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Review

Development of the jaw sensorimotor control and chewing - a systematic review

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ABSTRACT

Mastication is a complex sensorimotor interaction between the central nervous system and the peripheral masticatory apparatus. To understand the effect of oro-facial abnormalities on mastication, it is important to first understand the normal development of jaw sensorimotor control and chewing in healthy children. Original studies which investigated four main objective parameters of chewing, i.e. maximum occlusal bite force, electromyography (EMG), jaw kinematics and chewing efficiency in children were systematically searched using three established databases. The targeted sample was healthy children below the age of 18-years. All studies that subjectively assessed mastication, studies of children with abnormalities, or non-English studies were excluded. A total of 6193 papers were identified, 53 met the final inclusion criteria. Results are presented according to the dentition stage. Children below 6-years (primary dentition) had lower biting forces and EMG activity, and the frontal jaw movement pattern was more laterally displaced and less stable than children older than 6-years. EMG activities and bite forces increased in children 6- to 10-year-old (early mixed dentition) with a reduction in lateral jaw displacement and an increase in vertical jaw displacement. Twelve-year-old children were able to chew food into smaller particles compared to 6-year-olds. Gender differences were visible in all parameters except EMG activity in late mixed dentition (10- to 12-years). After 12-years, there was a significant increase in bite forces and EMG activities, and the frontal jaw pattern became similar to adults. Studied chewing parameters gradually improve with the development of the oro-facial structures and were mainly influenced by dental eruption. A significant development of chewing parameters occurs after 12 years of age. A transition to the adult-type of masticatory behavior occurs between 10- to 14-years of age.

1. Introduction

Chewing function is an essential aspect of oral and general health [1]. Several studies have indicated that impaired chewing ability affects the nutrient intake subsequently worsening the nutritional status and as a result affecting the general health status of the people [2–6]. Chewing for humans is a complex, rhythmic, learned behavior accomplished by a series of synchronized movements coordinated by the masticatory apparatus. The masticatory apparatus is involved in multiple other functions including swallowing, digestion, respiration, and speech. In addition to these functions, there is compelling evidence, particularly in animals, that chewing increases the blood flow to the cerebral cortex and hippocampus and may thus play an important role in improving subjective alertness and working memory [7–10].

The normal chewing process is complex and begins by the ingestion of food morsel in the mouth and subsequently placing the morsel in between the teeth and applying the required force to crush the food into smaller pieces. The chewing process is assisted by coordinated actions of the tongue, jaw and masticatory muscles to appropriately position the food morsel during the act of chewing. The process also triggers salivary secretion which helps in lubricating the food morsel and forming a soft, coherent and moistened bolus suitable for swallowing. This complex, rhythmic and semiautomatic process is further influenced by the physical properties of the food such as hardness and texture, taste, number of jaw movement cycles, masticatory muscle activity, biting forces and other contributing factors that determine successful food breakdown [11].

Mastication can be assessed by either objective (i.e., clinical tests) or by subjective (questionnaire) methods. Undoubtedly, the subjective assessment of mastication has the advantage over objective methods by not using specialized equipment. However, it is weakly correlated with objective methods [12], and they tend to give optimistic self-scoring of

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masticatory ability compared to the scores obtained by practitioners evaluation [13]. The objective clinical quantification of specific parameters involved during the act of mastication may be difficult or even impossible to perform without interfering with the normal chewing task. Measuring chewing bite forces, for example, requires a force sensor that is continuously placed between the teeth during the crushing of food morsel which is not possible unless incorporated within a prosthesis. Throughout the years, clinical studies concerning chewing performance searched for a quantifiable, objective parameter that could be performed in a clinical setting and is reliable enough to present the status of mastication. Several objective parameters were explored. These parameters could be broadly categorized into four main categories of objective determinants of mastication; maximum occlusal biting forces (MOBF), electromyography (EMG) of masticatory muscles during biting [14–17] or chewing, analysis of masticatory jaw movement time, cycles and trajectories, and chewing efficiency tests [18–22]. Although children begin to chew quite early in life and throughout their development, they are exposed to substantial oro-facial growth which put challenges to their chewing performance. It is not clear, however, how the above mentioned masticatory parameters adapt in response to oro-facial growth and when the acquisition of a matured adult-like sensorimotor control occur.

To strive to fill-up the lacunae in literature, this systematic review was devised to explore the normal development of jaw sensorimotor control and chewing parameters (MOBF, EMG, jaw kinematics and chewing efficiency) in healthy children below the age of 18-years. Cross-comparison of these parameters to adults and between boys and girls will be presented.

2. Materials and methods

The protocol for the current systematic review was registered a priori in PROSPERO (CRD42017069760) and presented according to PRISAM-P guidelines [23].

2.1. Information sources and search strategy

Two experienced librarians performed a systematic search on June 2017 and updated on March 2018. The search was conducted from inception in the following databases: Medline (Ovid), Embase (embase.com) and Web of Science Core Collection. The MeSH terms identified for searching Medline were adapted in accordance to corresponding vocabulary in Embase. Each search concept was also complemented with relevant free-text terms, and these were, if appropriate, truncated and/or combined with proximity operators (File 1, supplementary section).

