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Cineradiographic Examination of Articulatory Movement of Pseudo-Tongue, Hyoid, and Mandible in Congenital Aglossia

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Abstract

This research examined cineradiographic films (CRF) of articulatory movements in a person with congenital aglossia (PWCA) during speech production of four phrases. Pearson correlations and a multiple regression model investigated co-variation of independent variables, positions of mandible and hyoid; and pseudo-tongue-dependent variables, positions of mylohyoid and tongue base. Results suggest that backing/fronting of the mandible assisted the mylohyoid/tongue base in making mid-antero-posterior constrictions. Co-linearity findings suggest the best predictor of tongue base movement was mandible for back sounds. Hyoid movement was highly correlated with mandibular movement horizontally, but hyoid acted independently vertically and possibly with greater phonemic specialty in the PWCA. Findings suggest hyoid was a strong determinant of vertically dependent variable movement in all phrases. The extent of hyoid activity was a unique finding and one that may begin to explain relative intelligibility in this PWCA. Observed changes in vocal tract length may have influenced F2 transitional/vowel midpoint values.

Keywords

intelligibility, single-subject research methodology, speech/sound, articulation, speech-language pathologists (SLPs)

Introduction

This article is the third in a series of publications investigating the unique speech production in a case of a 16-year-old female with isolated congenital aglossia (PWCA). In 1986, cineradiographic films (CRF) and audio-visual recordings (AVs) were collected by the principle investigator (PI) of the present study on the PWCA. A thorough examination of the literature revealed these films to be the only reported AVs or CRFs of a PWCA's speech. In recent research that examined the AV recordings (McMicken et al., 2013; McMicken, Von Berg, & Iskarous, 2012), it was reported that the participant did not use compensatory techniques, such as pharyngeal expansion and lip spreading, to assist in vowel or consonant production. Observers in these perceptual studies reported the appearance of speech with *ventriloquistic-like* qualities. These same observers, as well as the authors of the present study, noted what appeared to be unusually active vertical movements of the larynx during speech. In addition, the CRFs demonstrated what appeared to be an unexpected degree of active vertical movement of the hyoid during speech recordings. These observations led to a path of inquiry, and ultimately, methods of scientific investigation that serve to provide some clarification of the compensatory articulatory movements used by the PWCA to achieve relatively intelligible speech.

The current investigation details an exploration into the intraoral structural relationships and articulatory movements evident in CRFs of speech phrases produced by the PWCA. The purpose of this investigation was to examine and quantify the articulatory movements of the pseudo-tongue structures that were determined to consist of the mylohyoid and tongue base, and their correlative interaction with the mandible and hyoid in the existing CRFs of speech phrases.

Background

As described in previous research, the speech of a PWCA has been reported to be intelligible, with few articulatory deviations (De Jussieu, 1718; McMicken et al., 2012; McMicken et al., 2013; Salles, 2008; Simpson & Meinhold, 2007). In addition, perceptual and acoustic analysis of both

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vowels and consonants has been reported by McMicken et al. (2012, 2013) and Simpson and Meinhold (2007). There is a consensus among authors that the mylohyoid and tongue base act as pseudo-tongue in some PWCAs; however, in reviewing the literature, there has been no attempt to visually scientifically document the structural relationships and articulatory movements that permit intelligible speech in a PWCA.

The articulatory structural movements involving the relationship between the mobile articulators of the tongue, mandible, and, in some cases, hyoid movements have been investigated during speech in normal subjects (Hiiemae et al., 2002; Matuso & Palmer, 2010; Menon & Shearer,1971; Ostry & Munhall, 1994; Westbury, 1988). Hiiemae et al. (2002) reported that during reading of the *Grandfather Passage*, the hyoid movement for normal subjects was noted to be irregular and not linked to jaw movement. Furthermore, the range of articulatory position of the hyoid during speaking was found to be quite limited. Matuso and Palmer (2010) reported on the kinematic linkage of the tongue, jaw, and hyoid during speech and eating. The authors tracked both the anterior and posterior surfaces of the tongue and found they were influenced differently by movements of the mandible and hyoid. Furthermore, they noted different relationships between the vertical and horizontal dimensions during speech. A striking finding of this study was revealed in regression analysis, which demonstrated nearly zero in beta (β) or standardized partial regression coefficient values for the hyoid contribution to both the anterior and posterior tongue movements during speech. The researchers reported that both the anterior and posterior tongue movements during speech appeared to have a high degree of independence from the hyoid movement. The authors suggested that future research models should consider the potential significant impact of both the mandibular and hyoid movement on anterior and posterior tongue surface motion. Because the PWCA in the present study has two pseudo-tongue structures, (i.e., the mylohyoid and the tongue base), it seemed a logical investigative step to follow the design and suggestions of Matuso and Palmer (2010).

