Interspeech 2018
2-6 September 2018, Hyderabad

Acoustic Features Associated with Sustained Vowel and Continuous Speech Productions by Chinese Children with Functional Articulation Disorder

Wang Zhang[1,2], Xiangquan Gui[1], Tianqi Wang[2], Manwa Ng[3], Feng Yang[4], Lan Wang[2] and Nan Yan[2,5]

[1]School of Computer and Communication, Lanzhou University Of Technology, Lanzhou, China
[2]CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China
[3]Speech Science Laboratory, University of Hong Kong, Hong Kong, China
[4]Department of Speech Therapy, Shenzhen Children's Hospital, Shenzhen, China
[5]Guangdong Provincial Key Laboratory of Robotics and Intelligent System, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China
nan.yan@siat.ac.cn, xqgui@lut.cn

Abstract

Functional articulation disorder (FAD) is a speech disorder commonly found in preschoolers, negatively affecting their day-to-day communication and in the long run their psychological development. Current FAD research mainly focused on the perceptual aspects, but not other means such as acoustic and physiological analyses. The present study aimed to evaluate the different acoustic features associated with sustained vowels and continuous speech produced by children with FAD and their age-matched controls. Speech samples produced by 67 children with FAD and 30 typically developing children were obtained from children's hospital and kindergartens, respectively. Articulatory-acoustic vowel space features, including formant centralization ratio (FCR3), F1 range ratio (F1RR), F2 range ratio (F2RR), and triangular vowel space area (TVSA), were calculated using the first two formant frequencies (F1 & F2) from vowels /a/, /i/, /u/. Voice onset time (VOT) values associated with the stop consonants /b/, /p/, /d/, /t/, /g/ and /k/ were also obtained. Results indicated that children with FAD exhibited articulatory undershooting with reduced range of articulatory movements, as well as poorer control over the release of oral occlusion when producing aspirated or unaspirated stops, when compared with normal counterparts. The findings support the notion that these acoustic features can be used to differentiate misarticulated speech from healthy speech, and could be used to objectively classify and evaluate FAD speech.

Index Terms: functional articulation disorder, acoustic feature, formant centralization ratio, formant range ratio, triangular vowel space area, voice onset time

1. Introduction

Functional articulation disorder (FAD) is a speech disorder characterized by inappropriate speech-sound deletions and substitutions [1]. This may result from deficits in sensory and motor development at a certain stage or caused by sensory integration dysfunction (SID) [2]. FAD is among the most prevalent speech disorders in preschool children [3]. Previous studies suggested that phonological disorders (including articulation disorders) represented approximately 10% of the population, of which 1% to 21% were FAD. Meanwhile, other studies suggested that prevalence of FAD among preschool and school-age children is approximately 10% [2].

FAD not only affects children's speech and communication skills, but also their education. It has been indicated that FAD children tended to show education failure at school, resulting in some degree of social exclusion and low quality of life [4]. Yet, it is encouraging to learn that 72.3% to 89.2% of children showed marked improvement after proper therapeutic interventions. Some children even reached 100% rehabilitation with the help of speech therapist [5]. It follows that identification of the acoustic features of FAD speech can be of foremost importance in preclinical stages, as this will be used to classify and evaluate the pathologic speech, which will guide therapeutic practice.

Speech signals carry measurable acoustic features which are related to certain aspects of speech production. Motor speech performance during speech production can also be reasonably revealed based on speech acoustics [6]. Yet, previous clinical studies on FAD mainly made use of subjective means, such as case study, clinical articulation function evaluation, and articulation error analysis [7-14]. Such methods were sensitive to therapists' judgements but not appear to be suitable for studies based on a large scale of speech data. Seeing such, we sought to evaluate different unbiased acoustic parameters that are associated with FAD speech, in the hope of guiding clinical practice with greater objectivity and accuracy.

