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Range of motion (ROM) in the lips and jaw during vowels assessed with 3D motion analysis in Swedish children with typical speech development and children with speech sound disorders

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ABSTRACT

Purpose: The aim was to compare movement patterns of lips and jaw in lateral, vertical and antero-posterior directions during vowel production in children with typical speech development (TSD) and in children with speech sound disorders (SSD) persisting after the age of six.

Methods: A total of 93 children were included, 42 children with TSD (6:0–12:2 years, mean age 8:9 ± 1:5, 19 girls and 23 boys) and 51 children with SSD (6:0–16:7 years, mean age 8:5 ± 3:0, 14 girls and 37 boys). Range of motion (ROM) in lips and jaw in the vowels [a, ʊ, ɪ] produced in a syllable repetition task and median values in resting position were measured with a system for 3D motion analysis. The analysis was based on the coordinates for the mouth corners and the chin centre.

Results: There were significant differences between the groups on movements in lateral direction in both lips and jaw. Children with TSD had generally smaller and more, symmetrical movements in the lips and jaw, in all three dimensions compared to children with SSD. There were no significant differences between the groups in resting position.

Conclusion: Children with SSD persisting after the age of six years show more asymmetrical and more variable movement patterns in lips and jaw during vowel production compared with children with TSD in a simple syllable repetition task. Differences were more pronounced in lateral direction in both lips and jaw.

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Introduction

Children with speech sound disorders (SSD) form a heterogeneous group and there is an ongoing debate regarding criteria and classification that is relevant in both clinical settings and research [1]. SSD is used as an umbrella term and includes several subtypes of the disorder. One subgroup of SSD is motor speech disorders which includes Childhood Apraxia of Speech (CAS), Developmental Dysarthria (DD) and Speech Motor Delay (SMD) [2]. Oral motor difficulties often co-occur in children with developmental speech and language disorders [3–5] as well as fine and gross motor difficulties. Thus, these motor difficulties influence the way children learn and develop skills needed for speech development [6,7] reflecting the complex, multifaceted interaction between motor and speech development [8]. Namasivayam et al. [2, p.17] argue that children with SSD may “occupy the low end of the speech motor skill continuum” and that speech sound errors may be a result of different individually developed coping strategies to compensate for those motor skill difficulties. It is clinically challenging to distinguish if symptoms are arising from phonological or motor disorders as those difficulties often overlap [2,9].

Speech is a complex motor behaviour involving the spatial and temporal control of a large number of muscles and sub-systems [10]. In early speech sound production and development, the jaw muscles play a significant role. Control and stability in the jaw is correlated to movements in the lips and tongue and is regarded as a prerequisite for almost all articulatory positions in the mouth [11]. The control of the jaw develops earlier than the control of the lips and tongue [12]. According to Green et al. [12], the coordination of jaw movements in syllables containing bilabials are already adult-like at 12 months of age, but lip and tongue movements continue to develop. The coordination between lip and jaw movements appears to be adult-like at six years of age [12], while the coordination between jaw and tongue develops later, with continued refinement into late adolescence [13]. Differentiation (separation) of lip movements from the jaw and between the upper and lower lip is an ongoing process throughout early childhood [12].

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Jaw control is the foundation of lip and tongue movement development [14]. In early speech production the jaw is suggested to be the most prominent articulator with the opening and closure of the jaw producing bilabial consonants and syllable gestures. Control of the jaw is also essential for complex speech [15]. The development of speech sounds follows oral motor development [16]. Bilabial sounds are established before labiodental sounds that need the motor control to separate the lower lip from the jaw [16]. Adults use mainly the jaw and the lower lip for lip closure and not the upper lip and six-year olds have similar involvement of lips and jaw as adults [12]. Still, children have less precise articulatory movements compared to adults. Increased maturation results in more stable movements and reduced variation during articulation [17]. Smith and Zelaznik [18] concluded that there is a gradual maturation with reduced variation in speech movements throughout childhood into adolescence. They found that most speech skills did not reach an adult-like pattern until around 14 years of age. In children with speech disorders this development has been disrupted. In an intervention study including children with severe to profound SSD, Namasivayam et al. [19] observed lateral jaw sliding, reduced jaw stability, limited jaw grading skill, excessive jaw movement, reduced lip rounding and overly retracted lips in 11/12 participants. Terband et al. [20] found deviant/unstable lateral jaw movements in children with SSD and CAS, compared with children with typical development but not for midsagittal jaw protruded movements. Grigos and Kolenda [21] showed that children with CAS have different jaw movements compared with typically developing children and that improved jaw stability resulted in improved precision and reduced variability in consonant production. Tükel et al. [22] found jaw movements to be significantly more affected compared to labiofacial function in a group of 18 children with CAS. In an intervention study of six children with speech impairment and cerebral palsy (CP) where kinematic data were used for assessment, Ward et al. [23] found lateral jaw movements during speech. They interpreted this as a sign of jaw instability. Jaw distance values indicated both reduced jaw movement grading and too large jaw movements. They suggested that limited jaw movements during speech could be a compensatory strategy to handle jaw instability [23]. The children with CP also exhibited difficulties with bilabial contact and excessive lip retraction compared to children with typical development [23]. This was also interpreted as a sign of jaw instability and poor integration of lip and jaw movements.

