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Jaw-neck movement integration in 6-year-old children differs from that of adults

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Abstract

Background: A functional integration between the jaw and neck regions during purposive jaw movements is well described in adults, but there is a lack of knowledge of such integration during jaw function in children.

Objectives: To determine the movement integration between the jaw and neck during jaw motor tasks in 6-year-olds, whether there is a difference between children and adults.

Methods: Jaw and neck movements were recorded with an optoelectronic 3D system in 25 healthy 6-year-olds (12 girls, 13 boys) and 24 healthy adults (12 women, 12 men) during paced jaw opening-closing and self-paced gum chewing. Jaw and neck movement amplitudes, intra-individual variation in movement amplitude, ratio between neck-jaw movement amplitudes and movement cycle time were analysed. Differences between children and adults were evaluated with Mann-Whitney *U* test for independent samples.

Results: Compared to adults, 6-year-old children showed larger neck movement amplitudes ($P = .008$) during chewing, higher intra-individual variability in amplitudes of jaw ($P = .008$) and neck ($P = .001$) movements, higher ratio between neck-jaw movement amplitudes for jaw opening-closing ($P = .026$) and chewing ($P = .003$), and longer jaw movement cycle time ($P \leq .0001$) during the jaw opening-closing task.

Conclusion: Despite integrated jaw-neck movements in 6-year-old children, the movement pattern differs from that of adults and may be interpreted as an immature programming of jaw-neck motor behaviour. The well-integrated movements observed in adults most likely develop over years, perhaps into adolescence, and needs further research including well-controlled longitudinal studies to map this development in order to provide appropriate age-related clinical treatment for functional disorders.

KEYWORDS
adult, child, head, jaw, motor activity, movements

1 | INTRODUCTION

Research on sensorimotor development is of great importance for the understanding of normal human motor control and applied to for instance the fields of eye motor control, reaching and grasping, eating and chewing. Many mechanisms for such normal development and their time perspectives and how to investigate them are however still unclear, and particularly in relation to movement disorders of various kinds. Natural jaw functions such as jaw opening, chewing and eating are complex sensorimotor tasks that develop over time in childhood and most likely continue over adolescence and that involve not only the jaw but also the neck.[1,2] Adequate jaw function is of substantial importance for perceived oral and general health. In adults, it is well known that there is a functional integration between the trigeminal and cervical regions, with concomitant jaw-neck movements during jaw function.[1-3] Thus, maximal jaw opening is paralleled by neck extension, and jaw closing by neck flexion with well-coordinated activation of jaw as well as neck muscles.[4] Furthermore, experimental studies in cats have shown an intersegmental reflex connection between jaw closing and neck muscles.[5,6] Disturbed jaw-neck movement behaviour may cause impaired jaw function, thus affecting eating behaviour.[7,8]

The development of normal jaw abilities starts in the foetal stage and continues in childhood and into adulthood with a presumed gradual refinement of motor performance. There is, however, a gap of knowledge with regard to the nature of this gradual maturation of the jaw-neck motor systems. The knowledge of development of jaw motor function and the link between jaw and neck motor systems is essential for understanding of complex jaw motor skills and disorders and their development. In order to obtain such knowledge, there is also a need for adequate methodology on how to assess such functions.

Foetal movements commence at the first trimester with general movements, followed by breathing movements and head, neck and jaw movements (eg, jaw opening, yawning and sucking).[9-11] It has been reported that foetal jaw function is linked to the neck sensorimotor system, with neck movements strongly associated with jaw movements.[12,13] After birth, jaw and neck movements remain strongly associated as exhibited in the 'rooting reflex' where perioral stimulation leads to ipsilateral head rotation. This demonstrates an innate integrated jaw-neck motor function between the trigeminal and cervical regions.