An attempt to retrieve all relevant papers/manuscripts not included in the databases mentioned above was made by searching terms, for example; chewing in children, bite force, electromyography and jaw kinematics on Google Scholar. The first one hundred hits were carefully screened. Unpublished literature was searched using the Open Grey database (system for information on grey literature in Europe). In addition, the backward and forward citations of the included studies, as well as the reference lists of major reviews, were manually searched. There were no restrictions on the date and type of publication, although only articles written in English were considered for inclusion in the review. The inclusion and exclusion criteria are described in Table 1.

2.2. Selection strategy

The Search results were exported to EndNote program in which duplicates were removed using the built-in duplicate removal feature and confirmed by manual screening. After de-duplication, the list was exported to Microsoft Excel in which two independent researchers (A.N. and K.A.) screened the titles and abstracts of the included articles and categorized them into excluded, included and undecided using a specific template. For articles over which there was indecision regarding eligibility for inclusion, the matter was resolved by a mutual discussion, and by consulting a third researcher (whenever necessary). If the inclusion/exclusion of an article remained undecided, the full-text was acquired. The two researchers conducted a full-text examination of the remaining list of potentially eligible papers, and articles which satisfy the inclusion/exclusion criteria were selected for inclusion in the review. Article exclusion was based on a clearly-stated reason, and articles over which inclusion/exclusion was undecided, again, the matter was resolved by a mutual discussion, and by consulting the third researcher. Any particular article for which further clarification is required, additional information was requested from the original author.

2.3. Quality assessment

The quality of the included studies was evaluated by the Joanna Briggs Institute critical appraisal tools (2017) [24]. Disagreements were resolved by mutual discussion, and by consulting a third researcher (File 2, supplementary section). It is important to note that no article was excluded based on the quality assessment. The following data were extracted from the eligible articles: country and date of publication, the aim of the study, method, study population, main results, study summary and remarks (File 3, supplementary section).

3. Results

The search strategy yielded 6193 papers, 4 of them were identified through Google Scholar and bibliography search (Fig. 1). A total of 53 articles met the final inclusion criteria; 6 were longitudinal, and the remaining were cross-sectional in design. Among the included studies, nine papers were judged by the two reviewers (N.A. and A.K.) to have a moderate-to-high quality [25–33]. The remaining studies were low-to-moderate quality.

The included studies covered the four commonly used parameters for jaw sensorimotor control and chewing in healthy children. The developmental milestones of these parameters will be reported in the current study based on the eruption time of primary and permanent dentition [34]. The developmental patterns of the four objective parameters obtained from the included studies are summarized in Table 2.

3.1. Maximum occlusal bite forces

MOBF is generally measured with gnathodynamometer or other suitable transducer and is traditionally used as one of the clinical measurements for assessing the dynamic action of masticatory muscles during the normal physiological act of chewing. Although the biting forces applied during normal chewing behavior are usually lower [35], knowing the maximum load applied by masticatory muscles could be helpful to establish a reference value that reflects the functional state of mastication [36] and to eliminate the diagnosis of any disturbances in the masticatory system [37].

Among the included studies in the review, twenty-one studies measured MOBF. Fourteen studies obtained the MOBF from healthy children only [28–30, 32, 38–47] and seven studies compared MOBF in children to healthy adults [25, 27, 48–52]. Different gnathodynamometers were used among the studies which had different designs and fork dimensions. Four studies used a custom-built transducer [40, 49, 51], one study used two transducers with different diameters, one is a custom-built device, and the other is commercially available (Kistler Corp., New York, USA) [25], two studies used MPX5700 (Motorola, Austin, TX, USA) [38, 42], one study used MPM-3000 (Nihon Koudenshi Co., Tokyo, Japan) [41], four studies used GM10 (Occlusal Force-Meter GM10, Nagano Keiki Co. Ltd., Tokyo, Japan) [28, 30, 39, 43, 47], another four studies used DDK (Dinamômetro Digital Kratos model DDK, Kratos Equipamentos Industriais Ltda., Cotia, Brazil) [29, 46, 48, 50], unspecified device was used by one study [27], and the

Table 1
The inclusion and exclusion criteria implemented in the screening and eligibility process.

Inclusion	Exclusion
● Objective chewing parameters i.e., maximum occlusal bite forces, electromyography, jaw kinematics and chewing efficiency. ● Healthy children (below 18-years). ● Studies with or without cross-comparison to healthy adults.	● Orofacial abnormalities and congenital defects such as cleft lip and/or palate, cerebral palsy, temporomandibular joint disorder, muscle pain, malocclusion, missing teeth and dental caries. ● General health conditions and syndromes such as ADHD, autism, obesity and other syndromes that might affect directly or indirectly the normal development of chewing. ● Subjective evaluation of mastication (questionnaires). ● Non-original studies (i.e., reviews, letter to editors, abstracts…etc.). ● Non-English studies.

remaining four studies used a U-shaped pressure sensitive sheet (Dental Prescale, Fujifilm Co. Ltd., Tokyo, Japan) which measures the pressure forces applied by all the occluding teeth [32, 44, 45, 52].

