Stylohyoid and posterior digastric recruitment pattern evaluation in swallowing and non-swallowing tasks.

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Abstract

Objectives: Electromyography is one of the few measurement methods that can be implanted, and it has been used in swallowing detection to measure superficial muscles, but has failed to provide satisfactory performances for a real-time detection. Yet, we seek to allow for the feasibility of an implantable active artificial larynx that would protect the airway during swallowing. Therefore, it requires a real-time detection of swallowing through measurements that must provide dedicated and early activity on swallowing, to close the airways soon as possible. In that regard, promising results were published about the stylohyoid and posterior digastric muscles, but no study provided simultaneous and independent measurements. So, This paper aims to evaluate both muscles with intra muscular EMG, in a large set of tasks, to evaluate their recruitment pattern for the feasibility of an implantable active artificial larynx.
Materials and methods: we used intramuscular EMG to measure the stylohyoid and the posterior digastric muscles independently. We also used surface electrodes to measure the submental muscles and provide a basis for comparison. Besides, the swallowing sound measurement method was used to locate the moment the bolus starts to enter the upper esophageal sphincter (UES). That moment defines a temporal limit after which the airway are in danger of aspiration and the temporal evolution of the muscles' is evaluated in comparison to that limit. The onsets and offsets of each muscles were located with a generalized likelihood ratio method, and the UES bolus passage was localized manually after the transformation of the signals with a Teager-Kaiser energy operator. 17 participants were measured, and were asked to perform 4 swallowing tasks and 13 non-swallowing tasks.
Results: we found a strong implication of the stylohyoid for swallowing and mastication. The posterior digastric showed a clear tendency towards swallow-related tasks, and especially swallowing, mastication, open mouth, jaw, and clench teeth. Both muscles provided significant activity before the temporal limit, with a characteristic pattern.
Conclusion: the stylohyoid and the posterior digastric muscles shows a net increase in potential for a detection, compared to the submental muscles, for the feasibility of an implantable active artificial larynx.

Keywords: swallowing detection, stylohyoid, digastric, total laryngectomy, electromyography, deglutition.

1. Introduction

when it comes to bio-signals, expectations are to get data that provide a clear insight into what is analyzed. But the intrinsic variability of physiological processes makes the measurement method a critical choice. The swallowing process is no exception, and several methods have been developed to better understand its functioning [29]. However, no unique approach exists to entirely reveal its subtleties and several of them are often used in combination to compensate. But very few can be used daily and even be implanted. Yet, we aim at the feasibility of an *implantable active artificial larynx* as a natural airway rehabilitation method, following total laryngectomy. Currently, the surgery permanently separates the air passage from the bolus passage with the creation of a tracheostomy: the trachea is sewn on the anterior neck to allow breathing, and no air passes through the mouth and the nose anymore. Previous attempts have already shown the possibility to implement an artificial larynx to set the trachea back in place and restore the natural airways [2, 3]. The prosthesis was entirely passive and allowed the patients to breathe and swal-

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low normally. However, food residues were found in the trachea [4] and the possibility to develop a *real-time* and *safe* detection of swallowing could significantly improve the safety of such a system, by allowing to close any active mechanism that would temporarily protect the airway during swallowing. This would therefore enable the development of an implantable active artificial larynx.

This translates into the need for an implantable physiological measurement that can provide meaningful swallowing data as early as possible, once the swallowing has started. This could allow to protect the airways as soon as possible before the bolus put the airway at risk of aspiration. Also, the data should be as dedicated as possible to swallowing, to forbid any swallowing detection failures. Indeed, the more diversified is the content of a signal, the more challenging it becomes to differentiate a specific activity (i.e swallowing). These requirements arise from the functioning of real-time detection algorithms, that can analyze the signals as they arrive and to discriminate the event in progress before it is completed. Therefore, the efficiency of such algorithms depends on the measured data, which requires looking for both suitable anatomical structures and implantable measurement methods.

In that regard, when it comes to physiological evaluation and identification of specific movements, muscle activity recording with electromyography (EMG) is the preferred method and comes with a large corpus of study in various fields. In addition, it is one of the few measurement methods that can be implanted [18]. It consists of the measurement of the seemingly random firing of all the muscle fibers situated within the sensitive area of an electrode. The content of the resultant signals is, therefore, inherently random, but it gives access to distinct muscle activity and allows to evaluate their recruitment intensity and their temporal relationships [1]. However, EMG has little been used in swallowing detection and was mostly combined with other measurement methods. Also, these approaches only used surface electrodes, which limits the access to swallowing-related data and showed limited detection accuracy with regard to the requirements we described for a real-time detection [18]. Therefore, these results mitigate the interest in an EMG-based swallowing detection so far, and further explorations are required to look for muscles that could provide earlier and more dedicated data.