Chewing is an innate rhythmic jaw activity generated by the central neural pattern generator (CPG) within the brainstem [14,15] and modified by sensory feedback.[16] During maturation, a pronounced shift in jaw motor behaviour occurs during tooth eruption (primary dentition developing from 6 to 36 months of age) when suckling and infantile swallowing develops into mastication and mature swallowing pattern and successively continues to develop through early childhood. Children under the age of 6 have more laterally displaced and less stable jaw movements than children above this age. With increased age, children aged 6-10 years display an increase in vertical jaw displacement (see eg[17]). To the best of our knowledge, there is only one study addressing the functional integration between the jaw-neck motor system in children, 4- to 7-year-olds, during jaw opening-closing movements.[18] The authors suggested that head extension in children helps to increase the jaw opening amplitude of mouth opening.

The importance of well-integrated jaw function is significant from a health perspective as it is crucial for many everyday tasks such as eating, talking, mouth hygiene and. However, a deeper understanding of the mechanisms regarding jaw and neck motor control, for the development of jaw motor skills in children, is scarce or how to capture this. To evaluate the functional maturation of the jaw-neck motor coupling in children, coordinated head and jaw movements of young children might be expected to differ from those of adults. We hypothesised that the movement integration between the jaw and the neck during standardised jaw motor tasks in 6-year-old children differs from that of adults with regard to jaw and neck movement variables, that is lower amplitudes, higher variability and smaller proportional involvement of neck movements.

The aim of this study was to evaluate the integration between the jaw and the neck during standardised jaw motor tasks for 6-year-old children, and whether there is a difference between children and adults.

2 | MATERIALS AND METHODS

2.1 | Subject

The study group consisted of 25 healthy 6-year-olds (12 girls and 13 boys, mean age 6.1 years) recruited from a pre-school in Umeå, Sweden, and 24 healthy young adults (12 women, 12 men, mean age: 26.4 years) recruited by advertising from students at Umeå University. The chosen age group for children was based on a pilot study, which tested the study protocol on children aged 4, 5 and 6 years of age. From the pilot study, we concluded that due to the demands on the attention span and compliance to follow the test procedures the protocol was feasible only for the 6-year-olds, but not for the younger children. Furthermore, also for 6-year-old children it was not deemed possible to extend the recording times, although this could affect the number of jaw movement cycles in each recording. Sample size was calculated based on the pilot data. For the mean jaw amplitude in a child group to be different from that of an adult group for ($P < .05$, $\beta = .8$) and with SD 8 at least 18 participants/group would be needed.

The inclusion criteria were (a) negative answers to three screening questions for oro-facial pain and dysfunction (3Q/TMD),[19] (b) no symptoms or signs of pain or dysfunction in the regions of jaw, face, temples, temporomandibular joint, head, neck, shoulders, or upper and lower back regions, and (c) for children normal dentition for the age (primary or early mixed dentition with first permanent molars present) and for the adults a full permanent dentition. Exclusion criteria for both children and adults were mild or severe physical disease with American Society of Anesthesiologists (ASA) class ≥ 2 (cardiovascular, renal, pulmonary or autoimmune disease or malignancy), psychiatric disease (bipolar disorder, ADHD, autism spectrum disorders, anorexia nervosa, bulimia nervosa, schizophrenia and personality disorders) or other disabilities that could affect jaw-neck movement integration. For the inclusion and exclusion criteria for the children, the questions were posed to the child with assistance of the accompanying parent. For the child group, no subjects had received any treatment. For the adult group, previous orthodontic treatment was not an exclusion criteria, but no individuals were under active treatment. For the children, the occlusion was skeletal class I (22 children), class II (one child) and class III (two children), and for the adults, all had skeletal class I. There were no individuals with anterior or posterior crossbite.

All subjects received information and signed a written informed consent prior to data collection. The children's participation was verified by their parents' written consent.

