Silent Aspiration Detection in High Resolution Cervical Auscultations

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***Abstract*— Aspiration is the most serious complication of dysphagia, which may lead to pneumonia. Detection of aspiration is limited by the presence of its signs like coughing and choking, which may be absent in many cases. High resolution cervical auscultations (HRCA) represent a promising non-invasive method intended for the detection of swallowing disorders. In this study, we investigate the potential of HRCA in detection of penetration-aspiration in patients suspected of dysphagia. A variety of features were extracted from HRCA in both time and frequency domains and they were tested for association with the presence of penetration-aspiration. Multiple classifiers were implemented also for aspiration detection using the extracted signal features. The results showed the presence of strong association between some HRCA signal features and penetration-aspiration, furthermore, they direct towards future directions to enhance prediction capability of aspiration using HRCA signals.**

Keywords—Swallowing, Penetration-Aspiration, Silent Aspiration, Dysphagia, Cervical Auscultations.

I. Introduction

Deglutition is a well-coordinated, yet complex process essential for the survival of humans, in which food and liquids are transported from the oral cavity to the stomach at a proper rate and speed [1], [2]. It involves the mechanical and neurological coordination between various anatomical structures such as swallowing, airway, and speech structures that are close in position and share several functions [2]. Being such a complex process makes it subject to a wide range of functional disorders secondary to many etiologies, including but not limited to stroke, Parkinson's disease, head and neck cancer, and brain injuries [2]–[4]. Deglutition dysfunction is referred to as Dysphagia and it affects 16%-22% of individuals older than 50 years, 12%-13% of short-term care patients, and up to 60% nursing home residents [5]–[7]. Aspiration, the entry of foreign materials into the airway below the true vocal folds, is the main clinically significant sign of Dysphagia, which can lead to the development of adverse outcomes including pneumonia, malnutrition, and dehydration [7]–[9], as well as reduced quality of life. The risk of developing pneumonia has been found to increase greatly in patients with aspiration compared to normal individuals [10].

Bedside non-instrumental assessment such as Toronto bedside test [11], the 3 ounce water challenge [12], and the modified MASA [13], are the first attempts to identify aspiration through the evaluation of the patient's behavior during swallowing [14]. However, sometimes assessment is deemed to be inconclusive or insufficient due to the absence of aspiration's overt signs such as coughing [14]–[16]. Videofluoroscopic swallowing study (VFSS) is an instrumental assessment tool of swallowing impairments and airway protection, in which radiographic image series are collected during the entire swallowing process for the oral , pharyngeal, and esophageal phases [17], [18]. Biomechanical properties of the swallow are subjectively interpreted from VFSS by clinicians to determine the risk of penetration aspiration. Severity of aspiration is rated using a standard scale called the Penetration Aspiration scale (PAS).

PAS is an 8-point scale used to determine the depth of entry of the material into airway and attempts made by the patient to clear the material out of the airway [19]. Complete airway protection is given a PAS score of 1, while the impermanent entry of the material into the laryngeal vestibule (above vocal folds) is given a score of 2. Penetration happens if the material was not cleared out of the laryngeal vestibule and is given a score of 3-5 according to the depth and amount. Scores 6-8 are given in case of aspiration, when the material crosses the vocal folds into the trachea [15].

Despite the usefulness of the PAS in quantifying airway protection and aspiration severity, it remains subjective and needs skilled clinicians to be conducted. In addition, VFSS requires the exposure of patients to x-ray radiation which limits the period of the evaluation process and reduces the probability of capturing penetration aspiration events. For such a reason, the development of an objective automatic method that is able to quantify penetration-aspiration, will be of great benefit to clinicians. Many dysphagia screening methods such as endoscopy [20], pulse oximetry [21], and electromyography [22] have been introduced in the recent years. In particular, cervical auscultations (CA) have received significant attention and demonstrated a promising value as a non-invasive and less expensive dysphagia screening method [23].