Current Research Focus

The CFRs collected from the PWCA in 1986 provide a consistent visual view of the activity of the mandible, hyoid, mylohyoid, and tongue base during speech; however, as the lips and larynx were not always within the viewing frame, full vocal tract shapes are not consistently visible. Four of the speech samples initially collected were selected to investigate movements that would normally be associated with the lingual articulatory parameters of the anterior and posterior tongue elevation. Each sample featured a different stop consonant: /t/, /d/, /k/, /g/.

To examine the articulatory consonantal movements in a PWCA, the present study examined the 1986 CRFs to trace the patterns of the dependent variables, which are defined as the positions of the mylohyoid and the tongue base, and to determine whether they were influenced by the independent variables, which are defined as the positions of the mandible and the hyoid in the PWCA. A limitation of the study was that co-articulation was not addressed due to the visual-only nature of the stimuli and the lack of acoustic markers for transitions from consonant into vowel and from vowel into consonant.

Research Questions

For this study, the following research questions were addressed through the use of correlation analysis and a multiple linear regression model:

Research Question 1: What is the extent of the PWCA's vertical and horizontal range of motion of the mobile articulators, consisting of the mylohyoid, tongue base, mandible, and hyoid, during phrase production?

Research Question 2: Does the vertical movement of the hyoid during speech appear to be greater in the PWCA than in normals?

Research Question 3: In both horizontal and vertical movement, are the dependent and independent articulatory variables correlated during phrase production?

Research Question 4: Do the independent variables demonstrate patterns of influence on the dependent variables in a regressive model?

Method

Speaker

The PWCA in this study was a 16-year-old girl who was referred in 1986 to the PI's hospital-based head and neck center by the speaker's mother for a speech and craniofacial assessment. The client's mother, in the presence of the PI, signed release of information forms, including acknowledgment that AV and CRF samples might be used for future research and educational purposes.

Intraoral inspection by members of the head and neck team at an urban medical center revealed a tongue rudiment in the region of the tongue root. According to the interpreting radiologist, the absence of the tongue was compensated for by elevation of the mylohyoid and tongue base as a means of making contact with the mid-anterior palate, posterior palate, and velum. There was no geniohyoid visible or present on palpation. This muscle mass-to-mid palate contact, which allowed the speaker to develop speech and swallowing functions, was also reported in a case study by Salles et al. (2008); however, for the PWCA in the current study, the mylohyoid was not observed to articulate with the upper alveolar ridge for lingua-velar consonant production. At the time of initial assessment, speech was deemed intelligible with some slight distortions (Allison, Salibian, McMicken, & Shoup, 1987).

Stimuli

A 32-frame-per-second lateral CRF of the speaker's output was obtained by implementing an imitative task for a series of phrases including the following:

1. Cut the Cake (CTC; /k/)
2. Go Get Gary (GG; /g/)
3. Did Doug Drive Down (DD; /d/)
4. Take Time to Talk (TT; /t/)

Each phrase was repeated once by the PI, and three times by the PWCA, with a rest period in between each phrase. Phoneme markers were placed on the X-ray film prior to the utterance of each of the four phrases to provide an identifier for the primary consonantal context (i.e., /k/, /g/, /d/, /t/). Because these data were originally acquired in 1986 for the purpose of analyzing intraoral movement for potential surgery, no attempt was made to match the linguistic, phonemic, or syntactic difficulty of the phrases, which is a limitation of the study.

Data Collection and Processing

The original CRFs were obtained using Kodak XX 35 mm cine film with General Electric TVX cineradiographic equipment. The cine film was processed by Fotokem Laboratories in 2007, by scanning the original 35 mm black and white X-ray film on a pin registered Arri scanner. The film was scanned to 2K log DPX files, which was then converted into a tiff sequence. An uncompressed QuickTime movie was generated from the tiff sequence. Individual phrases contained between 32 and 44 frames, depending on length of utterance (see Note 1). The PI and a computer animation engineer generated frame-by-frame individual mapping of the movement of (a) a medial point on the mylohyoid, (b) the highest point of the medial tongue base, (c) the anterior–inferior point of mandible, and (d) the anterior–superior point of hyoid.

