The association of high resolution cervical auscultation signal features with hyoid bone displacement during swallowing

Qifan He, Subashan Perera, Yassin Khalifa, Zhenwei Zhang, Amanda S. Mahoney, Aliaa Sabry, Cara Donohue, James L. Coyle, Ervin Sejdić

***Abstract*—Recent publications have suggested that high-resolution cervical auscultation (HRCA) signals may provide an alternative non-invasive option for swallowing assessment. However, the relationship between hyoid bone displacement, a key component to safe swallowing, and HRCA signals is not thoroughly understood. Therefore, in this work we investigated the hypothesis that a strong relationship exists between hyoid displacement and HRCA signals. Videofuoroscopy studies were collected for 129 swallows, simultaneously with vibratory/acoustic signals. Horizontal, vertical and hypotenuse displacements of the hyoid bone were measured through manual expert analysis of videofluoroscopy images. Our results showed that the vertical displacement of both the anterior and posterior landmarks of the hyoid bone was strongly associated with the Lempel-Ziv complexity of superior-inferior and anterior-posterior vibrations from HRCA signals. Horizontal and hypotenuse displacements of the posterior aspect of the hyoid bone were strongly associated with the standard deviation of swallowing sounds. Medial-Lateral vibrations and patient characteristics such as age, sex, and history of stroke were not significantly associated with the hyoid bone displacement. The results imply that some vibratory/acoustic features extracted from HRCA recordings can provide information about the magnitude and direction of hyoid bone displacement. These results provide additional support for using HRCA as a non-invasive tool to assess physiological aspects of swallowing such as the hyoid bone displacement.**

***Index Terms*—Keywords: High resolution cervical auscultation, swallowing accelerometry, swallowing sounds, dysphagia, signal processing, hyoid displacement.**

I. INTRODUCTION

EACH year approximately 1 in 25 adults in the United States is diagnosed with a swallowing disorder, known as dysphagia [1]. Swallowing is a complex neuromuscular process that involves a sequence of biomechanical events that must occur in a relatively consistent temporal order to ensure efficient and safe swallowing. Discoordination or impairment of these events may result in accidental passage of swallowed materials into the airway, leading to health complications such as aspiration pneumonia, malnutrition, dehydration, or death [2], [3], [4].

Hyoid bone displacement is one example of a swallowing biomechanical event accessible only through x-ray based videofluoroscopic (VF) imaging, that reflects the integrity of the mechanism responsible for timely and complete airway closure and opening of the upper esophageal sphincter (UES) which, in turn, enables clearance of material to the digestive system. Prior research indicates that hyoid bone displacement is highly correlated with airway protection and UES opening [2]. The superior-anterior movement of the hyoid bone reflects the actions of musculature that contracts somewhat sequentially in order to facilitate airway (laryngeal vestibular) closure and UES opening, thus directing swallowed materials away from the airway and into the esophagus. Clinicians typically assess and monitor these aspects of swallowing by measuring hyoid bone displacement in VF images. However, there is no noninvasive, non-imaging method that currently exits to measure these same physiologic events in patients for whom VF or other imaging methods are unavailable or unfeasible.

VF is one instrumental method used for assessing and diagnosing dysphagia. It provides a sequence of real-time radiographic images that capture the structure and biomechanical functions of the upper aerodigestive tract, and the flow of swallowed materials through oral and pharyngeal cavities [5], [6]. VF is used for identification of oropharyngeal kinematic impairments, airway protection deficits, and disordered transfer of swallowed materials into the digestive system and enables clinicians to determine appropriate interventions to remediate these errors [7], [8]. Unfortunately, VF is relatively expensive and not available at all facilities or to patients who are unable to participate in imaging studies [9], [10], [11], [12]. Moreover, VF allows for only limited observations of the patient swallowing function in order to limit radiation exposure depending on factors such as swallowing impairment severity, medical diagnosis, and clinician experience [11]. This requires clinicians to infer about the swallowing function during eating and drinking when VF is not used.