Given that articulation impairment is heterogeneous both within and across children with FAD (e.g., either vocalic or consonantal misarticulation, although a child can have both), we evaluated different acoustic features that are related to certain aspects of speech production. The most relevant acoustic parameters for vowel production are the first two formants, F1 and F2 [6]. In general, F1 varies inversely with the tongue height, and F2 varies inversely with tongue advancement during vowel production. Furthermore, both F1 and F2 values decrease when lips are rounded and increase when lips are retracted [15]. By the abovementioned general rules in acoustic-articulatory relationships, we can construct the triangular vowel space area (TVSA) by determining the F1 and F2 frequencies of the corner vowels /a/, /i/, /u/ [16]. Sapir et al. [6] proposed the Formant Centralization Ratio (FCR) and its

10.21437/Interspeech.2018-1521

inverse, the Vowel Articulation Index (VAI), as alternative metrics to differentiate dysarthric from healthy (vowel) speech, after identifying the inconsistent performance of vowel space area (VSA) when used as an acoustic metric of dysarthric speech. Such metrics have been used for acoustic analysis to differentiate between subjects with Parkinson's disease and healthy control groups, and monitor speech changes (improvement or deterioration) in previous studies conducted in the US [6,17], as well as in Germany [18]. These acoustic metrics also have implications for other types of dysarthria, such as that associated with cerebral palsy, traumatic brain injury, amyotrophic lateral sclerosis, and multiple sclerosis. However, few studies used these metrics to measure vowels produced by children with FAD.

Voice onset time (VOT), defined as the time interval between the release of a closure and the start of voicing of the following vowel [19], has also been regarded as a reliable acoustic parameter that indicates the phonetic contrast between voiced and voiceless stops [20]. Ackermann and Hertrich [21] measured the stop consonants /d/ and /t/ in sentence utterances (in German) produced by subjects with ataxic dysarthria and healthy control group, and found that a reduced categorical distinction of voiced and unvoiced stop consonants based on VOT was presented by the patient group. Other neurogenic communication disorders using VOT to explore phonemic and phonetic abnormalities include aphasia [22,23], and dysarthria [24,25]. Considering the uniqueness of Chinese, the present study, as a pioneering work, made use of VOT to analyze the production of aspirated and unaspirated stop consonants by children with FAD, compared with normal counterparts.

The present study aimed to evaluate objective acoustic features including FCR, TVSA, VOT and other relevant features, in sustained vowels and continuous speech produced by children with FAD and age-matched health controls. We hypothesized that children with FAD would have significantly lower FCR and TVSA than the matched controls due to their poor motor control. For the same reason, children with FAD may also demonstrate VOT abnormalities.

2. Methods

2.1. Participants

The current study consisted of 97 individuals divided into 2 groups: the FAD group and healthy control group. Participants in the FAD group included 67 children with FAD (50 boys and 17 girls) who were recruited from the Shenzhen Children's Hospital and confirmed by a professional speech therapist. Inclusion criteria included: children aged between 3 to 6 with normal hearing, intelligence, and social emotional and behavioral skills [3]. Children with FAD due to congenital disorders such as cerebral palsy, and with acquired etiologies such as brain tumors and traumatic brain injury [4] were excluded from the study. Thirty age-matched normal children (17 boys and 13 girls) were recruited from local kindergarten and served as the controls. All 97 child participants were native Mandarin speakers, and demographic information is shown in Table 1. Informed consent was obtained from each child's parent before the experiment, and the research protocol was approved by the Institutional Review Board of The First Affiliated Hospital at Shenzhen Institutes of Advanced Technology in accordance with the Code of Ethics of the World Medical Association.

Table 1: *The ages among participants*

	FAD		**Control**	
	Mean	SD	Mean	SD
Ages	4.67	0.944	4.77	0.935
(Range, in year)	(3.00-6.00)		(3.00-6.00)	

2.2. Materials

Speech materials included the sustained vowels /a/, /i/, /u/ and 42 Mandarin phrases containing consonants /b/, /p/, /d/, /t/, /g/, /k/. They were produced by a female native Mandarin speaker and prerecorded for the experiment. All phrases are either disyllable words, such as jian3 dao1 (scissors) and qian1 bi3 (pencil), or trisyllable words, such as zi4 xing2 che1 (bicycle) and ken3 de2 ji1 (Kentucky Fried Chicken).