The method of obtaining MOBF was different among the studies. The majority of the studies measured MOBF bilaterally [28–30, 38–41, 43, 46, 48, 51] while others measured MOBF during unilateral biting only [25, 42, 47, 49, 50]. The location at which the fork was placed in the mouth was also different across different studies. The fork was placed either in the premolar/deciduous molar region [38, 43, 47, 49], first permanent molar [25, 29, 30, 40, 46, 48, 51] or there was no clear mention of the location [27, 41, 42, 50]. Two studies obtained MOBF in primary first/second molar region in children under 8-years and on the permanent first molar in children older than that age [28, 39]. After recording bite forces either the average value [28, 30, 38–40, 48] or the highest applied value was taken as MOBF [29, 41, 42, 46, 49, 50]. However, six studies had no clear description of MOBF calculations [25, 27, 42, 43, 47, 51].

A schematic representation of the mean MOBF pooled from eleven studies which provided the descriptive data within gender across different age groups has been presented in Fig. 2 [27–30, 32, 40, 41, 43, 48, 50, 51]. An empirical observation of the trend lines shows an increase in MOBF with age where children below the age of 12-years applied lower biting forces than adults [27, 30, 39, 40, 48, 51]. The lowest MOBF was recorded in 3-year-old children. There is a slow and steady increase in MOBF with an increase in the age, and differences in MOBF between boys and girls occur in the range of 7- to 10-years [28, 41, 49]. It is believed that the differences of bite forces between girls and boys become dramatically apparent during the post-pubertal period [29, 30, 49, 50]. Bakke et al. studied healthy participants from 5- to 70-years and found that the MOBF increased with age until the age of 25. After this age, the forces decreased significantly in women, whereas this decrease in bite forces was only evident after the age of 45 in men [51]. However, the declining trend of MOBF in women after the age of 25-years was not observed in the pooled data in Fig. 2, where the decline of MOBF in women occurs after the age of 40-years.

3.2. Electromyography of masticatory muscles

The act of chewing involves an interaction between jaw-closing and jaw-opening muscles. The activity of masticatory muscles correlates well with the magnitude of chewing bite forces [53]. Nine studies evaluated the EMG of masticatory muscles during chewing [31, 54–61]. As it was observed in MOBF studies, studies on EMG were heterogeneous in their methodology and had a different approach in

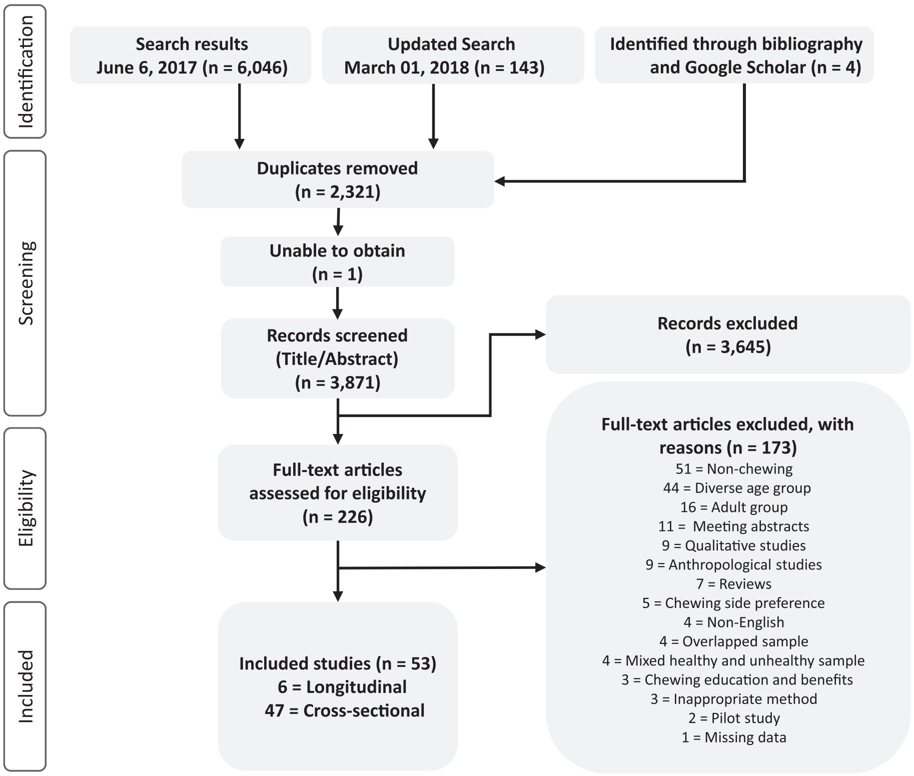

Fig. 1. PRISAM flow diagram capturing the screening and eligibility process. Note that four articles were identified through the bibliography and Google scholar search and one article could not be retrieved either as digital or paper forms.