Vowel acquisition has been less studied than the development of consonant production in both typically developing children and children with SSD [24]. The Swedish vowel system consists of eighteen vowel phonemes (nine distinct vowels that can be pronounced both long and short) [25]. Most vowels in Swedish are expected to be acquired at the age of three and at four years of age all vowels are expected to be established [26]. The corner vowels [i] [ɑ] [a] [u] tend to be acquired before non-corner vowels [27] and low back vowels before high front vowels [28]. The Swedish frontal, rounded vowels are known to be acquired later [29]. The reason could be related to the differentiated movement, and coordination of the jaw and tongue required in frontal vowels [28]. Both tongue and lip control are needed for the production of rounded vowels [28].

Accuracy in vowel production is important for speech intelligibility and speech acceptability [30]. Reduced vowel space area (VSA) has been observed in children with speech disorders of different origin [31]. VSA is an acoustic measure method and a larger VSA is associated with clearer and more intelligible speech. The reduced VSA in children with speech disorders can be explained by both auditory and motor limitations [31]. Vowel distortion is regarded as a common feature in children with CAS and could also be present in other motor speech disorders such as SMD and DD [2,32] and in phonological delay [33]. The difficulties with vowels described in English speaking children with both CAS and other SSD are changes in tense/lax vowel contrasts, backing, and diphthong reduction [24]. In a longitudinal study of three children with CAS, Davis et al. [24] reported impaired vowel accuracy despite generally intact vowel inventories. These context dependent difficulties with vowels seen in children with speech motor planning difficulties could be related to the motor planning deficits that impact the movement transition from consonant production to vowel production [34].

Aim and research questions

The aim of this study was to explore how children with TSD move lips and jaw in lateral, vertical and anteroposterior dimensions during the production of the vowels [a], [ʊ] and [ɪ] in a simple syllable task and to compare their results with those of children with SSD of unknown origin persisting after the age of six years. The literature on lip and jaw movements in children with SSD is sparse. Previous studies that have used different 3D motion analysis system and other analysis methods have shown deviant movement patterns in the lips [19,23] and jaw [19–21,23] during speech in children with speech impairment compared to children with typical speech development [19–21,23]. Thus, the hypothesis for this study was that Range of Motion (ROM) and symmetry in lips and jaw during syllable repetition will differ in children with SSD compared to children with typical speech development (TSD). In order to test this hypothesis, the following specific research questions were formulated: 1) What is the ROM in lips and jaw during the production of the selected vowels in children with TSD and children with SSD and 2) are the movements symmetrical? 3) Are there any differences in ROM between children with persistent SSD and children with TSD when age differences are considered?

Materials and method

This study comprised a total of 93 children divided into two groups, one with children with TSD and one with children with SSD. The TSD group consisted of 44 children, 6–12 years of age, recruited from the Public Dental Health service and personal contacts. The inclusion criteria were typical speech development and no known neurodevelopmental disorder. Two children were excluded due to insufficient video recordings, resulting in 42 children aged 6:0–12:2 years (mean age 8:7 ± 1:6), 19 girls and 23 boys. All children in the TSD group were screened with the Nordic Orofacial Test – Screening (NOT-S) [35] in order to make sure that no oral motor or speech sound disorders were found. Two children in the TSD group were bilingual but had Swedish as their first language.

The SSD group consisted of 62 patients referred to a national orofacial resource centre for a speech and oral motor examination. The inclusion criteria were SSD persisting after the age of six, no moderate or severe intellectual disability, cerebral palsy and/or severe autism spectrum disorder. Ten participants were excluded due to insufficient video recordings and one declined participation. In the end, 51 children with SSD aged 6:0–16:7 years (mean age 8:5 ± 3:0), 14 girls and 37 boys, were included.

All the children with SSD had speech difficulties to differing degrees [5]. They had impaired consonant production assessed by percentage consonants correct (PCC) based on the results of a picture-naming test, the Swedish Articulation and Nasality Test (SVANTE) [36]. PCC and percent vowels correct (PVC) was calculated based on transcriptions of single whole words according to instructions in Shriberg et al. [37]. PCC varied between 11% and 95% [median 72%, mean 69% (SD 18.2)]. PVC varied between 55% and 100% [median 95%, mean 92% (SD 9.3)]. To assess orofacial function the NOT-S [35] was used. The screening is divided into 12 domains (six domains in an interview part and six in an examination part). The maximum NOT-S score is 12, one score for each domain. The result of the orofacial function screening showed that the majority (86%) of children with SSD had a total NOT-S score of ≥ 2, demonstrating difficulties with orofacial functions in more domains than expected for their age [38]. Seven participants (14%) were considered to have typical orofacial function related to age (total NOT-S score < 2). The variation within the group was large and ranged from a total NOT-S score of 0–9 (median 3, mean 4 (3.92) (SD 2.2).

All children in the SSD group had a confirmed SSD at the time of referral to the clinic. The speech assessment was carried out to rule out or confirm an oral motor/speech motor involvement, but no assessment of language involvement was made. The syllables used in this study require minimal language skills and consists of speech sounds that should already be mastered in the present age range. The assessment resulted in a motor speech disorder diagnosis for all 51 children in the clinical group. Twenty children were assessed as having SMD, 17 CAS, 10 SMD/suspected CAS, three articulation impairment and one DD. However, due to few participants and an uneven distribution of individuals in the subgroups these subgroups will not be compared to one another. Thus, comparisons will be made between a combined group of children with SSD presenting with SMD, CAS, and/or SMD/suspected CAS and children with TSD.

Four participants in the SSD group were bilingual but had Swedish as their first language and two children were adopted internationally at 2:6 and three years of age. For detailed information on speech and orofacial function in the SSD group, see Mogren et al. [5].

The age range $\geq$6 years was selected based on several studies of typical speech development reporting that all Swedish consonants and vowels are established by the age of six years [26,36]. Thus, the aim was to study ROM during simple syllable production in children with persistent SSD defined as persisting after six years of age.