Indeed, thoroughly selected anatomical areas could provide more qualitative myoelectric data, and surface electrodes limit the measurements to the superficial muscles only. Moreover, EMG-based detection strategies have already shown promising results in the field of upper limb gesture recognition, both with surface [10, 23] and implanted electrodes [21], to measure the residual muscles of amputees. It allows for the myoelectric control of a robotic arm with multiple movements, which is meant to reproduce seemingly natural movements through real-time detection. Yet, the swallowing process is considered to be mostly reflex, driven by the central pattern generator, a group of neurons located in the brain stem. This makes it a quite stereotypical process, as opposed to limb movements, and the requirement of the airways to be protected actually falls down to an on/off detection. This encourages the idea that the swallowing process might provide robust data, and intramuscular EMG would allow to overcome the limit of surface electrodes, to evaluate deep muscles that have never been considered so far. In addition, while total laryngectomy removes the larynx and impairs various neck area, several muscles are only separated from the hyo-laryngeal complex via their insertion point and are left in place with no damage [15, 18]. This could therefore give access to their activity to an implantable real-time detection system, similar to a robotic arm that measures the activity of the residual muscles of the arm.

In this regard, the stylohyoid and the posterior digastric muscles have little been studied but few results hint toward their importance. First off, they are part of the suprahyoid muscles and are morphologically suited to act on the upward and forward movements of the hyoid bone [27]. Subsequently, the hyoid bone is joined together with the larynx and its movements directly act on the opening of the upper esophageal sphincter (UES), for the bolus to enter the esophagus safely. In other words, this suggests that the stylohyoid and the posterior digastric muscles essentially act on the stabilization of the hyoid bone. In comparison, although the submental muscles are well studied and have been shown to contain key swallowing muscles involved in hyoid bone movements [18, 27], they also constitute the floor of the mouth and support the tongue in its various actions. So, this latter point is likely to limit their ability to provide a swallowing dedicated activity. Besides, the particular attention that previous works have given to the submental muscles is likely due to their accessibility, but the stylohyoid and the posterior digastric muscles might deserve similar attention. Especially, for a real-time swallowing detection, we hypothesize that the stylohyoid and the posterior digastric muscles could provide more dedicated and potentially earlier data than the submental muscles.

This is further supported by recent investigations based on modern imaging methods that evaluated the physiological response of the stylohyoid and the posterior digastric [25]. The authors showed that they significantly activate during swallowing, but they did not provide comparisons with other activities. However, Kurt et al. [12] reported on both muscles, studied as a whole stylohyoid-posterior-digastric (*STH-PD*) complex with intramuscular EMG, and observed that it mainly activated for saliva swallowing, mastication and jaw opening. But the variety of tasks was limited and no strict and quantified comparisons were provided. Their study actually mainly focused on the nerve conduction evaluation of the muscles, which are innervated by the facial nerve. They emphasized that the *STH-PD* complex seems to have nothing to do with mimicry but has similar functions to the submental muscles, which are innervated by the trigeminal nerve. They suggest that this intermediary position may facilitate the electrophysiological identification of swallowing.

Besides, regarding the requirement in early data for the development of a real-time and safe detection of swallowing, the definition of a temporal limit after which the airway must be closed could allow us to better evaluate the potential of the measured signals. This time point is chosen to be the moment when the bolus passes through the UES, when the pressure in the throat suddenly increases and the airways are at the highest risk of aspiration [18]. This moment has been shown to be accessible via the swallowing sound measurement [19].

This paper, therefore, intends to evaluate the ability of the stylohyoid and the posterior digastric to provide early and dedicated data about swallowing, measured with intramuscular EMG. We specifically focused on their recruitment pattern and hypothesized that they exhibit a repetitive and potentially identifiable activity. We also measured the submental muscles with surface EMG, to provide a basis for recruitment comparison, and the swallowing sound with an contact transducer, to provide a basis for the evaluation of the temporal aspects of the muscles recruitment.

2. Materials and Methods

The data are extracted from signals that we acquired in a larger study, that we conducted to develop the first standardized procedure that allows direct functional measurement and evaluation of the stylohyoid and the posterior digastric muscles independently, through intramuscular EMG. We also measured the surface EMG of the submental muscles, which we included in the current investigation to provide a basis for comparison. Besides, the swallowing sound was measured with an contact transducer, to access the moment the bolus starts to flow through the UES. This later event will be called *UES bolus flow*, for conciseness. The acquisition method is briefly detailed hereafter, but the full procedure is available in the related paper [17].

2.1. Subjects

Seventeen healthy adults (8 males/ 9 females) with no history of dysphagia, neck surgery, immune deficiency, or any neurological impairment participated in this study. The mean age was 36.1 ± 13.6 and all enrolled participants met the following inclusion criteria: an age of 18 years or higher and a body mass index (BMI) of 25 or lower. Participants with BMI higher than 25 were intentionally excluded from this study to avoid a potentially excessive amount of fat in the region of the neck that would make the proper placement of the sensors more complex. This study was approved by the research ethics committee of Sud-Méditerranée III of Nîmes in France (Protocol ID: 38RC22.0096).

