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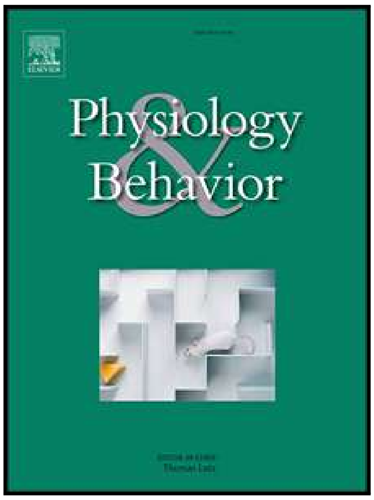

Developmental and age-related changes in sensorimotor regulation of biting maneuvers in humans

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Highlights:

- The study investigated age-related changes in sensorimotor regulation of biting maneuvers in children compared to adults
- A standardized food hold-and-split biting task was performed by children and adults
- Food holding forces were higher and more variable in children with primary to early-permanent dentition than adults
- During food splitting, children with primary and early-mixed dentition showed longer splitting duration than adults
- Younger children with primary dentition show signs of immature oral fine motor control during biting maneuvers

Developmental and age-related changes in sensorimotor regulation of biting maneuvers in humans

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Abstract

Previous studies indicated distinct differences in biting and chewing behaviors between children and adults. However, these studies used different methodologies and failed to study age-related changes in the fine motor control of biting from childhood to adulthood. Therefore, this study aimed to investigate age-related changes in oral fine motor control in healthy children in comparison to adults. Sixty-five healthy children (3-17 years) were equally divided into five age-groups based on their dental eruption stages. Each participant was asked to hold half a peanut rested on a force transducer between two opposing anterior teeth for 3-4 seconds before splitting it. The force applied on the transducer was continuously monitored and recorded during food holding and splitting. The data obtained from the children subgroups were compared to an adult group (18-35 years). Results showed that the force regulation during food manipulation was higher and more variable in children with primary to early-permanent dentition stages compared to adults. Additionally, children with primary and early-mixed dentition showed longer food splitting duration than adults and exhibited a predominantly step-wise ramp-increase of force. The results of the present study showed age-related changes in fine motor control of food biting maneuvers. The results of the study also suggested that younger children with primary dentition show signs of immature oral fine motor control. However, with an increase in age and the accompanying structural changes, the oral fine motor control eventually transits to a more matured "adult-like" biting maneuvers.

Key words: Motor control; Food; Child; Adult; Deciduous dentition; Permanent dentition

1. Introduction

The efficient execution of motor tasks necessitates efficient assimilation and processing of the sensory information in a process called sensorimotor integration [1,2]. By definition, sensorimotor integration is the complex process to achieve a task-specific motor output based on the integration of sensory information from relevant sensory receptors. The sensorimotor system, in general, is a product of evolution, development, learning, and adaptation that work in tandem in order to improve motor performance [3]. The development and emergence of voluntary motor behavior in children during reaching or grasping movements have been extensively studied in previous studies [4–8]. However, little is known, about how children acquire oral motor skills, adaptive force control, and how neural development facilitates the maturity of oral motor control.

The orofacial structures, including dentition, undergo massive developmental changes with age. These changes may exert considerable challenges on the sensorimotor regulation of biting and chewing behaviors. We have previously reported the age-related changes in jaw sensorimotor control and objective parameters of chewing [9]. Accordingly, it was shown that chewing parameters such as maximum voluntary bite force, jaw muscle activity, and jaw kinematics gradually change with the development of the orofacial structures and are mainly influenced by the dentition status [10–12]. Specifically, studies on jaw kinematics during chewing showed that children with primary dentition exhibit shorter and broader jaw trajectories than adults [13–17]. The pooled data obtained during the course of a “meta-analysis” suggested a transition to an “adult-like” regulation of bite force, jaw muscle activity, and jaw kinematics during the late-mixed to early-permanent dentition stages [9].

The human teeth harbor a specialized group of mechanoreceptors concentrated in the periodontium around the root. These periodontal mechanoreceptors (PMRs) signal vital sensory information about the temporal, spatial, and intensive aspects of the load applied on the teeth [18]. The sensory information is used by the central nervous system (CNS) to regulate the motor output program responsible for oral motor behavior. In light of the previous work, the current study aimed to investigate age-related changes in oral fine motor control in healthy children in comparison to adults. We hypothesized that children at different dentition eruption stages will demonstrate age-related changes in the sensorimotor regulation of forces during the oral fine motor control task. We also hypothesized that children during late-mixed to early-permanent dentition stages will demonstrate an adult-like optimization in force control.