The study was approved by the regional ethical review board in Gothenburg no 363-14. All participants received both oral and written information about the study. The parents signed an informed consent for their child's participation before any assessments took place.

The assessments were performed in a clinical setting. The entire procedure of speech assessment (SVANTE), orofacial function screening test (NOT-S) and the syllable repetition task took approximately 60 min. The child was seated in a stable sitting position for the whole assessment and during the video recorded syllable repetition the child was seated in front of the cameras and the examiner. The chair was an ergonomic work chair for children with manual handbrakes, adjustable backrest, neck support, armrest and foot plate (Mercado Medic).

Test items

The video recorded experiment started with a face-at-rest task that was used to assess median values for mouth corners and chin centre during resting position. The syllable repetition task consisted of three repetitions each of [mama], [mɪmɪ] and [mʊmʊ], which are words and names in Swedish but with a minimal language demand. The vowels were selected because they are cardinal vowels representing three distinct tongue and jaw positions in the vowel space; [a] is a non-rounded front vowel with open jaw position, [ɪ] is a non-rounded front vowel with closed jaw position, and [ʊ] is a rounded back vowel with closed jaw position.

The consonant [m] was selected as it is one of the first speech sounds established and involves occluded lips which is preferable when using visual motion analysis program. All the included children were expected to master the production of [m].

3D Motion analysis of lips and jaw

In earlier studies of lip and jaw movements during speech, visual motion analysis programs in 2D or 3D have been used. By using measurement points in the face (landmarks), it has been possible to calculate the duration, displacement and velocity in lip and jaw movements [39–41]. In most visual motion analysis programs only movements of visible articulators could be analysed [42].

In this study, ROM in lips and jaw was measured using the SmartEye® Pro-MME (Mimic Muscle Evaluation) (SmartEye AB, Gothenburg). MME is an add-on that tracks lip and jaw movements and has been shown to be a reliable instrument in earlier studies [41,43–45]. The SmartEye® Pro system was originally a head and gaze tracking system that measure head pose and gaze direction in full 3D. Infra-red (IR) diodes are used to illuminate the face and minimise the effects of varying lighting conditions [41]. Steps 3–5 below, were made after the experiment was finished and without the participant present in the room.

1. *Hardware setup:* A PC computer with SmartEye® Pro 5.7 – MME software was used. Two video cameras (Sony XC-HR50) with IR flashes were placed on a fixed metal bar, 25 cm apart. The cameras shoot 60 frames a second with a resolution of 640 × 480 pixels. The system compensates for head movements, provided that the face is captured by the cameras.
2. *Recording:* The participant was seated approximately 80 cm in front of the cameras. The cameras were calibrated, and camera focus and brightness were adjusted before recording. Five recordings were made in the following order: recording to create an individual profile; recording to capture face-at-rest while the participant was looking straight forward for 30 seconds; and three different syllable repetition recordings, [mama], [mimi] and [momo]. The child was instructed to repeat each syllable three times according to a model of the task provided by the examiner. The syllable repetition was rehearsed before the recording started. The target stimuli were used for practice and 1–2 repetitions were elicited.
3. *Creating an individual profile:* For profile generation, specific facial landmarks were marked manually on ten snapshots selected and extracted from the profile recording of each child (Figure 1). The following poses were captured: head upright, head turned slightly to the left and to the right, open mouth smile and lip pucker. The individual profile made it possible to automatically track the 3D position of mouth corners and chin centre while the recording was running.
4. *Tracking facial landmarks:* During tracking, the positions of the landmarks were visualised on the screen and information about the 3D positions (coordinates) were saved in log files. The log files included information on frame number, mouth width, the coordinates for right and left mouth corners and for the chin centre. The log files were exported to an MS Access application where extreme values (values due to momentary loss of tracking) were deleted and replaced with the closest accepted data. A visual review of the video recordings in tracking mode was made to ensure that the tracking procedure was performed correctly.
5. *Data analysis*: All analyses were based on running video recordings. The mouth width value was calculated from values of the left mouth width (LMW) and right mouth width (RMW) using an equation in which values from all three dimensions were included: $\sqrt{(x_{LMW}-x_{RMW})^2+(y_{LMW}-y_{RMW})^2+(z_{LMW}-z_{RMW})^2}$. Lip movement asymmetry was calculated by subtracting the movement of the left mouth corner from the movement of the right mouth corner. ROM was expressed in mm and was defined as the maximum displacement of the coordinates (x, y, z) located at the mouth corners and on the jaw (chin centre) during the syllable repetition task. Some missing data occurred due to difficulties with tracking and difficulties performing the tasks, especially for children in the SSD group. As a result, the number of participants varies somewhat across assessments.