2.2. Signal Acquisition

The participants were asked to comfortably sit on a chair and each sensor was placed by an otolaryngologist in the following order:

Swallowing Sound: The transducer (TN1012/ST, ADInstrument) was fixed with a hypoallergenic paper tape on top of the cricoid cartilage, as it was suggested to provide the greatest signal-to-noise ratio [5], and is placed to record the antero-posterior vibrations. The resulting signal has been shown to be made of 3 main bursts of sound, separated in time and associated with swallowing events, where the major burst was associated with the UES bolus flow and was the only one to be present 100% of the time [13, 19]. The possibility to precisely localize that event in time was shown in our previous work [17].

Surface EMG: 2 differential electrodes were placed under the left part of the submental area, with their center approximately 2*cm* apart, and a ground electrode was placed over the right clavicle (Spesmedica, DENIS15026). Both areas were first cleaned with a dedicated abrasive and conductive paste to reduce the electrode-skin impedance. This allowed us to effectively measure the submental muscles, as they have been shown to be mostly free of contamination from adjacent muscles when measures from that area [16, 22].

Intramuscular EMG: To isolate the stylohyoid and the posterior digastric activity, they are targeted close to their origin and insertion points with concentric needle electrodes (27-gauge, 30mm): the stylohyoid muscle was targeted next to its insertion point, at the level of the junction between the body and the greater horn of the hyoid bone. In that region, the posterior digastric is composed of its intermediate tendon, which cannot produce EMG signals and, therefore, cannot be mistaken for the stylohyoid muscle activity. As for the posterior digastric muscle, it was targeted in its posterior portion, close to its origin at the level of the mastoid notch. In that region, it separates from the stylohyoid, which originates from the styloid process upper in the neck. Besides, both muscles are directly accessible behind the skin. While the otolaryngologist was slowly inserting the needles, a second trained operator monitored the EMG activity on the computer to look for muscle activities. It could be requested to the participant to swallow to elicit an event. Once an event was visible on the signal, the needles were no further inserted. They were then secured with a Steri-Strip so that they cannot come out of the muscles.

All three signals were acquired with a Bio-Amp (FE234, 4 channels) pre-amplifier and a PowerLab (35 series, 4 channels) acquisition system from ADInstrument. All signals were first processed with analog filters. A $10-1000Hz$ band-pass filter was applied on both intramuscular EMG and a $10-500Hz$ band-pass filter was applied on the surface EMG. Each channel was then sampled with a 16 bits analog-digital-converter, at a rate of $4000Hz$. Once digitized, a 2^{nd} order high-pass Butterworth digital filter with a cut-off frequency of $20Hz$ is applied on all signals, followed by a 4^{th} order Butterworth notch filter to eliminate the $50Hz$ line noise.

2.3. Protocol

Four swallowing and 13 non-swallowing tasks were performed by the participants. Each task is first prepared, then 2 seconds with no motion are acquired, the task is performed upon vocal cue, and 2 more seconds with no motion are acquired. This ensures to record a clear event. Also, a button is pressed when the vocal cue is emitted and when the task is finished, to roughly temporally delineate the tasks.

Swallowing Tasks: the participants performed 5 swallowing of Saliva, water ($10ml$), thick liquid (compote), and solid bolus (madeleine).

Non-Swallowing Tasks: the participant performed (1) 3 times mouth opening, lips purseing, teeth clenching, smiling, whistling, coughing, blowing through a straw, speaking: counting from 1 to 10, vocalizing: saying *"iii"* in ascending and descending order. (2) 3 times movement tasks being lateral jaw movements, lateral head movements, and vertical (flexion-extension) head movements. (3) 5 times chewing, that are actually recorded at the moment the solid bolus swallowing tasks is performed, with a pause in between, to separate the two. All tasks are performed to a comfortable full extent and at a natural pace.

2.4. Features Extraction

Onset and offset of all muscles and for all activities were first localized for further feature extraction. All raw EMG signals are 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 [30]. Also, EMG is prone to background noise and especially spurious spikes from intramuscular EMG, because of a few surrounding muscle fibers that react to the presence of the needles. To effectively account for it, several methods were compared (integrated profile, sample entropy, Bayesian changepoint analysis) and the generalized likelihood ratio (GLR) method [17] was the most effective to abstract from the noise, as it allowed us to model the signals. It was computed on a $100ms$ sliding window as recommended by the original paper [32], and with an exponential probability density function to represent the TKEO-transformed raw EMG [28]. An adaptive threshold of 10% of the maximum of the current GLR signal is placed as a guideline. In addition, the root-mean-square (RMS) amplitude is computed on all raw EMG with a $100ms$ sliding window, and a 3 standard deviation threshold is also placed as a guideline. Then, the resultant GLR and RMS signals are compared, and the onset and offset of each event are manually placed accordingly, to avoid any false positive. Also, in case of transitory or absence of activity, the rough temporal markers previously placed during the tasks were used as the default onsets and offsets.

The RMS signals are then normalized for further analysis. However, the normalizing reference should be repeatable and stable, to preserve the variations within but reduce the variations between the participants, and meaningful, so that it allows for valuable comparisons [8]. Fort these reasons, we chose to normalize in relation to swallowing for its reflexive aspect, while non-swallowing tasks are conscious and may introduce additional variability. This strategy therefore allows for normalized amplitude higher than 100%, if any, but still retains relevant amplitude differences. Also, intramuscular and surface EMG measures the same phenomena but with different sensors, and the direct comparison of their amplitude may not be reliable. Therefore, to allow for RMS-amplitude comparison between the muscles, it is performed between the stylohyoid and posterior digastric muscles: for each subject, the RMS-amplitude is divided by the maximum RMS-amplitude from all swallowing tasks of all intramuscular EMG channels.