As in Matuso and Palmer (2010), Cartesian coordinates (0,0) were established by passing a line through the upper canine tooth and first molar markers (horizontal), and a line perpendicular to the upper occlusal plane at the upper canine (vertical; see Figure 1).

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 four phrases were analyzed to gather vertical and horizontal data points for the mylohyoid, tongue base, mandible, and hyoid (see Figures 2 and 3).

Reliability of the data point locations was judged by the PI, an expert in the anatomy and physiology of the speech mechanism, and a computer animation engineer, who had 5

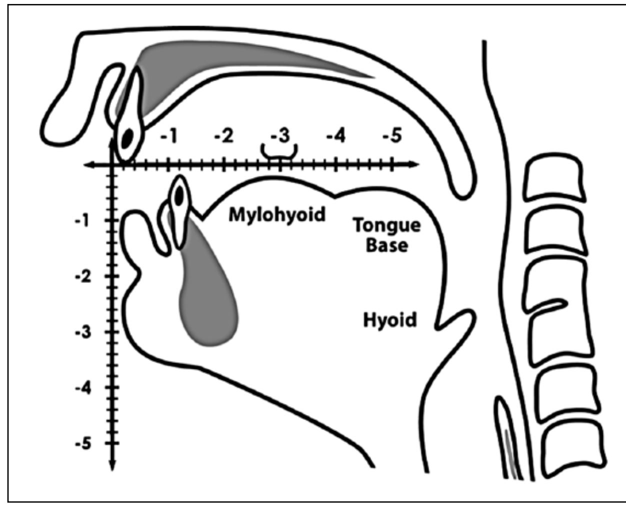

Figure 1. Sagittal section of a PWCA taken from CRF.
Note. PWCA = person with congenital aglossia; CRF = cineradiographic films.

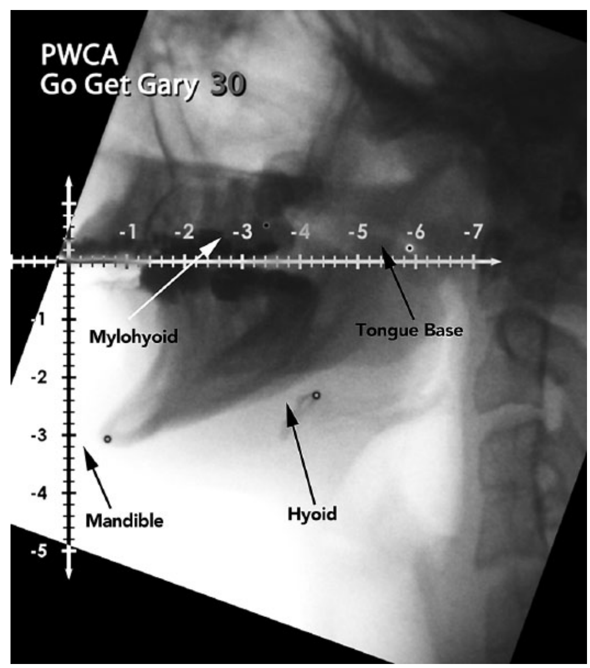

Figure 2. Frame 167 of CRFs during PWCA's production of *Go Get Gary*, demonstrating tracking point of the mandible, hyoid, mylohyoid, and tongue base.
Note. CRF = cineradiographic films; PWCA = person with congenital aglossia.

