muscles [3,4], as well as facilitating acceptance of more complex textures [5,6]. The transition to solids is gradual, and dependent on many factors including the development of oromotor skills for crushing and grinding [7,8] and the protracted emergence of deciduous teeth. Parental decisions about what foods are appropriate and when to advance to new textures are challenged by the disparate advice offered by health practitioners, parental advocate groups, and health policy organizations [1,7,9]. From a motor control perspective, children’s readiness for a given food will depend on the match between the developmental status of their oral anatomic and motor system, and the functional demands required to macerate the food. Despite the importance of chewing to growth, nutrition, safety, and overall well-being, the sensorimotor skills required to advance safely to solid foods are poorly understood. Such information is essential for designing developmentally appropriate foods, providing caregivers science-based guidance regarding the safety and appropriateness of new foods, and for identifying children at risk for choking or feeding impairments [9–11].

The neural control of chewing in adults is optimized for biomechanical efficiency. Mature chewing is characterized by rhythmic oscillations of the jaw that are driven by a consistent pattern of reciprocal activation among jaw depressor and elevator muscles [12–15]. In contrast, immature chewing coordination is characterized by significant temporal asynchrony among the activation of synergistic muscles that elevate the jaw as well as increased levels of co-contraction among the jaw antagonist muscles [13,16]. In comparison to mature chewing, other documented inefficiencies include increased...
chewing [8,37,38]. Although such descriptions have formed the basis of chewing development is largely based on visual observations of young children of the age ranges studied. Our current conceptualization of chewing motor mechanics), the level of analysis (spatial vs. temporal variables), and timelines of development vary depending on the methodology used to characterize chewing performance (visual observation vs. biomechanics), the level of analysis (spatial vs. temporal variables), and the age ranges studied. Our current conceptualization of chewing motor development is largely based on visual observations of young children chewing [8,37,38]. Although such descriptions have formed the basis for evaluating early feeding development, the proposed chewing development milestones have not often agreed with more objective biomechanically-based observations of chewing motor development [17,18,22]. Biomechanical-approaches are advantageous because they provide an objective means to (1) determine the developmental course of chewing motor control, and (2) detect changes in coordination and control that are not otherwise observable [39].

In summary, although studies on early feeding are unified by their search for factors governing the course of development, only a small number of feeding guidelines have been advanced that consider chewing development in the context of motor development and the match between a child's oral motor system and the properties of the food. The objective of this study is to identify age-related changes in chewing motor coordination and control and to determine if these changes are affected by the differing structural properties of solid foods. In addition, we preliminarily explored how factors, such as the emergence of teeth and bite force, may contribute to these changes. To achieve this goal, chewing biomechanics were assessed cross-sectionally at five ages: 9-, 12-, 18-, 24-, and 36-months. Both electromyographic (EMG) and 3D optical motion capture were recorded to obtain a comprehensive account of masticatory muscle coordination and control.

2. Materials and methods

This research was conducted at the Speech and Feeding Disorder Lab at the MGH Institute of Health Professions. The study protocol was approved by the Institutional Review Board of Spaulding Rehabilitation Hospital and was conducted in accordance with the Declaration of Helsinki, and registered at ClinicalTrials.gov under the number NCT02156986. Caregivers gave informed written consent.

2.1. Participants

Ten children across five age groups (9-, 12-, 18-, 24-, and 36-months) were enrolled in the current study. Table 1 shows the age ranges for each group. These age groups have been used in prior investigations [13,17,22] and represent previously documented stages of chewing development [38,40,41]. All children were born full term and the 9-month-olds had previously eaten solid foods. They had unremarkable medical histories with no history of feeding difficulties or food allergies, and demonstrated age appropriate development based on parental report.

2.2. Teeth

The number and type of teeth that children had at the time of data collection were recorded. Only teeth that had fully emerged through the gingiva were included in the analysis.

2.3. Anterior bite force

A Tekscan Flexifeel sensor (Tekscan Inc., Boston, MA) was embedded in a dental impression polymer that was used to protect the sensor from the occlusion force while still maintaining sufficient sensitivity. The sensors were calibrated using a texture analyzer with an applied force ranging from 9 N to 88 N. The teether was placed on the child's central incisors and the child was instructed to bite. The maximum bite force during that specific task was recorded. The data needs to be interpreted with caution, as it was unclear if children in the 9- and 12-month groups were biting to their maximal ability, due to their inability to follow instructions to bite maximally.

