Stylohyoid and posterior digastric timing evaluation

1st Adrien Mialland
Univ. Grenoble Alpes
CNRS, Grenoble INP, Gipsa-Lab
38000 Grenoble, France
0000-0001-5359-674X

2nd Ihab Atallah
Otorhinolaryngology
CHU Grenoble Alpes
38700 La Tronche, France
iatallah@chu-grenoble.fr

3rd Agnès Bonvilain
Univ. Grenoble Alpes
CNRS, Grenoble INP, Gipsa-Lab
38000 Grenoble, France
agnes.bonvilain@univ-grenoble-alpes.fr

***Abstract*—In the context of real-time and safe indwelling detection of swallowing, which would enable the conception of an implantable active artificial larynx, we evaluate the timing of the stylohyoid and the posterior digastric muscles. They were shown to activate at the beginning of swallowing, both from human and animal results, but only with an indirect imaging method on humans. Therefore, this paper analyses their onset, offset, and peak time through the first method, that we previously set up, which allowed their direct functional analysis with intramuscular electromyography, surface electromyography, and swallowing sound. We found that both muscles activate at the beginning of swallowing, are relatively stable, while the posterior digastric duration were the shortest.**

***Index Terms*—Swallowing detection, stylohyoid, digastric, total laryngectomy, electromyography, deglutition.**

I. Introduction

Swallowing detection is usually performed with sensors placed on the skin, in a non-invasive manner, and intends to assess the swallowing process in clinical practice. Also, the detection is most often performed offline and, even in the case of online strategy, no clear timing constraints are established. Yet, we aim at the feasibility of an implantable active artificial larynx as a natural airway rehabilitation method, following total laryngectomy. In such a system, the airway would need to be temporarily closed during swallowing, to protect them from bolus aspiration, with a dedicated *active closure mechanism*. This would, therefore, require a *real-time* and *safe* indwelling detection of swallowing. Also, such an implanted system would use low-power apparatuses, which limits the speed. Therefore, this requires a measurement strategy that provides early information about the swallowing process, ideally at its beginning, to protect the airways as soon as possible.

In that regard, we focused on the stylohyoid and the posterior digastric muscles which showed appropriate results [1]. However, while timing assessments from direct functional data have partially been done on animals, only indirect results from an imaging method are available on humans because of the difficulty to measure them. Indeed, studies involving decerebrate pigs investigated the swallowing reflex [2], [3]. The authors not only found that the stylohyoid activates at the beginning when a swallowing reflex is elicited, but also that these findings were in line with the behavior observed in neurally intact animals. But no data are available for the posterior digastric as pigs do not have one. On humans, a recent imaging method allowed to assess the shortening of both muscles [4]. The authors showed that they start to shorten during the initial part of swallowing, at the same time as the mylohyoid, during the upward movements of the hyoid bone. Yet, the mylohyoid is part of the submental muscles and is acknowledged to activate at the beginning of the swallowing [5]. Finally, even though other easily accessible muscles are known to activate early, the stylohyoid and the posterior digastric muscles are chosen for their potential to provide a more dedicated, and therefore stable, early activity. Especially, the nerve conduction of both muscles was studied simultaneously and the authors argued that these muscles may facilitate electrophysiological identification factors [6].

So, we intend to evaluate the onset, offset and peak time of the stylohyoid and the digastric muscles through intramuscular electromyography (EMG), and with submental EMG and the swallowing sound method to provide basis for comparisons.

II. Materials and Methods

The data were acquired with a standardized method that we developped [7] to allow the functional analysis of the stylohyoid and the posterior digastric muscles with intramuscular EMG. We also used surface EMG, to measure the submental muscles that activate at the beginning of swallowing [5], and an accelerometer, to measure the swallowing sound and access the moment the bolus passes through the upper esophageal sphincter (UES) [8]. The later event will be called *UES bolus flow* for conciseness, and its beginning is linked to the increase in pressure that drives the bolus down the pharynx. It is also suggested to be associated with the closure of the laryngeal vestibule [9]. So, We use it as the reference time point where any closure mechanism must be closed to protect the airways.