High resolution cervical auscultations (HRCA) include the use of a 3d accelerometer and a microphone to record the vibrations and sounds induced by the swallowing process. Perceptual screening of HRCA signals is confusing and doesn't usually lead to a valid outcome due to the presence of various artifacts like head movement, coughing, and speaking [24], [25]. However, previous studies have used advanced signal processing and machine learning techniques to explore the similarities and patterns existing in healthy swallowing signals, and the lack or delay of these patterns in signals with dysphagic swallows [26]–[28]. For instance, the swallowing accelerometry has been found to change with age, sex, and head position [26]. Moreover, another study has shown that HRCA signal features reflect the hyoid bone displacement and swallowed material consistency [29].

In this study, we collected swallowing accelerometry and sounds concurrently with VFSS in order to investigate the potential of HRCA signals in silent aspiration detection.

Furthermore, the results of this work were validated against the aspiration scores rated by experienced speech language pathologists.

II. Methodology

A. Participants

This study was approved by the Institutional Review Board of the University of Pittsburgh and all participants gave consent prior joining the study. Two hundred and sixty-five patients suspected with dysphagia were recruited for the study from the population referred to the University of Pittsburgh Medical Center for an oropharyngeal swallowing evaluation using VFSS. Of the sample, 48 patients were diagnosed with stroke while the remaining (217 patients) suffered from other conditions unrelated to stroke, like head or neck surgery and neck cancer. All participants were asked to swallow different materials in multiple head positions in the course of standard clinical swallow assessment rather than solely for research purpose.

B. Data Acquisition

Swallowing accelerometry and sounds were collected in a similar setup as the previous studies of the iMED laboratory [30]. A tri-axial accelerometer (ADXL 327, Analog Devices, Norwood, Massachusetts) and a lapel microphone (model C 411L, AKG, Vienna, Austria) were attached to the subject's anterior neck during the routine VFSS. The accelerometer was placed over the cricoid cartilage where it was proved to produce the best signal quality [31]. The first accelerometer axis was perpendicular to the coronal plane (anterior-posterior), the second axis was parallel to the cervical spine (superior-inferior), and the third axis was parallel to the axial/transverse plane (medial-lateral).

The microphone was placed a little over the suprasternal notch towards the right lateral side of the larynx. All signals were hardware bandpass filtered (0.1-3000 Hz) and digitized using National Instruments 6210 DAQ with a sampling rate of 20 kHz. Video from x-ray machine was captured using a video capture card (AccuStream Express HD, Foresight Imaging, Chelmsford, MA) simultaneously with the signals for a complete end-to-end synchronization.

C. VFSS Analysis

Over 3000 swallows were collected during this study. Trained experts segmented the videos into individual swallows based on the frame in which the bolus head reaches the ramus of the mandible (onset), and the frame in which the bolus tail passes the upper esophageal sphincter (offset). Two clinicians trained for PAS analysis performed the evaluation of segmented videos and rated each swallow with a PAS score.

D. Signal Preprocessing and Feature Extraction

The whole set of signals were downsampled to 4 kHz in order to overcome the presence of other physiological and kinematic events occurring simultaneously with swallowing (e.g. coughing) [32]. The start and end times for each swallow were taken from the labeled videos after applying the proper sampling conversion. Each signal component was filtered using a Finite impulse response (FIR) filter, designed specifically using an auto-regressive model for each sensor noise [33]. Acceleration signals were processed using a fourth order splines algorithm to remove the low-frequency components induced by head movement [34]–[36]. Moreover, the signals were all denoised using tenth order Meyer wavelet to reduce the effect of any extra noise [26].

A set of features in time, frequency, and time-frequency domains was carefully selected to investigate any relation between penetration-aspiration events and HRCA signals. This set of features has proven significance in swallowing kinematic analysis [29], [30], [33]. The features included mean, standard deviation, skewness, and kurtosis for the time domain [30]. In frequency domain, we extracted bandwidth, peak frequency, and spectral centroid [33], in addition to wavelet entropy in the time-frequency domain. Furthermore, we used entropy rate and Lempel-Ziv complexity to express the regularity and predictability of the signals [29], [30], [33].