2. Materials and methods

2.1. Study participants and protocol

The project was introduced to the children with their parents/guardians during their regular dental check-up at the Pedodontic Specialist Clinic, Karolinska Institutet, Sweden. Among them, sixty-five healthy children (age range: 3-17 years) agreed to participate in a single experimental session and were further sub-divided into five age groups based on the dental eruption stages (Table 1) [19]. Further, a control group of thirteen healthy adults (age range: 18-35 years) were invited to participate. All the participants had unremarkable general health with average body mass index, and no known oral or systematic health conditions, systematic diseases, or painful disorders. The oral and dental status were also unremarkable with no active caries, traumatic or restored anterior teeth, no gross malocclusion, active orthodontic treatment, or fixed retainers. The ethical permit was obtained from the Regional Ethics Review Board in Stockholm, Sweden, and the study adhered to the regulations of the declaration of Helsinki ethical principles for medical research involving human subjects. Prior to the start of the experiment, informed consents were collected from the parents/guardian of each child in the children group and from the participants in the adult group.

Table 1. Mean age (± 1 SD) in years and the number of participants in children dental subgroups and adults.

#	Group*	Number of participants	Age range (years)	Mean age (years)	SD
1	Primary dentition	13 (4 boys)	3.0 to 5.99	4.87	0.80
2	Early-mixed dentition	13 (8 boys)	6.0 to 8.99	7.74	0.84
3	Late-mixed dentition	13 (9 boys)	9.0 to 11.99	10.99	0.90
4	Early-permanent dentition	13 (4 boys)	12.0 to 14.99	13.32	0.83
5	Late-permanent dentition	13 (10 boys)	15.0 to 17.99	16.28	0.75
6	Adults (control)	13 (8 men)	18.0 to 35.0	25.22	4.92

*Group classification criteria:

Group 1: All the primary dentition are present in the mouth

Group 2: The eruption of permanent first molars and permanent incisors

Group 3: The eruption of either the permanent first and second premolars and canines

Group 4: The completed eruption of all permanent teeth except the permanent seconds and third molars

Group 5: All the permanent dentition are present in the mouth except the permanent third molars

Group 6: Completed eruption of the permanent dentition

2.2. Behavioral task and experimental procedure

The behavioral task was to hold and split half a roasted and salted peanut (Estrella ^{TM}, Estrella AB, Sweden) placed on a force transducer, as described in our previous studies [20–24]. The behavioral task simulates the natural situation of placing the food morsel between the teeth before crushing it during the act of chewing. In the current study, the principal investigator (NA) demonstrated the behavioral task to the study participants with the help of a video clip of a child performing the task. Accordingly, the force transducer was horizontally held by the investigator, and half a peanut was placed on the upper plate. The apparatus was then positioned into the participant's mouth to ensure that the food morsel was lying half-way between two antagonist central incisors. Each participant was asked to gently hold the peanut between the teeth with as little forces as possible. After about 3-4 seconds, each participant was asked to split the morsel. The trial was repeated with a new food morsel if any morsel was lost or unsuccessfully split. Prior to the start of the experiment, each participant was familiarized with the task by performing five practice trials. After the familiarization trials, participants did the experimental session, which consists of 5 trials of the hold-and-split task.

2.3. Apparatus

The force transducer (Department of Integrative Medical Biology, Umeå University, Umeå, Sweden) used in the study consisted of a 10-cm aluminum handle that was connected to two duralumin blocks (Fig. 1). The two duralumin blocks terminated into two thin plates. The test food is placed on the end of the upper plate. The strain-gauge based force transducer was designed to ensure an equal force recording irrespective of the point of force application on the plate. The lower plate had grooved plexiglass glued in order to facilitate proper positioning on the lower incisors. When the food is placed on the force transducer, the anterior teeth is separated by approximately 9-10 mm. For further details on the apparatus, see Trulsson and Johansson [20].