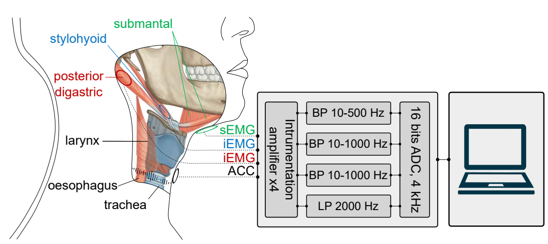

Fig. 1. Sensors locations, anatomical structures and acquisition set up. EMG: electromyography, sEMG: surface EMG, iEMG: intramuscular EMG, ACC: accelerometer, BP: band-pass, LP: low-pass. ADC: analogue digital converter.

This research has been funded by the Région Auvergne Rhône Alpes.

A. Subjects

Sixteen healthy adults (8 males/ 8 females) with no history of dysphagia, neck surgery or neurological impairment were included. The mean age was 36.1 ± 13.6. All participants met the following criterias: age of 18 years or higher, body mass index (BMI) of 25 or lower. BMI higher than 25 were excluded to avoid a potentially excessive amount of fat that would make the placement of the sensors more complex. This study was approved by the research ethics committee of Sud-Méditerranée III of Nîmes, France (Protocol ID: 38RC22.0096).

B. Signal Acquisition

Participants comfortably sat on a chair and an otolaryngologist placed each sensor (Figure 1) in the following order:

SWALLOWING SOUND: The accelerometer (TN1012, 1600Hz, ADInstrument) was fixed with paper tape on top of the cricoid cartilage [8] to record antero-posterior vibrations.

SURFACE EMG: Gel electrodes were used with two differential electrodes placed under the left part of the submental area, 2cm apart. The reference electrode over the right clavicle.

INTRAMUSCULAR EMG: Two concentric needles were used (27-gauge, 30 mm). The stylohyoid was targeted next to its insertion, at the level of the lesser horn of the hyoid bone. The posterior digastric was targeted in its back portion, next to its origin from the mastoid notch. The needles were secured with steri strips so they cannot come out of the muscles.

The four signals were acquired with a Bio-Amp (FE234) pre-amplifier and a PowerLab (35 series) from ADInstrument. They were first analog filtered with a band-pass of $10 - 1000Hz$ on the intramuscular EMG and $10 - 500Hz$ on the surface EMG, and a low-pass of $2000Hz$ on the swallowing sound. Each channel was then sampled with a 16 bits ADC at $4000Hz$. Then, a 2$^{\text{nd}}$ order high-pass Butterworth digital filter, with a cut-off frequency of $20Hz$, is applied on the EMG signals, and a 4$^{\text{th}}$ order Butterworth digital notch filter is applied to all signals to eliminate the $50Hz$ line noise.

C. Features Extractions

The volunteers were asked to swallow five times four bolus types: saliva, water ($10ml$), thick liquid (compote), and solid (madeleine). All signals were transformed with the Teager-Kaiser energy operator (TKEO) $\Psi[x(n)] = x(n)^2 - x(n-1)x(n+1)$, as it was shown to improve the signal-to-noise ratio [10]. Then, following features were extracted and normalized to the UES bolus flow time, used as a *0 second* reference time.

MUSCLE ONSET AND OFFSET: they were localized on each EMG signal. But, intramuscular EMG is prone to background noise such as spurious spikes, because of the reaction of the fibers to the needles. So, we used the generalized likelihood ratio method (GLR) to model the signals and effectively abstract from the noise. Using a $100ms$ sliding window, it continuously computes the likelihood ratio of a contracted muscle state hypothesis against a relaxed muscle state hypothesis, to estimate the time of onset and offset. So, an exponential probability density function is used as it was shown to closely represents the absolute value of the TKEO-transformed EMG [11]. Formal GLR description is available in our previous work [7] and in the original paper [12]. The onset and offset were manually placed accordingly to avoid false positives.