Given the drawbacks and limited accessibility of VF, clinicians would benefit from an alternative noninvasive method for assessing, monitoring, and treating aspects of swallowing impairments, including reduced hyoid bone displacement. Conventional cervical auscultation using stethoscopes and human judgment to observe and assess swallowing function has long been a popular solution to noninvasive testing. However, it

Qifan He, Yassin Khalifa, Zhenwei and Ervin Sejdić are with the Department of Electrical and Computer Engineering, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, PA, 15261, USA. E-mail: esejdic@ieee.org.

Subashan Perera is with the Division of Geriatric Medicine, Department of Medicine, University of Pittsburgh, Pittsburgh PA, 15261, USA

Amanda S. Mahoney, Aliaa Sabry, Cara Donohue and James L. Coyle is with the Department of the Communication Science and Disorders, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, PA, 15260, USA

has repeatedly been found to lack adequate objectivity and inter-observer reliability, due to the limitations of the human auditory system and the fact that stethoscopes are designed and tuned for specific purposes such as observing heart and lung sounds [13]. One promising non-invasive and automated alternative to VF is high-resolution cervical auscultation (HRCA). HRCA uses accelerometers and microphones attached to the neck to record swallowing vibrations and sounds [14], [15]. Advantages of HRCA include mobility, cost-effectiveness, non-invasiveness, and suitability for day-to-day monitoring. On the other hand, making decision and evaluation with HRCA alone is subjective and often with low accuracy, hence the development of algorithms for automatic analysis, can make diagnostic conclusions more objective and significantly decreases the number of erroneous diagnoses. Nevertheless, HRCA has yet to be fully investigated and confirmed as a suitable surrogate for imaging.

Several studies have investigated and confirmed the utility of accelerometry signals for screening swallowing function and diagnosing dysphagia [16], [17]. Healthy swallowing was found to follow a reproducible pattern while the acceleration response of abnormal swallowing was either absent or significantly delayed [18]. Previous studies have also found that magnitude of the signal depended on the extent of laryngeal elevation [19] while HRCA signal features were associated with laryngeal vestibule closure and re-opening, UES opening, and the position of the hyoid bone [20]. Previous contributions suggested that changes in several HRCA signals' features reflected both vertical and horizontal displacements of the hyoid bone during swallowing [21], [22]. Zoratto et al. have fit hyoid bone and arytenoids displacement to a quadratic model to predict the information of acceleration of the signals. They discovered that weak accelerometry signals recorded from a dual-axial accelerometer were related to reduced hyoid bone excursion compared to stronger signals reflecting more complete hyoid displacement [21].

HRCA offers much more than the ability to grossly monitor hyoid displacement. HRCA signal features of the time, frequency, and time-frequency domains provide rich information regarding the subtleties of structure displacement that lie beyond the limited visual inspection capabilities offered by VF, and warrant continued investigation to elucidate the diagnostic potential of HRCA in swallowing assessment. Therefore, we compared tri-axial accelerometry HRCA signal features in the time, frequency, and time-frequency domains in the anterior-posterior (AP), superior-inferior (SI), and medial lateral (ML) directions with concurrently recorded vertical, horizontal and hypotenuse hyoid bone displacements from VF images. We hypothesized that HRCA signal features would be strongly associated with hyoid bone displacement.

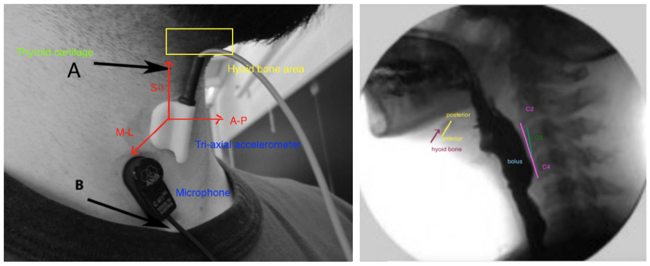

Fig. 1. Left: Device placement and its different axis. 'A' indicates the thyoid cartilage and 'B' the suprasternal notch. 'A', 'B' are used as reference to place the sensors [24]. Right: Location of anterior and posterior part, C3 compared to C2-C4.