2.4. Data analysis

The temporal force profile was sampled with 1000 Hz (low-pass filtered 250 Hz) and analyzed with a custom-made software (WinSC/WinZoom, Department of Integrative Medical Biology, Umeå University, Umeå, Sweden). The characterization of the temporal profile has been described in detail in the previous studies [20–24]. Two distinct phases were identified from the temporal force profile (Fig. 1). The holding phase, which was characterized by low and stable holding force, started 0.2 seconds after the initial contact with the peanut (a) and ended 0.2 seconds before the onset of the splitting phase (b). The splitting phase started where the force rate exceeded 5 N/s and was characterized by a rapid ramp increase of force, which leads to splitting the morsel (c) before the force fell sharply to zero. The two phases were reliably detected by the software and manually checked for accuracy. The average holding force was defined as the mean force between the two-time points that determined the onset and the end of the holding phase (a-b). The standard deviation of the holding force was determined as a measurement of force variability within individual trials (intra-trial variability) and between the five trials performed by the same participant (inter-trial variability). The splitting force was defined as the peak force obtained during the splitting phase, which was characterized by the rapid increase in the force until the peanut split. Further, the splitting duration was measured as the time taken in seconds from the onset of the splitting phase until the peak splitting force was attained (d). The pattern of the force increase during food splitting was manually assessed to determine the occurrence of a "step-wise" ramp-increase of force. In accordance with the previous studies [20,21,25,26], a step-wise ramp-increase of force is accounted when the force profile shows a bi- or multi-phasic force decay, which is followed by a "compensatory" force increase that leads to splitting the peanut.

The data pertaining to the holding and splitting phase are presented as mean (± SD). The sum of the trials exhibiting the step-wise ramp-increase of force from each participant was calculated. Further, the data pertaining to the step-wise ramp-increase of force is presented as frequency (%) of occurrence from the total trials from each age-group. The normality of the data was verified with the Shapiro-Wilk test and the skewness test. If any of the variables was not normally distributed, the data were log-transformed. The data were then subjected to one-way ANOVA with age-group as a categorical factor. Dunnett post hoc analysis was applied to determine the differences in each of the studied variables between the five children subgroups in comparison to the adults. A statistically significant result was considered if a p-value is less than 0.05**.**

3. Results

The force profile during the behavioral task in the children and adults was characterized by a steady yet very low holding force that lasted for a few seconds, followed by a rapid ramp-increase of force until the peanut split. All the participants performed the task reliably from trial to trial. The temporal force profiles from children and adults presented significant differences, which are presented below.

3.1. Holding phase

The holding forces during the holding phase were generally low but showed an age-related change demonstrated by a decrease in force with an increase in age (Fig. 2A and Fig. 4A). There was also a statistically significant main effect of age on the holding forces ($P<0.001$). Post hoc analysis showed that children in primary, early-mixed, late-mixed, and early-permanent dentition stages had significantly higher holding forces compared to adults (P<0.05 for all the groups). However, the holding forces were not statistically significant in children in late-permanent dentition compared to adults (P=0.17).

Additionally, we studied the between-trial variability of the averaged holding forces (i.e., standard deviation between the trials of an individual) between the studied age groups in comparison to adults. Similar to the mean holding forces, the between-trial variability showed age-related changes (Fig. 2B). There was also a statistically significant main effect of age on the between-trial variability of the holding forces (P<0.001). The adult group showed the lowest between-trial variability of the holding forces among the groups (0.26 ± 0.07 N), while children in the primary dentition group showed the highest variability (1.38 ± 0.78 N). The post hoc analysis showed that children in primary, early-mixed, late-mixed, and early-permanent dentitions had significantly higher between-trial variability compared to adults (P<0.01). However, children in late-permanent dentition did not differ in between-trial variability compared to adults (P>0.05).

On the other hand, the intra-trial variability (i.e., standard deviation within the individual trial) also presented an age-related change, where it decreased with the increase in age (Fig. 2C). The intra-trial variability in children with primary dentition was 1.80 ± 1.34 N, and was slightly higher in children with early-mixed dentition (1.87 ± 0.65 N), whereas, the intra-trial variability was drastically lower in adults (0.62 ± 0.15 N). There was also a statistically significant main effect of age on the intra-trial variability of the holding force (P<0.001). The post hoc analysis showed that children in early- and late-permanent dentition had similar intra-variability of the holding force compared to adults (P>0.05).

3.2. Splitting phase

The splitting phase during the behavioral task was characterized by a rapid ramp increase in force, ultimately leading to the split of the peanut. At times, the rapid ramp increase of force presented a step-wise compensatory force increases, which eventually led to split the peanut (Fig. 4B). However, there were no statistical differences in the splitting forces between any of the groups (P>0.05) (Fig. 3A).