2.4. Food products

Participants in this study were part of a larger investigation on the development of chewing. Children in the larger investigation were offered 5 to 7 age-appropriate and commercially available food products depending on their age group. The foods included Cheerios (General Mills), Puffs (Gerber), Arrowroot Cookies (Gerber), Rice Rusks (Hipp),

Table 1

| Age group | Age range | Number of participants | Sex |
|-----------|-----------|------------------------|-----|
|           |           |                        | Male | Female |
| 9 months  | ± 2 weeks | 10                     | 7    | 3     |
| 12 months | ± 1 month | 10                     | 3    | 7     |
| 18 months | ± 2 months| 10                     | 6    | 4     |
| 24 months | ± 2 months| 10                     | 3    | 7     |
| 36 months | ± 3 months| 10                     | 5    | 5     |
| Total     |           | 50                     | 24   | 26    |

- lateral jaw displacement [17], decreased vertical displacement [18], prolonged chewing time [19–22], and increased number of chewing cycles per bite [19–22]. Overall, these findings suggest that although the basic coordinative organization for chewing (i.e., the ability to reciprocally activate jaw elevators and depressors to open and close the mandible) is established in early infancy, chewing skills are refined over many years [13].

Experienced chewers are also adept at adapting their chewing patterns depending on the shape, size, and texture of the food [11,23–26]. For example, increased food hardness predictably elicits faster jaw movements, greater bite forces, and an increase in the number of chews per bite [27,28]. These adaptations are not only driven by rapid peripheral reflexes (i.e., digastic reflex) mediated by periodontal mechanoreceptors [29] but also by the knowledge about the requirements of the chewing task [30]. Little is known about how children learn to regulate occlusal force to accommodate foods with varying textures.

The effects of texture on chewing in children have been observed most consistently in the temporal aspects of jaw motor performance (e.g., chewing rate, chewing time) rather than the spatial aspects (e.g., jaw working space, lateral excursion and velocity) of jaw motor performance [17]. For example, in comparison to purees, solids have been observed to elicit a faster rate [22], longer durations, and increased number of chewing cycles per bite [19–21,31]. The few existing studies on the development of jaw motion during chewing suggests that texture effects on chewing performance are either variable or absent until 18 months of age [17,22] when vertical jaw closing speeds were observed to be faster for solids than for purees [17]. In these studies, a broad based classification system for foods (i.e., purees, soft solids, solids) was used and differences in mechanical properties for a specific food type were not studied.

Two potential driving factors in the responsiveness of chewing motor performance to texture in young children are the emergence of teeth and bite force. Deciduous teeth typically erupt between the ages of 6 and 36 months. Molars, for example, are essential for efficient and safe chewing of solids [32]. To our knowledge, the impact of deciduous tooth emergence on the development of jaw coordination and control is poorly understood. Bite force in young children has also been understudied despite its importance for the efficient breakdown of solid food and masticatory performance [33–35]. Kamemai et al. [36] reported the bite force for children aged 3–17 years, but no information is available for children younger than three years.

Although relatively few studies have reported the effects of texture on chewing performance in children, existing studies suggest that timelines of development vary depending on the methodology used to characterize chewing performance (visual observation vs. biomechanics), the level of analysis (spatial vs. temporal variables), and the age ranges studied. Our current conceptualization of chewing motor development is largely based on visual observations of young children chewing [8,37,38]. Although such descriptions have formed the basis for evaluating early feeding development, the proposed chewing development milestones have not often agreed with more objective biomechanically-based observations of chewing motor development [17,18,22]. Biomechanical-approaches are advantageous because they provide an objective means to (1) determine the developmental course of chewing motor control, and (2) detect changes in coordination and control that are not otherwise observable [39].

In summary, although studies on early feeding are unified by their search for factors governing the course of development, only a small number of feeding guidelines have been advanced that consider chewing development in the context of motor development and the match between a child's oral motor system and the properties of the food. The objective of this study is to identify age-related changes in chewing motor coordination and control and to determine if these changes are affected by the differing structural properties of solid foods. In addition, we preliminarily explored how factors, such as the emergence of teeth and bite force, may contribute to these changes.

Table 1

| Age group | Age range | Number of participants | Sex |
|-----------|-----------|------------------------|-----|
|           |           |                        | Male | Female |
| 9 months  | ± 2 weeks | 10                     | 7    | 3     |
| 12 months | ± 1 month | 10                     | 3    | 7     |
| 18 months | ± 2 months| 10                     | 6    | 4     |
| 24 months | ± 2 months| 10                     | 3    | 7     |
| 36 months | ± 3 months| 10                     | 5    | 5     |
| Total     |           | 50                     | 24   | 26    |
Banana Cookies (Gerber), Bebivita Barenkeks (Hipps), Chewy Bar (Enjoy Life), and Pretzels (Snyder’s of Hanover). For this study, only three of the solid foods were tested (Cheerios, Arrowroot Cookies, and Rice Rusks) because they (1) were the only products that were offered to all five age groups and (2) because they varied in aspects of their structural properties that are likely to diﬀerentially impact chewing performance.