II. Methodology

A. Data Acquisition

This study examined 129 single swallows collected from 46 adult patients with suspected dysphagia (27 males and 19 females, mean age: 64.66 ± 14.99) referred for VF at the University of Pittsburgh Medical Center. All participants signed informed consent and the data collection protocol was approved by the University of Pittsburgh Institutional Review Board. Swallows analyzed for this study were limited to those in which the entire body of the hyoid bone was visible on all VF frames. Since we are investigating relationships between HRCA signal features and displacement of the hyoid bone and not causal relationships between disease states causing dysphagia and HRCA signals, we did not limit inclusion based on diagnosis. Patients swallowed refrigerated Varibar thin liquid (Bracco Diagnostics, Inc.) ($<$ 5cPs viscosity) or Varibar nectar thick liquid (300 cPs viscosity) from a spoon (3-5mL) or a self-administered comfortable volume by cup with their heads in a neutral position.

VF was recorded at a rate of 60 frames per second with a resolution of 792×1008. HRCA recording equipment consisted of a tri-axial accelerometer (ADXL 327, Analog Device, Norwood, Massachusetts) affixed to the anterior neck over the palpable arch of the cricoid cartilage and a contact microphone (model C 411L, AKG, Vienna, Austria) affixed just lateral to the accelerometer so as not to interfere with VF observations of the airway column. Both were attached to the participants neck with double-sided tape [23]. Two of three accelerometer axes (SI and ML) were found in the frontal plane of the body with the SI axis parallel to the cervical spine, ML axis perpendicular to SI axis. The AP axis was perpendicular to the coronal plane. The left image of Figure 1 shows the position of the sensors and the three axes. The accelerometer was powered by 3-V external power supply (Model 1504, BK Precision, Yorba Linda, CA, USA) and the microphone was powered by the model B291 (Model B291, AKG, Vienna, Austria). Both microphone and acelerometer signals were bandpass filtered from 0.1 to 3000 Hz with an amplification factor of ten (model p55, Grass Technologies, Warwick, Rhode Island) and recorded with a National Instruments 6210 DAQ at a sampling rate of 20 kHz by the LabView Signal Express (National Instrument, Austin, Texas) [14].

B. Image analysis

A speech-language pathologist (SLP) trained in our lab to measure swallowing kinematic displacements determined the beginning and end of each swallow via frame-by-frame temporal analysis of VF recordings. The most anterior and posterior aspects of the hyoid bone were plotted on each

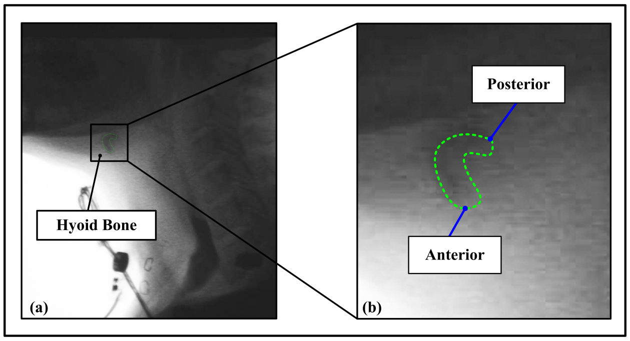

Fig. 2. Hyoid bone and tracking points. Green dotted line marks the outline of hyoid bone to improve visibility (a) X-ray image of hyoid bone, (b) Posterior and anterior points for tracking.

frame and used as vertices. The body of the hyoid has the shape of a tilted boomerang with two endpoints and a central curved mid portion (Figure 2). In the lateral VF view, one endpoint (superior-anterior) lies anterior to the other (inferior-posterior) endpoint. In previous studies the anterior landmark of the hyoid was marked as the midpoint on the anterior surface of the hyoid body which we considered subjective and insensitive to the rotation of the hyoid bone [25]. The precise location of anterior landmark enabled us to accurately track the hyoid bone movement as well as to measure its displacement during swallowing. The height of the anterior aspect of the third cervical vertebral body (C3) was used as an anatomic scalar to account for differences in participant height, and to equate hyoid displacement to a ”vertebral unit” that is visible during VF data collection and measurements. The C2-C4 linear measure is currently in widespread use and we are currently validating the use of C3 as a surrogate for C2-C4. The right image of Figure 1 shows the anterior and posterior part of hyoid bone as well as the length of C3 and C2-C4.