Interestingly, there was a significant effect of age groups on the duration of the splitting phase (time in seconds taken to split the food morsel) ($P<0.001$). The split duration decreased with age increase, where it was longer in children with primary dentition (0.41 ± 0.17 s) and was as low as 0.20 ± 0.07 s in adults (Fig. 3B). The post hoc analysis showed that only children in the primary dentition ($P<0.001$) and early-mixed dentition ($P<0.05$) had a statistically longer split duration in comparison to adults.

The frequency of the step-wise ramp-increase of force during the splitting phase was 68.75% in children with primary dentition, 57% in early-mixed dentition, 49.2% in late-mixed dentition, and 41.53% in early-permanent dentition (Fig. 4B) (see data analysis section). The frequency of occurrence of the step-wise ramp-increase of force further decreased to 32.31% and 29.23% in late-permanent dentition and adults, respectively. There was also a statistically significant main effect of age on the occurrence of the step-wise splitting pattern ($P<0.001$). Similar to the splitting duration, the post hoc analysis showed that only children in the primary and early-mixed dentition were statistically significant compared to adults ($P<0.001$ and $P<0.05$, respectively).

4. Discussion

The study investigated the age-related changes in oral fine motor control during a standardized hold and split biting tasks in children in comparison to adults. The results of the study demonstrated that children in the primary to early-permanent dentition stages showed higher and more variable holding forces than adults. The results also demonstrated that children in the late-permanent dentition group showed similar holding forces compared to adults. Further, the children in the primary and early-mixed dentition showed longer splitting duration compared to adults and displayed a predominantly step-wise ramp-increase of force. To our knowledge, this is the first attempt to investigate the age-related changes in the regulation of forces during oral fine motor control tasks in children at different dental eruption stages.

4.1. The development of dynamic force regulation during food manipulation

Previous studies on the biting maneuvers have suggested that the intensity and magnitude of forces, point of attack, and the direction of forces are significantly determined by the PMRs [18]. These studies have shown that healthy adults with intact periodontium automatically use low holding force, typically below 1 Newton, to optimize the information provided by the PMRs [18,27]. During the early stage of teeth-food-contact, the PMRs signal vital sensory information to regulate the forces required to breakdown the food [20,28–33]. The holding force in the adults was 0.8 N, which is comparable to previous studies in healthy individuals (0.6-0.8) N [20,21,26,27,34]. These studies have suggested that the low forces during the holding phase could be attributed to the increased sensitivity of PMRs at lower force levels [20,21,26,27,29,34].

Previous studies have also shown that when inputs from PMRs are blocked by dental anesthesia, the holding forces during biting maneuvers increase two to threefold [20,21,27,30,32]. Similarly, individuals who lack inputs from PMRs due to the absence of natural teeth (dental implant), the holding forces during biting maneuvers increase 2.5 to 3.5-fold [26,34]. These studies have suggested that the manipulative skills during the holding phase are challenged by the absence or alteration of signals from the PMRs. The effect of altered inputs are compensated by applying higher holding forces to control the food morsel [20,21,26,27,34]. Interestingly, the holding forces obtained by the children in the current study was comparable to previous results of individuals with PMRs signal alteration. Youngest children (in the primary dentition) employed holding forces that were 4-fold higher than adults, while the forces were 3-fold higher in children in early-mixed dentition and reduced with age to be 2-fold higher in children in late-mixed and early-permanent dentition (Fig. 2A).

It has been suggested that while manual skills are quite well developed in early childhood in comparison to infants, manual dexterity (fine coordination) is still immature (for review please see [35]). In the current study, the variability of the holding forces was higher in children from primary to early-permanent dentition stages, which decreased with the increase in age (Fig. 2B and C). The higher and more variable holding forces in the children might suggest an immature oral fine motor control in comparison to the adults. The different mechanoreceptors, in and around the oral cavity, provide viable information for the fine coordination of the jaw muscles during food positioning and biting maneuvers [18,36]. With the increase in age, the different orofacial structures exhibit massive developmental changes that may challenge the oral motor system to appropriately manipulate and chew food [9].