2.3. Procedure

Vocal tasks consisting of: (1) sustained vowel sounds, and (2) continuous speech were conducted separately. During the experiment task, each participant listened to the prerecorded vowels or phrases one at a time and repeated them 3 times in a sequence. The entire process was recorded in a noise attenuated room via a high quality microphone USB (Apple Blue Microphones Yeti Pro USB Microphone) positioned 6 cm from the lips. The samples were digitized with 44100 Hz sampling rate and 16-bit resolution. The speech samples produced by children with FAD were obtained over a month, while sample collection for the control group was completed in two days.

2.4. Data analysis

F1 and F2 values were obtained from vowels /a/, /i/, /u/ using *praat*. To avoid instability, only the medial 80% of the vowel portion was used for analyzing the average F1 and F2 values. The FCR3, F1RR, F2RR, and TVSA were constructed from the averaged F1 and F2 (in Hz) based on the formulas in [6]:

$$FCR3 = (F2_u + F2_a + F1_i + F1_u) / (F2_i + F1_a) \quad (1)$$

$$F1RR = F1_a / [(F1_i + F1_u) / 2] \quad (2)$$

$$F2RR = F2_i / F2_u \quad (3)$$

$$TVSA = 0.5 * abs\, [F1_i * (F2_a - F2_u) + F1_a * (F2_u - F2_i) + F1_u * (F2_i - F2_a)] \quad (4)$$

where FCR3 is the formant centralization ratio, which measures the vertical (elevation vs. depression) and horizontal (forward or backward) movement of tongue; F1RR is the F1 range ratio corresponding to tongue's vertical movement; F2RR is the F2 range ratio corresponding to the tongue's horizontal movement; TVSA is the triangular vowel space area calculated using Euclidean distances between F1 and F2 frequency of the corner vowels /a/, /i/, /u/, which depicts the dimensional configuration of the vocal tract resulting from the articulatory movement. Both FCR3 and TVSA reflect the coordination of the tongue during vowel production, yet previous studies found that VSA is highly sensitive to interspeaker variability such as gender, age, and idiosyncratic tongue postures [26].

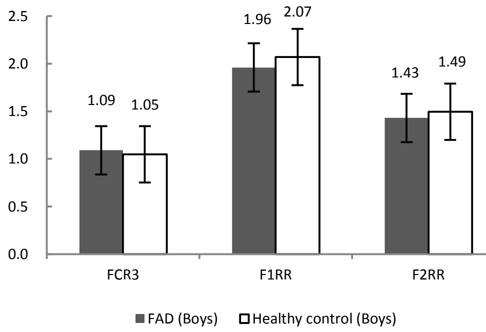
The consonants /b/, /p/, /d/, /t/, /g/, /k/ were manually annotated in the phrases and extracted by an experimenter by *praat*. VOT is defined as the duration between the release of the stop and the start of voicing, which is in line with the definition [21].

Considering the heterogeneous speech development between genders, all of the parameters were calculated separately for boys and girls.

3. Results

3.1. FCR3, F1RR and F2RR

Formant centralization ratio, F1 and F2 range ratio of the FAD group and healthy control group were separately calculated for boys and girls, which are shown in Figure 1. Both FAD boys and girls had lower F1RR than their counterpart, but there was only a significant difference in girls (boy: $t = 0.049$, $p = 0.961$; girl: $t = -2.258$, $p = 0.040$). FAD boys had slightly lower F2RR than controls ($t = -0.614$, $p = 0.543$), while FAD girls had slightly higher F2RR ($t = 1.252$, $p = 0.231$). Besides, FCR3 was larger in FAD groups (both boys and girls), but significant difference was only found in girl's group (boy: $t = 0.506$, $p = 0.616$; girl: $t = -2.249$, $p = 0.041$).