Besides, to allow for RMS-amplitude comparisons between the tasks: for each subject, the RMS-amplitude is divided by the maximum RMS-amplitude from all swallowing tasks of the current channel. Finally, the previously localized onsets and offsets are used to segment the RMS-amplitudes, and the peak and mean values are extracted.

Besides, to localize the UES bolus flow, the swallowing sound signals are first transformed with TKEO. Then, the swallowing sound exhibits a major burst of activity when the bolus enters the UES, and the TKEO-transform signals allowed to bring that event out. Its beginning could therefore easily be placed manually [17].

2.5. *Statistical Analysis*

All statistical analyses were performed using IBM SPSS statistics premium version 28. A linear mixed model analysis was chosen for its ability to deal with unbalanced and missing data points, and to model complex covariance structure [9]. In comparison, the traditional repeated-measure ANOVA would simply delete incomplete cases and assumes equality of residual variances. In our case, this would result in a substantial number of data points deletion and add a significant bias, while the potential variations in amplitude among muscles and tasks would require a more suitable covariance structure.

Therefore, linear mixed models were used to evaluate the differences in peak and mean RMS-amplitude between the stylohyoid and posterior digastric muscles in the swallowing tasks. Also, linear mixed models were used to evaluate the differences in peak and mean RMS-amplitude between all tasks, within all three muscles independently. For each model, tasks and muscles were set as fixed factors, and participants as random effect to account for repeated measurements. Besides, the compound symmetry, heterogeneous compound symmetry, and diagonal covariance structures were compared, and the Akaike's information criterion was used to select the covariance structure that best fit the data. The level of significance was set to $\alpha = 0.05$ for all comparisons. Post-hoc analysis with pair-wise comparison is only conducted in case of significant effect, adjusting for multiple comparisons using the Bonferroni correction. Cohen's d is also computed to report effect sizes [11], and the effect is considered *small*, *medium* or *large* if Cohen's d is about 0.2, 0.5 or 0.8 respectively. Also, the intra-class correlation (ICC) coefficient was used and is define as $ICC = variance_{wp}/(variance_{wp} + variance_{bp})$ [14] where wp stands for *within participant* and bp for *between participant*. It was used to explore the amount of variation explained by the clustering effect of participants. In other words, the lower is the value, the more alike are the participants and the more stable is a muscle across participants. Finally, any tasks that had a median value that was below the 75th percentile of noise level, were considered mostly about noise level.

3. Results

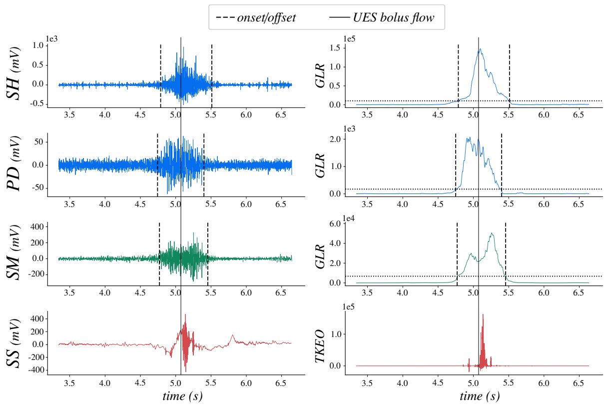


Figure 1: Raw signals example of saliva swallowing (left) and the corresponding processing for the onsets/offsets/UES bolus flow localization (right). SH: stylohyoid, PD: posterior digastric, SM: submental, SS: swallowing sound, UES: upper esophageal sphincter, GLR: generalized likelihood ratio, TKEO: Teager-Kaiser Energy Operator. All signals provide distinguishable events. The burst of higher amplitude and frequency in the ACC signal corresponds to the UES bolus flow, which defines the temporal limit for the detection. The full acquisition protocol is detailed in our previous work [17].

All 17 participants completed the full acquisition procedure. Few additional swallowings were performed when necessary, to ensure the required number of repetition in post-processing. Few swallowing could not be processed for feature extraction, because of bad signal quality, and were excluded. Finally, no non-swallowing tasks were excluded. This resulted in 89 saliva, 77 water, 81 thick, 81 solid, and 86 mastication acquisition, and 51 acquisition for each of the remaining non-swallowing tasks. A swallowing example is presented in Figure 1 and the temporal profile of each muscle is shown in Figure 2a. As for covariance structures, compound symmetry and diagonal systematically yielded the worst and won't be considered in the following.