Specifically, the hardness and the saliva absorption of the products were measured to relate the mastication performance to the physical properties of the products (see Table 2). The oral mechanical breakdown of the products was simulated using a simple fracture test using a TA.XT + texture analyzer (Stable Microsystems, UK) with a blunt edge blade considered to best mimic the geometry of the molars or gums of the children in the age range of interest, while allowing measurements independent of a speciﬁc tooth geometry. Tests were conducted at a nominal velocity of 10 mm/s. To account for the eﬀect of saliva on the mechanical properties of the foods, the products were fully immersed in artiﬁcial saliva at 37 °C and the compression tests were conducted after 10, 20, 30, 60 and 120 s of immersion. Human artiﬁcial saliva recipe was used as a standardized procedure, knowing that human saliva composition changes with age, time of eating, and foods eaten [42–45].

Table 2 shows that Rice Rusks was the hardest product and remained the hardest after 10 s in saliva despite high saliva absorption. Arrowroot Cookies was the second hardest product but broke down after 10 s in the saliva to completely disappear. Cheerios were the weakest and had an intermediate absorption of saliva. Based on a sensory qualitative descriptive analysis, the diﬀerent products were characterized as: arrowroot cookies = “crunchy” and “crumbly”; Cheerios = “crispy”, “easy to break and swallow” and “absorbed moisture”; and Rice Rusks = “dry”. Because size and volume of food are known to aﬀect chewing performance [46,47], products for all age groups were cut to the size of one Cheerio with a similar approximate volume.

2.7. Records of mandibular muscle activity

In addition to 3D kinematic data, EMG data were also collected. The EMG and kinematic data were synchronized at the time of collection. EMG data were collected using a Biopac MP150 data acquisition system (Biopac Systems Inc., Goleta, CA) with disposable electrodes (Natus, Middleton, WI and 3 M RedDot, St. Paul, MN). At the time of collection, a 5 kHz low pass ﬁlter, a 100 Hz high-pass ﬁlter, and a 60 Hz notch ﬁlter was used with a gain of 1000. Electrodes were placed on the anterior belly of the digastric (jaw depressor) and the left and right masseters (jaw elevators). The electrodes for the masseter were placed on the main belly in line with the angle of the jaw. The electrodes for the anterior belly of the digastric were placed under the chin over the main mass of the muscle approximately 1 cm lateral to the midpalatal plane (see Fig. 1).

2.8. Signal editing and data analysis

Data were parsed into individual chewing sequences based upon the kinematic data using the software program Cortex (version 4.0, Motion Analysis Corporation). A chewing sequence began after the food was placed in the mouth at the point of maximum jaw closure and ended before the onset of the first swallow [17,22]. Swallowing was determined by lip pursing and cessation of chewing using both the video and kinematics data. A chewing sequence was required to have a minimum of three chewing cycles and be free of interruptions such as talking, putting fingers in the mouth, or spitting out the food (interruptions were frequent for the younger age groups). If the chewing sequence had an interruption, the usable portion of the chewing sequence was parsed; because of this, one chewing sequence may have resulted in two partial sequences. Files that had interruptions were not used to calculate the duration and number of chews in the chewing sequence (see Table 3 for the number of children who had complete and partial chewing sequences). After a chewing sequence was identiﬁed, it was trimmed to include only the middle 80% of the file so that movements related to food placement or swallowing were excluded [17].

Data preprocessing was conducted using a custom MATLAB-based program, SMASH [51]. The raw EMG signal was preprocessed to extract the envelope of the signal from each chewing sequence. A constant and linear detrend was applied. The signal was then rectiﬁed and low pass ﬁltered (Fp = 32 Hz).

Data analyses were conducted using a custom MATLAB-based program, SMASH [51]. Fig. 2 illustrates the post-processed EMG and kinematic data. From each chewing sequence, the following EMG and kinematic variables were derived.

2.8.1. Jaw motor performance

2.8.1.1. Speed and displacement of jaw movements. The anatomically based coordinate system was used to determine the 3-dimensional jaw movement trajectories. The jaw movement trajectories were fitted with
used to create an anatomically based coordinate system. JR = jaw right; JC = jaw center; JL = jaw left; RTH = right top head; LTH = left top head; RBH = right bottom head; LBH = left bottom head. Panel B shows the placement of the EMG electrodes on the jaw elevators (left and right masseters) and depressor (ABD). ABD = anterior belly of the diastagom.