For example, the width of upper and lower jaws increases exponentially with age–in order to occupy the changing dentition–which fully matures around the late-mixed to early-permanent dentition stages [37]. Paralleling the dimensional skeletal changes of upper and lower jaws, masticatory muscles present age-related changes in fiber composition and structures [38]. Additionally, from the age of six years, the primary dentition begins its prolonged transit to the permanent dentition, which may indicate a concomitant development of PMRs. However, the developmental characterization of PMRs in humans during the transition of dentition is yet to be fully elucidated. In animals such as cats and rats, the development of PMRs paralleled the development of dentition [39,40], where they were denser in permanent teeth than in primary teeth [40]. Anatomically, the human's primary central incisors have shorter and thinner root structures compared to their permanent successors. If the results from the animal studies could be generalized to humans, they would suggest that the primary central incisors have reduced PMRs density which may further be compromised by the resorption of the primary roots by permanent incisors. This implies that they would perhaps rely on other less sensitive orofacial mechanoreceptors that disturb the manipulative skills during food holding. Furthermore, the delayed attainment of the adult-like holding forces could be explained by the late development of the roots of permanent central incisors which do not fully develop until early adolescence (between the ages of 10- to 11-years) [41]. This could imply a delayed characterization of the apically located PMRs, hence delayed attainment of the adult-like oral fine motor control.

4.2. The development of force regulation during food splitting

Splitting forces in the current study were similar between all the groups. This indicates that the splitting forces are not influenced by the inputs from the PMRs [21,25,26,34,42]. Instead, splitting forces are primarily influenced by the mechanical properties and perhaps to the sharpness of the incisal edge of the biting teeth [20,21]. However, earlier studies suggested a pivotal role of PMRs on the food splitting duration [21,25,34]. The duration of the splitting phase in the current study showed age-related changes, where it was significantly longer in younger children (with primary dentition) than adults by approximately 50% (Fig. 3B). Further, the pattern of force increase during the splitting phase also showed age-related changes from children to adults. Where, more than two-thirds of the trials performed by the children with primary dentition showed a step-wise ramp-increase of force during the splitting phase but, it occurred in only one-third of the trials performed by adults (Fig. 4B). Both the duration of the splitting phase and the occurrence of the step-wise ramp-increase of force decreased with age, where the attainment of the adult-like splitting phase was achieved during the late-mixed dentition stage. The splitting duration of the adult group was similar to previous studies of healthy adults of about 0.2 seconds [21,25,26,34]. Whereas, the longer splitting durations of children in primary and early-mixed dentition stages (0.41 and 0.35 s, respectively) were comparable to the splitting duration reported by individuals with dental anesthesia and periodontitis (0.47 and 0.4 s, respectively) [21,25]. The current results of longer splitting duration and the predominantly step-wise ramp-increase of force during the splitting phase in children with primary and early-mixed dentition stages may indicate a compensatory mechanism during biting in response to immature oral fine motor control. Previous studies have attributed higher levels of motor noise, less efficient sensorimotor integration, and inability to produce adequate muscle force to explain differences in motor performance between younger and older adults [43,44]. We suggest that the resultant immature fine oral motor control in the children may indicate an increased vulnerability of the neural networks responsible for integrating sensorimotor information [45].

5. Conclusions

The results of the present study revealed age-related changes in fine motor control of biting maneuvers. Specifically, an adult-like force control during the food manipulation phase is achieved during the late-permanent dentition stage. Whereas an adult-like regulation of forces during the food splitting phase is achieved during the late-mixed dentition stage. The results of the study suggest that younger children with primary dentition show signs of immature oral fine motor control. However, with an increase in age and the accompanying structural changes, the oral fine motor control eventually transits to a more matured adult-like biting maneuvers.

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7. Declaration of interest

The authors declare no conflict of interest.