3.1. *Muscles Amplitudes in Swallowing Tasks*

Mean rms-amplitude: a statistically significant main effect was observed for both the muscle type, $F(1, 399.816) = 835.728, p < 0.001$, and the bolus

Table 1: Muscles comparison: normalized mean and maximum RMS-amplitude of each muscle and for each bolus type, reported as mean (SD). Values are percentages referenced to the maximum swallowing RMS-amplitude from both SH and PD muscles, within each subject.

	mean RMS-amp			**max RMS-amp**		
	SH	PD	SM*	SH	PD	SM*
Saliva	35.860 (15.168)	15.043 (9.320)	15.984 (9.683)	61.505 (23.535)	28.773 (18.117)	27.680 (15.637)
Water	33.094 (10.931)	8.578 (5.390)	15.629 (9.760)	59.140 (20.273)	13.039 (9.132)	27.558 (17.805)
Thick	31.457 (10.713)	11.608 (7.653)	17.591 (12.253)	55.109 (19.222)	19.153 (11.583)	30.268 (19.219)
Solid	33.187 (10.990)	16.099 (8.741)	25.444 (21.333)	59.956 (20.810)	28.992 (15.460)	45.522 (34.480)

* Surface EMG (SM) cannot be directly compared to intramuscular EMG (SH and PD). SM is added as an indication.

Table 2: Tasks comparison: normalized mean and maximum RMS-amplitude of each muscle and for each task, reported as mean (SD). Values are percentages referenced to the maximum swallowing RMS-amplitude from the current channel, within each subject.

	mean RMS-amp			**max RMS-amp**		
	SH	PD	SM	SH	PD	SM
Saliva	40,822 (12,56)	34.311 (12.965)	28.027 (11.191)	70.402 (20.156)	63.103 (20.510)	50.279 (21.565)
Water	38,038 (10,04)	23.708 (12.073)	25.892 (9.153)	67.621 (17.819)	34.804 (17.973)	46.663 (17.083)
Thick	36,698 (10,58)	28.329 (11.995)	29.723 (8.411)	63.747 (17.202)	45.696 (15.956)	52.165 (14.277)
Solid	39,035 (11,02)	39.456 (16.350)	41.181 (10.186)	70.085 (19.595)	69.480 (23.122)	75.680 (18.905)
mastication	21,082 (9,766)	23.673 (12.770)	26.176 (10.121)	78.410 (42.975)	81.035 (64.106)	76.677 (56.807)
mouth opening	8,621 (5,366)	29.605 (21.463)	31.420 (21.751)	18.879 (12.381)	71.973 (58.153)	80.185 (68.813)
lateral jaw	7,605 (4,531)	18.101 (7.606)	20.059 (15.965)	17.217 (11.154)	38.194 (18.539)	48.967 (45.222)
lips purseing	6.569 (4,662)	12.689 (7.076)	23.124 (14.149)	13.282 (11.204)	31.026 (27.857)	56.284 (37.308)
teeth clenching	7.112 (4,688)	26.757 (36.787)	8.902 (5.306)	12.425 (7.885)	37.557 (78.678)	17.487 (11.100)
smiling	6.155 (4,502)	11.288 (8.071)	17.705 (11.262)	10.295 (7.376)	19.839 (13.994)	36.260 (26.611)
blowing	6,425 (4.061)	12.062 (6.090)	20.917 (12.073)	12.164 (9.097)	24.462 (12.316)	43.816 (30.346)
whistling	6.469 (4.148)	13.087 (7.417)	18.809 (9.835)	12.182 (7.835)	28.371 (18.335)	39.165 (19.971)
speaking	8,444 (6.546)	11.313 (7.506)	9.459 (4.155)	22.928 (17.158)	31.287 (23.859)	29.334 (12.143)
vocalizing	8.838 (6.676)	9.761 (7.548))	9.461 (4.222)	20.476 (13.224)	20.746 (14.941)	28.437 (22.100)
coughing	7.186 (4.924)	9.239 (5.472)	9.519 (7.756)	16.969 (10.169)	27.2111 (24.644)	25.771 (19.796)
vertical head	4,817 (2.871)	9.673 (7.028)	4.982 (2.394)	10.825 (7.023)	21.139 (15.183)	11.401 (6.684)
lateral head	4.811 (3.060)	10.203 (7.145)	3.297 (1.563)	9.097 (6.498)	21.649 (12.800)	7.150 (6.387)