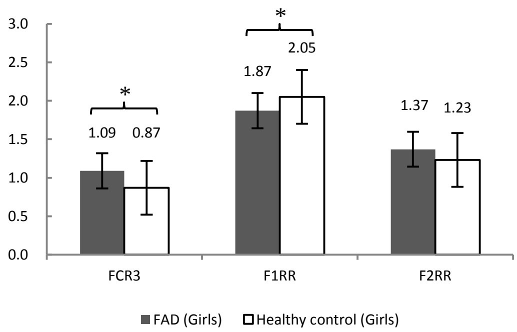
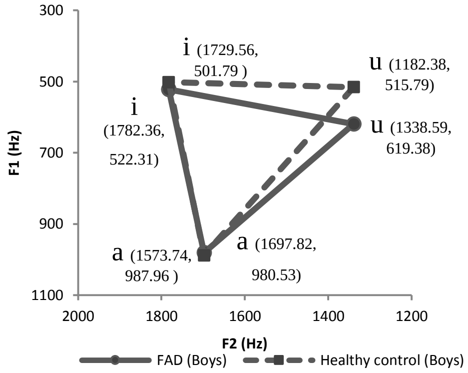


Figure 1: *FCR3, F1RR and F2RR (Hz) of the FAD group (dark bar) and the control group (white bar). The upper bar chart is for boys and the lower is for girls. Asterisks indicate where the differences between the two groups are significant.*

3.2. Triangular vowel space area

Figure 2 is the vowel chart that shows the range of possible vowel quality. The corners are the (F1, F2) of the three vowels /a/, /i/ and /u/, which were linked together to form a triangle, the size of which is equivalent to TVSA.The TVSA of FAD boys and controls were 119.20 and 139.46 separately, while that of FAD girls and controls were 116.48 and 96.74 separately. Results of Student's t-test indicate that TVSAs were not significantly different between the FAD group and the control group for both boys ($t = -0.766$; $p = 0.449$) and girls ($t = 0.559$; $p = 0.586$). Figure 2 is the vowel chart that shows the range of possible vowel quality.



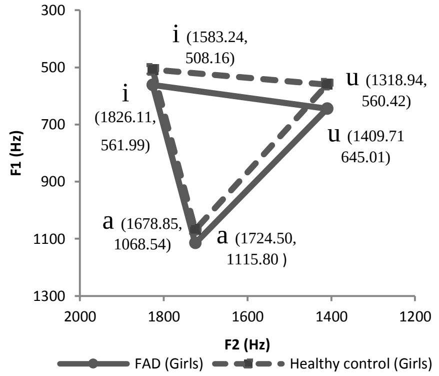


Figure 2: *The vowel charts for boys (upper) and girls (lower). The corners are the (F1, F2) of the three vowels. The tongue positions of /a/, /i/, /u/ are linked by solid lines for FAD group, and dashed lines for the control group.*

3.3. Number of noticeable vowel sound distortions

Specific articulatory abnormalities of FAD group in vowel sounds /a/, /i/, /u/ were separately investigated, and the number of vowel sound distortions was shown in Table 2. /u/ was more likely to be misarticulated by boys, while girls tended to produce more articulatory abnormalities in /i/.

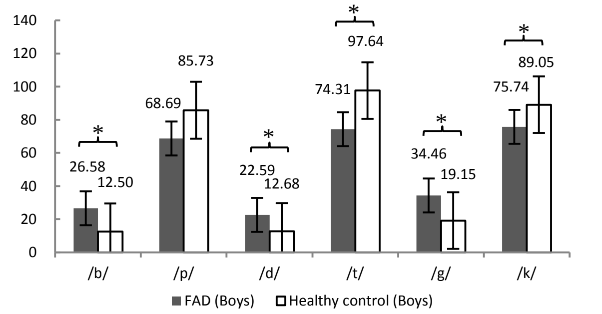
Table 2: *Number of noticeable vowel sound distortions in FAD group*

	Boys	**Girls**
/a/	8	4
/i/	5	5
/u/	9	5

3.4. VOT

Figure 3 shows the averaged VOT of unaspirated stop consonants /b/, /d/, /g/ and aspirated stop consonants /p/, /t/, /k/ in both FAD groups and control groups. The result showed that FAD boys had longer VOTs than the control group when producing unaspirated stop consonants /b/, /d/, /g/, and the differences between the two groups were significant (/b/: $t = 4.445$, $p = 0.000$; /d/: $t = 6.148$, $p = 0.000$; /g/: $t = 7.510$, $p = 0.000$). However, FAD boys had shorter VOTs than controls in terms of aspirated stop consonants. Significant differences were found in /t/ ($t = -3.155$, $p = 0.002$) and /k/ ($t = -2.494$, $p = 0.017$), but not in /p/ ($t = -1.940$, $p = 0.057$).