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Figure legends

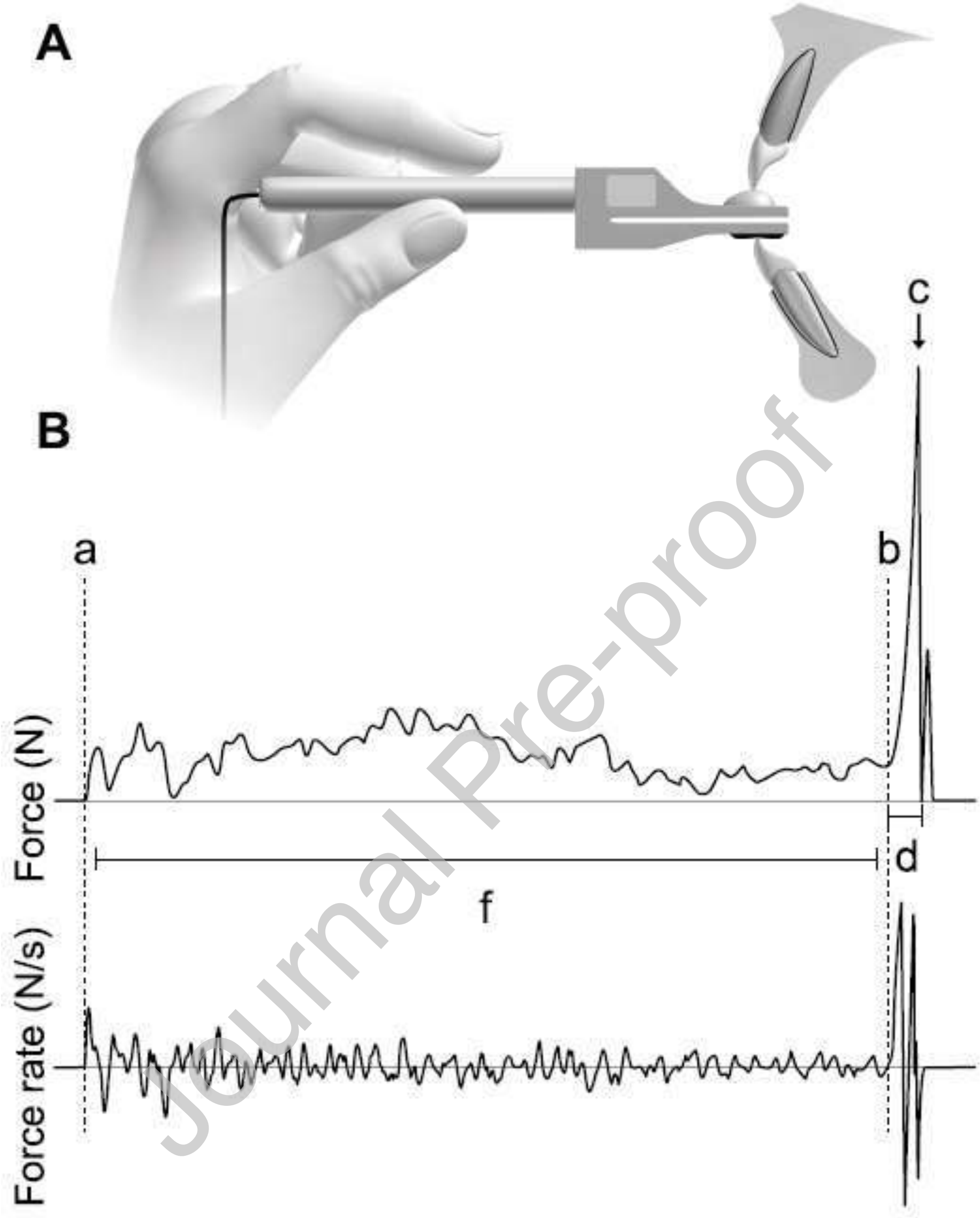

Fig. 1. (**A**) Illustrates the apparatus used in the current experiment. The apparatus consists of a hand-held force transducer which terminates into two rectangular plates. The food morsel was placed on the upper plate of the transducer and positioned into the mouth and held between two antagonist central incisors for 3-4 seconds before splitting it. The lower plate of the transducer is equipped with a grooved plexiglass to facilitate the positioning of the transducer into the mouth. (**B**) Shows the schematic representation of the obtained force and force rate profiles (upper and lower traces,

respectively) of a single trial of the hold-and-split task. Time-point (**a**) defines the initial contact of the peanut; (**b**) defines the start of the splitting phase (where the force rate exceeded 5 N/s); (**c**) demarcate the splitting force and the splitting phase ending; (**d**) defines the duration of the splitting phase in seconds; and (**f**) defines an interval in the holding phase which begins 0.2 seconds after the initial peanut contact and ends 0.2 seconds before the start of the splitting phase.