C. HRCA signal feature extraction

Four axial-specific finite impulse response filters were created via an auto-regressive model [26] to annul the effect of each sensor’s noise on the collected signals. The least-square spline approximation algorithm [27], [28] was used to attenuate the low frequency component associated with head movement. We fit a low-frequency ($\leq$ 2 Hz) trend to the time-domain signal and then subtracted the low-frequency trend from the time-domain recording. To further reduce the impact of noise, a ten-level wavelet transform using the Meyer wavelet with soft thresholding was used to denoise the filtered signal [29].

Nine features were extracted from the tri-axial swallowing accelerometry and microphone sound signals. All features were calculated independently for all four signals (AP vibrations, SI vibrations, ML vibrations, and swallowing sound). The features provided key statistical information about the relationship between cervical auscultation signals and the vertical and horizontal hyoid bone displacements during swallowing [26], [30], [31], [32]. In the time domain, standard deviation, skewness, and kurtosis were extracted. We extracted information-theoretical features as well including the Lempel-Ziv complexity and the entropy rate. In the frequency domain, we calculated peak frequency and spectral centroid. A time-frequency domain feature known as the wavelet entropy was also extracted to help identify the disordered signal. A summary of all measures and their meanings can be found in Table 1.

D. Statistical analysis

SAS version 9.3 (SAS Institute, Inc, Cary, North Carolina) was used for analyses to examine the association between hyoid bone displacement and HRCA signal features. We fit a series of linear mixed models with each displacement (anterior or posterior hyoid) in three directions (horizontal, vertical, hypotenuse) as response variables, and HRCA signal features, one at a time, as independent variables.

III. RESULTS

Table 2 depicts the values of HRCA signal features. Table 3 shows the values of the horizontal, vertical, and hypotenuse displacements of the anterior and posterior aspects of the hyoid bone normalized by the C3 length. Table 4 shows the relationship between HRCA signal features and displacement of the aspects of hyoid bone in different directions. Positively and negatively correlated features are indicated as well.

The horizontal displacement of the anterior aspect of the hyoid bone is negatively correlated with skewness of the SI signal and the peak frequency of the ML signal. It is positively correlated with the peak frequency of the microphone signal, with small coefficients (-0.024, -0.004, 0.001 respectively).

The vertical displacement of the anterior aspect of the hyoid bone is negatively correlated with wavelet entropy, the Lempel-Ziv complexity of the AP signal, and the peak frequency of the ML signal. While the rise of wavelet entropy and peak frequency reflects little decrease of displacement (0.104 unit and 0.009 unit), one unit increase of Lempel-Ziv complexity reflects a 1.190 units decrease of vertical displacement. One unit of displacement refers to the length of C3.

The hypotenuse displacement of the anterior aspect of the hyoid bone is associated with several AP (skewness, wavelet entropy, Lempel-Ziv complexity), SI (skewness, Lempel-Ziv complexity, kurtosis) and ML (peak frequency) features. Among them, Lempel-Ziv complexity of the AP and SI signals are the most influential. One unit increase of Lempel-Ziv complexity in the AP direction results in a decrease of 1.200 units of vertical displacement, whereas one unit increase of Lempel-Ziv complexity in the SI direction results in an increase of 1.740 units of vertical displacement.

The horizontal displacement of the posterior aspect of the hyoid bone is associated with the skewness and peak frequency of the SI signal, peak frequency of the ML signal, and the standard deviation of the microphone signal. While other features have little influence on the value of displacement, the standard deviation increases one unit per every 2.880 units of displacement.