Table 2
The main findings of the normal development of the four main categories of objective chewing parameters obtained from the included studies. Horizontal arrow (→) indicates a gradual increase in a chewing parameter, while a significant increase represented by a vertical upward arrow (↑). Triple bar (≡) indicates a stage of transition of chewing parameter from child-like to adult-like performance. The equal sign (=) indicates a stage at which a specific parameter becomes similar to adults. Combined upward and downward arrows (↕) represent conflicting results of increase or decrease between the studies. Unavailable data represented by the non-applicable sign (NA). For each parameter in each age category, the differences between boys and girls were presented. The equal symbol (=) represents no differences in chewing performance between boys and girls, triple bar (≡) represents an age at which differences between boys and girls start to show, and unequal sign (≠) represents different performance between boys and girls.

Chewing parameters		Primary dentition 0 to < 6 years	Early-mixed dentition 6 < to < 10 years	Late-mixed dentition 10 < to < 12 years	Permanent dentition 12 < to < 18 years
Maximum occlusal bite force	General trend	→	→	↑	=
	Sex differences	=	≠	≠	≠
Electromyography	General trend	→	→	↑	=
	Sex differences	NA	NA	=	=
Chewing time and cycle	General trend	↕	↕	↕	↕
	Sex differences	=	≡	≠	≠
Jaw movement pattern	General trend	→	→	≡	=
	Sex differences	NA	NA	NA	NA
Length of jaw trajectories	General trend	↕	↕	=	=
	Sex differences	NA	NA	NA	NA
Food trituration	General trend	→	→	→	NA
	Sex differences	NA	NA	≠	NA
Bolus kneading	General trend	→	→	→	↑
	Sex differences	NA	NA	NA	≠

interpreting EMG data. One study recorded the longitudinal development of the onset and offset of EMG burst activity and computed the cross-correlation function across EMG data of the right and left masseter and temporalis muscles and the anterior belly of digastric in healthy young children (12- to 48-months) [54]. Another study only computed the cross-correlation function of EMG of the same muscles in healthy 9-month-old infants [55]. Two studies recorded the maximal mean voltage amplitude of the temporalis, masseter muscles and lips in 9- to 13-year-old children [31, 56]. Maximal integrated EMG activity of the temporalis and masseter muscles was recorded for children and adults in one study [57]. Another study recorded the EMG onset and offset burst activity of the posterior temporalis and inferior orbicularis oris muscles in 11 -year-old healthy children [58]. Another study computed the percentage of EMG activity of the anterior and posterior temporalis and masseter muscles to the total EMG activity in healthy children 4- to 12-year-old [59]. The EMG signals of the bilateral temporalis and masseter muscles in 7- to 80-year-old healthy participants were recorded in one study and normalized based on EMG activity during clenching behavior [60]. The last study computed EMG signals of the right and left masseter and the anterior belly of digastric and computed the autocorrelation and the Fast Fourier Transformation of signals in healthy young children (9- to 36-months) [61].