Table 3
Number of children with complete and partial chewing sequences.

|                | 9 months | 12 months | 18 months | 24 months | 36 months |
|----------------|----------|-----------|-----------|-----------|-----------|
|                | Children | Sequences | Children  | Sequences | Children  |
|                | 10       | 36        | 10        | 34        | 10        |
| Cheerios       | 9        | 36        | 10        | 33        | 10        |
| Arrowroot      | 9        | 38        | 7         | 19        | 9         |
| Cookies        | 6        | 12        | 5         | 8         | 7         |
| Rice           | 7        | 11        | 6         | 6         | 6         |
| Rusk           | 2        | 2         | 5         | 5         | 5         |
| Total number of chewing sequences (complete and partial) | 36 | 35 | 19 | 10 | 10 |

Note. Only complete chewing sequences were used to calculate the duration and number of chews. All other variables were derived using the complete and partial sequences.

a two-standard deviation ellipsoid. From that fit, the lateral and vertical displacement of jaw movements were calculated. Also, the vertical speed of jaw movements was calculated (see Fig. 2).

2.8.1.2. Chewing rate. Chewing rate was calculated on the rectified and filtered EMG signals. The rate was computed by using a Fast Fourier Transformation (FFT) on the left masseter (if not available, then right masseter). An autocorrelation was performed on the EMG signals prior to the FFT. The signal produced from the autocorrelation was then high-pass filtered (Fhp = 0.2 Hz) to remove any linear trends in the data. The FFT was then run on the resulting data using a Hamming window. A peak coefficient was taken.

2.8.1.3. Duration of the chewing sequence. The duration in seconds was measured for each chewing sequence. For this variable, only files containing complete chewing sequences were used.

2.8.1.4. Number of chews in the chewing sequence. The number of chewing cycles was estimated by multiplying the rate of chewing by the duration of the sequence. This method allowed for a fully automated method to determine number of chews, as exact chewing cycles are difficult to determine in infants and young children. The automated method of calculating the number of chews is strongly correlated to the manual method of counting chews based on a video [39]. For this variable, only files containing complete chewing sequences were used.

2.8.2. Mandibular muscle coordination

2.8.2.1. Coupling of synergistic and antagonistic muscle pairs. The coupling between synergistic and antagonistic muscle pairs was calculated using a cross-correlation analysis [13]. Correlations were determined for the following combination of muscles: anterior belly of the diastagom x left masseter (antagonists) and left masseter x right masseter (synergists). The cross-correlation function was used to identify the absolute value of the peak coefficient within a 200 ms window. A peak coefficient with a higher value represents stronger coupling between pairs.

2.9. Statistical analysis

For all the chewing variables, the median was calculated for each product for each participant. The median data were used to account for the effect of outliers. The median data were normally distributed and were then used for the following two analyses. For the first one, a mixed model (participants as random effect for each age group. In the second model, a one-way ANOVA was performed to determine the product effect for each age group. In the first model, a one-way ANOVA was performed to determine the age effect for a given product. For both models, post hoc comparisons were performed (regardless of the global p-value) using the Fisher’s least significance difference (LSD). As this is an exploratory study with relatively low power, no correction for multiplicity of tests was applied, meaning that an average of 5% false positives is expected. For each figure shown in the results, age groups with different capital letters (A, B) are statistically significant different from one another. Products with different lower case letters (a, b) are statistically significantly different. Descriptive statistics were calculated to characterize the emergence of teeth as a function of age. The Kruskall-Wallis test, followed by the Wilcoxon-Mann-Whitney test for pairwise comparisons, was used to determine the differences between the age groups for the anterior bite force data. R software (R [52]) was used to perform the statistical analysis.
3. Results

3.1. Jaw motor performance

3.1.1. Vertical speed of jaw movements

The overall developmental trend for vertical mandibular speed was an increase with age as shown in Fig. 3 (an average increase of 20 mm/s). Lateral mandibular speed is not reported as it did not show age or product effects.

No significant differences between the age groups were found when children ate Cheerios. The 36-month group showed the greatest vertical mandibular speed and differences between 12- and 36-month groups and the 18- and 36-month groups were found when children chewed Arrowroot Cookies. When children chewed Rice Rusks, the 36-month-olds showed the greatest vertical speed with differences between the 9- and 36-month groups, 12- and 36-month groups, 18- and 36-month groups, and 24- and 36-month groups.

Only the 36-month-olds showed a difference between products. The Rice Rusks had a faster vertical speed than the Cheerios.

3.1.2. Displacement of jaw movements

Fig. 4 shows the changes in lateral and vertical displacements with age for each product. For Cheerios, the 9-month-olds had a larger lateral displacement than the 24-month-olds (9 vs. 7 mm), and also, the 9-month-olds had a larger vertical displacement than the 12- and 24-month-olds (10 vs. 8.4 and 8.2 mm).

Arrowroot cookies resulted in the greatest lateral displacement for the 9-month group with differences between the 9-month and the other groups. A difference between the 9- and 24-month group was found for
vertical displacement with the 9-month-olds showing a greater vertical displacement than the 24-month-olds (11 and 9 mm respectively).

Similarly, when eating Rice Rusks, the 9-month-olds showed the greatest lateral displacement. Significant differences between the groups for lateral displacement were found between the 9- and 24-month groups, 9- and 36-month groups, 12- and 24-month groups, 12- and 36-month groups, 18- and 24-month groups, and 18- and 36-month groups. No differences between the groups were found for vertical displacement.