Student's t-test was also conducted for unaspirated and aspirated stop consonants between FAD girls and the control group. In terms of unaspirated stop consonants /b/, /d/, /g/, VOTs were significantly longer in the FAD group (/b/: t = 4.658, p = 0.000; /d/: t = 6.968, p = 0.000; /g/: t = 5.227, p = 0.000), while that of aspirated stop consonants /p/, /t/, /k/ were not significantly different between the two groups (/p/: t = -1.027, p = 0.314; /t/: t = -0.037, p = 0.971; /k/: t = -1.038, p = 0.309).



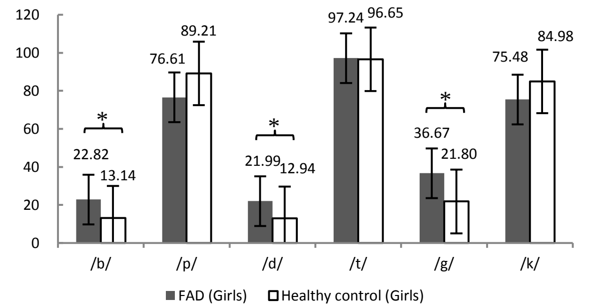


Figure 3: *VOT (ms) of the FAD group (dark bar) and the control group (white bar). The upper bar chart is for boys and the lower is for girls. Asterisks indicate where the differences between the two groups are significant.*

4. Discussion

The current study attempted to evaluate the different acoustic features, including FCR3, F1RR, F2RR, TVSA and VOT, in sustained vowel pronunciation as well as continuous speech from children with FAD and typically developing children that are matched on age. Considering gender difference in speech development, we compared the abovementioned acoustic features within the gender group. Results showed that the FAD group (boys and girls) has greater FCR3 values than the control group, although significant difference was only found for girls. It has been well documented that formant centralization ratio reflects the vertical and horizontal movement of the tongue [6]. Since girls with FAD presented reduced vertical articulatory movement to a great extent compared with the control group indicating by the significantly lower F1RR, while their horizontal articulatory movement did not present such difference, FAD girls' vowel centralization can be attributed mainly to their reduced range of vertical movement. In terms of noticeable vowel sound distortions, FAD girls exhibited greater misarticulation when producing the high-front vowel /i/, articulated with the tongue placed at the upper-front part of the vocal tract. This can be explained by our findings that FAD girls had difficulties in elevating their tongues instead of forwarding their tongues, for their articulatory movement are impaired in the vertical direction while remain intact in the horizontal direction. As for boys with FAD, both of their F1RR and F2RR were not significantly lower than the control group, although some presented obvious articulatory undershooting when we went through all the independent cases. It is believed that the interspeaker variability might have masked the differences when making a between-group comparison.

TVSA has been used as a measure of vowel articulation impairment, while previous studies suggested that the parameter performed more effectively than formant centralization ratio because of its high sensitivity to interspeaker variability (e.g., [26]). Our study also testified this effect as FAD girls had significantly larger FCR values than the control group, while their TVSA was not smaller than their counterpart. In future studies, the logarithmically scaled version of the TVSA could be used as an alternative of TVSA [27] as the inter-speaker variability might be reduced if frequencies are in a ratio form.

To the best of our knowledge, VOT was rarely used to study the motor control ability of children with FAD [28-30]. Previous studies [21] measured the VOT of the stop consonants /d/ and /t/ produced by subjects with ataxic dysarthria, finding that the patient group reduced categorical distinction between the VOT of voiced stop consonants and unvoiced stop consonants. In our study, both children with FAD (boys and girls) and the typically developing children have longer VOT in aspirated stop consonants /p/, /t/, /k/ and shorter VOT in unaspirated stop consonants /b/, /d/, /g/. However, children with FAD have shorter VOTs in aspirated stop consonants (except /t/ in girls with FAD) and longer VOTs in unaspirated stop consonants when comparing to the control group. This will make the FAD group reduce its categorical distinction between the VOT of aspirated stop consonants and unaspirated stop consonants, which is in accordance with [21]. Previous studies have attributed these phenomena to the patients' poor control over their respiration and the release of oral occlusion when producing aspirated or unaspirated stops. Our results also document that the FAD children might have deficits on coordinative movements of respiratory and articulatory system.