TABLE 1
A SUMMARY OF HRCA FEATURES EXTRACTED FOR THIS STUDY

Feature	**Definition**
Standard deviation	Describes the fluctuation of the signal around mean; higher values indicate a greater variation around mean value.
Skewness	Describes the asymmetry of amplitude distribution; negative skewness indicates that distribution of signal amplitudes lies predominantly on the right of the mean amplitude, positive skewness indicates the values are predominantly on the left of the mean amplitude.
Kurtosis	Describes how the signal is peaked or flat around its mean value
Lempel-Ziv complexity	Measures the complexity-predictability of the signal; higher values indicate a less predictable, more complex signal, lower values indicate a more predictable, less complex signal.
Entropy rate	Quantifies the regularity of a signal when a relationship among consecutive data points is anticipated.
Peak frequency	The maximum spectral power.
Spectral centroid	The frequency that divides the spectral power distribution into two equal parts.
Bandwidth	The difference between the uppermost and lowermost frequencies/range of frequencies in the signal.
Wavelet entropy	Measures the degree of time-frequency based order-disorder of the signal; high values represent disordered behavior with significant equivalent contributions from all frequency bands.

The vertical displacement of the posterior aspect of the hyoid bone is related to several features (AP: skewness, wavelet entropy, Lempel-Ziv complexity; SI: skewness, Lempel-Ziv complexity; ML: peak frequency; MIC: bandwidth). Lempel-Ziv complexities in the AP and SI directions have the most notable relationship (-2.380 units and 1.071 units respectively).

The hypotenuse displacement of the posterior aspect of the hyoid bone is associated with wavelet entropy (2.750 units) of the AP signal, Lempel-Ziv complexity (0.940 unit) of the SI signal, and standard deviation (5.041 units) of the microphone signal.

While the peak frequency of the ML signal is associated with displacements in all directions, the coefficients are small (≤ 0.130). Lempel-Ziv complexities in the AP and SI directions, and the standard deviation of the microphone signal have a robust influence on the horizontal and hypotenuse displacement of the anterior aspect of the hyoid bone and vertical displacement of the posterior aspect of the hyoid bone.

The relationship between hyoid bone displacement and clinical features of patients is shown in Table 5. The hypotenuse displacement of both the anterior and posterior hyoid landmarks are significantly correlated with participant age (with p-value equals to 0.040 and 0.016 respectively) and there are no other correlations.

IV. DISCUSSION

A. *Feature extraction from cervical auscultation recording*

One component of this study analyzed the relationship between features extracted from different axes of HRCA signals. We found that four signals (AP vibrations, SI vibrations, ML vibrations and swallowing sounds) had low standard deviations, low skewness and high kurtosis. This implies that the signals were evenly distributed around the mean value with small variation. All four signals were relatively regular and predictive with low Lempel-Ziv complexity and high entropy rate. All features had low peak frequency, large bandwidth, and spectral centroid around 88 Hz (with AP slightly higher). This suggests that the signals reflected similar levels of structure. Wavelet entropies of SI, AP, and swallowing sound were close to one, with the ML signal slightly smaller. The results from the extracted features are consistent with previous research [14], [33].

B. *Hyoid bone displacement and cervical auscultation recordings*

Research suggests that vertical displacement of the hyoid bone contributes to airway protection and UES opening [34], [35]. Therefore, we sought to determine whether there was a relationship between hyoid bone displacement and HRCA signal features.

The vertical displacement of both the anterior and posterior aspects of the hyoid bone were highly correlated with Lempel-Ziv complexity features, which suggests that the vertical displacement of the hyoid bone influences the complexity and predictability of the AP and SI signal. As the vertical displacement increased, the Lempel-Ziv complexity of the AP signal became smaller and the Lempel-Ziv complexity of the SI signal became larger. In other words, the AP signal became more organized in swallows with greater vertical hyoid displacement while the SI signal became more complex and less predictable. It is possible that greater hyoid vertical displacement during swallowing, which in turn produces greater superior traction forces on the UES and airway closure mechanism, generates more organized HRCA signals than reduced displacement which is often observed in patients with various forms of dysphagia. This observation may represent a significant advancement toward the use of noninvasive technology to monitor swallowing function since reduced hyoid displacement is a well-known source of impaired airway protection and UES opening. The hypotenuse displacement had the same effect on the SI and AP signals as the vertical displacement because the hypotenuse is a combination of horizontal and vertical, and therefore increased the SI signals unpredictability.