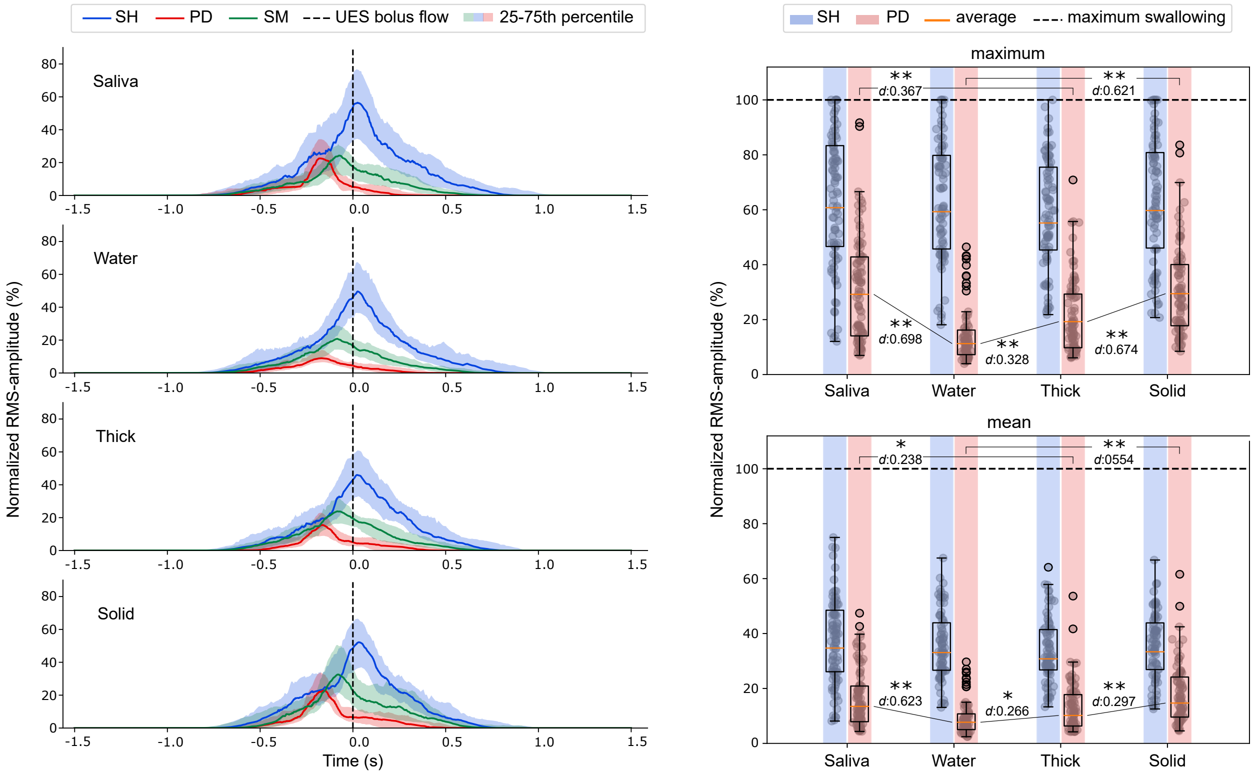
Table 3: Bolus main effect on normalized mean and maximum RMS-amplitude, based on estimated marginal means over SH and PD.

	mean RMS-amp		**max RMS-amp**	
	Mean diff	Effect size	Mean diff	Effect size
Saliva - water **	4.503	0.243	8.836	0.252
Saliva - Thick **	3.874	0.209	7.880	0.230
Saliva - solid	0.886	0.043	0.707	0.018
Water - thick	-0.629	0.042	0.956	0.031
Water - solid **	-3.616	0.209	8.129	0.235
Thick - solid *	-2.988	0.173	7.173	0.212

$*$: $p < 0.01$, $**$: $p < 0.001$, both for mean and max RMS-amp.

type, $F(3, 214.072) = 9.665, p < 0.001$. For muscle type, the posterior digastric had the lowest mean RMS-amplitude, $d = 1.128, 95\%$ CI $(1.051, 1.205)$. For bolus type, saliva and solid formed a first group, and water and thick formed a second group and had the lowest mean RMS-amplitude (Table 3). A statistically significant interaction was also observed for bolus and muscle, $F(3, 217.724) = 5.443, p = 0.001$. First, for each bolus (Figure 2b), the posterior digastric muscle was consistently lower than the stylohyoid muscle. Second, the stylohyoid muscle showed no mean RMS-amplitude differences between boluses. Third, the posterior digastric muscle showed substantial variations between boluses. While saliva and solid showed no statistically significant differences, thick was significantly lower, followed by water that was significantly lower than thick. The largest effect was between saliva and water, $p < 0.001, d = 0.623$.

Maximum rms-amplitude: a statistically significant main effect was observed for both the muscle type, $F(1, 450.22) = 736.425, p < 0.001$, and the bolus type, $F(3, 211.737) = 11.836, p < 0.001$. For muscle type, the lowest max RMS-amplitude was from the posterior digastric, $d = 1.06, 95\%$ CI $(0.983, 1.136)$. For bolus type, a first group was formed by saliva and solid, and a second group that had the lowest max RMS-amplitude was formed by water and thick (Table 3). Besides, bolus and muscle also showed a statistically significant interaction, $F(3, 208.263) = 6.572, p < 0.001$. First, for each bolus (Figure 2b), the stylohyoid muscle was consistently higher than the posterior digastric muscle. Second, no max RMS-amplitude differences between boluses was observed for the stylohyoid muscle. Third, substantial variations between boluses was observed for



(a) Muscles temporal profile: median (50th percentile) level of activity in each of the time point