5. Conclusions

In the present study, we evaluated different objective acoustic features associated with sustained vowels and continuous speech produced by children with FAD and the typically developing children. Results indicated that FCR3 and F1RR can distinguish misarticulated vowels from the normal ones in girls. In addition, there were significant difference in VOT in both aspirated and unaspirated stop consonants pronunciation between FAD children and the control group. Our findings are in line with previous studies that children with FAD exhibited reduced range of articulatory movements and poorer control over the release of oral occlusion when producing aspirated or unaspirated stops. These findings also imply that the acoustic features we selected can be used to differentiate pathological from healthy speech, and might be considered as part of objective assessments of FAD speech especially when evaluating outcomes of clinical intervention.

6. Acknowledgements

This study was jointly supported by a grant from National Natural Science Foundation of China (NSFC 61771461 and U1736202), Shenzhen Speech Rehabilitation Technology Laboratory and Health and Health Services Research Fund (HHSRF), Shenzhen Fundamental Research Program JCYJ20170413161611534. Wang Zhang, Xiangquan Gui and Tianqi Wang contributed equally to this work.

7. References

[1] L. D. Shriberg, J. B. Tomblin, and J. L. Mcsweeny, "Prevalence of speech delay in 6-year-old children and comorbidity with language impairment," Journal of Speech Language & Hearing Research, vol. 42, no. 6, p. 1461, 1999.

[2] L. Tung, C. Lin, C. Hsieh, C. Chen, C. Huang, and C. Wang, "Sensory integration dysfunction affects efficacy of speech therapy on children with functional articulation disorders," Neuropsychiatr Dis Treat., vol. 9, no. default, pp. 87-92, 2013.

[3] J. A. Gierut, "Treatment efficacy: functional phonological disorders in children," Journal of Speech Language & Hearing Research, vol. 41, no. 1, pp. 85-100, 1998.

[4] N. M. L Pennington, S Robson, "Speech therapy for children with dysarthria acquired before three years of age," Cochrane Database of Systematic Reviews, vol. 29, no. 4, p. CD006937, 2009.

[5] D. U. Zhihong, B. Peng, S. Yang, Z. Huang, and Z. Chen, "Study on Error Pattern of Consonant of Children with Functional Dysarthria," Rehabilitation Medicine, 2015.

[6] S. Sapir, L. O. Ramig, J. L. Spielman, and C. Fox, "Formant Centralization Ratio (FCR): A proposal for a new acoustic measure of dysarthric speech," Journal of Speech Language & Hearing Research, vol. 53, no. 1, pp. 114-125, 2010.

[7] E. T. Carter and M. Buck, "Prognostic testing for functional articulation disorders among children in the first grade," Journal of Speech & Hearing Disorders, vol. 23, no. 2, p. 124, 1958.

[8] M. Ishige, M. Abe, and S. Niimi, "A Case of Functional Articulation Disorder with Tongue Retraction as Main Symptom," Japan Journal of Logopedics & Phoniatrics, vol. 38, no. 4, pp. 329-336, 1997.

[9] Y. J. Zhao and H. W. Sun, "Analysis of Articulation Errors and Speech Therapy in Children with Functional Articulation Disorders," Chinese Journal of Rehabilitation, vol. 21, no. 2, pp. 93-95, 2006.

[10] Q. J. Zhou, H. Yin, and B. Shi, "Error analysis of functional articulation disorders in children," West China Journal of Stomatology, vol. 26, no. 4, p. 391, 2008.

[11] E. Y. Oh, Y. H. Kim, H. S. Lee, I. G. Lee, J. S. Lee, and E. S. Jang, "Clinical Aspects of Functional Articulation Disorder," J Korean Child Neurol Soc, 2008.

[12] Y. Fukusako, M. Sawashima, and M. Abe, "A clinical note on articulation disorders in children," Jpn.j.logop.phoniatr, vol. 17, no. 2, pp. 60-71, 2010.