UES BOLUS FLOW TIME: it was localized on the accelerometer signal. It is characterized by a major burst of activity when the bolus enters the UES, and the TKEO-transformed signal allowed to bring that event out. Its beginning could therefore easily be placed manually [7].

MUSCLE PEAK TIME: it was localized on each EMG signal. Their amplitude was continuously estimated with the RMS value of a sliding window of $100ms$. The peak time was the moment of the maximum amplitude of the swallowing event.

D. Statistical Analysis

All statistical analyses were performed using IBM SPSS statistics premium version 28. Two-way 3 x 4 repeated measure ANOVAs were conducted. The first factor was muscle type: stylohyoid, posterior digastric, and submental. The second factor was bolus type: saliva, water ($10ml$), thick liquid (compote), and solid (madeleine). Three dependent variables were evaluated: onset, offset and peak time. Each feature was related to the UES bolus flow time, used as the *0 second* reference time. The level of significance was set to $\alpha = 0.05$ for all comparisons. Mauchly's test of sphericity was conducted to evaluate the homogeneity of variances and the Greenhouse-Geisser correction was used in case of significance [13]. Post-hoc analysis is conducted in case of statistical significance of ANOVAs. Level-wise one-way repeated measure ANOVAs or pairwise comparisons with Bonferroni correction were used. Cohen's d is also used to report on effect sizes [14].

III. RESULTS

All 16 volunteers completed the full acquisition procedure. Few acquisitions could not be processed for further temporal features extraction, because of bad signal quality. This yielded a total of 75 swallowings per bolus type. The mean and standard deviation of all 3 extracted features are shown in Table I. Also, the onset of all muscles and for all 300 swallowings occurred before the UES bolus flow, with $-0.047s$ as the closest value and with 98.33% before $-0.1s$ (Figure 2).

A. Onset

No interaction was revealed by the ANOVA for bolus and muscle on the onset, $F(4.49, 332.29) = 0.802, p = 0.537$, but a statistically significant main effect of bolus was observed, $F(2.397, 177.378) = 7.982, p < 0.001$. A post-hoc analysis was conducted with the associated marginal means and the results of the pairwise comparisons are shown in Table II. Significant differences were observed between saliva and water, saliva and thick, and thick and solid (Figure 2).

B. Offset

No interaction was revealed by the ANOVA for bolus and muscle on the offset, $F(5.284, 391.041) = 2.034, p = 0.069$, but a statistically significant main effect of bolus, $F(2.625, 194.267) = 17.896, p < 0.001$, and muscle,

TABLE I
ONSET, OFFSET, AND PEAK TIME OF EACH MUSCLE AND FOR EACH BOLUS TYPE, REPORTED AS MEAN (SD).

	onset*			offset*			peak time*		
	SH	PD	SM	SH	PD	SM	SH	PD	SM
Saliva	-0.487 (0.225)	-0.502 (0.272)	-0.510 (0.228)	+0.404 (0.136)	+0.063 (0.265)	+0.296 (0.178)	-0.036 (0.183)	-0.185 (0.137)	-0.136 (0.183)
Water	-0.416 (0.197)	-0.423 (0.199)	-0.410 (0.154)	+0.496 (0.219)	+0.148 (0.252)	+0.394 (0.145)	+0.038 (0.264)	-0.151 (0.188)	-0.044 (0.115)
Thick	-0.356 (0.179)	-0.388 (0.231)	-0.393 (0.176)	+0.487 (0.158)	+0.171 (0.239)	+0.430 (0.156)	+0.061 (0.167)	-0.158 (0.128)	-0.038 (0.169)
Solid	-0.449 (0.256)	-0.446 (0.251)	-0.470 (0.271)	+0.459 (0.122)	+0.187 (0.237)	+0.392 (0.177)	+0.051 (0.133)	-0.189 (0.131)	-0.113 (0.187)

* Onset, offset, and peak time are related to the UES bolus flow time. UES: upper esophageal sphincter.