At a given age, minimal product effects on vertical displacement were observed. Only the 36-month-olds showed a difference between the Rice Rusks and Cheerios with the Rice Rusks resulting in larger vertical movements. However, the products had an impact on lateral displacement for the 9-, 12-, and 18-month groups. For the 9-month group, Cheerios resulted in smaller lateral movements than the Arrowroot Cookies. For the 12-month group, Cheerios resulted in smaller displacements than the Rice Rusks and for the 18-month group, Arrowroot Cookies resulted in smaller displacements than the Rice Rusks.

### 3.1.3. Chewing rate

No significant age-effects in chewing rate were detected when children were offered Cheerios and Rice Rusks. A difference in chewing rate for the 12- and 24-month groups and the 12- and 36-month groups was found for the Arrowroot Cookie. The 24- and 36-month-olds had a faster chewing rate than did the younger children with that food. Chewing rate did not result in any product effects. Fig. 5 shows the age and product differences for chewing rate.

### 3.1.4. Duration of the chewing sequence

With age, the duration of the chewing sequence became shorter (see Fig. 6). When eating the Cheerios, the 36-month-olds had a shorter duration than the 9-month-olds and for the Arrowroot Cookies, the 36-month-olds had a shorter duration than the 18-month-olds. When eating the Rice Rusks, the 12-, 18-, 24-, and 36-month-olds had shorter durations than the 9-month-olds. The 36-months group also had shorter durations than the 12- and 18-months group.

For the 9-month group, Rice Rusks had a longer duration than the Cheerios and Arrowroot Cookies. For the 12-month group, the Rice Rusks had a longer duration than the Cheerios. Both the Arrowroot Cookies and Rice Rusks had a longer duration than the Cheerios for the 18-month group. No statistically significant product effects were found for the 24-month group. For the 36-month group, the Arrowroot Cookies had a longer duration than the Cheerios.

### 3.1.5. Number of chews in the chewing sequence

Fig. 7 shows the number of chewing cycles. There were no age-effects for the Cheerios and Arrowroot Cookies, but for the Rice Rusks, the number of chews decreased with age. The 12-, 18-, 24-, and 36-month group had fewer chews than the 9-month group. The 12-month-olds had fewer chews than the 18-month-olds.

The 9-month-olds had a greater number of chewing cycles when eating the Rice Rusks than the Arrowroot Cookies and Cheerios. The 18-month-olds also had a greater number of chews when eating the Rice Rusks as compared to the Cheerios and the 36-month-olds had a greater number of chews when eating the Arrowroot Cookies versus the
than in the 36-month-olds; antagonistic muscle coupling was weaker in the 9-, 12- and 18-month-olds than in the 24- and 36-month-olds.

For Arrowroot Cookies, synergistic muscle coupling was similarly weaker in the 9-, 12- and 18-month-olds than the 36-month-olds; antagonistic muscle coupling was weaker in the 9- and 12-month-olds than in the 24- and 36-month-olds.

Differences in synergistic muscle pairs for Rice Rusks were found between the 9- and 36-month groups, the 12- and 36-month groups, and the 18- and 24-, 36-month groups with the 36-month-olds showing the strongest coupling. For the antagonistic muscle pairs, Rice Rusks showed the greatest number of differences between age groups including differences between the 9- and 18-month groups, 9- and 24-month groups, 9- and 36-month groups, 12- and 18-month groups, 12- and 24-month groups, and the 12- and 36-month groups.

At a given age, minimal product effect on muscle coordination was observed. The 9-month group had stronger synergistic coupling for the Cheerios than the Arrowroot Cookies and the 12-month group had stronger antagonistic coupling for the Cheerios than the Arrowroot Cookies.

### 3.3. Emergence of teeth

The number of teeth increased with age and only children in the 18-, 24-, and 36-month groups had molars. In the 18-month group, six children had at least 1 or more molar emerge and four children had no molars. Table 4 shows descriptive statistics for the number of teeth and molars for all the age groups. Our participants had, at least, two molars by 24 months and eight by 36 months of age. Twenty-four children had no molars, 9-, 12- and four, 18-month-olds, and twenty-six children had at least one molar, 24-, 36-, and six, 18-month-olds.

### 3.4. Anterior bite force

Bite force increased with age. There were no significant differences between the 9- and 12-months age group, $p = 0.07$, the 9- and 18-months age group, $p = 0.22$, the 12- and 18-months age group, $p = 0.96$, the 12- and 24-months age group, $p = 0.17$, the 18- and 24-months age group, $p = 0.09$, and the 24- and 36-months age group, $p = 0.46$. Significant differences were found between the 9- and 24-months age group, $p = 0.004$, the 9- and 36-months age group, $p < 0.001$, the 12- and 36-months age group, $p = 0.02$, and the 18- and 36-months age group, $p = 0.01$. The median values are shown in Table 5.