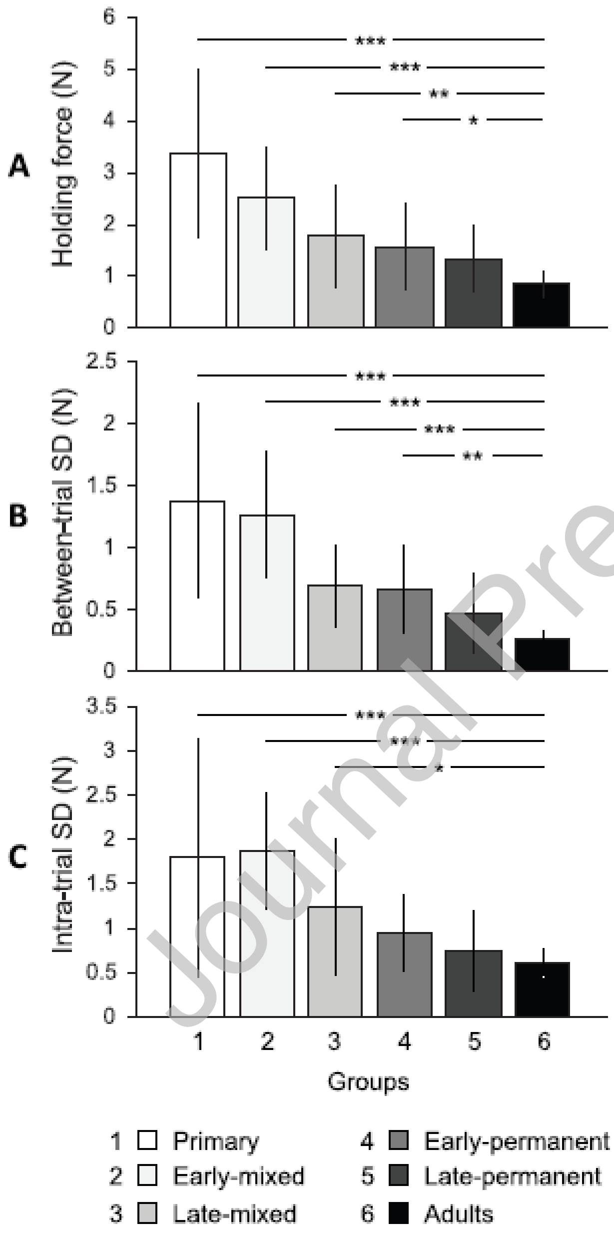

Fig. 2. Bar graphs show the mean (± 1 SD) of the holding forces in Newton (**A**) during the holding phase. Bar graphs **B** and **C** show the between-trial variability and the intra-trial variability of the mean holding forces (standard deviation) for children subgroups and adults, respectively. The horizontal axis represents children's dental subgroups and adults.