2.2 | Study design

The clinical examination was carried out by an experienced specialist in oro-facial pain/TMD using the DC/TMD criteria.[20] The examiner has been trained and calibrated to stage 3 of the DC/TMD education

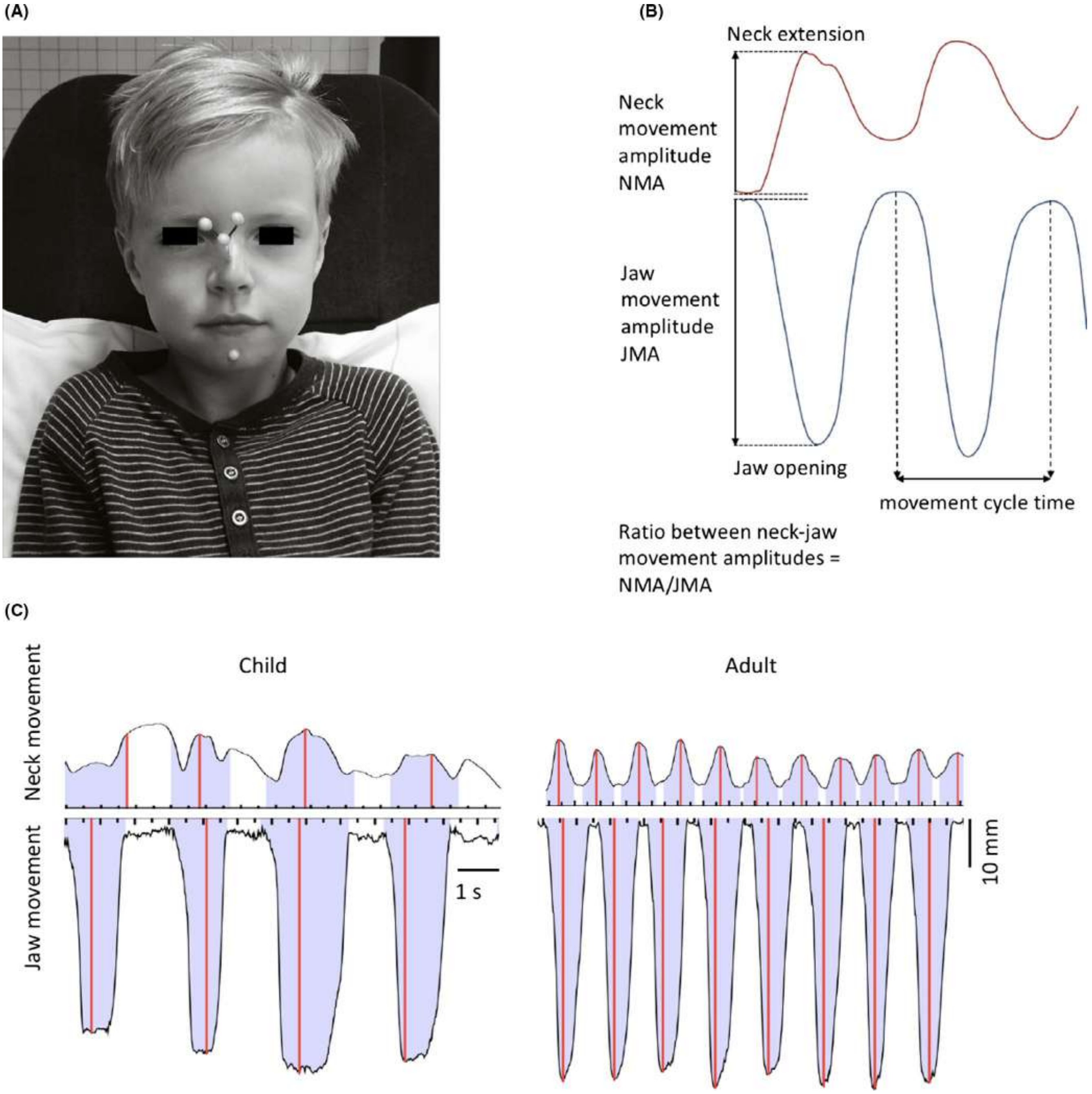

FIGURE 1 A, Set-up of reflective skin markers attached to the head and chin on a child participant. B, Schematic definition of outcome variables (jaw movement amplitude, neck movement amplitude, neck/jaw movement ratio and movement cycle time). C, An example of an original recording from a child and an adult participant during jaw opening-closing task. The curves show simultaneous neck movements during jaw opening-closing task

protocol. The clinical examination was carried out according to the DC/TMD protocol for adults. For the child group, we used an abbreviated version of the adult DC/TMD, in line with the current workshop discussion (http://www.iadr.org/INfORM).