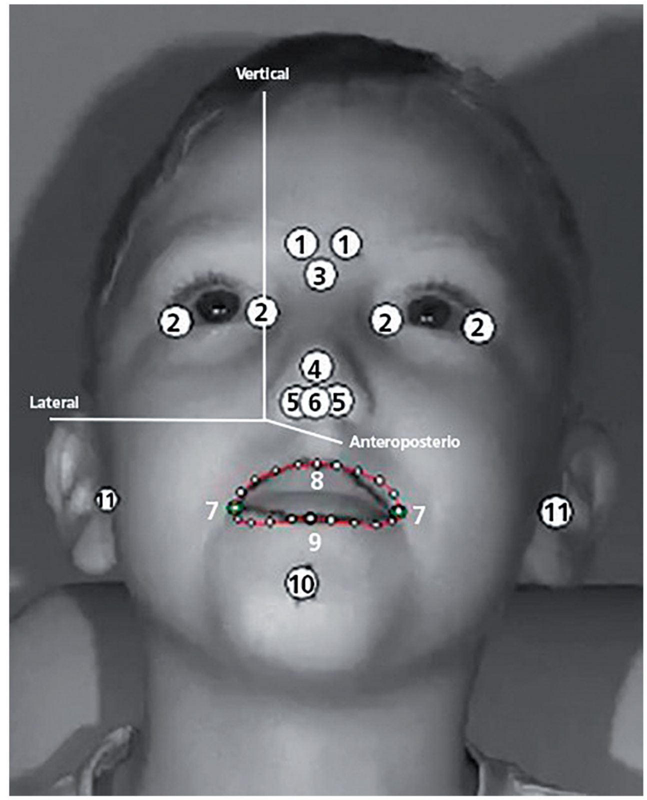

Figure 1. Head Model. The head model is used by the system to locate the facial features in the stream of pictures from the cameras and contains information about the 3D location of all facial features such as inner eyebrows (1), inner and outer eye corners (2), nasal ridge (3), nose tip (4), nostrils (5), nasal septum (6), mouth corners (7), middle upper lip (8), middle lower lip (9), chin centre (10) and ears (11). The lines are showing lateral, vertical, and anteroposterior angles of the head model. The coordinates from positions 7–10 are used for the present study.

Reliability

All individual profiles were constructed by the same examiner. Individual profiles from 19 (20%) randomly selected participants (nine from the TSD group and ten from the SSD group) were reconstructed to assess intra-examiner reliability. Based on the new profiles, new trackings were made and compared with the original results. A single-measurement, absolute-agreement, 2-way mixed-effects model was used for the measurement of Intraclass Correlation

Coefficient (ICC). The overall ICC was 0.85 with a 95% confident interval (CI) of 0.83–0.87. ICC for the TSD group was 0.88 (CI = 0.85–0.91) and for the SSD group 0.82. (CI = 0.78–0.85). Based on the ICC results, it was concluded that the intra-examiner reliability for the study was good.

Statistical analysis

All the data were analysed using the Statistical Package for the Social Sciences (SPSS statistics 22). The level of significance was set at $p < .05$ throughout. Descriptive statistics were used for the background features (PCC, PVC, NOTS, age, sex) of the participants. Parametric tests were used for comparisons since continuous data were used based on relatively large participant groups. The independent samples *t*-test was used to analyse differences in ROM in lips and jaw between children with TSD and SSD in three different syllables, and Pearson's *r* to analyse correlations between age and ROM.

Results

Resting position of lips and jaw

There were no statistically significant differences regarding the resting position in the lips and jaw between children in the TSD and the SSD groups (Table 1).

ROM and lip movement asymmetry in selected vowels

Only results from the variables of mouth width, lip movement asymmetry and jaw movements (chin centre) are presented, as the measurements from the left and right mouth corner are included in the lip movement asymmetry values. In total there were 21 variables assessed for the 3 vowels, 7 variables/vowel. The variables were: mouth width, lip movement asymmetry (lateral, vertical, anteroposterior) and jaw movements (lateral, vertical anteroposterior) in [mama], [mɪmɪ] and [mʊmʊ].

Several statistically significant differences in ROM between children with TSD and SSD were found. Especially regarding lateral movements in both lips and jaw (Tables 2–4). In [mama] there were significant differences in mouth width ($p = .004$), lateral lip movement asymmetry ($p = .031$), and lateral jaw movements ($p < .001$). In [mɪmɪ] and [mʊmʊ] there were significant differences in lateral lip movement asymmetry ($p = .005$, $p = .011$), and lateral jaw movements ($p = .037$, $p = .002$).

The ROM in the lips and jaw was generally small in all dimensions for children with TSD and the variation between individuals was also small (Tables 2–4). Lateral lip movements were ≤3mm in all but one of the TSD participants. Most participants in the TSD group (80–86%) had an asymmetry of <2 mm (Figure 3).

Children with SSD had a larger lateral ROM and more asymmetrical movements in both lips and jaw compared to

Table 1. Median values in the lips and jaw during 30-second resting position in three dimensions in children with typical speech development ($n = 41$) and children with speech sound disorder ($n = 49$).

	Typical speech development		Speech sound disorder		
Rest position	Mean ± SD mm	CI mm	Mean ± SD mm	CI mm	*p* Value
Mouth width	43.0 ± 3.1	[42.0;44.0.]	42.6 ± 4.7	[41.2,44.0]	.490
L mouth corner					
Lateral	21.5 ± 1.8	[21.0;22.1]	21.0 ± 3.0	[20.2;22.0.]	.172
Vertical	26.6 ± 2.2	[25.9;27.3]	26.4 ± 3.2	[25.5;27.3]	.689
Anteroposterior	77.6 ± 8.2	[75.0;80.3]	75.6 ± 7.6	[73.4,77.8]	.203
R mouth corner					
Lateral	21.1 ± 2.1	[20.5;21.8]	21.2 ± 2.7	[20.4;22.0]	.981
Vertical	26.9 ± 2.6	[26.1;27.8]	26.7 ± 3.1	[25.8;27.6]	.715
Anteroposterior	77.8 ± 7.9	[75.2;80.4]	76.2 ± 7.9	[74.0;78.5]	.354
Jaw movements					
Lateral	1.6 ± 1.2	[1.3;2.0]	2.0 ± 1.7	[1.5;2.4]	.254
Vertical	50.5 ± 3.7	[49.3;51.7]	48.9 ± 5.8	[47.2;50.6]	.147
Anteroposterior	82.9 ± 7.7	[80.4;85.4]	80.2 ± 8.8	[77.7;82.8]	.141

p Values from an independent sample *t*-test are included.