### 3.4. Summary of Data

The developmental trends for the variables as a function of age and products are shown in Table 6. Table 7 shows the effect of products for each age group.

### 4. Discussion

The purpose of this exploratory investigation was to determine (1) age-related changes in mandibular coordinative and control during chewing using a comprehensive set of biomechanic measures, and (2) how chewing motor performance is affected by solid foods with varying structural properties. We also explored factors that may contribute to the age- and product-related changes. Overall, these findings support the suggestion that the development of chewing solids is a protracted process that may be impacted by the structural properties of food and the emergence of teeth and molars. Based on the discontinuity in the development of chewing motor performance, we hypothesized that the development of chewing could be characterized into two broad phases: premolar and molar chewing. The current findings help inform emerging explanatory models of feeding development that predict rapid changes in oral motor performance secondary to spurts in anatomic growth, such as the emergence of teeth, and motor development learning that coincided with upgrades in textures [50].
Muscle Pair Coupling (Synergists)

Muscle Pair Coupling (Antagonists)

Fig. 8. The synergistic and antagonistic coupling of muscle pairs. A higher coefficient represents muscle pairs that are more tightly coupled. Age groups with the different capital letters (A, B) represent statistically significant differences between age groups, p < 0.05. Products with different lower case letters (a, b) represent significant differences between those products, p < 0.05.

Table 4
Number of teeth and molars

| Age group | Teeth (average) | Teeth (range) | Molars (average) | Molars (range) |
|-----------|-----------------|---------------|-----------------|---------------|
| 9-months  | 2.5             | 0–4           | 0               | 0             |
| 12-months | 4.6             | 0–8           | 0               | 0             |
| 18-months | 11.5            | 4–16          | 1.9             | 0–4           |
| 24-months | 15.8            | 14–16         | 3.8             | 2–4           |
| 36-months | 20.0            | 20–8          | 8               | 8             |

Table 5
Anterior bite force

| Age group | Min (N) | Median (N) | Max (N) | Significance letter |
|-----------|---------|------------|---------|--------------------|
| 9-months  | 2       | 15         | 30      | A                  |
| 12-months | 7       | 22         | 56      | A,B                |
| 18-months | 11      | 19         | 59      | A,B                |
| 24-months | 17      | 38         | 99      | B,C                |
| 36-months | 19      | 53         | 83      | C                  |

Note. Age groups with the different capital letters (A, B, C) represent statistically significant differences between age groups, p < 0.05.

4.1. Which features of chewing motor performance changed with age?

Eight chewing performance variables were measured to comprehensively characterize developmental changes in chewing motor control and coordination. Among all the variables, the most robust age effects were observed for chewing duration, jaw muscle coupling, and jaw lateral displacement. It is notable that the 9-month-olds consistently demonstrated longer chewing, weaker muscle coupling and larger lateral and vertical displacements of the jaw, which characterized the early stages of the premolar phase of chewing development.

The decrease in duration of the chewing sequence with age is consistent with Gisel’s findings [20] that both the number of chews and the duration decreased between 6- and 24-months when children ate Cheerios. In the current study, both variables similarly decreased with age for the Rice Rusks but only the duration decreased for the Cheerios.

Previous EMG studies show that mature chewing is characterized by tight activation coupling between synergistic and between antagonistic muscle pairs [15]. In the current study and others [13,16], the strength of activation coupling of synergist and antagonist muscles increased significantly with age. Age effects for the synergists were primarily between the younger groups (9- to 18-months) and the 36-month-old groups across consistencies. Antagonistic coupling similarly increased with age, and statistical differences were observed among adjacent age groups (primarily for the Rice Rusks product). These increases in coupling are likely to be driven by better-defined (i.e., increased burst amplitude relative to resting activity levels) and more consistent muscle activation patterns that occur with age (see Fig. 8).

Consistent with prior findings, lateral jaw displacement decreased with age and then plateaued at 24- and 36-months [17]. This transition to an arguably more energetically efficient chewing pattern may represent a critical process by which children implicitly learn to optimally tune the intrinsic dynamics of the movement system to match the requirements of the task [53], and could explain why the younger age groups (9-, 12-, and 18-months) were more affected by the differences between the products than the older age groups. When infants are learning to walk, external perturbations are more likely to affect their...
stability, whereas infants with more walking experience are less affected by perturbations [54]. Excessive movement or “movement overshoot” has been observed in jaw movement during early speech [50] and arm movement during early reaching [53].