For the movement recording, the subjects were seated in a height adjustable chair with back support in natural head posture that allowed unrestricted neck movements. Head posture cannot be fixed when assessing dynamic jaw-neck movement as this will affect both the head and lower jaw movement.[21] Retroreflective spherical markers were attached to the skin with adhesive tape on anatomical landmarks in the face (see description below). One practice test of jaw opening-closing was performed to check that the set-up was steadfast and that the participant understood the instructions. During each test, the subjects were instructed to sit in an upright position, sit still without talking and to look straight ahead with their teeth in the intercuspal position (light teeth contact).

Jaw and neck movements were recorded during the following jaw motor tasks:

- Paced continuous jaw opening-closing movement
- Self-paced chewing on chewing gum (V6), two pieces (2 g) for children, and three pieces (3 g) for adults.

Each test was recorded during a period of 25 seconds that was repeated once. The whole study session, including information, screening questions, clinical examination and movement recording, lasted approximately 40 minutes.

2.3 | Movement recording

Simultaneous jaw and neck movements were recorded with an optoelectronic three-dimensional (3D) recording system (MacReflex®; Qualisys AB, Gothenburg, Sweden)[22] using skin-attached retroreflective spherical markers (5 mm in diameter)—a tripod was attached to the bridge of the nose to track head movements, and a single marker attached at the tip of the chin to track lower jaw movements (Figure 1A). Two cameras acted as illuminators and detectors of the reflective markers with a sampling frequency of 50 Hz. Details of the set-up have been described previously.[1] All movement variables were measured with the MacReflex optoelectronic recording system, calibrated in accordance with the manufacturers details (merit value for each camera <5).

2.4 | Movement analysis

The recording volume of the lower jaw and the head movements was 45 × 55 × 50 cm, with a spatial resolution of 0.02 mm. During recording, the 2D locations of the reflex markers were determined online by the system hardware and digitally sampled, whereas the 3D locations of the markers were computed off-line. For the mandibular movements, the marker on the chin in relation to the tripod marker on the head determines an arbitrarily oriented plane in relation to the head. This allows calculation of the 3D mandibular movements in relation to the head, despite simultaneously occurring head-neck movements. This enabled the jaw and neck movement amplitudes to be calculated as the shortest 3D distance between the positions.[1,23] The starting point for the jaw movement cycle was defined as the time point at which the lower jaw began the downward, jaw opening movement. The lower jaw movement cycle time was defined as the time between two consecutive starting points. For each movement cycle, the jaw movement amplitude was defined as the distance from the starting point to the most inferior position of the lower jaw. The corresponding head movement amplitude was defined as the distance between the starting position and the most superior position of the head. Jaw and head movement amplitudes and cycle time were calculated as an average of the seven consecutive cycles in each trial for jaw opening-closing movement and eleven consecutive cycles in each trial for chewing. The defined key events (start, peak and end of movement cycles) were identified, and the parameters under study were quantified from the recorded signals using customised software (Figure 1B).

2.5 | Data analysis

The MacReflex files were tracked and exported into comma separated values files. The data were processed in a custom-made software ('Compensation'). Statistics were performed using the software GraphPad Prism version 8.

The jaw-neck movement integration was estimated by the following quantitative variables:

- Mean jaw and neck movement amplitudes (mm)
- Ratio between neck and jaw movement amplitudes (%)
- Intra-individual variability in movement amplitudes for both jaw and neck expressed as a coefficient of variation (CV), defined as the ratio of the standard deviation to the mean
- Movement cycle time (seconds)

Descriptive statistics, medians and 25th/75th percentiles are presented. The significance of difference between children and adults was calculated with the Mann-Whitney *U* test. A probability level of $P < .05$ was considered statistically significant.

3 | RESULTS

Examples of original recordings of neck and jaw movements during jaw opening-closing in an adult and a child are shown in Figure 1C.

3.1 | Movement amplitudes

Compared to the adults, children showed smaller jaw ($P \le .0001$) but not neck ($P = .313$) movement amplitudes during the jaw opening-closing task. During the chewing task, there was no difference in jaw movement amplitudes for children compared to adults ($P = .442$), but the children showed larger neck movement amplitudes ($P = .008$; Table 1 and Figure 2).