E. Analysis

A series of linear mixed models have been used to investigate the association between each individual HRCA signal feature and the PAS scores. PAS scores were transformed to binary values using a threshold for classification purposes. Healthy swallows were considered as swallows of PAS equals 2 or less, and dysphagic swallows were taken as swallows of PAS of 3 or more. Multiple classifiers were then tested in order to determine the predictability of PAS scores from HRCA signal features. Support vector machine (SVM), K-means and Naive Bayes classification were all implemented with\without principal component analysis (PCA) applied for feature dimensionality reduction. In each case, classifier accuracy was calculated using 10-fold cross-validation. The accuracy of the model is best described through overall accuracy (correct classifications per overall classifications), sensitivity (true positives per true positives and false negatives), and specificity (true negatives per true negatives and false positives). Sensitivity is a critical aspect in the classification of possible swallowing impairment: if someone is incorrectly classified as having dysphagia, the health consequences would not be as severe as if a swallowing impairment went undetected. All implementations were performed in R environment (The R Foundation) for statistical computing and Matlab (The MathWorks, Inc).

III. Results

This study yielded over 3000 swallows, which were distributed as shown in Fig. 1.

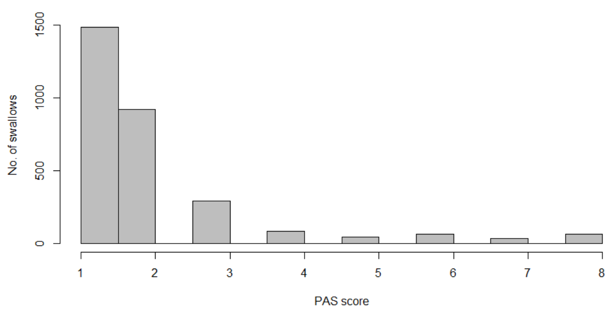

Fig. 1. Number of swallows collected in each PAS score.

We can clearly see that most of the swallows are in the category of PAS = 1 and 2 which represent aspiration-free swallows. The most severe aspiration happens in swallows with PAS = 7 and 8 in which, the material goes through the airway without any reaction or effort from the patient to expel the material out. Fig. 2 depicts how the aspiration (PAS=8) looks in VF images compared to aspiration-free swallowing (PAS=1) as well as in HRCA signals.

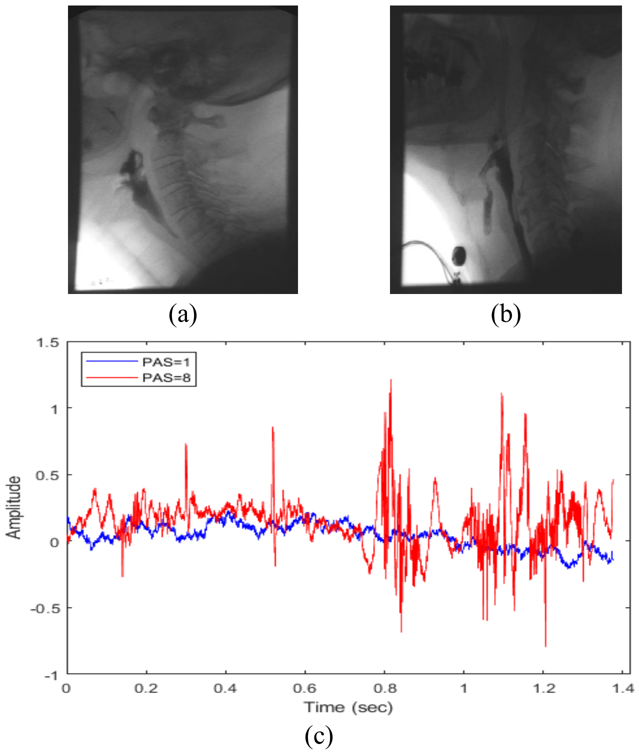

Fig. 2. Differences between normal and dysphagic swallows. (a) a swallow with PAS=1. (b) a swallow with PAS=8 (aspiration happened). (c) shows a comparison between A-P acceleration component of HRCA between the two swallows.