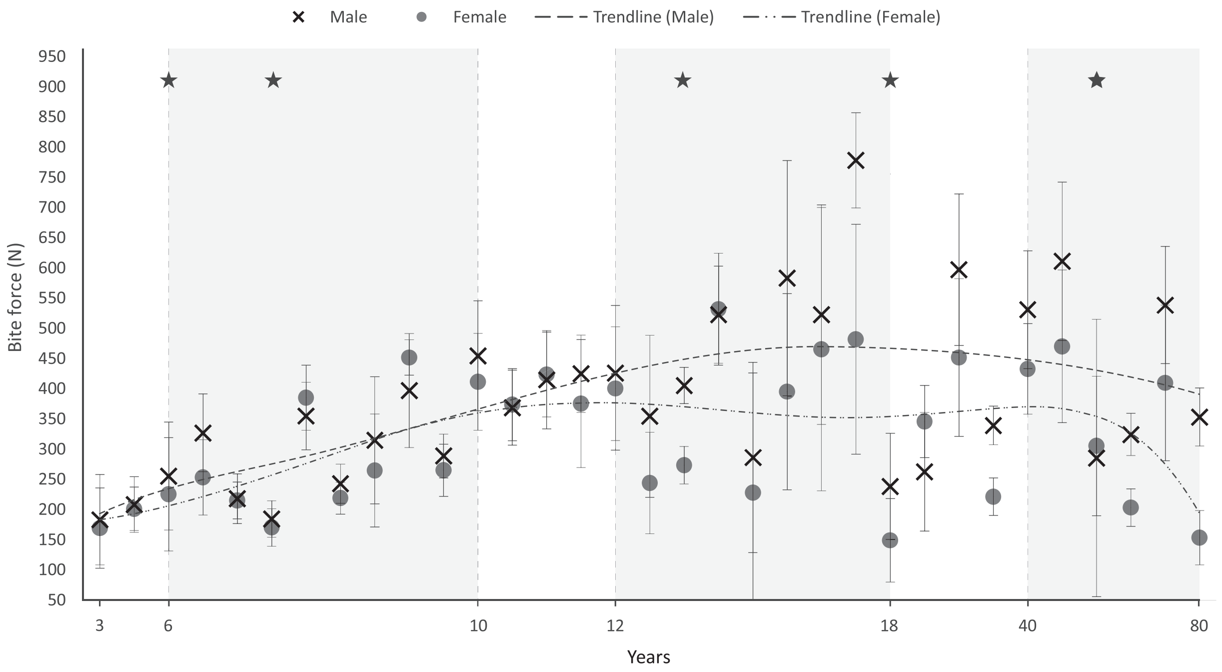

Fig. 2. The trend lines of the pooled means and standard deviation of posterior maximum occlusal bite forces of boys and girls that were reported by 11 studies. The y-axis represents the mean bite forces in Newton, and the x-axis represents the years. The total sample constitutes of 2002 participants below the age of 18-years (1003 boys and 999 girls) and 252 adults (124 men and 128 women). Note that the age categories represent the age groups that were studied among the included papers. They were categorized as follows: between 3- to 6-years represent the stage of primary dentition; between 6- to 10-years represent the early stage of transition of primary dentition to permanent dentition; above 10- to 12-years represent late stage of dental transition; above 12- to 18-years represent the permanent dentition stage; and 40- to 80-years represent the adult agegroup. Values annotated with ((★)) indicate an age group overlapped between two age categories.

Nine-month-old children had increased variability in EMG burst duration and pattern of activation compared to older children and adults [54, 55]. The synchrony of bilateral masseter muscles was greater than temporalis and anterior belly of digastric [55]. Chewing behavior becomes more efficient with age from 12- to 48-months of life [54]. It was characterized by a decrease in EMG burst length and duration with a reduced intra-trial variability during chewing cycle and the onset and offset activity of jaw-closing muscles become more synchronized [54]. In addition, there was a greater synchronization of the onset and offset between agonist and antagonist muscles [54, 61].

The EMG activity was higher and more prolonged in chewing behavior than in swallowing [31, 56, 57]. Children who exhibit higher EMG amplitude of the temporalis and masseter muscles during maximal biting were also showing higher amplitudes during chewing behavior [31]. The increase in the number of teeth was found to correlate significantly with higher masseter muscle activity and lower chewing time and cycle [31]. Takada et al. found that hard food increases the onset of EMG burst for posterior temporalis muscle in children at the age of 11 years [58]. Eleven-year-old children performed similar integrated EMG activity of temporalis muscle and lower activity in the masseter muscle compared to 25-year-old adults [57]. Additionally, children aged 9- to 13-years showed similar EMG activity on the right and left sides of masseter, posterior and anterior temporalis muscles, and there was no significant sex difference between boys and girls [59]. Palinkas et al. [60], observed that 7- to 12-year-old healthy children applied the lowest muscular activity compared to older age groups from 13- to 80-year-old and found that there was a significant increase in muscle activity at 13 years of age which corresponds to the period at which the differences of MOBF among genders become significant [29, 30, 49, 50].

3.3. Masticatory jaw kinematics

Chewing can be evaluated by recording and tracking the mandibular movements in reference to the maxilla. This jaw motion in response to the act of chewing could be analyzed in anterior-posterior, lateral and vertical dimensions. The number of cycles needed to chew a specific food and the total time taken before swallowing that particular food could also be helpful to understand and analyze the chewing performance. Based on these measurements, there were 22 papers studied the jaw movement pattern, length of chewing trajectories and chewing time and cycles. Eight studies were using different optoelectronic devices [62–69], six studies used videography technique [26, 70–74] and four studies used different motion capture systems [75] [76] [77] [78]. Among the last four studies, two used magnetic jaw tracking system [58, 79] and the other two papers used a custom-built recorder and replicator system [80, 81].

3.3.1. Chewing time and cycles

The pooled mean and standard deviation of chewing time and cycles of different food consistencies performed by children aged 2- to 8-years are shown in Fig. 3 [71, 73, 74]. Eating behavior was affected by food hardness [61, 71, 73, 74], and it seems that chewing time and cycles of children stabilized earlier for solid food than for viscous and pureed foods, but the time needed to eat solid food was longer than the other two consistencies [26, 58, 71].On a longitudinal follow-up of 11 children from the age of 9-months to 30-months, Wilson et al. showed that the speed of jaw closing phase decreased with age, but there were no differences in closing speed between puree and regular foods until the age of 18- to 24-months. After this age, the time needed to chew puree was faster than the regular consistency [75]. With age increase, the intra-individual variability was reduced [72], but conflicting results were found regarding the time and the number of cycles needed to chew natural food. Some found a decline in chewing cycle duration with age [26, 61, 70, 71, 73, 74, 76] while others found an increase [64, 65, 68, 72]. It seems that girls chew slower than boys during 4- to 8-years of age, but after this age, they chew faster than boys and the trend remains until adulthood [72].

3.3.2. Jaw movement pattern

The most common jaw movement pattern of children during chewing behavior was characterized by a broad lateral opening phase towards the food side, then a closing phase that is more medially than the opening phase [81], but adults performed an opposite jaw pattern that is characterized by medial opening and more laterally projected closing path [66, 67, 80, 81]. In 9-month-old infants, mandibular trajectories were indistinctive during chewing behavior [77]. With development, there was an increase in vertical jaw displacement and a decrease in lateral jaw displacement in children from the age of 9- to 36-months [61]. It was shown that at the age of 12- to 14-years a total shift to the adult-like jaw pattern occurs which was characterized by a medial opening towards the balancing side and a lateral closing phase [80, 81]. This, again, coincides with the significant increase in biting forces and muscular activities during chewing [29, 30, 49, 50].