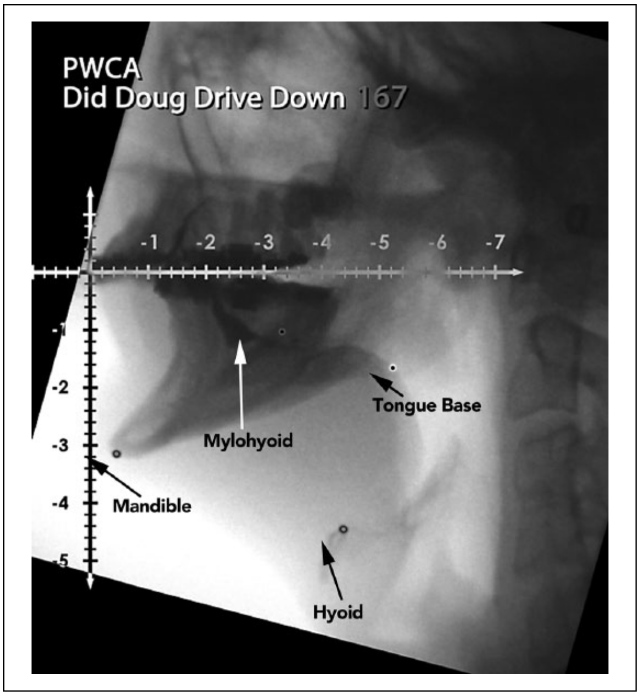

Figure 3. Frame 167 of CRFs during PWCA's production of *Did Doug Drive Down*, demonstrating tracking point of mandible, hyoid, mylohyoid, and tongue base.
Note. CRF = cineradiographic films; PWCA = person with congenital aglossia.

years' supervised experience in the anatomy tracing of sagittal X-ray frames. Twenty-five frames per individual phrase were analyzed, for a total of 100 frames. The data coordinates were subjected to reliability analysis. The Pearson correlation between judges was .974, which indicates an excellent variable point selection consistency.

The movement tracking of the dependent and independent variables was accomplished using the Adobe After Effects program. As detailed in Matuso and Palmer (2010) and Palmer, Hiiemae, and Liu (1997), the positions of displacement of the mylohyoid, tongue base, mandible, and hyoid were expressed as X (horizontal) and Y (vertical) coordinates.

Data Analysis

For this study, the dependent variables were defined as the positions of the mylohyoid and tongue base, and the independent variables were defined as the positions of the mandible and hyoid. Data from points of maximum excursion for each of the articulatory variables in the three repetitions of each of the four phrases (i.e., CTC, GG, DD, and TT) were first compared for repetition correlation. Two of the three repetitions of each phrase with the greatest statistical correlation were then averaged to obtain mean data for the horizontal and vertical movement excursion. As in Matuso and Palmer (2010) and Hiiemae et al. (2002), these data points were used to analyze range, correlation, and regression analysis.

Table 1. Mean of Combined Vertical and Horizontal Range of Movement of Each Independent and Dependent Variable.

Phrase	Base of tongue	Mylohyoid	Hyoid	Mandible
CTC	1.7153	1.1678	1.6045	0.7398
GG	2.3832	1.4813	1.4969	0.4646
DD	1.1336	1.4406	1.4707	0.9641
TT	1.4337	0.7655	1.1422	1.0966

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.

An independent Pearson correlation and a separate multiple linear regression analysis were calculated to determine the mean horizontal and vertical movements for each phrase spoken. In the regression model, correlation coefficients (r) and standardized partial regression coefficients (β) were calculated. An adjusted r^2 was utilized because it represents a modification to account for model complexity and provided a conservative comparison of model performance. Betas represented both the raw coefficients from z-scores and the standardized coefficients, which are identical to the latter. The values for r^2 represented the association between the position of the mylohyoid and the tongue base, and those of the mandible and the hyoid. The beta values represented the influence of the mandible or the hyoid on determining the location of the mylohyoid and the tongue base.

High absolute beta values were indicative of a high degree of influence. Statistical analysis was performed with SPSS software, Version 21.0. Pearson correlation values were statistically significant at the value of $p < .01$. Multiple regression models were statistically significant at the value of $p < .05$

Results

Horizontal Movement: Range and Correlations

The tables of the mean range of movement, correlations, and regression analysis data from both X (horizontal) and Y (vertical) coordinates demonstrate distinct patterns among and between phrases (see Tables 1–6).

Production of Phrase 1 (CTC). Overall mean range of motion (X, Y) of the articulators was noted to follow a hierarchy of the tongue base (1.7153) > the hyoid (1.6045) > the mylohyoid (1.1678) > the mandible (0.7398; see Tables 1 and 2).

The independent variables of the positions of the mandible and the hyoid were strongly correlated (.904, $p < .01$; see Tables 3–6).

Table 2. Individual Phrase Mean, Range, and Standard Deviation of Horizontal and Vertical Movement of Each Independent (I) and Dependent (D) Variable.

