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Articulatory Movement during Production of Lingua-Alveolar Stop Consonants in a Case of Congenital Aglossia

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Abstract

Background: This manuscript, the sixth in a series, discusses an investigation into production of lingua-alveolar stop consonants /tʌ/ and /dʌ/ by a person with congenital aglossia (PwCA), and the specific anatomical and physiological properties and kinematics involved.

Methods: In this study, a modified barium swallow study was performed to analyze the PwCA's oral and pharyngeal tract, in addition to a video speech recording made during a series of imitative tasks isolating specific English phonemes (/tʌ/ and /dʌ/). Researchers evaluated the PwCA's vertical and horizontal range of motion (ROM) of the mobile articulators (i.e., mylohyoid, tongue base, lower incisors, hyoid) during /tʌ/ and /dʌ/ production, and whether these phonemes could be predicted by their ROM and graphic representation. Additionally, researchers analyzed horizontal and vertical movement to identify correlational patterns between dependent (DVs) (i.e., lower incisors, hyoid) and independent variables (IVs) (i.e., lower lip, mylohyoid, tongue base) during production of /tʌ/ and /dʌ/, and the relationships of variables during movement and predictive variable correlation values.

Results: Results revealed that /tʌ/ and /dʌ/ were distinct in specific horizontal and vertical distances of ROM and corresponding horizontal and vertical relationships. Additionally, although the horizontal correlation patterns for IVs and DVs were similar in statistical significance, this was not found between hyoid and mylohyoid. Significant positive correlations were found for /dʌ/ ($r=0.581$, $p<0.05$), but not /tʌ/ ($r=295$, $p>0.05$). In vertical axis for /dʌ/, both DVs were significantly correlated with all IVs except mylohyoid with lower incisor ($r=0.233$, $p>0.05$). For /tʌ/, only three correlations were significant. Hyoid was significantly correlated with tongue base ($r=0.648$, $p<0.05$), and lower incisors were significantly correlated with mylohyoid ($r=0.420$, $p<0.05$), and lower lip ($r=0.923$, $p<0.05$). Finally, multiple distinct ROM differences and significant correlations were observed that made kinematics of /dʌ/ distinct and identifiable from /tʌ/.

Keywords: Congenital aglossia; Articulation; Intelligibility; Syllable production; Oral tract structural modifications

Introduction

Congenital aglossia (CA), a rare condition in which an individual is born without a tongue [1,2], presents unique challenges when considering the anatomical and physiological demands of speech, tasting, chewing, and swallowing. It also presents unique opportunities to study the compensatory measures used by individuals with CA who are able to accomplish these tasks successfully and without medical, surgical, or therapeutic intervention. However, due to the rarity of the disorder and the low survival rate [1,2], there have been few opportunities to conduct in-depth studies of this population to determine the specific mechanisms that are used to compensate for the role of the tongue in these processes [3]. Fortunately, in 1986, one person with CA (PwCA) was identified, and became the participant of subsequent research based on cineradiographic films (CRFs), audio/visual recordings, videoflouroscopy, electropalatography (EPG), taste testing, and in-vivo analysis that has provided a wealth of information regarding the adaptations in vocal tract resonance characteristics, modifications to articulatory processes, alternate neurological pathways to taste discrimination, and altered patterns of chewing and swallowing. Five previous manuscripts have detailed this research [4-8]. The current manuscript discusses an investigation into the production of the lingua-alveolar stop consonants, /t/ and /d/, produced by the PwCA and the specific anatomical and physiological properties and the kinematics involved in these intelligible articulatory productions.

Background

The initial research papers [4,5] provided an in-depth explanation of the disorder, background on the participant, the process of data collection, and analysis of CRFs and audio/visual recordings, as well as an exploration of listener perception and acoustics of vowels produced in isolation and in the contexts of consonant-vowel (CV) and vowel consonant (VC). Results demonstrated greater typicality of back vowels than front vowels. This distinction was attributed primarily to the influence of the vertical and horizontal movement of the vestigial tongue base that allowed the structure to be positioned appropriately for back vowels, but not front vowels, which resulted in relatively characteristic and normal acoustics for posterior phoneme combinations. The main theoretical conclusion drawn from the results of the first examination was that even though the PwCA was able to compensate in general for the lack of a tongue, she did not use certain expected compensatory maneuvers that were available to her, such as pharyngeal expansion and/or lip spreading, to make the front vowels more typical, and thus more intelligible.