TABLE II
ONSET ESTIMATED MARGINAL MEAN PAIRWISE COMPARISONS IN POST-HOC ANALYSIS, FOR BOLUS MAIN EFFECTS.

	Mean difference	p value	Effect size
Saliva - water	0.840	0.011*	0.215
Saliva - thick	0.120	<0.001*	0.364
Saliva - solid	0.045	0.334	0.130
Water - thick	0.037	0.674	0.107
Water - solid	0.039	1.000	0.079
Thick - solid	0.076	0.031*	0.195

* Statistically significant difference. All p values have been adjusted with Bonferroni correction for multiple comparisons.

TABLE III
PEAK TIME COMPARISON WITH THE UES BOLUS FLOW.

	SH		PD		SM	
	p value	Effect size	p value	Effect size	p value	Effect size
Saliva	0.094	-0.196	<0.001	-1.349	<0.001	-0.745
water	0.210	0.146	<0.001	-0.805	0.001	-0.385
thick	0.002	0.369	<0.001	-1.230	0.056	-0.224
solid	0.002	0.379	<0.001	-1.441	<0.001	0.606

No Statistically significant differences within the group.

$F(1.182, 87.448) = 139.434, p < 0.001$, were observed. For bolus, only saliva yielded a statistically significantly lower mean value, $t(224) = -5.873, p < 0.001, d = -0.392, 95\%\ CI\ (-0.527, -0.256)$. For muscles, in all cases posterior digastric muscle offset occurred first, followed by submental muscle and then the stylohyoid muscle (Figure 2).

C. Peak Time

A significant interaction was observed for bolus and muscle on peak time, $F(3.954, 292.565) = 2.55, p = 0.04$. In all cases, the posterior digastric peak time occurred first, followed by the submental muscles, then the stylohyoid (Table III). The posterior digastric and the submental muscle peak time occured before the UES bolus flow. It occurred after for the stylohyoid for water, thick and solid (Figure 2). Finally, only the posterior digastric muscle yielded no difference in peak time, $F(2.322, 171.799) = 2.398, p = 0.085$, and it showed the strongest deviation from the UES bolus flow, $t(299) = -19.945, p < 0.001, d = -1.152, 95\%\ CI\ (-1.297, -1.005)$.

IV. DISCUSSION

A *real-time* and *safe* detection of swallowing would allow the development of an implantable active artificial larynx, but it requires muscles that activate at its beginning, and the stylohyoid and the posterior digastric have been promising. So, we provided the first functional analysis with intramuscular EMG, submental surface EMG, and the swallowing sound measurements to evaluate their onset, offset, and peak time.

The UES bolus flow is used as the *0 seconds* reference to provide a temporal limit where the airway must be closed. It is associated with a drastic increase in pressure and deformation in the pharynx [15], that changes the relaxed conditions and would objectively require the airway to be protected. The swallowing sound measurement of that event generates a burst of activity suggested to be linked to the laryngeal vestibule closure [9]. It is related to the physiological closure of the airway, which support our choice to use it as a time limit.

As for onset, only the bolus type had an effect while each muscle activated at the same time (Figure 2), with only small to medium effects (Table II). We thus confirmed that the stylohyoid and the posterior digastric muscles activate at the beginning, as the submental muscles lead the pharyngeal swallowing [5]. This was first suggested in decerebrate pig with intramuscular EMG, but on the stylohyoid only [3]. The authors showed that it activated with the mylohyoid muscle, before the beginning of the epiglottis movement, involved in airways protection. Also, comparable results were later found in neurally intact pigs [2] and is explained by the reflexive aspect of the pharyngeal swallow, considered to be driven by the *central pattern generator* in the brainstem [16]. Concerning human, one study reported on activation sequence, but with the use of an indirect imaging method [4], where they delineated muscles in 3D space. They showed the sequence of activation of known muscles, along with the stylohyoid and the posterior digastric. Again, they were confirmed to activate at the same time as the mylohyoid muscle and were correlated to the upward movement of the hyoid bone. So, our study confirms the early activation of the stylohyoid and the posterior digastric muscles in human. Besides, in a total of 300 swallowing from 4 bolus types, no muscle ever activated after UES bolus flow, and 98.33% started before $-0.1s$ (Figure 2).

regarding offset, both the bolus and muscle types showed significant variations. First off, saliva caused all 3 muscles to stop earlier than the other boluses. But the largest variations were between muscles and were reproducible for all 4 types of bolus: the posterior digastric terminates first, with most of its activity that occures before the UES bolus flow (Figure 2), followed by the submental muscles, then the stylohyoid.