Table 2. Range of motion in the lips and jaw and mouth asymmetry in three dimensions of [a] the syllable [mama] in children with typical speech development ($n = 40$) and children with speech sound disorder ($n = 49$).

	Typical speech development		Speech sound disorder		
Range of motion – [mama]	Mean ± SD mm	CI mm	Mean ± SD mm	CI mm	*p* Value
Mouth width	4.5 ± 2.0	[3.9;5.2]	6.3 ± 3.2	[5.3;7.2]	**.004**
Lip movement asymmetry					
Lateral	0.7 ± 0.7	[0.5;1.0]	1.1 ± 0.8	[0.9;1.4]	**.031**
Vertical	1.7 ± 1.5	[1.2;2.2]	1.8 ± 1.6	[1.3;2.3]	.925
Anteroposterior	1.3 ± 1.2	[0.9;1.7]	1.6 ± 2.1	[0.9;2.2]	.522
Jaw movements					
Lateral	2.3 ± 1.1	[2.0;2.7]	3.8 ± 2.6	[3.1;4.6]	**<.001**
Vertical	10.2 ± 3.3	[9.0;11.2]	10.3 ± 3.5	[9.3;11.4]	.964
Anteroposterior	7.7 ± 2.0	[7.1;8.5]	8.3 ± 2.3	[7.6;9.0]	.282

p Values from an independent sample *t*-test are included. Significant values in bold.

Table 3. Range of motion in the lips and jaw and mouth asymmetry in three dimensions of [ɪ] in the syllable [mɪmɪ] in children with typical speech development ($n = 42$) and children with speech sound disorder ($n = 47$).

	Typical speech development		Speech sound disorder		
Range of motion – [mɪmɪ]	Mean ± SD mm	CI mm	Mean ± SD mm	CI mm	*p* Value
Mouth width	5.3 ± 2.8	[4.2;5.9]	5.1 ± 2.6	[4.3,5.9]	.843
Lip movement asymmetry					
Lateral	0.6 ± 0.8	[0.4;0.9]	1.3 ± 1.2	[0.9,1.6]	**.005**
Vertical	1.6 ± 1.3	[1.2;2.0]	1.7 ± 1.5	[1.1,2.1]	.815
Anteroposterior	1,5 ± 2.2	[0.8;2.2]	1.7 ± 1.5	[1.2,2.2]	.581
Jaw movements					
Lateral	2.6 ± 1.2	[2.1;2.9]	4.1 ± 4.0	[2.8,5.3]	**.011**
Vertical	9.1 ± 2.6	[8.1;9.6]	8.1 ± 2.4	[7.4,8.9]	.071
Anteroposterior	7.4 ± 3.4	[6.3;7.4]	7.4 ± 3.1	[6.5,8.4]	.938

p Values from an independent sample *t*-test are included. Significant values in bold.

Table 4. Range of motion in the lips and jaw and mouth asymmetry in three dimensions of [ʊ] in the syllable [mʊmʊ] in children with typical speech development ($n = 42$) and children with speech sound disorder ($n = 49$).

	Typical speech development		Speech sound disorder		
Range of motion – [mʊmʊ]	Mean ± SD mm	CI mm	Mean ± SD mm	CI mm	*p* Value
Mouth width	5.3 ± 3.5	[4.2;6.4]	5.9 ± 2.6	[5.1,6.6]	.322
Lip movement asymmetry					
Lateral	0.7 ± 0.7	[0.5;1.0]	1.1 ± 1.1	[0.8,1.4]	**.037**
Vertical	1.0 ± 0.9	[0.7;1.3]	1.2 ± 1.2	[0.9,1.6]	.273
Anteroposterior	1.6 ± 1.3	[1.2,2.0]	1.8 ± 2.0	[1.2,2.4]	.577
Jaw movements					
Lateral	2.0 ± 1.1	[1.8;2.4]	3.2 ± 2.3	[2.6,3.9]	**.002**
Vertical	4.9 ± 2.3	[4.2;5.6]	5.1 ± 2.0	[4.5,5.6	.732
Anteroposterior	6.3 ± 1.7	[5.8;6.8]	7.1 ± 4.2	[5.9,8.3]	.208

p Values from an independent sample *t*-test are included. Significant values in bold.

children with TSD (Tables 2–4 and Figures 2 and 3). ROM in the vertical dimension of jaw movements and mouth width for [ɪ] in [mɪmɪ] were the only variables where the SSD group had smaller movement than the TSD group. The difference for ROM in vertical jaw movements in [mɪmɪ] was close to reaching statistical significance ($p = .071$).

The differences in performance among children with SSD were more prominent, with a larger standard deviation in 16/21 (76%) of the variables compared to children with TSD.

In Figure 4, an example of lateral jaw movement during repetition of the syllable [mɪmɪ] from one participant from each group is shown. The participant with TSD had limited lateral jaw movement compared to the participant with SSD. The movement was much larger during the first repetition of the syllable.

Age

Two modest correlations in anteroposterior jaw movements were found between age and ROM in the TSD group in [mama] ($r = -0.327$, $p = .039$) and [mɪmɪ] ($r = -0.366$, $p = .017$).