In the second paper [5], which detailed a study of semantic/phonemic listener confusions and consonant acoustics, it was concluded that the unusual acoustic characteristics that may have influenced the confusions in listener perceptions could be due to: (a) use of the mylohyoid/geniohyoid, which allows for partial, but insufficient constriction in the anterior oral cavity region, (b) both backing and fronting of the mandible as a means of assisting the mylohyoid/geniohyoid and tongue base in producing a point of constriction with the palate, (c) the presence of craniofacial macrosomia, retrognathia, and micrognathia, which limit the size of the oral space and therefore the vowel space, (d) reduced articulatory movement, notably lip spreading, which inhibits the production and interpretation of front vowels and consonants, and (e) co-articulatory limitations, present in CV and VC production, that require close constrictions or wide serial movements. It should be noted that in the CV and VC syllables, stimuli consisted of both real words and nonsense syllables, with no significant or descriptive statistical difference in listener perception between the real words and nonsense syllables [3,4].

The researchers hypothesized that these five limitations presumably led to the deviations in formant values, voicing, listener perceived consonantal substitutions, and the resultant confusions in intelligibility. In this examination, it was noted that the primary cue for intelligibility of the lingua-alveolar stop consonants /t/ and /d/ was the direction and extent of second formant transition. Inexplicably, however, the bilabial stop consonants /p/ and /b/, were often perceived by listeners as lingua-alveolar stop consonants. Further, there was a higher level of accuracy in listener perception of lingua-alveolar consonants than there was for other consonants; the overall listener intelligibility of initial consonants /t/ and /d/ was 95.8%. The questions that arose from these findings led to investigations into the physiology of the production of these lingua-alveolar stop consonants produced without the presence of a tongue.

The third study [6] detailed an investigation into the compensatory articulatory strategies employed by the PwCA. This study revealed atypical and extensive hyoid activity, which was a unique finding, and one that may begin to explain the relative intelligibility of this PwCA. As reported in McMicken et al. [4,5], during speech production there were vocal tract length changes occurring that may have influenced second formant transitional values and vowel midpoint values. Further, when viewing productions of /t/ and /d/ in the CRFs, there was a suspected visualization of dental-alveolar contact, in addition to the use of use of mylohyoid as anterior pseudo-tongue for constriction. Originally, it had been suspected that the PwCA was activating the mylohyoid, which would be consistent with reports of another PwCA who used this strategy to achieve alveolar constriction [9]. However, images analyzed in the CRFs introduced the possibility that the participant may use the lower incisors as additional intraoral structures for articulatory consonant constriction. This potential compensatory strategy was identified as an additional area of future investigation.

The findings in this third study suggested that the PwCA had learned to use compensatory movements; however, these movements were different from those posited in the first two papers. Rather than employing lip spreading and pharyngeal expansion, it appeared that this PwCA used increased mandibular and hyolaryngeal movements to aid the mylohyoid and tongue base in completing mid-antero-posterior constrictions to produce the acoustic correlate of lingua-alveolar stop consonants. There was also the visualization of dental/alveolar contact as a substitute for lingua-alveolar placement. The main clinical conclusion drawn from these results was that speakers who present with either congenital or acquired structural and/or physiologic reductions to the speech mechanism may, in many cases, demonstrate the capacity to recruit other non-impaired structures to produce intelligible speech, findings which were suggested in a retrospective study of audio/visual recordings of a PwCA by Simpson and Meinhold [3].

The forth study involved the use of EPG to document detailed activity of the articulatory oral structures during speech. Analysis of the EPG electrode activation pattern of the PwCA revealed that labial, dental, mylohyoid, and tongue base contacts were possible and that these contact patterns were similar to normals, but with far fewer electrodes activated in the PwCA. Results were consistent with previous studies [4,5], which revealed a high degree of intelligibility (79%) for this PwCA. Analysis of the lateral view of the maxilla-to-mandible relationship observed in the CRFs documented that the lower incisors were fitting neatly into the alveolar aspect of the maxilla. This observation supports early impressions of the primary investigator (PI) that this PwCA accomplishes anterior contact using the lower incisors. Indeed, this PwCA was able to produce alternating motor rates (AMRs) for the lingua-alveolar stop consonants /t/ and /d/ at approximately 4-5 per second. These rapid AMRs are not only within normal limits [10], but the consonants were produced quickly enough to support a perceptually normal rate of speech. Another plausible explanation for the anterior intraoral contacts might be that the PwCA generates lingu-alveolar sounds by making contact between the lower lip and the lower incisors, as reported in the case of another PwCA by Salles, et al. [9]. Indeed, this PWCA engages in rapid labial contacts that appear to produce sounds other than bilabials such as the lingua-alveolar stop consonants /t/ and /d/; however, the movement is so rapid that it is impossible to determine the lips' role in the coarticulation of phonemes that are being generated in milliseconds. Further studies in this area would require the use of video fluroscopy during speech, which may elucidate other points of constriction and vocal tract changes that augment consonant constriction. The question remains as to the exact nature of the articulatory compensations and adjustments that allow this PwCA to speak in an intelligible fashion and produce consonants that are perceptually correct and distinguishable from each other.