3.3.3. Length of jaw trajectories

Intra-individual variability of chewing cycle was more prominent in 4- to 6-year-old children compared to adults [62, 64, 69]. The total chewing trajectory was shorter in children 4- to 8-years compared to adults [62, 64, 68, 69]. In contradiction to this finding, other studies have found an increase in mandibular trajectories in 1- to 2-year-old children compared to 3- to 5-year-olds [78] and in 9- to 10-year-old children compared to 13- to 15-year-olds and young adults [63]. Eating hard food requires children to move their mandible in broader lateral movements than soft food [58]. Interestingly, in 10- to 14-years, the duration of chewing trajectories and between-cycle variability were similar to adults [72].

3.4. Chewing efficiency

Eleven studies evaluated the chewing efficiency based on food trituration skills and bolus kneading of color-changeable gums in healthy children [27, 29, 33, 39, 41–43, 46, 47, 52, 82]. There were three methods used in these studies to determine the efficiency of food breakdown. The first was the sieving method, which is based on filtering the chewed particles of a particular test food into different sieves and better performance is determined by smaller particle size and particle distribution. This particular method was done in a jelly-based test food in one study [82], artificial silicon tablets alone [27, 42] or combined with a colorimetric evaluation of chewing performance using color-changeable gums [33, 46]. Six studies done the colorimetric evaluation of the color-changeable gums alone [29, 39, 43, 46, 47, 52]. This method uses a xylitol gum that contains citric acid and three dyes (red, blue and yellow). During the continuous chewing task, the citric acid is released, and the yellow and blue pigments are gradually washed-out which transforms the color of the chewing gum from green to red color. After a certain chewing time, the chewed gum is flattened to a certain thickness, and the end-color is evaluated to determine the chewing performance. The strength of the red color indicates an increase in chewing performance. In the included studies, the evaluation of the end-color was either using a spectrophotometer [39, 43, 52], a 10-grade color scale [29, 46] or both [47]. A different concept of colorimetric methodology was adopted by one study [33]. It used two-color chewing gum (violet and green), and after a chewing task, the two colors are mechanically mixed, and the end-color is evaluated with the help of a specific program to determine the variance of hue. Fewer variations in hue indicate an increase in chewing performance. The last study used a sac filled with coated-particles composed of adenosine disodium triphosphate (ATP) [41]. Continuous chewing task brakes the coat and releases the ATP. The particles then are filtered in a distilled water, and the distribution of ATP is measured with a spectrophotometer to determine the degree of food trituration.