In the SSD group, there were some correlations between age and ROM. For [mɪmɪ]: lateral jaw movements ($r = -323$, $p = .027$), and anteroposterior lip movement asymmetry ($r = -336$, $p = .027$). For [mʊmʊ]: lateral jaw movements ($r = -299$, $p = .037$), anteroposterior jaw movements ($r = -299$, $p = .037$) and vertical lip movement asymmetry ($r = -330$, $p = .020$). For [mama], no correlations with age were found in the SSD group. Only negative correlations were found between age and ROM in both the TSD group and the SSD group, indicating that younger children had larger movements.

Discussion

In the present study, ROM in children with TSD and children with SSD were compared using 3D motion analysis. Results confirmed the hypothesis that children with SSD have deviant ROM in lip and jaw during a simple syllable repetition tasks compared to children with TSD. In lateral direction of both lips and jaw, children with SSD had larger lateral movements for all three vowels which is in line with earlier kinematic studies of children with SSD [19–21]. Furthermore, the 3D motion analysis system used showed good reliability and detected differences in lip and jaw movements in children with TSD and SSD on a group level.

ROM and lip movement asymmetry in selected vowels

Children with TSD had small, symmetrical movements in lips and jaw, during vowel production in all the measured dimensions. One explanation of the small differences in the TSD group could be the easy syllable task used in this study. The children with TSD were not expected to have any difficulties with this task and selected vowels are typically established early in speech development. There was some

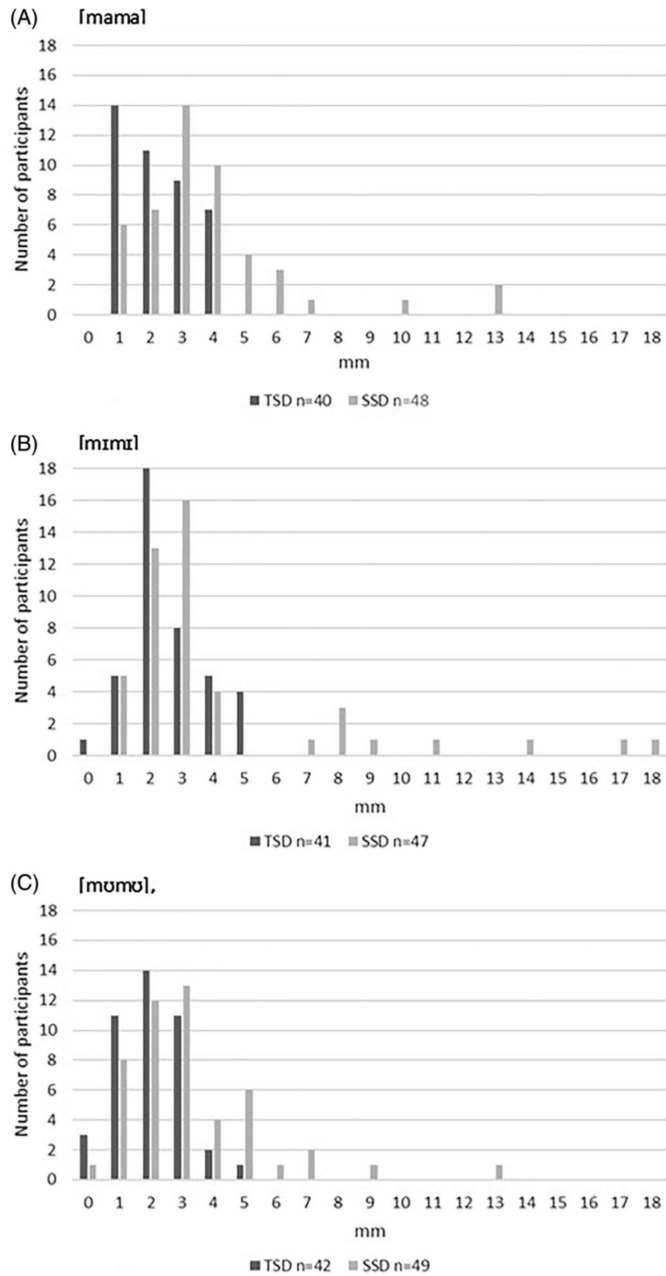

Figure 3. Comparison between children with typical speech development (TSD) and children with speech sound disorder (SSD) in range of motion of lateral jaw movements in [a], [ɪ] and [ʊ] in the syllable [mama], [mɪmɪ], [mʊmʊ], Figures (A)–(C) respectively. Individual values that show overlapping tendencies among groups.

asymmetry during movements in vowel production in the TSD group, but for most participants this asymmetry was below 2 mm. This is probably too small to perceive visually, but it is detectable by a kinematic assessment such as Smarteye MME.

Differences in ROM and lip movement asymmetry between children with persistent SSD and children with TSD

There was a significant difference between the groups on several (33%) of the studied variables and the individual variation in the SSD group was larger reflected in higher