For the peak time, only muscle type showed a clear tendency, with the same sequencing as offset, for all 4 boluses. Also, the posterior digastric peak occured first, with no signif-

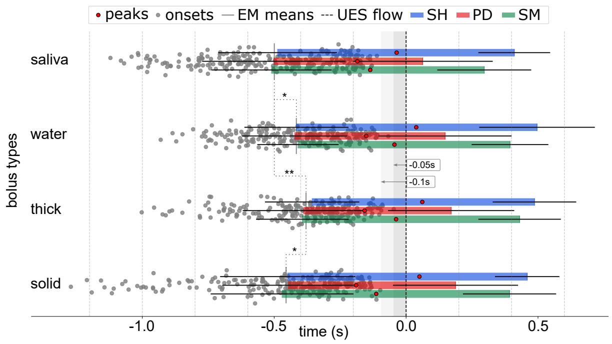

Fig. 2. Stylohyoid, posterior digastric and submental muscles timings, per bolus, relative to the UES bolus flow. *: $p < 0.05$, **: $p < 0.001$. EM mean: estimated marginal mean of each bolus type, UES: upper esophageal sphincter, SH: stylohyoid, PD: posterior digastric, SM: submental. All onsets occurred before the UES bolus flow, with 98.33% before $-0.1s$. PD peak showed no significant difference, occurred first, and most of PD activity occurred before the UES bolus flow. SH peak were more stable than SM peak.

icant effect of bolus (Table III). The temporal pattern of those muscles has not directly been explored but few studies allow indirect comparison. The hyoid bone was shown to adopt a circular-like movement, starting upward and then forward, and then back to its resting position [5]. Along with our results, this suggest that the posterior digastric is primarily involved in the first elevation of the hyoid bone. In addition, recent imaging method correlated the shortening of the posterior digastric with the upward displacement of the hyoid bone [4], which is in line with the analysis of its structure [17]. Besides, the peak of the stylohyoid was relatively more stable than the submental muscles, but it also was the latest and mainly situated around the UES bolus flow (Table III). This suggests its implication in the hyoid bone stabilization during UES opening for bolus flow, which requires further investigation to be confirmed.

Finally, from the perspective of an implantable active artificial larynx, the measured anatomical structures should provide an early, and stable activity. The *real-time* and *safe* indwelling detection of swallowing requires the airway to be protected as early as possible and we found that the earliness is met for all 4 types of bolus tested. Also, the field of hand gesture recognition provides numerous examples of myoelectric control with comparable timing constraints to detect multiple gestures in real-time [18], while swallowing essentially reduces to an on-off detection. This is encouraging and goes along with a previous nerve conduction study that suggests the stylohyoid and the posterior digastric to be more suited to electrophysiological identifications [6]. So, investigations on recruitment pattern are ongoing to compare swallowing with various tasks, acquired in our previous work along with swallowing [7].

V. Conclusion

We evaluated the onset, offset, and peak time of the stylohyoid and the posterior digastric muscles with intramuscular EMG. The onset of swallowing was accessed with the submental muscles via surface EMG, and an accelerometer measured the moment the bolus passes through the UES. We showed that they activate at the beginning, along with the submental muscles, with no muscles that fired after the passage of the bolus through the UES, and with 98.33% that activated $0.1s$ before. Besides, their peak activity was relatively stable, and most of the posterior digastric activity occurred before the passage of the bolus through the UES. These results are in line with the requirements of an active implantable artificial larynx, that we seek to develop in the context of total laryngectomy. Airway restauration and closure of the tracheostomy requires the trachea to be closed as early as possible to forbid bolus aspirations. The earliness and stability of the stylohyoid and posterior digastric muscle could allow the development of an *real-time* and *safe* indwelling detection of swallowing and the analysis of their recruitment pattern in various task is ongoing.