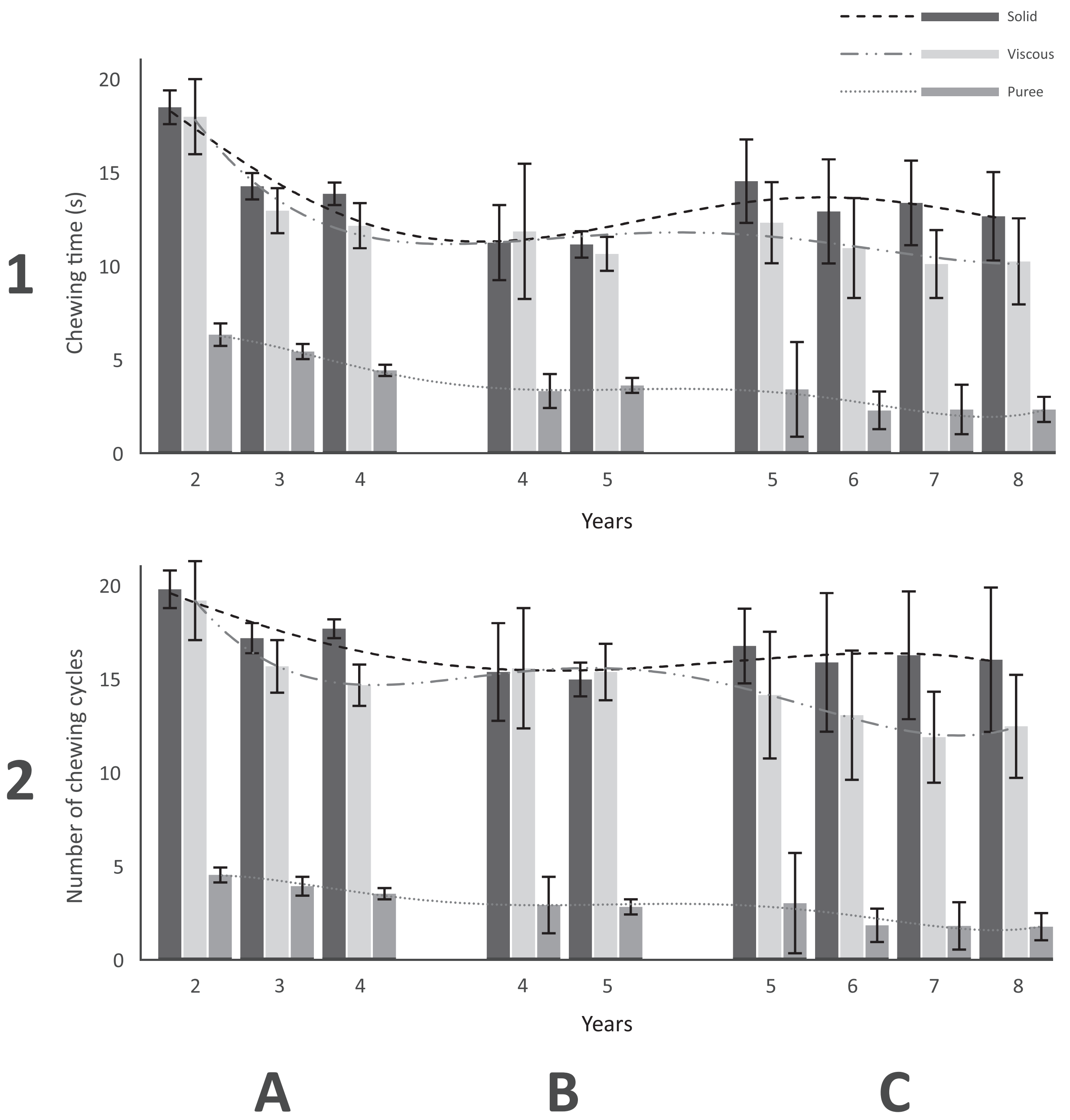

Fig. 3. The trend lines of pooled mean and standard deviation of chewing time in seconds (1) and number of chewing cycles (2) of three food consistencies; solid (Graham crackers), viscous (raisins) and puree (apple sauce). These were reported by three studies using videography technique; A: Schwaab, et al. (1986) studied 2-, 3- and 4-year-old children, B: Schwartz, et al. (1984) studied two age groups (4- and 5-year-olds), and C: Gisel (1988) studied 5-, 6-, 7- and 8-year-old children. It was observed that chewing time and cycles taken to chew hard food was stabilized around the age of 4- to 5-years while viscous and pureed foods stabilized later in life around the age of 7- to 8-years.

3.4.1. Food trituration in children

Based on the distribution of ATP particles, it seems that the sex differences of food trituration do not appear until the age of 9-years with boys being better performers than girls [41]. Children aged 12-years as compared to 6-year-olds got a better eating performance by breaking test foods into a higher number of particles and the size and distribution of these particles were lower which indicate more chewing efficiency [42, 82]. Children in the mixed dentition, although being better performers than younger children, had larger/less number of particles which were broadly distributed compared to adults [27, 33].

3.4.2. Bolus kneading in children

The colorimetric evaluation of color-changeable gums indicated in adolescents aged 14- to 17-years that the boys had better chewing performance than girls with more chewing strokes performed in one minute [29]. The chewing of color-changeable gums and number of strokes in one minute increased with age [33, 39]. Children (4- to 6-years) had fewer strokes and worse performance than older children (9- to 11-years) and adults [52]. The number of teeth was the only variable that is positively correlated with efficient chewing [47]. Children who received training sessions performed better chewing performance compared to children who had no training [43].

4. Discussion

The current systematic review attempts to enhance our understanding of the age-dependent changes of jaw sensorimotor control and chewing parameters in healthy children. Chewing is a complex interaction of neural, skeletal, muscular and dental components. These components transform and evolve in parallel with each other throughout the normal development of children. The normal development of human mandibular length, for example, follows a two-plateau of growth acceleration, one during early childhood and the other during puberty [83]. The width of mandibular arch increases exponentially after the second year with a steady increase until the age of 13-years, when the mandibular width is fully matured [84]. Further, the intensity of pubertal growth is more pronounced in boys than in girls [83, 85]. Interestingly, the same trend of mandibular growth was observed in the normal development of MOBF obtained from the included studies (Fig. 2).

The continuous dimensional growth of the jaws is a prerequisite to accommodate the prolonged eruption of primary and later the permanent teeth. The most obvious function of teeth is to comminute food morsels, and it is not surprising to know that the number of occluding contacts and the dentition stage are the most influential factors of efficient mastication [86]. Usually, children between the ages of 3- to 6-years have all of their primary teeth fully present in the mouth. These teeth, however, are anatomically different than their permanent successors in terms of smoother occlusal surfaces and smaller and thinner anchoring roots. It is well-established that a group of specialized mechanoreceptors embedded within the periodontium surrounding the roots together with other oro-facial mechanoreceptors in muscles, oral mucosa, and temporomandibular joints, play an important role in modulating the jaw motor control [87–93]. The histological characterization of periodontal mechanoreceptor during the transitional stage from deciduous to permanent dentition is poorly understood in humans. In cats, however, a study on the distribution of periodontal nerve endings showed that the primary teeth have an identical distribution of nerve endings as in permanent teeth but are less dense [94]. If this assumption could be generalized to humans, this could perhaps explain the lower regulation of forces and jaw movement in children younger than 6-years of life.