	Horizontal movement			Vertical movement		
Phrase	*M*	Range	*SD*	*M*	Range	*SD*
Base of tongue (D)						
CTC	1.1106	−05160–0.5946	0.2874	1.7922	−0.2060–1.5492	0.5339
GG	1.0633	−0.4909–0.5724	0.2525	2.9180	−0.5620–2.3559	0.9176
DD	1.0944	−0.4420–0.6524	0.3370	1.2593	−0.3420–0.9173	0.4507
TT	1.2010	−0.3007–1.0223	0.3676	1.9395	−0.5323–1.4072	0.4537
Mylohyoid (D)						
CTC	0.5433	−0.1373–0.4060	0.1574	1.1437	−0.0652–1.1567	0.4122
GG	0.6563	−0.3723–0.2840	0.1463	1.5128	−0.0425–1.4703	0.5079
DD	0.7536	−0.3915–0.3621	0.1917	1.7853	−0.3533–1.4339	0.5995
TT	0.5419	−0.2193–0.4323	0.1621	1.1266	−0.5097–0.6169	0.3867
Hyoid (I)						
CTC	0.8106	−0.6747–0.1359	0.2343	1.5943	−0.0033–1.5910	0.5383
GG	0.7218	−0.6057–0.1161	0.1674	1.6449	−0.1597–1.4852	0.6240
DD	0.6140	−0.3492–0.2647	0.2979	2.2089	−0.7846–1.4243	0.5875
TT	0.8390	−0.6522–0.3646	0.2874	2.0223	−0.8996–1.1232	0.4505
Mandible (I)						
CTC	0.7996	−0.5316–0.2680	0.2955	0.7574	−0.2706–0.4868	0.2065
GG	0.6319	−0.3632–0.2687	0.1501	0.4060	−0.3213–0.0847	0.1587
DD	0.7743	−0.5068–0.2675	0.2244	0.9253	−0.9253–0.0000	0.2609
TT	0.9051	−0.3134–0.5917	0.2417	0.9256	−0.9248–0.0008	0.2528

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.

Table 3. Correlation Models for Tongue Base and Mylohyoid Using Positions of Mandible and Hyoid as Independent Variables, Horizontal Range of Movement.

	Independent variable	
Dependent variable	Mandible	Hyoid
Phrase 1: CTC		
Tongue base	0.703*	0.700*
Mylohyoid	0.326	0.369
Phrase 2: GG		
Tongue base	0.688*	0.671*
Mylohyoid	0.256	0.039
Phrase 3: DD		
Tongue base	0.899*	0.821*
Mylohyoid	0.856*	0.741*
Phrase 4: TT		
Tongue base	0.830*	0.882*
Mylohyoid	0.794*	0.832*

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.
*Correlation is significant at the 0.01 level.

- Tongue base movements were significantly correlated ($p < .01$) with mandible (.700) and hyoid movements (.703).
- Mylohyoid movements were not significantly correlated ($p > .01$) with mandible (.326) and hyoid movements (.369).

Production of Phrase 2 (GG). Overall mean range of motion (X,Y) of the articulators was noted to follow a hierarchy of the tongue base (2.3832) > the hyoid (1.4969) > the mylohyoid (1.4813) > the mandible (0.4646; see Table 1).

The independent variables of the positions of the mandible and the hyoid were strongly correlated (.755, $p < .01$)

- Tongue base movements were significantly correlated ($p < .01$) with mandible (.688) and hyoid movements (.671).
- Mylohyoid movements were not significantly correlated ($p > .01$) with mandible (.256) and hyoid movements (.039).

Production of Phrase 3 (DD). Overall mean range of motion (X,Y) of the articulators was noted to follow a hierarchy of the hyoid (1.4707) > the mylohyoid (1.4406) > the tongue base (1.1336) > the mandible (0.9641; see Table 1).

The independent variables of the positions of the mandible and the hyoid were strongly correlated (.635, $p < .01$)

Table 4. Correlation Models for Tongue Base and Mylohyoid Using Positions of Mandible and Hyoid as Independent Variables, Vertical Range of Movement.

	Independent variable	
Dependent variable	Mandible	Hyoid
Phrase 1: CTC		
Tongue base	−0.601*	−0.915*
Mylohyoid	−0.564*	−0.857*
Phrase 2: GG		
Tongue base	0.626*	0.902*
Mylohyoid	−0.489*	−0.982*
Phrase 3: DD		
Tongue base	−0.024	−0.833*
Mylohyoid	−0.035	−0.907*
Phrase 4: TT		
Tongue base	0.385	−0.920*
Mylohyoid	0.252	−0.841*

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.
*Correlation is significant at the 0.01 level.