References

[1] A. Mialland, I. Atallah, and A. Bonvilain, "Toward a robust swallowing detection for an implantable active artificial larynx: A survey," *Medical & Biological Engineering & Computing*, 2023.
[2] R. Z. German, A. W. Crompton, and A. J. Thexton, "Integration of the Reflex Pharyngeal Swallow Into Rhythmic Oral Activity in a Neurologically Intact Pig Model," *Journal of Neurophysiology*, 2009.
[3] A. J. Thexton, A. W. Crompton, and R. Z. German, "Electromyographic activity during the reflex pharyngeal swallow in the pig: Doty and Bosma (1956) revisited," *Journal of Applied Physiology*, 2007.
[4] T. Okada *et al.*, "Dynamic change in hyoid muscle length associated with trajectory of hyoid bone during swallowing: analysis using 320-row area detector computed tomography," *Journal of Applied Physiology*, 2013.
[5] D. Park *et al.*, "Normal contractile algorithm of swallowing related muscles revealed by needle EMG and its comparison to videofluoroscopic swallowing study and high resolution manometry studies: A preliminary study," *Journal of Electromyography and Kinesiology*, 2017.
[6] T. Kurt *et al.*, "Electrophysiologic identification and evaluation of stylohyoid and posterior digastricus muscle complex," *Journal of Electromyography and Kinesiology*, 2006.
[7] A. Mialland, I. Atallah, and A. Bonvilain, "Stylohyoid and Posterior Digastric Measurement with Intramuscular EMG, Submental EMG and Swallowing Sound," in *Proceedings of the 16th International Joint Conference on Biomedical Engineering Systems and Technologies*, 2023.
[8] S. Morinière *et al.*, "Pharyngeal Swallowing Sound Profile Assessed after Partial and Total Laryngectomy," *Dysphagia*, 2011.
[9] A. Kurosu *et al.*, "Detection of Swallow Kinematic Events From Acoustic High-Resolution Cervical Auscultation Signals in Patients With Stroke," *Archives of Physical Medicine and Rehabilitation*, 2019.
[10] S. Wang, S. Zhu, and Z. Shang, "Comparison of different algorithms based on TKEO for EMG change point detection," *Physiological Measurement*, 2022.
[11] E. Selvan *et al.*, "Unsupervised Stochastic Strategies for Robust Detection of Muscle Activation Onsets in Surface Electromyogram," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2018.
[12] Q. Xu *et al.*, "An Adaptive Algorithm for the Determination of the Onset and Offset of Muscle Contraction by EMG Signal Processing," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2013.
[13] M. Roberts and R. Russo, *A Student's Guide to Analysis of Variance*. Routledge, 2014.
[14] J. Kotrlik and H. Williams, "The incorporation of effect size in information technology, learning, information technology, learning, and performance research and performance research," *Information Technology, Learning, and Performance Journal*, 2003.
[15] A. Pal *et al.*, "Intrabolus pressure gradient identifies pathological constriction in the upper esophageal sphincter during flow," *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 2003.
[16] A. Jean, "Brain Stem Control of Swallowing: Neuronal Network and Cellular Mechanisms," *Physiological Reviews*, 2001.
[17] W. G. Pearson, S. E. Langmore, and A. C. Zumwalt, "Evaluating the Structural Properties of Suprahyoid Muscles and their Potential for Moving the Hyoid," *Dysphagia*, 2011.
[18] A. Jaramillo-Yánez, M. E. Benalcázar, and E. Mena-Maldonado, "Real-Time Hand Gesture Recognition Using Surface Electromyography and Machine Learning: A Systematic Literature Review," *Sensors*, 2020.