The linear mixed models showed that PAS scores are strongly associated with the entropy rate of both the A-P and S-I axes of acceleration, and the standard deviation of the M-L axis acceleration with a confidence level more than 95%. TABLE I summarizes the performance of each of the classifiers used to detect penetration-aspiration in HRCA signals. The results show that the K-means achieved the best classification accuracy, however, it showed poor performance in terms of sensitivity. The rest of classifiers also showed close performance in terms of accuracy but with higher values for sensitivity.

TABLE I. PERFORMANCE MEASURES OF DETECTING PENETRATION ASPIRATION FROM THE HRCA SIGNAL FEATURES IN COMPARISON TO CONCURRENT VIDEOS RATED BY JUDGES

Classifier	**Accuracy**	**Sensitivity**	**Specificity**
SVM	69.342	20.443	81.347
Naïve Bayes	76.779	14.310	92.102
K-Means	78.751	6.474	96.488

IV. DISCUSSION

In this study, we investigated the association between selected HRCA signal features and PAS scores through running multiple individual linear mixed models against this set of features. The results showed that only a handful of these features are associated with PAS scores including the entropy rate for two axes of acceleration and the standard deviation of the third. Nothing came from the microphone signal, which is completely reasonable when dealing with silent aspiration with no occurrence of coughing or choking. This may give an indication that the set of features under investigation in this study, are not truly significant for the addressed problem, although they have achieved strong association with different swallow kinematic events in the literature.

In terms of overall accuracy, K-means achieved the highest correct classifications per overall classifications, but when considering sensitivity, SVM and Naive Bayes classification performed significantly better. All of the classifiers were able to classify a high percentage of negative cases correctly, but due to the imbalance in the ratio of negative/positive cases, they had difficulty correctly classifying positive cases. The percentage of silent aspiration in the collected dataset was around 5%. Although, we have tried many routes to overcome the imbalance problem in the dataset, the used classifiers did not achieve higher performance (in terms of sensitivity, at least).

The presented results didn't take into account many factors that might have contributed to this insignificant performance. One of these factors is that the study depends on the fact that the swallows occurs in a swallow by swallow basis. However, this may not be completely true in a real clinical setup like the one used in this study, where the patients performed multiple and sequential swallows. Moreover, the material consistency wasn't considered also in this study, which was proven to affect the HRCA signal features in multiple studies [29], [37].

V. CONCLUSION

In this paper, we investigated the significance of HRCA signals in prediction of penetration-aspiration and specifically silent aspiration. The results showed that there exists association between PAS scores which represent penetration-aspiration and some signal features. We proposed also the use of these signal features in predicting silent aspiration. The performance of the classifiers didn't come as expected especially in terms of the true positive rate. There were some flaws in the hypothesis we made that we think may have contributed to the results. We intend to overcome this through considering the type of swallows and the viscosity of the swallowed materials in the classification scheme for PAS scores. Moreover, we will try to investigate the efficiency of using a deep neural network in forecasting PAS scores based on raw HRCA and/or signal features.

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REFERENCES

[1] A. J. Miller, "The neurobiology of swallowing and dysphagia," *Dev. Disabil. Res. Rev.*, vol. 14, no. 2, pp. 77–86, 2008.

[2] N. Bhattacharyya, "The Prevalence of Dysphagia among Adults in the United States," *Otolaryngol. Neck Surg.*, vol. 151, no. 5, pp. 765–769,

2014.

[3] J. Murray, *Manual of Dysphagia Assessment in Adults*. Cengage Learning, Inc, 1998.

[4] C. Lazarus and J. A Logemann, "Swallowing disorders in closed head trauma patients," *Arch. Phys. Med. Rehabil.*, vol. 68, pp. 79–84, 1987.

[5] I. J. Cook and P. J. Kahrilas, "AGA technical review on management of oropharyngeal dysphagia," *Gastroenterology*, vol. 116, no. 2, pp. 455–478, 1999.