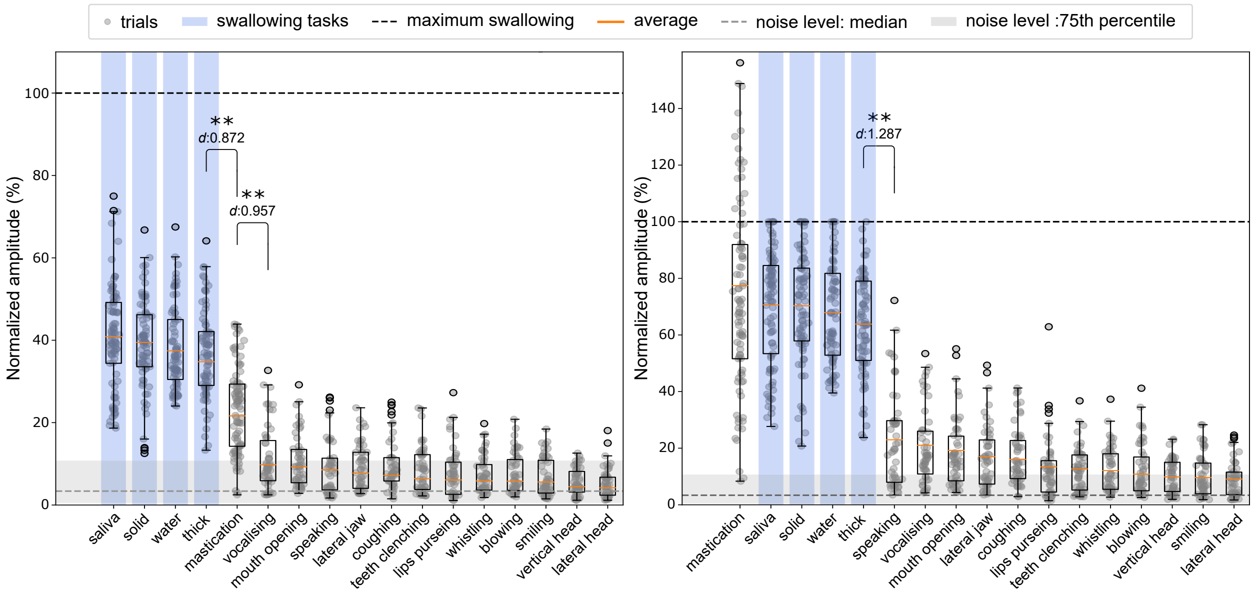
(b) Muscles maximum (top) and mean (bottom) level of activity in each of the trial

Figure 2: SH: stylohyoid, PD: posterior digastric, SM submental, UES: upper esophageal sphincter. *: $p < 0.05$, **: $p < 0.001$, d: Cohen's d. Each trials are normalized to the maximum swallowing RMS-amplitude from both SH and PD muscles, within each subject. SM is added as an indication. Since it has been measured with surface EMG, it cannot be directly compared to the intramuscular EMG used for PD and SH muscles. (a) each muscle provide a substantial activity before the UES bolus flow, with most of the PD muscle's activity that occurs before it. (b) PD muscle shows significantly lower RMS-amplitude than SH muscle. SH muscle shows no significant variations between bolus, while the PD muscle does.

the posterior digastric muscle. Indeed, saliva and solid showed no statistically significant differences but thick was significantly lower. Then, water follows with a significantly lower max RMS-amplitude than thick. Finally, the difference between saliva and water was the largest, $p < 0.001, d = 0.698$.

3.2. *Tasks Amplitudes per Muscle*

Mean RMS-amplitude: a statistically significant difference was observed between tasks for SH, $F(16, 109.487) = 161.861, p < 0.001$, PD, $F(16, 93.299) = 63.638, p < 0.001$, and SM, $F(16, 67.247) = 214.338, p < 0.001$. Note that in the following description, the referenced figures orders the tasks by their value from Table 2, from highest to smallest. For SH muscle (Figure 3a), all 4 swallowing tasks showed no statistically significant difference and have the highest mean RMS-amplitude. The minimum difference between swallowing and non-swallowing tasks was between thick and mastication, $p < 0.001, d = 0.872$. Mastication was, in turn, statistically significantly different from the remaining tasks, with a minimum difference with vocalizing, $p < 0.001, d = 0.957$. All the remaining tasks were non-swallowing tasks and were mostly about noise level. For PD muscle (Figure 4a), it showed no statistically significant difference between adjacent tasks, except between lateral jaw and whistling, $p = 0.039, d = 0.374$, that formed two separate groups. The second group was only composed of non-swallowing tasks and was mostly about noise level. For SM muscle (Figure 5a), most adjacent tasks were showing no statistically significant difference, except between smiling and coughing, $p < 0.001, d = 0.498$, teeth clenching and vertical head, $p < 0.001, d = 0.558$, and between vertical head and lateral head, $p = 0.002, d = 0.532$. Vertical head and lateral head tasks were about noise level. For ICC, it was 0.184 for SH, 0.247 for PD, and 0.266 for SM. This suggest that, for each muscle respectively, 18.4%, 24.7%, and 26.6% of



(a) Stylohyoid: mean RMS-amplitude per task

(b) Stylohyoid: maximum RMS-amplitude per task

Figure 3: Tasks comparison: mean and maximum RMS-amplitude within the stylohyoid muscle. The tasks are ordered by their corresponding value from highest to smaller, from Table 2.

the variability in mean RMS-amplitude occurs between participants.