TABLE 1 The results for outcome variables for the jaw and neck (movement amplitudes, coefficient of variation in movement amplitudes, ratio between neck-jaw movement amplitudes and movement cycle time) in children compared with adults for jaw opening-closing and chewing task

	Movement amplitudes (mm)		Coefficient of variation in movement amplitudes (CV)		Ratio between neck-jaw movement amplitudes (%)	Movement cycle time (s)
	Jaw	Neck	Jaw	Neck		
Jaw opening-closing						
Children	45.8*** (39.0-51.1)	12.3 (8.7-17.6)	0.1 (0.0-0.1)	0.6* (0.4-1.0)	30.2* (18.2-34.3)	2.7*** (2.4-3.0)
Adults	59 (51.6-63.6)	10.1 (4.8-14.4)	0.04 (0.03-0.1)	0.5 (0.3-0.6)	17.1 (8.9-24.4)	1.7 (1.5-2.1)
Chewing						
Children	12.5 (10.7-14.3)	1.7** (1.3-2.3)	0.3** (0.2-0.4)	1.2** (0.9-1.5)	15.3** (8.5-19.2)	0.7 (0.6-0.9)
Adults	14 (11.6-15.4)	1.1 (0.6-1.8)	0.2 (0.1-0.2)	0.8 (0.6-1.1)	8.7 (6.1-11.9)	0.7 (0.6-0.8)

Note: Medians and percentiles (25th/75th) for children (n = 25) and adults (n = 24) for the jaw opening-closing and chewing tasks are presented.
**P* value .01-.05, significant.
***P* value .001-.01 very significant.
****P* value <.001, very significant.

3.2 | Intra-individual variability in movement amplitude

Compared to adults, children showed larger intra-individual variability for neck (*P* = .040) but not for jaw (*P* = .384) movement amplitudes during the jaw opening-closing task. For chewing, children had larger intra-individual variability for both neck (*P* = .001) and jaw (*P* = .008) movement amplitudes (Table 1 and Figure 3).

3.3 | Ratio between neck-jaw movement amplitudes

Compared to adults, children showed higher ratio between neck and jaw movement amplitudes for both jaw opening (*P* = .026) and chewing (*P* = .003) tasks (Table 1 and Figure 4).

3.4 | Movement cycle time

Compared to adults, children showed longer jaw movement cycle time, that is a lower frequency during jaw opening-closing (*P* ≤ .0001), but not during chewing (*P* = .436; Table 1 and Figure 5).

4 | DISCUSSION

The main findings from this study were that children displayed integrated jaw-neck movements at the age of 6 years old, but compared to adults the children displayed lower amplitudes, higher variability of integrated jaw-neck movements, larger proportional involvement of the neck movements (neck-jaw movement ratios)

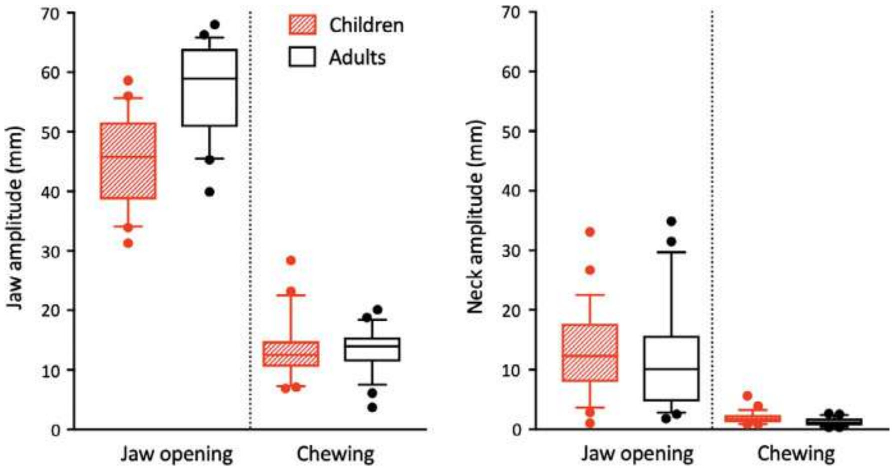

FIGURE 2 Movement amplitudes. Box plot diagram (median with 10th to 90th percentile and outliers) of jaw and neck amplitudes during the jaw opening and chewing task for children and adults

and longer movement cycle times during jaw motor tasks. The results indicate that the functional integration between the jaw-neck motor systems is clearly established at 6 years of age, although it is not fully mature.