Table 5. Multiple Regression Models for Tongue Base and Mylohyoid Using Mandible and Hyoid as Predictor Measures, Horizontal Range of Movement.

	Standardized beta coefficient		
Dependent variable	Mandible	Hyoid	Adjusted r^2
Phrase 1: CTC			
Tongue base	.703	—	.471
Mylohyoid	—	—	—
Phrase 2: GG			
Tongue base	.688	—	.456
Mylohyoid	—	—	—
Phrase 3: DD			
Tongue base	.634	.419	.909
Mylohyoid	.646	.331	.787
Phrase 4: TT			
Tongue base	.370	.597	.825
Mylohyoid	.376	.543	.738

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.

- Tongue base movements were significantly correlated ($p < .01$) with mandible (.899) and hyoid movements (.821).
- Mylohyoid movements were significantly correlated ($p < .01$) with mandible (.856) and hyoid movements (.741).

Table 6. Multiple Regression Models for Tongue Base and Mylohyoid Using Mandible and Hyoid as Predictor Measures, Vertical Range of Movement.

	Standardized beta coefficient		
Dependent variable	Mandible	Hyoid	Adjusted r^2
Phrase 1: CTC			
Tongue base	—	−.915	.831
Mylohyoid	—	−.857	.723
Phrase 2: GG			
Tongue base	−.252	−.781	.853
Mylohyoid	—	−.982	.962
Phrase 3: DD			
Tongue base	—	−.833	.685
Mylohyoid	—	−.907	.818
Phrase 4: TT			
Tongue base	.136	−.881	.856
Mylohyoid	—	−.841	.700

Note. CTC = cut the cake; GG = go get Gary; DD = did Doug drive down; TT = take time to talk.

Production of Phrase 4 (TT). Overall mean range of motion (X, Y) of the articulators was noted to follow a hierarchy of the tongue base (1.4337) > the hyoid (1.1422) > the mandible (1.0966) > the mylohyoid (0.7655).

The independent variables of the positions of the mandible and the hyoid were strongly correlated (.771, $p < .01$).

- Tongue base movements were significantly correlated ($p < .01$) with mandible (.830) and hyoid movements (.882).
- Mylohyoid movements were significantly correlated with mandible (.794) and hyoid movements (.832).

Horizontal Regression Analysis

Multiple regression models (see Tables 5 and 6) were used for the mylohyoid and tongue base horizontal movements using mandibular and hyoid movements as predictor measures. In examining mylohyoid movement, neither the mandible nor the hyoid predicted the mylohyoid movement for CTC and GG. This finding was expected due to the insignificant correlations between the mylohyoid, the mandible, and the hyoid. There was a strong co-linearity between the mandible and the hyoid that was statistically significant ($p < .05$), and this statistical significance had impact on the predictive model. The tongue base r^2 values for CTC and GG ranged between .456 and .471. Because of the co-linearity, the best predictor of tongue base movement was the mandible in CTC ($\beta = .703$) and in GG ($\beta = .688$). Any movement of the hyoid was insignificant and did not enter the model.

With DD and TT, both the mandible and the hyoid enter the model as predictors of the tongue base and the mylohyoid. The adjusted r^2 for the regression models ranged between .909 and .738. The primary predictor for DD was the mandible followed by the hyoid, whereas in TT, the hyoid was the primary predictor followed by the mandible.

Vertical Movement: Range and Correlations

Significant correlations ($p < .01$) were noted for the mandible, hyoid, mylohyoid, and tongue base in Phrases CTC and GG; however, the hyoid demonstrated a stronger correlation with both the tongue base (CTC = −.915, GG = −.902) and the mylohyoid (CTC = −.857, GG = −.982), than did the mandible with the tongue base (CTC = −.601, GG = −.626) or mylohyoid (CTC = −.564, GG = −.489). In regression analysis, the primary predictor in CTC and GG was the hyoid. The mandible entered only weakly in the equation with the tongue base for GG; otherwise, it did not enter. The independent variables of positions of the mandible and the hyoid were strongly correlated in CTC (.635, $p < .01$) and moderately in GG (.479, $p < .01$).