The fifth study in this series involved a return to the 1986 data to analyze the articulatory kinematics during connected speech production and saliva swallow [8]. Results of this study led the authors to hypothesize that the PwCA was making hyoid adjustments, and thus vocal tract adjustments, to alter F2, which rendered speech more intelligible. As discussed previously, the PwCA presents with craniofacial macrosomia, retrognathia, and micrognathia, and as would be inferred from these physiological constraints, a smaller mandible may lead to reduced range of motion for anterior-posterior adjustments. Further, the retrognathic mandible may also assist in the positioning of the lower incisors to aid with mid-palatal constrictions for the lingua-alveolar and mid-palatal sounds. The limited two-dimensional lateral views provided by the CRFs and video recordings precluded the opportunity to visualize more specific movements of the structures involved in the previous and current study.

Research questions

For this sixth and current study, listener perception of the lingua-alveolar stop consonants /t/ and /d/ was not included as it has been well established that the PwCA could produce these phonemes in a perceptually intelligible and distinctive manner [4,5,7]. Therefore, the following multi-part research questions were addressed through the analysis of data derived from articulatory variable range of motion, correlation analysis, and videotape observation of PwCA speech by the authors:

Research question 1: What is the extent of the PwCA's vertical and horizontal range of motion (ROM) of the mobile articulators, consisting of the mylohyoid, tongue base, lower incisors, and hyoid during /tʌ/ and /dʌ/ production, and can the phonemes /tʌ/ and /dʌ/ be predicted by their ROM and graphic representation?

Research question 2: In both horizontal and vertical movement, are the positions of the dependent (i.e., lower incisors, hyoid) and independent articulatory variables (i.e., lower lip, mylohyoid, tongue base) correlated during the production of the lingua-alveolar stop consonants /tʌ/ and /dʌ/, what is the relationship of the variables during movement, and can the phonemes /tʌ/ and /dʌ/ be predicted by their variable correlations?

Methods

Participant

The participant for this study was a 44-year-old female PwCA who was self-referred in 2014 to the same radiologist who performed the original CRF studies of her speech and swallow in 1986. The participant, a co-author on multiple investigations, wanted to determine if her speech, swallowing, and craniofacial structure had changed since initial assessment. The participant and co-authors were also interested in attempting to delineate the anatomical and physiological method by which production of various consonants were generated, including production of /tʌ/ and /dʌ/ during AMRs. The participant, in the presence of the PI, signed release of information forms, including acknowledgment that audiovisual samples might be used for future research and education purposes.

For a complete review of the history of isolated CA and the PwCA discussed in these manuscripts, please see previous manuscripts [4-8]. For the convenience of the reader, a brief description of the PWCA follows. In 1986 during the initial examination, the PwCA presented with craniofacial macrosomia, retrognathia, micrognathia,, and a severe Class II malocclusion. All upper and lower teeth were present, but had collapsed medially due to the absence of the tongue. Intraoral inspection revealed a "wart-like" tongue rudiment medially on the mylohyoid. The expected loss of function caused by the lack of the tongue was partially compensated for by the fact that the floor of the mouth was hypertrophied and, along with the rudiment of tongue base, could be elevated to contact the palate. Similar to the case study by Salles et al. [9], this contact between muscle-masses and palate had allowed the speaker to develop speech and swallowing functions [6-8]. This hypothesis was confirmed by information provided by the PwCA's mother who reported that her daughter had required only minor adaptations for feeding as an infant in the form of widening the bottle nipple lumen for feeding; however, no other medical, surgical or therapeutic assistance was offered or necessary.

In 1986 and to the present day, the PwCA's speech was deemed highly intelligible. Initially, however, in an article written in 1987 [11] it was reported that unless the subject matter was highly predictable, her speech was characterized by marked distortions of vowels and phoneme combinations, notably for single- and two-word utterances. It was suspected that the reduced range of motion noted in the pseudo-tongue in the anterior aspect of the oral cavity was associated with these distortions. However, further examinations of data collected in the past [4,5] and present [7] revealed highly intelligible speech. The question remained as to the exact nature of the articulatory compensations and adjustments which allow the PWCA to speak in an intelligible fashion and produce consonants, particularly the lingua-alveolar stop consonants /t/ and /d/, which were found perceptually correct and distinguishable from each other.

Stimuli

In 2014, a modified barium swallow study (MBSS) was performed at a hospital-based radiology center. In addition to the MBSS, a speech video was recorded with the subject's oral and pharyngeal vocal tract coated with barium. The recordings were collected using a Sony RDR-GXD455 Single Deck DVD recorder, Sony professional camera, and unidirectional microphone. A DVD of the speaker's spoken output was obtained by implementing an imitative task for a series of isolated vowels, monosyllabic and polysyllabic words, diadochokinesis of /pʌ/, /tʌ/, /kʌ/ and /bʌ/, /dʌ/, /gʌ/, and phrases containing specific phonemes of the English language. Only the diadochokinetic tasks of /tʌ/ and /dʌ/ were analyzed in this present study.