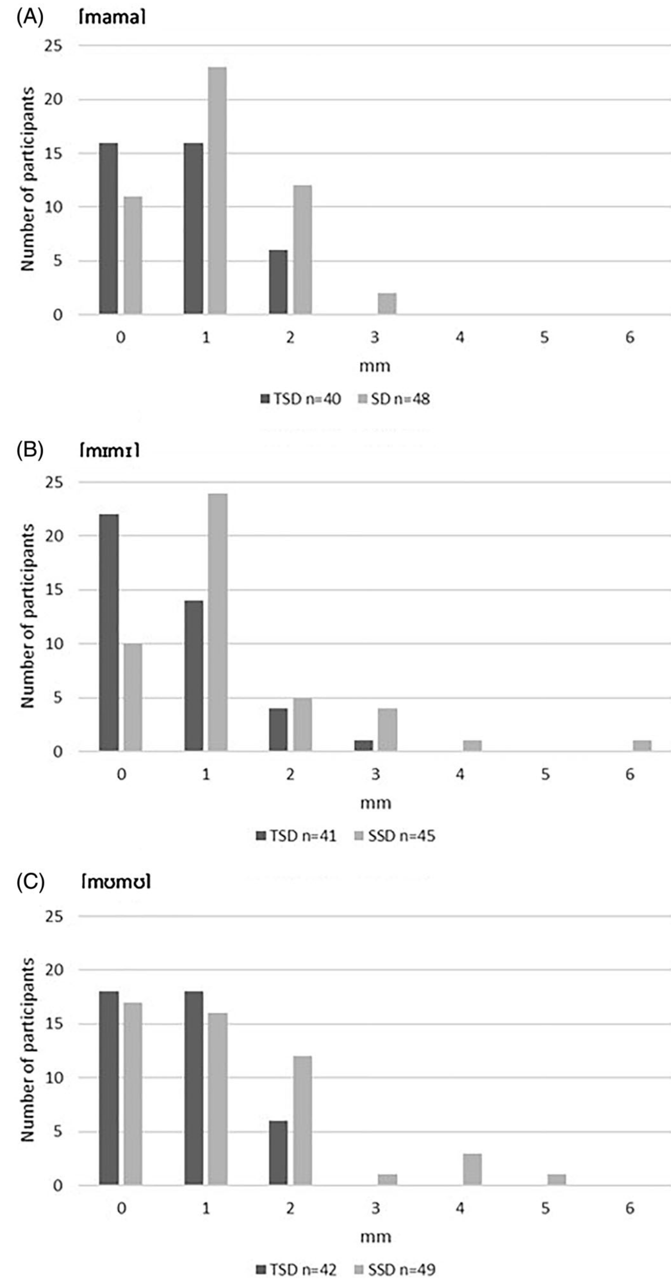

Figure 2. Comparison between children with typical speech development (TSD) and children with speech sound disorder (SSD) in range of motion for lip movement asymmetry expressed in mm in the lateral direction [a], [ɪ] and [ʊ] for the syllable [mama], [mɪmɪ] [mʊmʊ], Figures (A)–(C) respectively. Individual values that show overlapping tendencies among groups.

standard deviations in a majority (76%) of the studied variables. Differences were especially pronounced in lateral direction of both lips and jaw. No differences were found between the groups for the resting position. Children with SSD had larger lateral movements and were more asymmetrical in both the lips and jaw compared with children with TSD.

Mouth width

The ROM in mouth width in children with SSD differed significantly from that of children in the TSD group in [mama], where children with SSD had a larger ROM. The

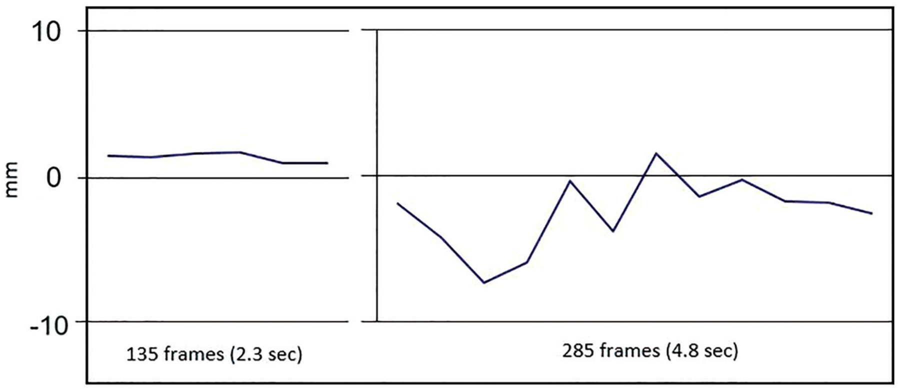

Figure 4. Example of lateral jaw movement (chin centre) during the syllable [mɪmɪ] in one participant with typical speech development (left) and one with speech sound disorder (right).

children with SSD also had a larger mouth width in [mʊmʊ], even if this difference was not significant. The opposite was found for the vowel [ɪ] in [mɪmɪ], where children with SSD had a slightly smaller, but not significant, ROM. Both larger and smaller movements could be a sign of deviant co-articulation and less accurate movements during speech [19,23]. This difference in movement patterns could be related to impaired co-articulatory ability, showing that the children with SSD did not change lip position enough to meet the full requirement of the vowel for lip protrusion and/or retraction.

Lip movement asymmetry

There was a significant difference between the SSD group and the TSD group in lip movement asymmetry in lateral direction for all three assessed vowels. Asymmetry was assessed during speech movements and should therefore not be affected by skeletal asymmetry as the range of movement was assessed. The lip movement asymmetry found in this study could be a sign of instability and variability in lip articulation. Earlier studies of children with the motor speech disorder CAS have shown a higher variability in lip movements [46,47]. Children with CAS have also been found to have less control over the lower lip compared to children with TSD [48]. Children with SSD did not show the same difficulties with lip movements as the children with CAS [48]. An asymmetry in orofacial muscles can also lead to dental malocclusion [49] which needs to be further studied in this group.

Jaw movements (chin centre)

The most pronounced difference between the groups was found in the lateral direction of the lower jaw (mandible). This difference was present in the production of all three vowels. These results are in line with earlier studies of jaw movements during speech in children with SSD [19–21]. It is hypothesised that the specific difficulties with jaw stability and jaw grading skills (control of jaw height), seen in children with SSD, result in compensatory patterns that can inhibit motor development. The excessive jaw movements and fixed lip retraction in a young child with CAS, is an example of such compensatory patterns [21].