For DD and TT, the hyoid was noted to demonstrate strong significant correlations ($p < .01$; range = −.833 to −.920) with the tongue base and the mylohyoid, but was insignificant with the mandible. Based on the correlation model, the expectation would be for the hyoid to control the tongue base and mylohyoid movement in all phrases. The independent variables of the positions of the mandible and hyoid were insignificantly correlated in DD (−.013, $p > .01$) and weakly correlated in GG (−.282, $p > .01$).

Vertical Regressive Analysis

Beta values representing horizontal movement were noticeably different from those representing vertical movement. The mandible did not enter the model for CTC and DD, but entered as a weak second step for tongue base in GG (β = −.252) and tongue base in TT (β = .136). So although the mandible did enter, it did not greatly contribute to the adjusted r^2 values. The hyoid contributed the majority to the adjusted r^2 values, which ranged from .685 to .856 across phrases for tongue base and .700 to .962 across phrases for the mylohyoid.

Discussion

This study's primary objective was to investigate the articulatory patterns of a PWCA that allowed for relatively intelligible speech. CRFs of four phrases were examined frame by frame, and the articulatory pattern of the mylohyoid, tongue base, mandible, and hyoid were traced and plotted for the four phrases. Pearson correlation and regressive analysis were performed on data from a total of 2,336 positional coordinates in 584 frames. The following research questions were addressed:

Research Question 1: What is the extent of the PWCA's vertical and horizontal range of motion of the mobile articulators, consisting of the mylohyoid, tongue base, mandible, and hyoid, during phrase production?

Research Question 2: Does the vertical movement of the hyoid during speech appear to be greater in the PWCA than in normals?

Research Question 3: In both horizontal and vertical movements, are the dependent and independent articulatory variables correlated during phrase production?

Research Question 4: Do the independent variables demonstrate patterns of influence on the dependent variables in a regressive model?

Research Questions 1 and 2

The Cartesian coordinates for range of articulatory movement were based on C4 vertical (1.40 cm) and horizontal (1.25 cm) dimensions. The range values verified previous reports of visualization of extensive laryngeal movement during speech on the AV recordings and hyoid movement on the CRFs. In contrast to previous studies' findings revealing small relative vertical or horizontal hyoid movement for normal speakers, there was increased relative vertical and horizontal movement for the PWCA. The relative vertical hyoid movement in the PWCA during production of CTC averaged 1.6 cm, with GG 1.7 cm, DD 2.2 cm, and TT 2.0 cm. These movements are relative in that they are based on the dimensions of C4 measured on an X-ray in the PWCA. For each phrase, the average vertical hyoid movement was greater than the relative height of C4 (1.40 cm). Horizontal movement during production of CTC averaged 0.81cm, with GG 0.72 cm, DD 0.61cm, and TT 0.84 cm, all less than the relative width of C4 (1.25 cm) but still demonstrating considerable variation. As suggested in McMicken et al. (2012), this increased relative movement may have been developed to compensate for smaller than normal oral and resonating cavities.

It has been established that this PWCA did not use lip rounding or spreading or pharyngeal expansion during speech to change vocal tract shape (McMicken et al., 2012, 2013). Because the larynx is suspended from the hyoid, it is suspected that extensive hyolaryngeal raising and lowering are a compensatory articulatory strategy used by the PWCA to change the shape of the vocal tract during speech production. Although other muscles contribute to laryngeal raising and lowering, they could not be visualized in the CRFs, and only the activity of the mylohyoid and tongue base could be visualized and measured. Because vocal tract lengthening and shortening are known to change formant values and therefore shape vowels (Peterson & Shoup, 1966), it appears that this may be one mechanism used by the PWCA to make speech more intelligible.

Research Questions 3 and 4

Pearson correlations and the regression model revealed that movements of the dependent variables of the positions of the mylohyoid and tongue base showed differing correlations with the movements of the independent variables, the positions of the mandible and the hyoid, depending on the consonantal context of the four phrases and dimensions measured. In the Pearson correlations of variable interaction during CTC, the horizontal movement of the tongue base showed a strong correlation with both the mandible and the hyoid. The regressive model demonstrated a greater contribution of the mandible to tongue base movement with the hyoid not entering the model. Mylohyoid movement was not significantly correlated with either the mandible or the hyoid movement, and did not enter the regressive model as being influenced by either of the independent variables in subsequent stepwise regression ($p < .05$). The same pattern was revealed for GG, with significance reached only by horizontal mandibular motion influencing tongue base position.