Data collection and processing

The Sony RDR-GXD455 Single Deck DVD recorder had a recording rate of 32 frames-per-second. The PI and a computer animation engineer generated frame-by-frame individual mapping of the movement of (a) the anterior/superior point of lower lip, (b) the anterior/superior point of the lower incisors, (c) a medial point on the mylohyoid, (d) the highest point of the medial tongue base, (e) the anterior-inferior point of mandible, and (f) the anterior-superior point of hyoid. As in Matuso and Palmer [12], Cartesian coordinates (0,0) were established by passing a line through the lower border of the upper canine incisor and first molar (horizontal), and a line perpendicular to the upper occlusal plane at the upper canine (vertical; see Figure 1).

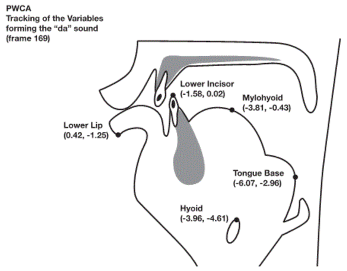


Figure 1: An example of XY values of variable positions derived from Cartesian coordinates.

The X,Y relative coordinate dimensions were developed using pixel conversion to centimeters with the mean selected from 100 random frame samples, of medial height and width of C4 (fused vertebra, 1.25 × 1.40 cm) as a conversion measurement. The individual frames of each of the /tʌ/ and /dʌ/ responses were analyzed to gather vertical and horizontal data points for the lower incisors, mylohyoid, tongue base, mandible, and hyoid.

Reliability of data point locations had been previously established [3,5]. Data were judged by the PI, an expert in the anatomy and physiology of the speech mechanism, and a computer animation engineer, who had 5 years supervised experience in the anatomical tracing of sagittal X-ray frames. The Pearson Product-Moment Correlation between judges was 0.974, which indicated an excellent variable point selection consistency. Movement tracking of the positions of the variables was accomplished using the Adobe After Effects program. As detailed in Matuso and Palmer [12] and Palmer, Hiiemae, and Liu [13] and with the addition of the lower lip and incisor, the positions of displacement of the lower lip and incisor, mylohyoid, tongue base, mandible, and hyoid were expressed as X (horizontal) and Y (vertical) coordinates.

Data Analysis

During data analysis, it was suspected and confirmed that the positions of the lower incisors and mandible would have an overall correlation of 0.999, and therefore terminology identifying the dependent variables was reduced to lower incisors and hyoid. For this study, the dependent variables were defined as the positions of the lower incisors and hyoid, and the independent variables were defined as the positions of the lower lip, mylohyoid, and tongue base. Data from points of maximum excursion for each of the articulatory variables in the 6 repetitions of /tʌ/ and /dʌ/ were compared for repetition correlation. Two of the repetitions of each phoneme with the greatest statistical correlation were then averaged to obtain mean data for the horizontal and vertical movement excursion. As in Matuso and Palmer [12] and Hiiemae et al. [13], these data points were used to analyze range of motion (ROM) and Pearson Product-Moment Correlations. The statistical program utilized was SPSS 22 with significance defined as $p<0.05$

Results

In observing the PwCA's face during data collection, it was apparent that in production of the lingua-alveolar stop consonants /t/ or /d/, the subject appeared to be making bilabial plosives, as her lips came together prior to release of the phoneme. This visually noted behavior would account for the listener reported perception of /tʌ/ for /pʌ/ and /dʌ/ for /bʌ/ [4] and the unusual acoustic analysis locus equations associated with /d/ [5]. When asked how she made these sounds, the PwCA reported "I use my lips to make /t/ and /d/ sounds" (Rogers, [6]). This behavior was also corroborated by EPG tracings, in which activation of electrodes associated with lips, teeth and alveolar ridge during production of /t/ and /d/ were observed [7]. Range of motion of articulators during production of /tʌ/ and /dʌ/ demonstrated both dissimilar and similar patterns, with noted differences in voiced and unvoiced articulatory behavior as discussed in detail below.

Question 1: Range of Motion (ROM)

Interpretation of vertical range of motion

As seen in Table 1, there was slightly greater ROM in production of /dʌ/ than in /tʌ/ in the variables lower lip (9%), lower incisors, (10%), and hyoid (10%), There was an over 50% difference greater ROM in the production of /dʌ/ than in /tʌ/, with the variables of tongue base (51.8%) and mylohyoid (54.5%).

Variable	Lower Lip	Tongue Base	Mylohyoid	Hyoid	Lower Incisors
/dʌ/					
ROM	1.3337	1.3271	1.2539	0.9938	0.5869
SD	0.1713	0,2264	0.274	0.1814	0.1224
/tʌ/					
ROM	1.2566	0.6877	0.6831	0.8519	0.5598
SD	0.1901	0.1698	0.0722	0.1279	0,1135

Table 1: Mean Vertical (Y) Range of Motion (ROM) and Standard Deviation (SD) for Articulatory Variables (in centimeters)*. Mean was calculated by averaging all syllable repetitions with same timing and number of frames.