In this study jaw movements in the SSD group was in general larger than the jaw movements in the TSD group, except for ROM in vertical jaw movements in [mɪmɪ]. A smaller range of movement could be a sign of a compensatory fixing pattern as it is a clinical observation in some children with SSD having a fixed jaw position and clenched articulation pattern. This pattern has been suggested to be compensatory in order to stabilise the jaw and allow lips and tongue to move more freely [23].

Age

There were only two correlations with age in the TSD group, both in anteroposterior jaw movements. The movements were larger in the younger children in all the variables that correlated with age, both in the TSD and the SSD group. Larger movement could indicate a more immature speech motor system and could also be a sign of more instability and more variable movement patterns [48,50]. There were more correlations with age in children with SSD and those correlations were probably related to the severity of the speech impairment and a more variable and instable speech motor patterns in children with SSD. The younger children with SSD had lower PVC and PCC [5]. There were no correlations with age and the earliest developed syllable, [mama] in the SSD group. Also, the production of [mama] requires less co-ordination between lips and jaw. The syllable task used in this study is simple and even if motor development for speech is a protracted process throughout childhood and adolescents [18] strong correlations with age when using simple syllables with minimal language demands were not expected. This was also the case in the TSD group with a modest correlation with age only for the anteroposterior jaw movement. Variability in lip and jaw movement patterns have been shown to decrease with age in typically developing children [18,51]. The control of tongue and jaw muscles is expected to be developed for all the included vowels at three years of age [26].

Study limitations

One limitation of the system used in this study is the lack of audio recordings synchronised with the video recordings, which makes acoustic and perceptual analysis of the repeated syllables difficult. Only movements of visible articulators could be analysed in this study. Future studies using more complex kinematic recording systems, also involving information on tongue movement, would add valuable knowledge related to the complexity of speech motor performance.

The rather large number of excluded participants due to insufficient video recordings is unfortunate. One reason for the lost recordings could be that some of the excluded children in the SSD group also had shorter attention span. Even if the system compensates for body movements to some extent, the child's face must remain within camera range, or the automatic tracking of facial landmarks is lost. Nevertheless, the automatic tracking procedure worked very well for most participants. The cameras are sensitive to loss of calibration if touched or moved, which was sometimes challenging when used with children with motor and attention difficulties. In a few cases, the recordings were lost due to a child involuntarily touching the cameras. This implies that in order to be clinically useful for all patient groups, further development of the technical equipment is needed.

There was a wide age range in this study with participants varying between 6 and 17 years of age. This heterogeneity could have influenced the results, but the syllable tasks were simple and with no associated language demands. Performance was therefore not expected to differ much between younger and older participants. Earlier studies have shown that motor skills are more variable in children with developmental language disorders depending on the language demands in the speech task used [52]. The correlation with age and performance on some of the variables seen in the SSD group are interpreted as being related to the severity of SSD. If more complex syllables or words had been used, even more children probably had exhibited difficulties with lip and jaw movements during speech. In this study ROM were analysed and not the size of the mouth or jaw. It cannot be excluded that the size of the mouth could influence the size of the movement. However, the size of the mouth differs between different individuals and is not only related to age. The differences between the groups were only detected during speech movements.

Clinical implications

Even minor speech difficulties can affect intelligibility and the listener's perception [53]. Deviant speech can also have a negative impact on social life and future employments for the individual [54]. This strongly suggests that it is important to identify and offer effective treatment for children with speech disorders. Vowel production is important for intelligibility in both typical speech [55] and speech disorders [39] and vowel acquisition is less studied than consonant production in both children with TSD and SSD. The results of this study confirm earlier observations relating to jaw instability in children with motor speech disorders [5,19]. Jaw instability and asymmetric lip movements were observed in children with SSD in this study. Both jaw and lip movements are crucial for vowel production. It is likely that the difficulties in vowel production already seen in a simple syllable repetition task could generate pronounced difficulties in speech demanding more challenging co-articulation. Compensatory fixing patterns such as retracted lips or clenching articulation (fixed jaw) could be a result when underlying motor difficulties are not accounted for. In some intervention studies, it has been reported that increased jaw stability may lead to improved consonant production [19–21]. Identifying jaw instability and addressing this in intervention may be important for children with SSD. There are several therapeutic concepts, such as PROMPT (Prompts for Restructuring Oral Muscular Phonetic Targets), developed for improving accuracy and stability of speech production using tactile-kinaesthetic proprioceptive input [56]. Namasivayam et al. [56] found significant improvement in speech motor skills in children with SMD after 10 weeks of PROMT intervention. The PROMPT focuses on integration of jaw, lip, and tongue movements and improvements in timing and co-ordination of movements [23]. The jaw instability found in this study may represent a commonly overlooked difficulty in children with motor speech disorders resulting in difficulties with vowels related to limited jaw grading control. The literature on lip and jaw movements in children with SSD is sparse and this study adds knowledge to the field of motor speech control in children with SSD.

Conclusion

Children with SSD persisting after the age of six years displayed more asymmetrical and variable movement patterns in the lips and jaw during vowel production compared to children with TSD. Differences were more pronounced in lateral direction for both lips and jaw. These findings confirm findings from previous studies. Using kinematic video assessments in 3D can reveal and confirm smaller speech motor deficits in children with SSD. The results may motivate intervention methods addressing lip control and jaw stability in children with motor speech disorders and orofacial dysfunction as a way to improve speech motor skills.

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