4.1 | Amplitudes

The maximum jaw opening amplitudes reported in clinical studies for children of similar ages[24,25] are in line with those of the children in our study. The finding of smaller magnitudes of jaw movement amplitudes in children compared to adults was expected, since children have smaller sized jaws and their maximum jaw movement is thus limited by existing biomechanics. However, for neck movements, children showed significantly larger movement amplitudes during chewing compared to adults. It is possible that this finding of larger and more variable neck movements in children are partly related to a not yet fully matured motor strategy with immature motor programs in a developing brain[16,26] and partly a consequence of a larger cervical range of motion in children[27] compared to adults.[28,29]

The central nervous system (CNS) must combine different elements, sensorimotor signalling and muscle synergies, to establish the natural motor behaviour. The CNS selects the appropriate muscle activity to generate adequate movements in order to achieve a natural motor behaviour.[30] The ability to generate appropriate and efficient movements increases with practice and with experience of the specific motor task.

When comparing the jaw opening-closing and chewing tasks, the involvement of neck movements was task-dependent with larger neck movements during larger jaw movements, that is during jaw opening-closing for both children and adults. Larger neck movements during maximal jaw opening-closing tasks, compared to chewing, were previously reported for adults,[1,3] but our study is the first to report this relationship also in children. The findings from the present study indicate that the proportional involvement of the neck motor system in jaw function with larger neck movements during larger jaw movements is established as early as 6 years of age.

4.2 | Ratio between neck-jaw movement amplitudes

The proportional involvement between the cervical and trigeminal motor systems is reflected in the ratio between neck and jaw movement amplitudes. For the jaw tasks evaluated in the present study, these neck-jaw movement ratios were almost twice as high in children compared to adults. It has been shown that experimental restriction of neck movements can lead to a 20% reduction in maximal jaw opening amplitudes, which indicate that reduced neck mobility can impair jaw function.[21] Based on findings in other studies, a feed-forward activation of neck motoneurons for positioning of the head in jaw activities has been suggested.[1] Neck extension may provide biomechanical advantages, facilitating co-ordination of jaw and neck movements and optimising force production in jaw muscles. In line with this, it has been suggested that a more extended head position may facilitate jaw opening,[21] increase jaw muscle activity and maximum bite force,[31,32] and increase the stability of jaw closing movements.[32,33] A more extended head position may also increase the muscle length [34] and torque of suprahyoidal muscles, which could in turn increase force production in the jaw opening muscles.[35] Corresponding studies in children are sparse. One study on girls and boys aged 7-13 years suggested a possible relation between bite force and head posture, but a clear correlation was not demonstrated.[36] The finding in the present study of larger involvement of the neck movements for children compared to adults during different jaw motor tasks strengthens the notion that jaw-neck integration may optimise the jaw opening ability and the positioning of the gape, albeit this is expressed as immature movement behaviour in children.

4.3 | Intra-individual variation in movement amplitude

Generally, we observed large intra-individual variability in jaw and neck movement amplitudes, and in accordance with previous reports in adults, neck movements showed higher variation between movement amplitudes than jaw movements.[7] Our study showed that children compared with adults displayed a higher degree of