4.2. Texture adaptation: Age and product interaction effects

Significant age- and product-related changes were observed from 9 to 36 months. The observation of age-related effects for a given texture was cautiously interpreted to suggest that the immature oral-motor system was less well adapted to manage that texture; conversely, the absence of age-related effects for a given texture was cautiously interpreted to suggest that even the beginning chewers were capable of efficiently chewing that texture. Among all the foods, the greatest age-related differences in chewing behavior was for the Rice Rusks product; similar age effects were not observed for Cheerios, suggesting that the immature chewing motor system is well adapted to chew this product, whereas the Rice Rusks in comparison to the Cheerios, were mechanically challenging for the beginning chewers (i.e., 9-month-olds).

The differing structural properties of the three solid foods affected chewing motor performance (i.e., consistency effects) at all the ages studied except 24 months. Le Révérènd and colleagues (2016) speculated that the rate of oral processing of a food may be due to the dry matter, density, fracture force, and saliva absorption. These properties varied across the products that were studied and, therefore, could have differentially challenged the immature oral motor system. Age-related changes in chewing performance were observed for all of the consistencies but were most evident for the Rice Rusks. Rice Rusks, the hardest food (i.e., the food with the highest fracture force, see Table 2) resulted in longer durations, increased number of chewing cycles, and greater lateral jaw movements. Cheerios, the softest product, had the lowest values for parameters such as, duration, number of chews, lateral displacement and it had stronger synergist muscle coupling. The contrasting physical properties of Rice Rusks and Cheerios may help to explain the presence and absence of age-related effects on mastication behavior. Other external factors could also explain this age effect, such as the emergence of teeth and the increase of bite force.

4.3. Structural factors: Potential impact of molars and bite force on chewing motor development

The emergence of teeth and molars may account for several of the age-related changes we observed in chewing performance. The number of molars and bite force nearly doubled between 18- and 24-months of age to the necessary number of molars (2–4) needed for oppositional crushing. The large lateral displacements for the 9-, 12-, and 18-month-olds when chewing Rice Rusks and vertical displacements for the 9-month-olds in the young children may have been due to the increased space afforded by the absence of teeth. Teeth, and particularly molars, could also provide a source of biomechanical stability to the jaw and help to explain the decrease of lateral displacement with age and the increase in anterior bite force. The improved jaw muscle coupling and movement scaling, for example, may have been a consequence of the positive effects of occlusal contact on the mechanical stability of the temporomandibular complex and sensorimotor guidance (via periodontal receptors), which could also help provide essential information needed to scale jaw movements in real-time and adapt to changes in food hardness [55,56].

4.4. Two hypothesized phases of early chewing motor development

Large changes in chewing biomechanics were observed from 9- to 36-months as our participants progressed from beginning to more advanced chewers. We hypothesized that these changes could be characterized by two predominate phases, with the first phase between 9- and 18-months (premolar phase) and the second between 24- and 36-
months (molar phase).

4.4.1. Premolar phase

Children in the premolar phase were 9- and 12-month-olds, who had limited experience chewing solid foods, as well as the 18-month-olds who had more chewing experience, but their chewing behaviors were not yet equitable to the two older age groups. Most children in this phase lacked molars and overall their median bite force was lower than the children in the later phase. Although these children appeared to have the basic muscular coordinative patterns for chewing, their mandibular control and coordination were inefficient. This interpretation is supported by the data showing, for example, that although 9-month-old children produced chewing rates that were similar to that of the older children, their lateral displacements were much larger than that of the older children and their jaw muscle coupling was weaker for both synergists and antagonists (see Fig. 8). The developmental changes throughout this phase were evidenced by the gradual decrease in lateral displacement for the 18-month-olds supporting that they were beginning to gain control over the intrinsic dynamics of the jaw control system.

4.4.2. Molar phase

During the molar phase, which included 24- and 36-month-olds, few differences in chewing performance were observed between these groups, and compared to the younger children their chewing was characterized by stronger jaw muscle activation coupling and faster vertical speed. The control of jaw movement became more efficient, for example, the overshoot in the lateral displacement observed in the first phase decreased. This gradual decrease in movement overshoot reflects the maximization of biomechanical efficiency. The refinement phase seen in chewing is consistent with other motor skills, such as walking [57] and the coordination of the jaw and lips for speech [58]. Although the children in this phase showed improved chewing performance as compared to the children in the previous phase, studies suggest that refinement of feeding skills continues well into childhood [19,21,22,31,59]. Furthermore, prior work by Le Révérend and colleagues (2016) on adults eating similar products demonstrated that chewing biomechanics were affected by the products in this study, confirming that the masticatory skills of 36-month-olds are not as mature as adults as they cannot yet adapt to the differences in product textures.