In parallel with the normal morphological changes of skeletal and dental structures, the growth of masticatory muscles presents age-related alterations in composition and structure [95, 96]. Children aged 3- to 7-years had a linear increase in the diameter of type I fiber only, where type I fiber were larger in diameter than type II. In comparison to adults, the relative number of type I fiber was lower, and the mean diameter was smaller by about 1.8 times in young children than in adults [95]. Interestingly, regardless of changes in fiber structure and composition, the morphology of masseteric muscle spindles at this very young age is fully matured [96]. Perhaps, the early morphological maturation of muscle spindles, compared to the later maturation of the extrafusal fiber population, indicates that early on in life there is an increased demand of reflex control needed for learning and performing motor control tasks.

It seems that the peak-maturity of chewing parameters occurs with the maturity of all oro-facial apparatus during pubertal and post-pubertal years. This growth pattern could be assumed following the results obtained from the included studies (Fig. 2 and Table 2). The masticatory motor behavior in healthy young adults is characterized by higher bite forces and fine-tuned and well-synchronized activity of the jaw elevator and the depressor muscles. The frontal pattern of their jaw motor movement is consistent and dominantly vertical in direction. These features all together ensure an efficient chewing of food morsels into smaller particles with little chewing cycles. Conversely, young infants (9-month-old) had immature jaw sensorimotor control related to chewing behavior, but with age, there was a gradual yet steady maturation of all studied parameters within the included studies. Simione et al. [61], suggested two developmental phases of chewing in healthy young children (9- to 36-months). At 9- to 18-months of age, the chewing behavior is characterized by inefficient mandibular control and coordination in which the overshoot in lateral jaw displacements is commonly observed. In addition, the efficiency of eating hard food is lower compared to older children. Unlike the first phase, the molar phase (24- to 36-month-old children) is characterized by more stability in the lateral jaw displacement, increased speed in the vertical jaw movement, stronger muscle coordination and increased eating efficiency of hard food [61].

An increase in between-cycle variability characterizes the motor act of chewing in children under 6-years of life compared to older children and adults. The increase in between-cycle variability seen in young children is not exclusively observed in chewing studies alone, in fact, other non-chewing behavioral studies reported an increase in motor variability in young healthy children [97–101]. The contemporary literature infers variability as an essential background for exploration and selection, and an essential parameter in the normal development of motor performance [102, 103]. Motor variability in young children reflects their increased ability to select from a vast repository of solutions to execute specific motor task [104]. Perhaps, the adult-like jaw sensorimotor control in adolescents is enforced by experience and cognition together with a maturity of oral and dental structures that make their chewing parameters similar to adults.

The sensorimotor control of chewing function lacks well-described developmental milestones. It was observed that walking is acquired quite early in life (around the age of one year), but the refinement of the motor control of walking progresses slowly until adulthood [105]. It was suggested that around the age of 7- to 8-years, the characteristics of children's pattern of walking become similar to adults [106, 107]. On the other hand, a series of studies on the normal development of the human precision grip showed that the adult-like sensorimotor control of the hand is reached around 8- to 11-years of age [108–112]. Interestingly, this gradual development towards a mature motor control of the hand involves a transition from a predominantly feedback motor command to a predominantly feedforward motor command. The motor control of speech production was shown to have a protracted time course development that matures later on in life, beyond the age of 16 years [113]. In relation to the normal development of these sensorimotor functions, we could speculate from the cumulative knowledge gathered from the included studies that a transition to adult-like jaw sensorimotor parameters occurs during the pubertal and post-pubertal periods. However, there is an urge to define and establish functional milestones in chewing jaw sensorimotor control, knowing this will be beneficial to identify deviations from the normal chewing behavior.

5. Limitations

It is important to point out that the generated results were obtained from heterogeneous studies. Chewing efficiency in most studies is determined by the chewing duration and the number of chewing cycles and is further suggested to be influenced by the texture of food [26, 61, 70, 71, 73, 74, 76]. Eating food with hard texture prolongs the chewing time and chewing cycles in comparison to soft food [26, 58, 71]. In the current review, since a wide variety of test food were used, the results could be susceptible to contamination by the test food textures. However, to achieve meaningful results, we have pooled the results obtained from three studies that used similar methods and food textures (Fig. 3).

In addition, measuring bite forces requires the same degree of teeth separation as well as the same location at which the force transducer is placed in the mouth. Different transducer thickness or locations will increase the variability of bite force values [25]. Surface EMG recordings, on the other hand, are reproducible during chewing tasks [114] but differences in experimental settings and applied instruments necessitate a careful standardized protocol [115, 116]. The lack of standardization and normalization in the included studies poses a considerable challenge to achieve an overall consensus in comparing the values obtained from the studies. However, in our report, we have not focused on the absolute values per se, but rather on the developmental trends (increase or decrease) of the specific chewing parameter.

6. Conclusion

Studied chewing parameters gradually improve with the development of the oro-facial structures and were mainly influenced by the dental eruption. After the age of 12-years, there was a significant development of bite forces, EMG activities, and jaw kinematics. A transition to the adult-type of masticatory behavior occurs between 10- to 14-years of age. The clinical implication of this review is to study the developmental milestones of jaw sensorimotor control and chewing behavior in healthy children which may help identify and diagnose signs of sensorimotor impairment in children with diseases.

Conflicts of interest statement

All authors declare no conflicts of interest.

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Appendix A. Supplementary data

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