[6] S. Lindgren and L. Janzon, "Prevalence of swallowing complaints and clinical findings among 50-79-year-old men and women in an urban population," *Dysphagia*, vol. 6, pp. 187–192, 1991.

[7] H. Siebens *et al.*, "Correlates and consequences of eating dependency in institutionalized elderly," *J. Am. Geriatr. Soc.*, vol. 34, no. 3, pp. 192–198, 1986.

[8] B. Martin-Harris and B. Jones, "The Videofluorographic Swallowing Study," *Phys. Med. Rehabil. Clin. N. Am.*, vol. 19, no. 4, pp. 769–785, 2008.

[9] R. Ishida, J. B. Palmer, and K. M. Hiiemae, "Hyoid Motion During Swallowing: Factors Affecting Forward and Upward Displacement," *Dysphagia*, vol. 17, no. 4, pp. 262–272, Dec. 2002.

[10] L. Pikus *et al.*, "Videofluoroscopic Studies of Swallowing Dysfunction and the Relative Risk of Pneumonia," *Am. J. Roentgenol.*, vol. 180, no. 6, pp. 1613–1616, Jun. 2003.

[11] R. Martino *et al.*, "The Toronto Bedside Swallowing Screening Test (TOR-BSST) Development and Validation of a Dysphagia Screening Tool for Patients With Stroke," *Stroke.*, vol. 40, pp. 555–561, 2008.

[12] D. M. Suiter and S. B. Leder, "Clinical Utility of the 3-ounce Water Swallow Test," *Dysphagia*, vol. 23, no. 3, pp. 244–250, Sep. 2008.

[13] N. Antonios *et al.*, "Analysis of a Physician Tool for Evaluating Dysphagia on an Inpatient Stroke Unit: The Modified Mann Assessment of Swallowing Ability," *J. Stroke Cerebrovasc. Dis.*, vol. 19, no. 1, pp. 49–57, 2010.

[14] J. M. Dudik, J. L. Coyle, A. El-Jaroudi, Z.-H. Mao, M. Sun, and E. Sejdić, "Deep learning for classification of normal swallows in adults," *Neurocomputing*, vol. 285, pp. 1–9, 2018.

[15] C. M. Steele, E. Sejdić, and T. Chau, "Noninvasive Detection of Thin-Liquid Aspiration Using Dual-Axis Swallowing Accelerometry," *Dysphagia*, vol. 28, no. 1, pp. 105–112, Mar. 2013.

[16] E. Sejdić, C. M. Steele, and T. Chau, "Classification of Penetration--Aspiration Versus Healthy Swallows Using Dual-Axis Swallowing Accelerometry Signals in Dysphagic Subjects," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 7, pp. 1859–1866, 2013.

[17] J. L. Coyle *et al.*, "Oropharyngeal Dysphagia Assessment and Treatment Efficacy: Setting the Record Straight (Response to Campbell-Taylor)," *J. Am. Med. Dir. Assoc.*, vol. 10, no. 1, pp. 62–66, 2009.

[18] M. R. Spieker, "Evaluating dysphagia," *Am Fam Physician*, vol. 61, no. 12, pp. 3639–3648, Jun. 2000.

[19] J. C. Rosenbek, J. A. Robbins, E. B. Roecker, J. L. Coyle, and J. L. Wood, "A penetration-aspiration scale," *Dysphagia*, vol. 11, no. 2, pp. 93–98, 1996.

[20] G. J. J. W. Bours, R. Speyer, J. Lemmens, M. Limburg, and R. De Wit, "Bedside screening tests vs. videofluoroscopy or fibreoptic endoscopic evaluation of swallowing to detect dysphagia in patients with neurological disorders: systematic review," *J. Adv. Nurs.*, vol. 65, no. 3, pp. 477–493, 2009.

[21] B. Sherman, J. M. Nisenboum, B. L. Jesberger, C. A. Morrow, and J. A. Jesberger, "Assessment of Dysphagia with the Use of Pulse Oximetry," *Dysphagia*, vol. 14, no. 3, pp. 152–156, May 1999.