4.5. Limitations

Due to the intensive process of data collection and data processing when studying infants and young children, the sample size in each age group was relatively small. Although age-trends were not observed for some performance variables, it is premature to conclude that they are not sensitive to age or experience because of the relatively small n in each group. For some variables, the absence of an age-trend may have been due to high inter- or intra-subject variability, which could obscure underlying age trends. In addition to the small n, there were missing data for some variables due to the nature of collecting physiologic data with infants and young children which may have also affected the trends. Furthermore, products in this study were all safe for the respective age groups, which may have reduced the range of textures investigated and the range of mastication abilities. Given the explanatory nature of this study, in the future, a longitudinal study may help to reduce the variability across children.

5. Conclusions

The purpose of this study was to identify age-related changes in chewing motor coordination and control during chewing development at five different age groups (9-, 12-, 18-, 24-, and 36-months) and to determine the effects of differing structural properties of foods, as well as preliminarily explore explanatory variables, including the emergence of teeth and molars and bite force. The results of this study found that children made gains in their chewing motor control and coordination and the structural differences in foods affected chewing performance. Our findings revealed that Rice Rusks, a food with a high fracture force resulted in the most age-related differences while Cheerios resulted in few age-related differences suggesting the immature motor system is well adapted to chew this food. Based on the findings, we hypothesized that the development of chewing could be characterized into two broad phases: the premolar (9-, 12-, and 18-months) and molar (24- and 36-months) phases. Children in the premolar phase lacked molars and had the basic coordinative organization, but their jaw movements were still inefficient as compared to the children in the molar phase. The children in the later phase had begun to refine their chewing motor performance. The findings from this study can inform science-based recommendations regarding the safety and appropriateness of foods, the design of developmentally appropriate foods, and the identification of children at risk for feeding impairments. To promote the development of chewing skills, successful feeding should be the result of the right fit between the child’s developmental skills and the food.

Funding source

This work was supported by funds provided by Nestec Ltd and from NIH grant K24DC016312.

Conflicts of interest

The sponsor, Nestec, Ltd. played a role in the design of the study, analyses and interpretation of data, in the writing of the manuscript, and in the decision to publish the results.

Author contributions

The experiment was conducted at the Speech and Feeding Disorders Lab, MGH Institute of Health Professions in Boston, MA. CL, BLR, MM, MDV, MA, and JG conceived and designed the experiments. MS, BR, and JG performed the experiments. MS, CL, BLR, BR, MM, and JG made contributions to analysis and interpretation of data, in the writing of the manuscript, and JG wrote the paper.

References

[1] G. Miles, A.M. Siega-Riz, Trends in food and beverage consumption among infants and toddlers: 2005–2012, Pediatrics 139 (6) (2017) 2005–2012, http://dx.doi.org/10.1542/peds.2016-3290.
[2] C.M. Taylor, S.M. Wernimont, K. Northstone, P.M. Emmett, Picky/fussy eating in children: review of definitions, assessment, prevalence and dietary intakes, Appetite 95 (2015) 349–359, http://dx.doi.org/10.1016/j.appet.2015.07.026.
[3] N. Kawai, R. Sano, J.A.M. Korfage, S. Nakamura, N. Kinouchi, E. Kawakami, ... E. Tanaka, Adaptation of rat jaw muscle fibers in postnatal development with a different food consistency: an immunohistochemical and electromyographic study, J. Anat. 216 (6) (2010) 717–723, http://dx.doi.org/10.1111/j.1469-7580.2010.01255.x.
[4] N. von Cramon-Taubadel, Global human mandibular variation reflects differences in agricultural and hunter-gatherer subsistence strategies, Proc. Natl. Acad. Sci. 108 (49) (2011) 19546–19551, http://dx.doi.org/10.1073/pnas.1113050108.
[5] T.M. Dovey, P.A. Staples, E.L. Gibson, J.C.G. Halford, Food neophobia and “picky/fussy” eating in children: a review, Appetite 50 (2–3) (2008) 181–193, http://dx.doi.org/10.1016/j.appet.2007.09.009.
[6] K. Northstone, P. Emmett, F. Nethersole, The effect of age of introduction to lumpy solids on foods eaten and reported feeding difficulties at 6 and 15 months, J. Hum. Nutr. Diet. 14 (1) (2001) 43–54, http://dx.doi.org/10.1046/j.1365-277x.2001.00264.x.
[7] N. Butte, K. Cobb, J. Dwyer, I. Graney, W. Heird, K. Rickard, The start healthy feeding guidelines for infants and toddlers, J. Am. Diet. Assoc. 104 (3) (2004) 442–454, http://dx.doi.org/10.1016/j.jada.2004.01.027.
[8] B.R. Carruth, J.D. Skinner, Feeding behaviors and other motor development in healthy children (2-24 months), J. Am. Coll. Nutr. 21 (2) (2002) 88–96, http://dx.doi.org/10.1080/07315724.2002.10719199.
[9] WHO, Infant and young child feeding, World Health 155 (May) (2011) A3929, http://dx.doi.org/10.1111/j.1740-8709.2009.00234.x.