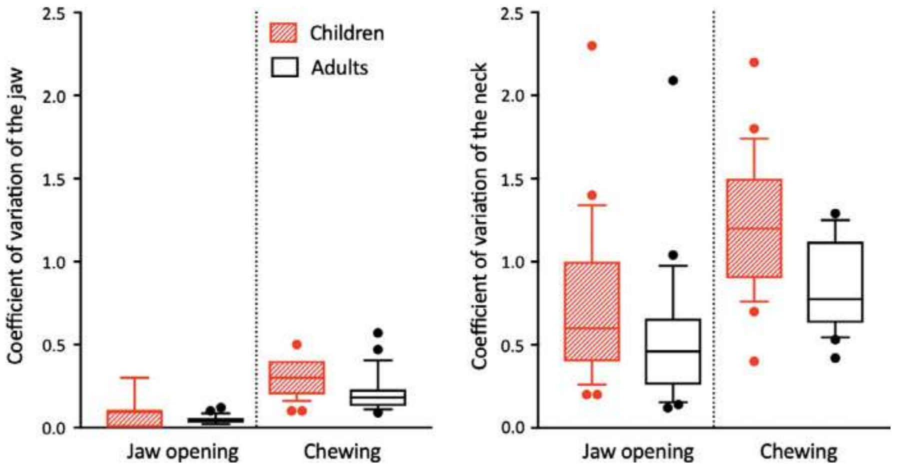

FIGURE 3 Intra-individual variability in movement amplitudes. Box plot diagram (median with 10th to 90th percentile and outliers) of intra-individual variation in movement amplitudes for both jaw and neck expressed as a coefficient of variation (CV) for children and adults

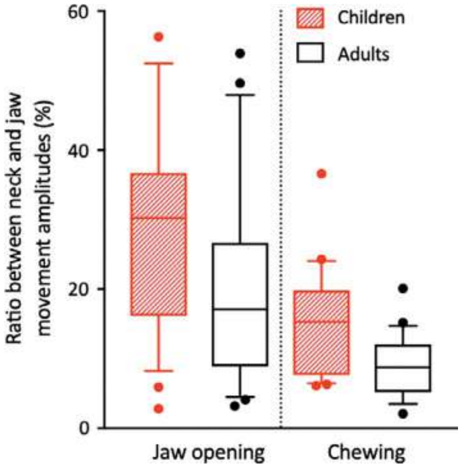

FIGURE 4 Ratio between neck-jaw movement amplitudes. Box plot diagram (median with 10th to 90th percentile and outliers) of the ratio between neck-jaw movement amplitudes during jaw opening and chewing for children and adults

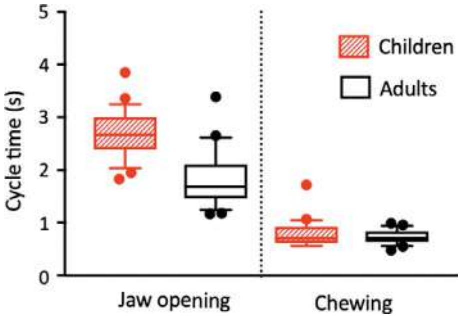

FIGURE 5 Movement cycle time. Box plot diagram (median with 10th to 90th percentile and outliers) of movement cycle time during jaw opening-closing for children and adults

intra-individual variability for neck movement amplitudes during jaw opening and chewing task. Movement variability during development is not necessarily negative, and it can be functional for skilful development.[37] During childhood, the motor system adapts and refines with experience and learning; thus, over time movement variability is reduced.[38,39] This is also in line with the child's cognitive and behavioural development with the brain network undergoing an optimisation processes throughout childhood.[40]

Chewing relies on both feed-forward anticipatory and feedback reactional activation of motoneurons resulting in complex execution of movements. The basic motor programs for jaw opening-closing and chewing are established early, and during chewing the CPG network receives sensory feedback triggered by the food bolus, oral mucosa, periodontal receptors and muscle spindles; this input continuously modulates the motor patterns for chewing.[16,41] This sensory input varies with each chewing cycle and gradually modifies the jaw muscle activity[42] and provides feedback to the CNS thereby developing and optimising the final motor behaviour. For children, this simultaneous processing and recruitment of neuromotor functioning is more immature than in adults, thus resulting in higher variability and less precise movement control in jaw-neck movements.