Horizontal variable movement patterns differed for phrases DD and TT. Pearson correlations were strong for both independent variables of the positions of the mandible and the hyoid and their relationship to tongue base and mylohyoid movement. The adjusted r^2 value was nearly equal in the amount of influence of the independent variables on the dependent variables; however, the primary predictor in regressive analysis for DD dependent variables was clearly the mandible, and for TT, it was the hyoid, closely followed by the mandible.

Vertical movement was clearly influenced by the independent variable of the position of the hyoid for all phrases. Pearson correlations were strong in CTC and GG for the hyoid, and moderate to less strong for the mandible. Regression analysis, however, revealed the hyoid accounting for vertical movement, with an insignificant contribution from the mandible with the tongue base in GG.

The hyoid continued to be the strongest predictor of dependent vertical variable movement for DD and TT. Pearson correlations as well as regressive analysis revealed insignificant relationships of the mandible and the dependent variables of position of the tongue base and the mylohyoid.

As expected in the vertical dimension, the hyoid was a key predictor of movement throughout the phrases. These statistical associations may reflect some of the diverse coordination patterns of the anterior and posterior aspects that make up the pseudo-tongue.

In contrast to the Matuso and Palmer's (2010) study on normal intraoral kinematics, the hyoid movement was highly correlated with the mandible movement horizontally but was observed in the vertical dimension to act independently or with greater phonemic specialty in the PWCA speech production (see Table 4).

Conclusion

It must be emphasized that the present study was an initial attempt to understand some of the compensatory articulatory strategies of a PWCA. In this present investigation, it was clear that the mandible controlled horizontally dependent variable movement in phrases consisting of back sounds. This finding supports assertions by McMicken et al. (2013) who suggested that the backing and fronting of the mandible assisted the mylohyoid and the tongue base in making mid-anterior and posterior constrictions. Indeed, co-linearity findings suggest that the best predictor of tongue base movement was the mandible for back sounds.

It was also clear that the hyoid is the strong determinant of vertical dependent variable movement in all phrases. The extent of hyoid activity was certainly a unique finding and one that may begin to explain the relative intelligibility of this PWCA. Obviously, there were changes in vocal tract length occurring, which may have influenced F2 transitional values and vowel midpoint values, as reported in McMicken et al. (2013). Perhaps it is this phenomenon that allowed for relatively accurate speech perception with unusual vocal tract shapes.

Interestingly, in viewing the CRFs showing productions for /t/and/d/, there was a suspected visualization of dental–alveolar contact, rather than use of pseudo-tongue. It was originally suspected that the PWCA was using the pseudo-tongue (mylohyoid), which would be consistent with reports of another PWCA who used this gesture to achieve alveolar constriction (Salles et al., 2008). However, visualization of the CRFs introduces the possibility that the subject may use the lower front teeth as an additional intraoral structure for articulatory consonant constriction. This potential compensatory strategy will be considered an additional area of future investigation.

In the first article of this series, the authors suggested that this PWCA was not using certain compensatory maneuvers, such as lip spreading and pharyngeal expansion, that might increase intelligibility. The authors assumed that the PWCA would have adopted these compensatory techniques because these were thought to alter F2 to render speech more intelligible. The findings in this study suggest that the PWCA *did* learn to use compensatory gestures; however, these gestures are different from those suggested in the original manuscript.

Rather than engaging in lip spreading and pharyngeal expansion, it appears that this PWCA engages in increased mandibular and hyolaryngeal movements to aid the mylohyoid and tongue base in completing mid antero-posterior constrictions to produce the acoustic correlate of consonants. These articulatory adjustments are idiosyncratic to this individual and are not unlike reports of compensatory gestures used by other PWCAs. Simpson and Meinhold (2007), for example, reported on a PWCA who engaged in tongue base contacts with the palatoglossal arches to produce velar-like stops.

The main clinical conclusion to be drawn from these results is that speakers who present with either congenital or acquired structural and/or physiologic reductions to the speech mechanism may present, in many cases, with the capacity to recruit other non-impaired structures to produce intelligible speech. It is the role of the speech-language pathologist to recognize the myriad structural and physiologic dynamics available to clients and assist them in capitalizing on segmental and suprasegmental strategies to increase functional verbal speech.

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Note

1. The cineradiographic films (CRF) of the four phrases may be viewed at http://youtu.be/cfNoLU1p1eo with 50% slow motion.

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