[22] C. Ertekin *et al.*, "Electrodiagnostic methods for neurogenic dysphagia," *Electroencephalogr Clin Neurophysiol*, vol. 109, no. 4, pp. 331–340, Aug. 1998.

[23] J. M. Dudik, J. L. Coyle, and E. Sejdić, "Dysphagia Screening: Contributions of Cervical Auscultation Signals and Modern Signal-Processing Techniques," *IEEE Trans Hum Mach Syst*, vol. 45, no. 4, pp. 465–477, Aug. 2015.

[24] J. A. Y. Cichero and B. E. Murdoch, "Acoustic Signature of the Normal Swallow: Characterization by Age, Gender, and Bolus Volume," *Ann. Otol. Rhinol. Laryngol.*, vol. 111, no. 7, pp. 623–632, Jul. 2002.

[25] C. Borr, M. Hielscher-Fastabend, and A. Lücking, "Reliability and Validity of Cervical Auscultation," *Dysphagia*, vol. 22, no. 3, pp. 225–234, 2007.

[26] E. S. and C. M. S. and T. Chau, "A procedure for denoising dual-axis swallowing accelerometry signals," *Physiol. Meas.*, vol. 31, no. 1, p. N1, 2010.

[27] D. C. B. Z. and T. C. and C. M. Steele, "Hyolaryngeal excursion as the physiological source of swallowing accelerometry signals," *Physiol. Meas.*, vol. 31, no. 6, p. 843, 2010.

[28] J. L. and C. M. S. and T. Chau, "Time and time–frequency characterization of dual-axis swallowing accelerometry signals," *Physiol. Meas.*, vol. 29, no. 9, p. 1105, 2008.

[29] C. Rebrion *et al.*, "High resolution cervical auscultation signal features reflect vertical and horizontal displacement of the hyoid bone during swallowing," *IEEE J. Transl. Eng. Heal. Med.*, p. 1, 2018.

[30] J. M. Dudik, A. Kurosu, J. L. Coyle, and E. Sejdić, "A statistical analysis of cervical auscultation signals from adults with unsafe airway protection," *J. Neuroeng. Rehabil.*, vol. 13, p. 7, Jan. 2016.

[31] K. Takahashi, M. E. Groher, and K. Michi, "Methodology for detecting swallowing sounds," *Dysphagia*, vol. 9, no. 1, pp. 54–62, 1994.

[32] S. Damouras, E. Sejdic, C. M. Steele, and T. Chau, "An Online Swallow Detection Algorithm Based on the Quadratic Variation of Dual-Axis Accelerometry," *IEEE Trans. Signal Process.*, vol. 58, no. 6, pp. 3352–3359, 2010.

[33] E. Sejdic, V. Komisar, C. M. Steele, and T. Chau, "Baseline characteristics of dual-axis cervical accelerometry signals," *Ann Biomed Eng*, vol. 38, no. 3, pp. 1048–1059, Mar. 2010.

[34] F. Movahedi, A. Kurosu, J. L. Coyle, S. Perera, and E. Sejdic, "Anatomical Directional Dissimilarities in Tri-axial Swallowing Accelerometry Signals," *IEEE Trans Neural Syst Rehabil Eng*, vol. 25, no. 5, pp. 447–458, 2017.

[35] E. Sejdić, C. M. Steele, and T. Chau, "The effects of head movement on dual-axis cervical accelerometry signals," *BMC Res. Notes*, vol. 3, no. 1, p. 269, Oct. 2010.

[36] E. Sejdic, C. M. Steele, and T. Chau, "A method for removal of low frequency components associated with head movements from dual-axis swallowing accelerometry signals," *PLoS One*, vol. 7, no. 3, p. e33464, 2012.

[37] I. Jestrović, J. M. Dudik, B. Luan, J. L. Coyle, and E. Sejdić, "The effects of increased fluid viscosity on swallowing sounds in healthy adults," *Biomed. Eng. Online*, vol. 12, no. 1, p. 90, 2013.