It is reasonable to assume that these complex motor behaviours in jaw-neck movements will develop in parallel with the general motor development during childhood. Higher variability and less precise movement control is in line with the development of fine manipulative and grasping control in children; this is shown to not reach the adult pattern until around 12 years of age or later (see for example[43]). Moreover, with regard to gender differences, estimated grip strength is also equally strong in girls and boys at this age, albeit with high variability within subjects.[44]

4.4 | Movement cycle time

The result showed longer movement cycle times in children during the jaw opening-closing task compared with adults, whereas the movement cycle time during the chewing task was comparable between children and adults. The jaw opening-closing may be viewed as a simple task but is still dependent on the development of complex jaw motor execution in synergy with neck extension-flexion that require sensory input mainly from muscle spindles and joint receptors to achieve the necessary sensorimotor output. Moreover, the head is proportionally larger and heavier in a child than in an adult, which places a higher demand on balancing the head since the centre of gravity of the head lies in front of the atlanto-occipital junction when an individual is in an upright position. Therefore, when we are standing or sitting, the neck extensor muscles have to counteract gravity to prevent the head from tilting forward.[45,46] The degree of activation of the neck muscles is dependent on the type of task, and for chewing depends also on the size and texture of the bolus.[4] During normal chewing, the CPG evokes the basic spatial and temporal pattern for the masticatory rhythm and a dynamic interaction between peripheral such as teeth and bolus and central nervous mechanism adjust the rhythm and force to the bolus size and texture. During the chewing task in the present study, the size or texture of the chewing gum does not change, although the shape and position of the gum in the mouth varies; but for both children and adults, the cycle time during chewing depends mostly on the rhythm generated by the CPG.[14]

4.5 | Limitations

Some methodological limitations of the study need attention. One concern is that we did not evaluate the reliability of the measurements in the two groups. In previous studies from our research group that have been carried out in adults of different ages, men and women, and healthy individuals as well as patient groups with post-traumatic neck pain, we have reported that repeated measures in healthy (pain-free) adults show low intra-individual variability both between cycles and between repeated trials. This has been evaluated in terms of amplitudes of head and jaw movements, movement cycle times and with a Spatiotemporal Index in a short- and long-term perspective. A high degree of spatiotemporal consistency and high reproducible trajectory patterns values, both in short- and long-term perspectives were demonstrated for concomitant mandibular head-neck movements.[7,47,48]

Another limitation was that the number of jaw movement cycles analysed was few (seven cycles in jaw opening-closing task) due to the large variability in the number of performed self-paced jaw cycles in the children group. Moreover, with skin-attached retroreflective markers, there is a risk for displacement. However, the skin displacement is acceptable within the aim of this study.[49] The sampling frequency of 50 Hz is low, but still this sampling rate can be considered acceptable in the recording precision[50] and sufficient for the parameters of interest in the present study.

To fully evaluate maturity of complex motor programs related to the integration between jaw and neck function in children, a longitudinal study design would be beneficial, and indeed, we aim for that as the next stage. However, cross-sectional studies are the starting point in many projects, and in the area of dynamic jaw-neck movements in children, we have only been able to identify one previous study (also cross-sectional in design).[18] Thus, in a cross-sectional design there are confounding variables (skeletal relationship, malocclusions, functional disturbances, breathing, tongue position etc) that relate to head posture and position, often investigated, and controlled for, in relation to static tasks such as clenching. Our current aim, however, was to evaluate integrated dynamic jaw-neck movements, where some of these variables (such as head posture and position) cannot be controlled. Furthermore, some of these variables will change in a longitudinal study as in growing individuals jaw-facial skeleton morphology undergoes growth and remodelling throughout childhood. As a consequence, changes in skeletal relationship, occlusion, the transversal occlusion in relation to the temporomandibular joint[51] and transitions in functions (breathing, tongue position) are confounding variables that could change over time.

5 | CONCLUSIONS

Despite integrated jaw and neck movement in the 6-year-old children, the movement pattern is far from that of adults and may be interpreted as an immature programming of jaw-neck motor behaviour. The well-integrated movements observed in adults most likely develop over years, perhaps into adolescence, and need further research including well-controlled longitudinal studies to map this development in order to provide appropriate age-related clinical treatment to chewing disorders.

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CONFLICT OF INTEREST

The authors state explicitly that there is no conflict of interests in connection with this article.

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