Interpretation of horizontal ROM

As seen in Table 2, there was slightly greater ROM in production of /dʌ/ than in /tʌ/ in the variables lower lip (9%), and tongue base (13%). There was an unexpectedly high difference with ROM in production of /dʌ/ than in /tʌ/ with the variables of mylohyoid (230%) and less with hyoid (33%). There was slightly greater movement in /tʌ/ more than /dʌ/ with lower incisors (9%).

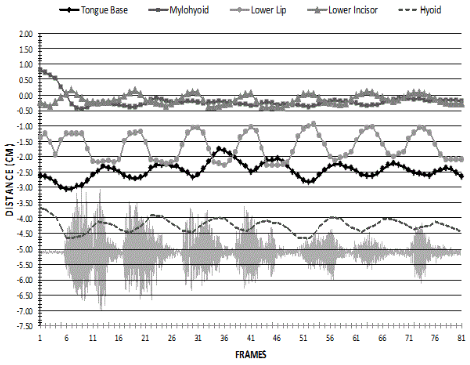
Variable	Lower Lip	Tongue Base	Mylohyoid	Hyoid	Lower Incisors
/dʌ/					
ROM	0.7805	1.0455	1.4236	0.9286	0.4587
SD	0.431	0.269	0.223	0.214	0.1594
/tʌ/					
ROM	0.7235	0.8031	0.3287	0.6	0.5096
SD	0.4335	0.1408	0.1037	0.1319	0.1513

Table 2: Mean Horizontal (X) ROM and SD for Articulatory Variables (in centimeters).

Analysis of the results suggest that it is possible through variable ROM to predict which phoneme utterance /dʌ/ or /tʌ/ is being produced by the PwCA. The consonant /dʌ/ demonstrated over twice as much movement of the tongue base and mylohyoid vertically and the mylohyoid horizontally.

ROM variable movement graphical representation

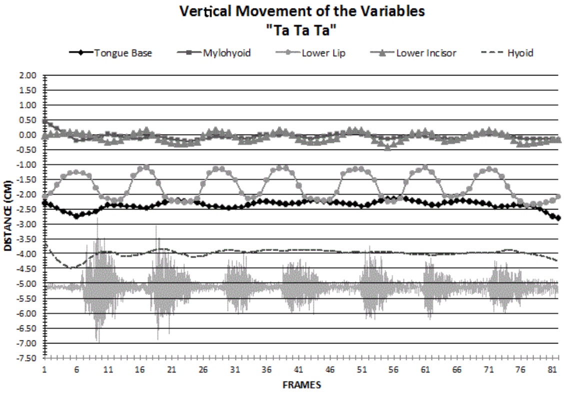
Vertical: /dʌ/. As seen in Figure 2, mylohyoid and lower incisors move within a 0.5 cm plane in a predictable symmetrical and asymmetrical variance. Lower incisors elevate prior to release of utterance. Lower lip and tongue base each move within a nearly overlapping 1.5 cm plane in a predictable, but opposite symmetrical variance. Lower lip elevates and tongue base depresses prior to release of utterance. Hyoid movement is symmetrical with tongue base with a 0.5 cm excursion.



Each dot represents one frame from the fluoroscopy.

Figure 2: Vertical movement of the variables during production of /dʌ/ with corresponding sound wave.

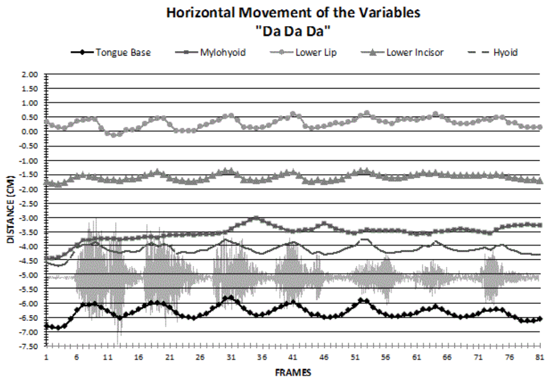
Vertical: /tʌ/. As seen in the Figure 3, mylohyoid and lower incisors move within a 0.25 cm plane with a primarily symmetrical variance, with ROM of lower incisors slightly greater than myhohyoid. Lower incisors elevate prior to release of utterance. Lower lip has greater movement than tongue base, moving within a 1.5 to 2.0 cm plane with a predictable, but opposite and symmetrical variance. Tongue base ROM values are between 0.25-1.0 cm. Lower lip elevates and tongue base slightly depresses prior to release of utterance. Movement of hyoid is slightly and only partially symmetrical with tongue base.