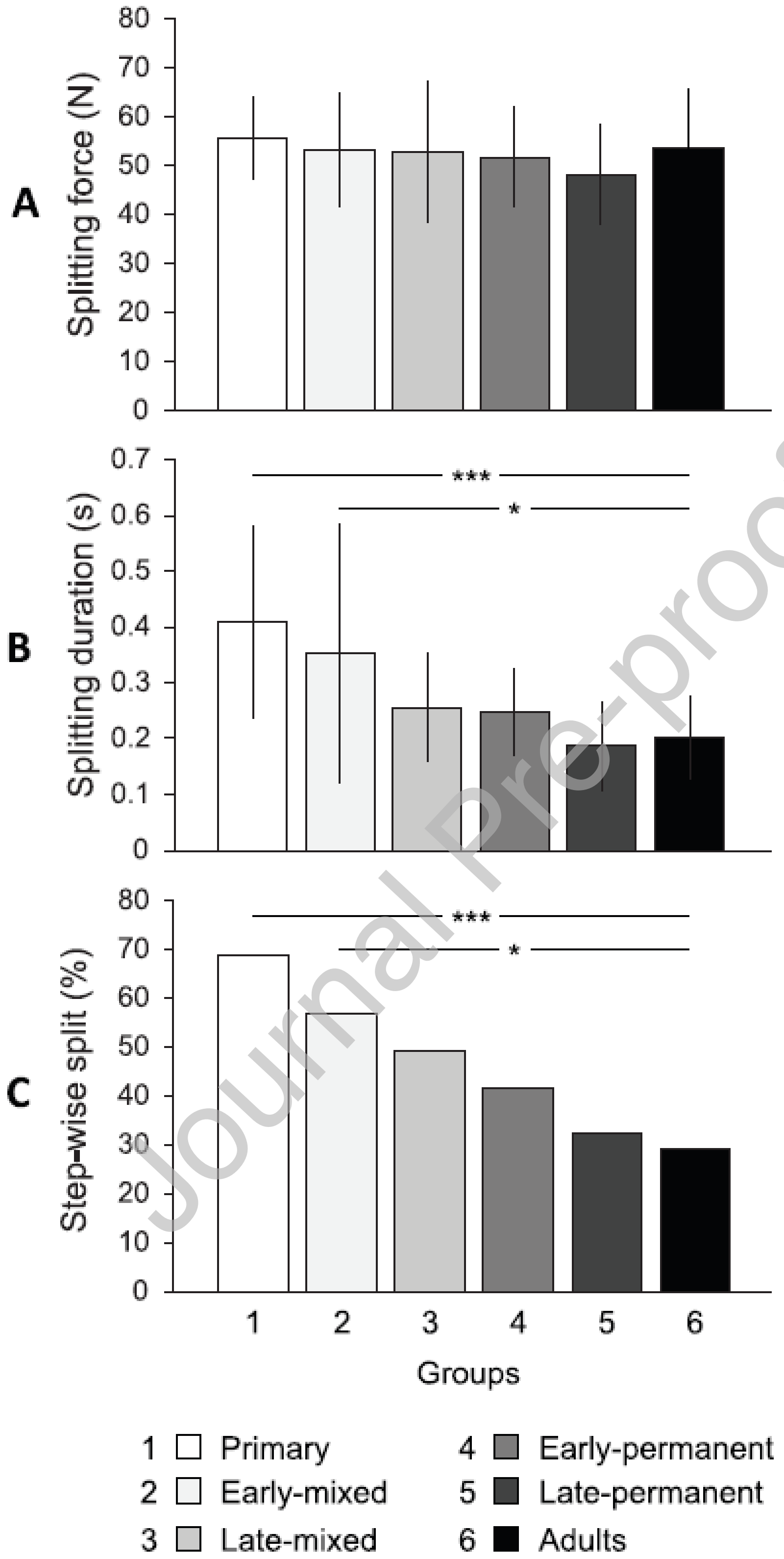

Fig. 3. Bar graphs show the mean (± 1 SD) of (**A**) splitting force in Newton, (**B**) splitting duration in seconds and, (**C**) the pooled percentages of trials presented with a step-wise ramp increase of force during the splitting phase. The horizontal axis represents children's dental subgroups and adults.

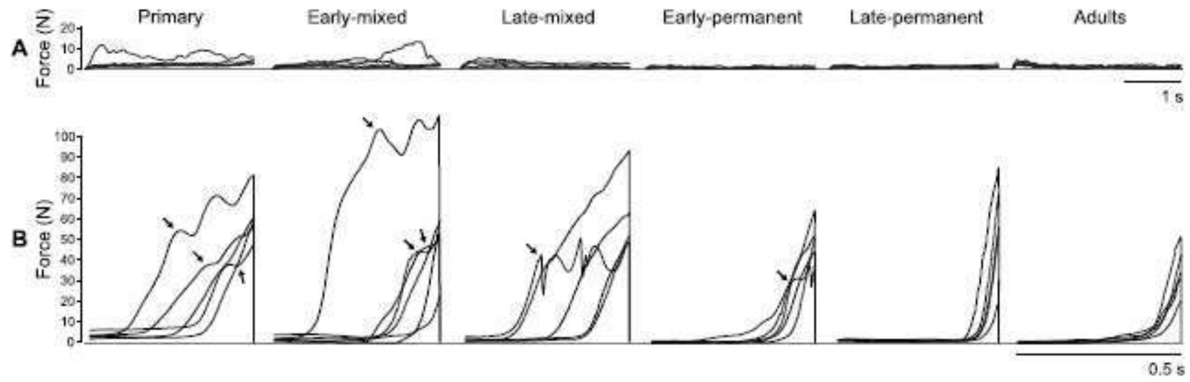

Fig. 4. Example of five temporal force profiles obtained from one individual in each of the children's dental subgroups and adults. (A) Represents the first three seconds of holding phase (superimposed at the start of the force profile), and (B) represents the same force profiles 0.5 seconds before the splitting force (superimposed to the peak splitting force). Arrows in B indicate trials where the peanut broke in a step-wise pattern.