Previous research showed a correlation between HRCA swallowing sounds and UES opening [20]. The increases in horizontal and hypotenuse displacement of the posterior aspect of the hyoid bone in the current study resulted in an increase in the standard deviation of swallowing sound. This may be related to the opening of the UES and a reflection of the ability

TABLE 2
MEAN AND STANDARD DEVIATION OF CONSIDERED FEATURES.

Extracted features	**SI**	**ML**	**AP**	**MIC**
Time Domain Features				
Standard deviation	0.045 ± 0.040	0.014 ± 0.013	0.024 ± 0.025	0.019 ± 0.018
Skewness	-0.317 ± 2.914	0.124 ± 3.869	0.582 ± 4.891	-0.629 ± 2.542
Kurtosis	35.524 ± 75.390	44.299 ± 149.917	65.198 ± 181.910	29.577 ± 84.654
Information-theoretic Features				
Lempel-Ziv complexity	0.233 ± 0.083	0.190 ± 0.079	0.175 ± 0.072	0.238 ± 0.073
Entropy rate	0.904 ± 0.047	0.943 ± 0.034	0.934 ± 0.035	0.921 ± 0.035
Frequency Features				
Spectral centroid	86.198 ± 82.190	83.002 ± 170.852	121.301 ± 175.674	60.464 ± 151.457
Peak frequency	20.292 ± 49.219	19.336 ± 128.315	19.789 ± 60.976	14.223 ± 78.503
Bandwidth	100.350 ± 63.467	146.927 ± 151.692	161.871 ± 152.930	96.578 ± 108.380
Time-frequency Features				
Wavelet entropy	0.969 ± 0.738	0.648 ± 0.624	0.823 ± 0.729	0.830 ± 0.679

*AP: anterior-posterior, *ML:medial-lateral, *SI: superior-inferior, *MIC microphone

TABLE 3
MEAN AND STANDARD DEVIATION OF THE VERTICAL, HORIZONTAL, HYPOTENUSE DISPLACEMENT OF ANTERIOR AND POSTERIOR OF THE HYOID BONE RELATED TO C3 DIMENSION

Displacement/length of C3		**Values**
Anterior	**horizontal**	0.761 ± 0.260
	vertical	1.083 ± 0.403
	hypotenuse	1.354 ± 0.385
Posterior	**horizontal**	0.861 ± 0.275
	vertical	1.049 ± 0.369
	hypotenuse	1.387 ± 0.358

of high resolution acoustic recordings, in lieu of traditional use of stethoscopes to observe sounds, to identify key aspects of swallow physiology that the human auditory system and/or stethoscopes are not designed to observe or transmit.

Finally, we observed that the peak frequency of the ML signal appeared to be related to displacements of the hyoid bone in all three directions. However, the coefficients were small (≤ 0.013) compared to other features. Therefore, it is not clear whether the ML signal will be a useful reference for hyoid bone displacement.

C. Hyoid displacement and patient characteristics

Results from this study indicated that vertical hyoid bone displacement was greater than horizontal displacement and was approximately the length of C3. This visually salient observation during diagnostic testing with VF may provide clinicians with an objective estimate of adequate hyoid displacement during the examination, and enable quicker intervention for impaired hyoid displacement.

Results revealed that horizontal displacement of the posterior aspect of the hyoid bone was greater than that of the anterior aspect, while the vertical displacements of the anterior and posterior aspects were approximately the same. This finding suggests that the anterior and posterior aspects of the hyoid bone move at different magnitudes during swallowing and reflects the rotational aspects of hyoid body displacement.

Consistent with prior research, our study showed that HRCA signals of hyoid bone displacement were not influenced by sex or stroke history [36], [37]. Our study did not find an association between hyoid bone displacement and swallows of small and larger volume boluses. This contrasts with earlier studies that found an association between greater hyoid bone displacement and larger bolus volumes [38], [39]. However, since we did not systematically evaluate contrasting pairs of known large and small bolus volumes, this result may represent artifact of a design limitation. Early studies demonstrated a dependency between age and horizontal hyoid bone displacement [36], [38], whereas our study only revealed age affected on hypotenuse displacement. One explanation for this contrast, and a limitation of the study, is that we did not include swallows for patients younger than 48 years old. Another limitation is the inclusion of only thin and nectar-thick liquids and single swallows. Future investigations should consider various bolus volumes and viscosities, multiple swallows, and swallows from older and younger patients to explore the relationship between hyoid bone displacement and HRCA feature signals.