Each dot represents one frame from the fluoroscopy.

Figure 3: Vertical Movement of the Variables During Production of /tʌ/ with Corresponding Sound Wave.

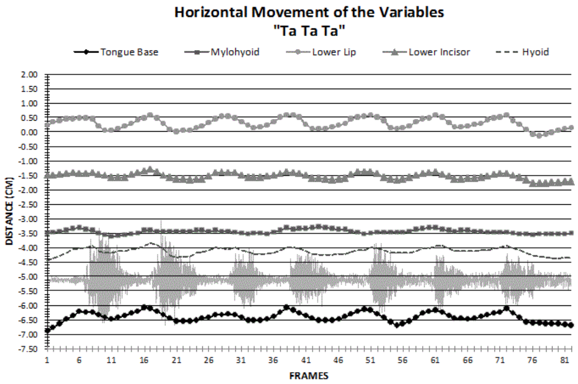
Horizontal: /dʌ/. As seen in Figure 4, lower lip, tongue base, lower incisors, and hyoid each move within a 0.5 cm plane in a predictable and symmetrical variance. Lower incisors and hyoid demonstrate less excursion. All structures increase in motion prior to release of utterance. Mylohyoid increases initially with all variables, but then maintains a more stable position during production of /dʌ/.



Each dot represents one frame from the fluoroscopy.

Figure 4: Horizontal movement of the variables during production of /dʌ/ with corresponding sound wave.

Horizontal: /tʌ/. As seen in Figure 5, similar to /dʌ/, lower lip, tongue base, lower incisors, and hyoid each move within a 0.5 cm plane in a predictable symmetrical variance. Lower incisors and hyoid demonstrate less excursion. All structures increase in motion prior to release of utterance. Mylohyoid maintains a more stable position, without variance during production of /tʌ/.



Each dot represents one frame from the fluoroscopy.

Figure 5: Horizontal movement of the variables during production of /tʌ/ with corresponding sound wave.

Question 2: Horizontal and Vertical Correlation

Horizontal: /dʌ/. As seen in Table 3, the movement of the dependent variable lower incisors had a highly strong relationship with the movement of the independent variables of tongue base ($r=0.810$, $p<0.05$) and lower lip ($r=0.833$, $p<0.05$). Additionally, the movement of the lower incisors demonstrated a highly strong relationship with the other dependent variable, hyoid ($r=0.837$,$p<0.05$. Hyoid movement demonstrated a highly strong relationship with tongue base ($r=0.943$, $p<0.05$,) and strong relationship with lower lip ($r=0.636$, $p<0.05$).

Variable	Tongue Base	Mylohyoid	Lower Lip	Lower Incisor	Hyoid
	R	R	R	R	R
Tongue Base		0.25	0.608*	0.810*	.943*
Mylohyoid	0.25		0.1	0.206	.385*
Lower Lip	.608*	0.1		0.833*	.636*
Lower Incisor	.810*	0.206	0.833*		.837*
Hyoid	.943*	.385*	0.636*	0.837*	

Table 3: Horizontal (X axis) Movement: Pearson Product-Moment Correlation (R) During Repetition of /dʌ/. *P<0.05.

Vertical: /dʌ/. As seen in Table 4, the movement of the dependent variable lower incisors had a highly strong relationship with the movement of the independent variables of lower lip (r=0.832, p<0.05,) and strong relationship with tongue base (r=-0.627, p<0.05,). Additionally, the movement of the lower incisors had a strong relationship with the other dependent variable, hyoid (r=-0.610, p<0.05). Hyoid movement was strongly influenced by the movement of two independent variables: mylohyoid (r=0.581, p<0.05), tongue base (r=0.526, p<0.05), and moderately by lower lip (r=-0.475, p<0.05).

Variable	Tongue Base	Mylohyoid	Lower Lip	Lower Incisor	Hyoid
	R	R	R	R	R
Tongue Base		-0.135	-0.654*	-0.627*	0.526*
Mylohyoid	-0.135		-0.034	-0.233	0.581*
Lower Lip	-0.654*	-0.034		0.832*	-0.475*
Lower Incisor	-0.627*	-0.233	0.832*		-0.610*
Hyoid	0.526*	0.581*	-0.475*	-0.610*	

Table 4: Vertical (X axis) Movement: Pearson Product-Moment Correlation (R) During Repetition of /dʌ/. *P<0.05.

Horizontal: /tʌ/. As seen in Table 5, the movement of the dependent variable lower incisors had a highly strong relationship with the movement of the independent variables of lower lip (r=0.910, p<0.05) and tongue base (r=0.793, p<0.05). Additionally, the movement of the lower incisors had a strong relationship with the other dependent variable, hyoid (r=0.775, p<0.05). Hyoid movement was strongly influenced by the movement of two independent variables: tongue base (r=0.895, p<0.05) and lower lip (r=0.790, p<0.05).