[13] B. Prathanee, C. Seepuaham, and T. Pumnum, "Original article. Articulation disorders and patterns in children with a cleft," Asian Biomedicine, vol. 8, no. 6, pp. 699-706, 2017.

[14] Z. H. Du, B. W. Peng, X. J. Li, Z. F. Huang, S. Y. Yang, and Z. M. Chen, "[Property analysis of the finals mispronunciation in Chinese-speaking children with functional articulation disorder]," Zhonghua er ke za zhi = Chinese journal of pediatrics, vol. 54, no. 10, p. 752, 2016.

[15] R. D. Kent, G. Weismer, J. F. Kent, H. K. Vorperian, and J. R. Duffy, "Acoustic studies of dysarthric speech: methods, progress, and potential," Journal of Communication Disorders, vol. 32, no. 3, pp. 183-186, 1999.

[16] R. D. Kent and Y. â J. Kim, "Toward an acoustic typology of motor speech disorders," Clinical Linguistics & Phonetics, vol. 17, no. 6, pp. 427-445, 2003.

[17] S. S, S. JL, R. LO, S. BH, and F. C, "Effects of intensive voice treatment (the Lee Silverman Voice Treatment [LSVT]) on vowel articulation in dysarthric individuals with idiopathic Parkinson disease: acoustic and perceptual findings," Journal of Speech Language and Hearing Research, vol. 50, no. 4, pp. 899-912, 2007.

[18] S. Skodda, W. Visser, and U. Schlegel, "Vowel Articulation in Parkinson's Disease," Journal of Voice, vol. 25, no. 4, pp. 467-472, 2011.

[19] Peter Ladefoged, Keith Johnson. A Course in Phonetics (6th Edition).Wadsworth Publishing, 2010.

[20] C. O. Pascal Auzou, Richard J. Morris, Mary Jan, Francis Eustache, Didier Hannequin, "Voice onset time in aphasia, apraxia of speech and dysarthria: a review," Clinical Linguistics & Phonetics, vol. 14, no. 2, pp. 131-150, 2000.

[21] H. Ackermann and I. Hertrich, "Voice onset time in ataxic dysarthria," Brain & Language, vol. 56, no. 3, p. 321, 1997.

[22] S. R. Baum and L. Ryan, "Rate of speech effects in aphasia: voice onset time," Brain & Language, vol. 44, no. 4, pp. 431-45, 1993.

[23] J. Ryalls, H. Provost, and N. Arsenault, "Voice onset time production in French-speaking aphasics," Journal of Communication Disorders, vol. 28, no. 3, pp. 205-215, 1995.

[24] R. J. Morris, "VOT and dysarthria: a descriptive study," Journal of Communication Disorders, vol. 22, no. 1, pp. 23-33, 1989.

[25] W. J. Hardcastle, R. A. M. Barry, and C. J. Clark, "Articulatory and voicing characteristics of adult dysarthric and verbal dyspraxic speakers: An instrumental study," International Journal of Language & Communication Disorders, vol. 20, no. 3, pp. 249-270, 2011.

[26] M. Hashi, J. R. Westbury, and K. Honda, "Vowel posture normalization," Journal of the Acoustical Society of America, vol. 104, no. 4, p. 2426, 1998.

[27] B. Yang, "A comparative study of American English and Korean vowels produced by male and female speakers," Journal of Phonetics, vol. 24, no. 24, pp. 245–261, 1996.

[28] I. Lundeborg, E. Nordin, M. Zeipelstjerna, and A. Mcallister, "Voice onset time in Swedish children with phonological impairment," Scandinavian Journal of Logopedics & Phoniatrics, vol. 40, no. 4, pp. 149-155, 2015.

[29] V. Y. Yu et al., "Changes in voice onset time and motor speech skills in children following motor speech therapy: Evidence from /pa/ productions," Clinical Linguistics & Phonetics, vol. 28, no. 6, p. 396, 2014.

[30] K. Forrest and B. K. Rockman, "Acoustic and perceptual analysis of word-initial stop consonants in phonologically disordered children," Journal of Speech & Hearing Research, vol. 31, no. 3, p. 449, 1988.