V. CONCLUSIONS

In this study, we analyzed the relationship between hyoid bone displacement during swallowing and features extracted from HRCA signals. Our study confirmed that hyoid bone displacement can be inferred from HRCA features. The results revealed associations between vertical displacement and the AP and SI signals complexity and predictability. The variation of the Lempel-Ziv complexity of the AP and SI signals will allow us to estimate the vertical displacement of the hyoid bone. This finding is of clinical value given the relationship between vertical hyoid bone displacement, airway protection, and UES opening. We also equated vertical hyoid displacement to an anatomic scalar (C3) and identified a strong indication that vertical hyoid displacement was roughly the same as the height of C3. During clinical VF testing, clinicians are required to identify impairments and react to

TABLE 4

RELATION BETWEEN DISPLACEMENT OF HYOID BONE AND HRCA FEATURES. POSITIVE VALUE INDICATES A POSITIVE CORRELATION, NEGATIVE VALUE INDICATES A NEGATIVE CORRELATION.

	HRCA features	**ant_h_C3**	**ant_v_C3**	**ant_hp_C3**	**pos_h_C3**	**pos_v_C3**	**pos_hp_C3**
AP	**Skewness**			-0.014		-0.014	
	Wavelet Entropy		-0.104	-0.101		-0.071	2.749
	LZC		-1.198	-1.989		-2.385	
SI	**Skewness**	-0.024		-0.048	-0.030	-0.035	-0.054
	LZC			1.739		1.071	0.939
	Kurtosis			0.002			
	Peak Frequency				-0.001		
ML	**Peak Frequency**	-0.004	-0.009	0.010	0.005	-0.010	0.012
MIC	**Peak Frequencey**	0.001					
	Standard Deviation				2.881		5.036
	Bandwidth					-0.0005	
	Spectral Centroid						-0.0003

*ant-h-C3: anterior horizontal displacement of hyoid bone normalized by the length of C3
*ant-v-C3: anterior vertical displacement of hyoid bone normalized by the length of C3
*ant-hp-C3: anterior hypotenuse displacement of hyoid bone normalized by the length of C3
*pos-h-C3: posterior horizontal displacement of hyoid bone normalized by the length of C3
*pos-v-C3: posterior vertical displacement of hyoid bone normalized by the length of C3
*pos-hp-C3: posterior hypotenuse displacement of hyoid bone normalized by the length of C3

TABLE 5

RELATION BETWEEN DISPLACEMENT OF HYOID BONE AND CLINICAL VARIABLES. '+' INDICATES A SIGNIFICANT CORRELATION

Clinical variable	**ant_h_C3**	**ant_v_C3**	**ant_hp_C3**	**pos_h_C3**	**pos_v_C3**	**pos_hp_C3**
Stroke						
Sex						
Age			+			+
Volume						

*ant-h-C3: anterior horizontal displacement of hyoid bone normalized by the length of C3
*ant-v-C3: anterior vertical displacement of hyoid bone normalized by the length of C3
*ant-hp-C3: anterior hypotenuse displacement of hyoid bone normalized by the length of C3
*pos-h-C3: posterior horizontal displacement of hyoid bone normalized by the length of C3
*pos-v-C3: posterior vertical displacement of hyoid bone normalized by the length of C3
*pos-hp-C3: posterior hypotenuse displacement of hyoid bone normalized by the length of C3

them immediately with appropriate treatment interventions. This finding could accelerate the deployment of intervention by providing immediate evaluation of the efficacy of trial interventions rather than current methods relying on post-examination visual inspection of the VF data which negates deployment of treatment efficacy trials during VF. Future research work should explore associations between HRCA signals and other swallow kinematic events such as laryngeal vestibular closure, upper esophageal sphincter opening, and initiation of the pharyngeal swallow to improve the use of HRCA for assessment of swallowing and biofeedback during dysphagia therapy.

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