Variable	Tongue Base	Mylohyoid	Lower Lip	Lower Incisor	Hyoid
	R	R	R	R	R
Tongue Base		0.319	0.783*	0.793*	0.895*
Mylohyoid	0.319		0.380*	0.307	0.295
Lower Lip	0.783*	0.380*		0.910*	0.790*
Lower Incisor	0.793*	0.307	0.910*		0.775*
Hyoid	0.895*	0.295	0.790*	0.775*	

Table 5: Horizontal (X axis) movement: Pearson product-moment correlation (R) during repetition of /tʌ/. *P<0.05.

Vertical: /tʌ/. As seen in Table 6, the movement of the dependent variable lower incisors had a highly strong relationship with the movement of the independent variable of lower lip (r=0.923, p<0.05) and was moderately influenced by mylohyoid (r=0.420, p<0.05). The movement of hyoid and lower incisors did not demonstrate a significant correlation. Hyoid movement was strongly influenced by the movement of two independent variables: tongue base (r=0.648, p<0.05) and lower lip (r=0.790, p<0.05). No other relationships were significant.

Variable	Tongue Base	Mylohyoid	Lower Lip	Lower Incisor	Hyoid
	R	R	R	R	R
Tongue Base		0.095	-0.214	-0.297	0.648*
Mylohyoid	0.095		0.24	0.420*	0.308
Lower Lip	-0.214	0.24		0.923*	-0.096
Lower Incisor	-0.297	.420*	.923*		-0.144
Hyoid	0.648*	0.308	-0.096	-0.144	

Table 6: Vertical (X axis) movement: Pearson product-moment correlation (R) during repetition of /tʌ/. *P<0.05

Discussion

The purpose of this paper was to explore production of the lingua-alveolar stop consonants /tʌ/ and /dʌ/ in a case of a PwCA, and to determine if articulatory movement was different and distinctly identifiable in each phoneme production. As seen in the results section, the ROM and graphic representations of /tʌ/ and /dʌ/ are distinctive and identifiable from each other in ROM and correlation relationships. As identified on both the X and Y axis, production of /dʌ/ consistently demonstrated greater ROM than /tʌ/ in all measured variables, except lower incisors, which were equivalent; a higher static position of mylohyoid was also present in /dʌ/ productions. The correlations between the independent variables (i.e., lower lip, mylohyoid, tongue base) and the dependent variables (lower incisors, hyoid) horizontally were similar, except for the significant relationship noted between hyoid and mylohyoid in the case of /dʌ/, but not in /tʌ/. In the vertical axis for /dʌ/, both the dependent variables of hyoid and lower incisors were strongly influenced by the movement of the independent variables of tongue base and lower lip. For /tʌ/, only the dependent variable hyoid was strongly influenced by the independent variable tongue base and dependent variable lower incisors were strongly influenced by the independent variables mylohyoid and lower lip. There are distinct variable correlations which make the identification of /dʌ/ distinct from /tʌ/.

Based on the characteristics of this PwCA, it was understood that the articulatory movements would be different from unimpaired speakers, but up until this current exploration, the exact articulatory movements were unknown and undefined. Further, it was known from previous studies that lower lip, lower incisors, and, mylohyoid would be active, but the exact nature of the activity and interaction of the

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variables was unknown. Based on the results described above, it can now be stated with confidence that the lower lip is the most active anteriorly mobile articulator of the vocal tract in this PwCA, with the greatest range of motion during the periods of closure and release of the lingua-alveolar stop consonants /tʌ/ and /dʌ/. This pattern is highly unusual and is thought to account for the listener and observer confusions of bilabial plosives for lingua-velar stops 5 because of the use of labial gestures to articulate those sounds. Unseen to the observer, but active in the articulatory process, was the movement of the lower incisors into constriction with the anterior palate. Less active, but present in the anterior narrowing of the vocal tract, was the anterior and superior movement of the mylohyoid. Notably active, particularly in both horizontal and vertical graphic movement tracings, was the activity of the tongue base, which was consistently more dynamic for the phoneme /dʌ/. The interaction of these five variables (i.e., lower incisors, mylohyoid, hyoid, lower lip and tongue base) provided the positioning constriction and release for the consonants /tʌ/ and /dʌ/.

Vertical movement of the hyoid and tongue base were more apparent for the voiced consonant /dʌ/ than for the unvoiced consonant /tʌ/. There was consistent symmetry with the hyoid and the lower lip with /dʌ/. Apparent on the graphs (Figures 2-5) was a reversal of the symmetrical and asymmetrical patterned movement of the mylohyoid and lower incisors with voiced and unvoiced productions, indicating vocal tract changes that were apparent between the voiced and unvoiced consonant.

In the horizontal perspective, there was an overall decreased range of motion, and a measurable difference between the articulatory movement for /tʌ/ and /dʌ/, with /dʌ/ demonstrating greater range. In the case of /dʌ/, the tongue base and lower lip were the primary delineators of syllable production with lower incisors, showing similar but less movement. The only variable that did not act in a symmetrical movement fashion was mylohyoid; it appeared to assume a more static placement. In the case of the syllable /tʌ/, variables showed less overall ROM and appeared to behave in a more symmetrical fashion, again indicating that vocal tract changes were apparent between production of the voiced and unvoiced consonants.

Conclusion

The ability to produce intelligible speech with the congenital absence of a tongue, arguably the most important and versatile articulatory structure [3,14], demonstrates the remarkable ability of individuals to employ compensatory strategies that override physiological limitations. In the case of this PwCA, where an individual's phonetic system develops concomitantly and unconsciously with the musculoskeletal system, research has demonstrated that structures outside of those typically associated with speech (e.g., glottis, glossopalatal arches, sublingual ridge, hypertrophied mylohyoid) can be recruited to generate sufficient constriction to produce intelligible consonants [2,3,4,5,15]. Although this PwCA did not receive any therapeutic intervention to address sucking, chewing, swallowing, or speaking, it is likely that the energetic suck and swallow activity that occurred in infancy in the absence a tongue resulted in hypertrophying of oral-peripheral structures including the mylohyoid, tongue base, velum, and pharyngeal walls, which ultimately acted as compensatory structures for speech. It may have also provided for greater than normal elevation and depression of the larynx, which was traced on videofloroscopy as equvalent with the movement of the hyoid.

Over the course of the multiple articles on this PwCA, and in addition to the discovery process, the authors have attempted to understand the compensations this PwCA employs to substitute for the absence of tongue. This information could be possibly be used as a basis of a therapeutic process to assist other individuals with congenital aglossia and /or acquired aglossia who do not demonstrate a functional level of intelligibility. The speech science and compensatory maneuvers that underlie this PwCA's intelligibility, once understood, could potentially be applied to the rehabilitation of selected cranio-facial and glossectomy patients.

However, at present this capacity to generate intelligible speech in the case of the PwCA exists in sharp contrast to the speech produced in the case of the surgical removal of the tongue as a result of injury or disease, as in the case of full or partial glossectomies, where lack of tongue mobility and bulk has been highly correlated with consonantal unintelligibility [16]. This correlation may be related in some cases to the replacement of oral tissue with non-oral tissue or the residual effects of radiation, chemotherapy, or surgical scarring, which may contribute to lack of flexibility. A logical question follows from this inference: could the introduction of post-surgical sucking exercises in these patients improve mobility and eventual intelligibility of speech?

Although the PwCA in this study demonstrates a visually confusing representation of the lingua-alveolar stop consonants /t/ and /d/, this aberrant substitution pattern of lower incisors, lower lip, and tongue base, and mylohyoid to constrict the anterior oral cavity allows for intelligible production. As discussed previously [5], listeners were unable to synchronize the auditory reality of lingua-alveolar stop consonants with the visual representation of the production. This pattern is compensatory with respect to the use of atypical structural modifications to produce intelligible phonemes. Based on the results of this study, the authors would not discourage the use of a visually aberrant pattern if perceptual intelligibility is the result. The focus of treatment should be the acoustic reality of the phoneme rather than the visually structural typical positions. Perhaps visual observer confusion would be then be outweighed by the lack of listener confusion for individual phonemes based on the overall redundancy, and hence intelligibility of language.

The authors offer two suggestions for speech-language pathologists who work with this population toward this end: (1) do not focus on an abnormal substitution pattern if that substitution pattern primarily allows for intelligibility, and (2) attempt the introduction of an energetic suck and swallow exercise program to develop compensatory articulation which would employ and mobilize structures not generally used in normal English phoneme production.

Limitations and Future Research

Limitations of this study include those specific to the research methods used herein and those limitations that apply more generally to case studies. With respect to the former, these limitations consist primarily of the data collection methods that involved two-dimensional videoflourography and the inherent distortions that can be present in film-capture rate. In this situation, the depth of image could not be adjusted and an attempt was made to keep the radiation exposure to a minimum, hence the lack of multiple repetitions of stimuli and a greater variety of response. The second set of limitations reflects those intrinsic to the use of case-study research that was used to conduct and in-depth analysis of this participant. Because of this subjectivity and specificity, one can only generally hypothesize whether these findings can be applied to other, similar participants. However, these limitations do not diminish the overall value of the this study in that the findings present a potential to bridge the gap between theoretical constructs and what has been observed in this research. This research allows researchers to compare findings or observations obtained through other methods of research.

Future research will focus in analysis of real-time, three-dimensional magnetic resonance imaging data of speech, which is currently being collected. Pilot data has been completed and will serve as a sagittal model of vocal tract changes that occur during speech production and swallowing.

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