Maximum rms-amplitude: a statistically significant difference was observed between tasks for SH, $F(16, 110.192) = 157.795, p < 0.001$, PD, $F(16, 94.878) = 46.936, p < 0.001$, and SM, $F(16, 90.766) = 141.708, p < 0.001$. Note that in the following description, the referenced figures orders the tasks by their value from Table 2, from highest to smallest. For SH muscle (Figure 3b), it showed that mastication, saliva, solid, water, and thick that had no statistically significant differences and had the highest max RMS-amplitude. The minimum difference between this first groups of tasks and the remaining (non-swallowing) tasks was between thick and speaking, $p < 0.001, d = 1.287$. Speaking had no statistically significant difference with vocalizing and the same goes for all the remaining adjacent tasks. Also, teeth clenching, whistling, blowing, vertical head, smiling, and lateral head were mostly about noise level. For PD muscle (Figure 4b), no statistically significant differences was shown between adjacent tasks, except between saliva and thick, $p < 0.001, d = 0.489$. Lateral Head and vocalizing were mostly about noise level. For SM muscle (Figure 5b), no statistically significant differences was shown between adjacent tasks, except between solid and lips purseing, $p = 0.039, d = 0.406$, teeth clenching and vertical head, $p < 0.001, d = 0.558$, and vertical head and lateral head $p < 0.036, d = 0.385$. Lateral head was mostly about noise level. For ICC, it was 0.111 for SH, 0.118 for PD, and 0.183 for SM. This suggest that, for each muscle respectively, 11.1%, 11.8%, and 18.3% of the variability in max RMS-amplitude occurs between participants.

4. Discussion

On the hypothesis that deep swallowing muscles could provide suitable data for a real-time detection of swallowing, which would enable de feasibility of an implantable active artificial larynx, this paper evaluated the recruitment pattern of the stylohyoid (SH) and the posterior digastric (PD) muscles through intramuscular EMG. The submental (SM) muscles were also measured with surface EMG, to provide a basis for comparison, and the swallowing sound measurement was used to compare the temporal evolution of each muscle to the moment the bolus starts to pass through the UES (UES bolus flow). The beginning of that event represents a drastic increase in the risk of aspiration, and we used it as a temporal limit for a swallowing to be detected. We found that the PD muscle mostly activated before the temporal limit while the SH muscle spanned the whole swallowing (Figure 2). Also, the SH muscle consistently had the highest mean and maximum RMS-amplitude, and only the PD muscle exhibited significant variations between bolus (Figure 2b). Besides,

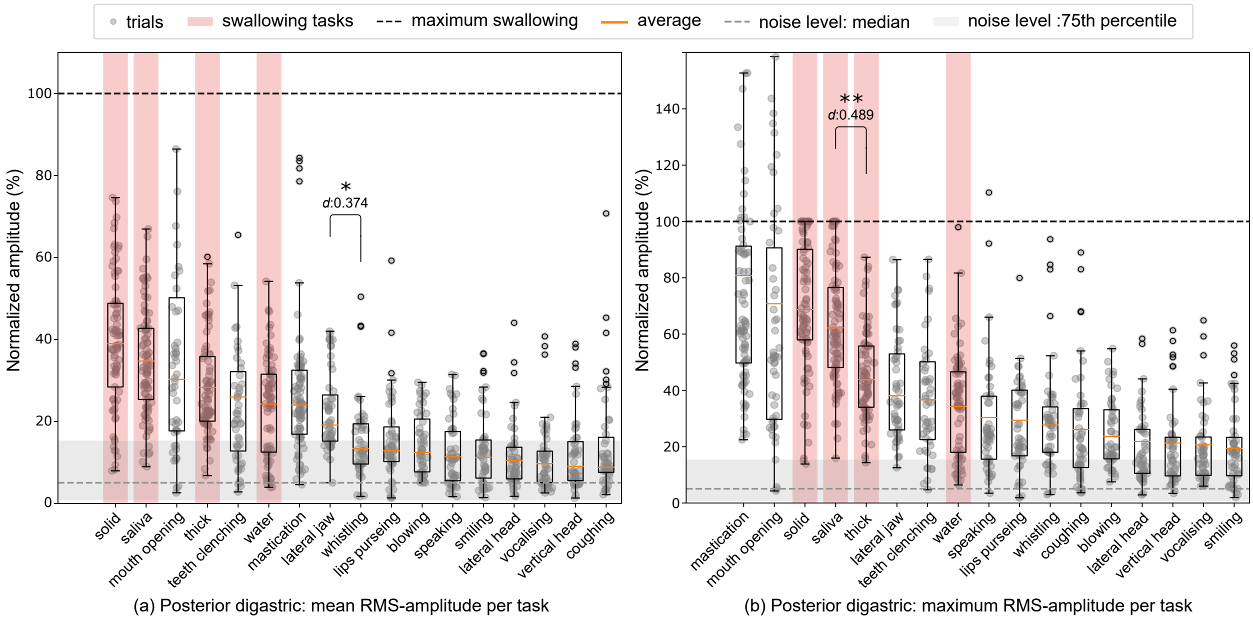
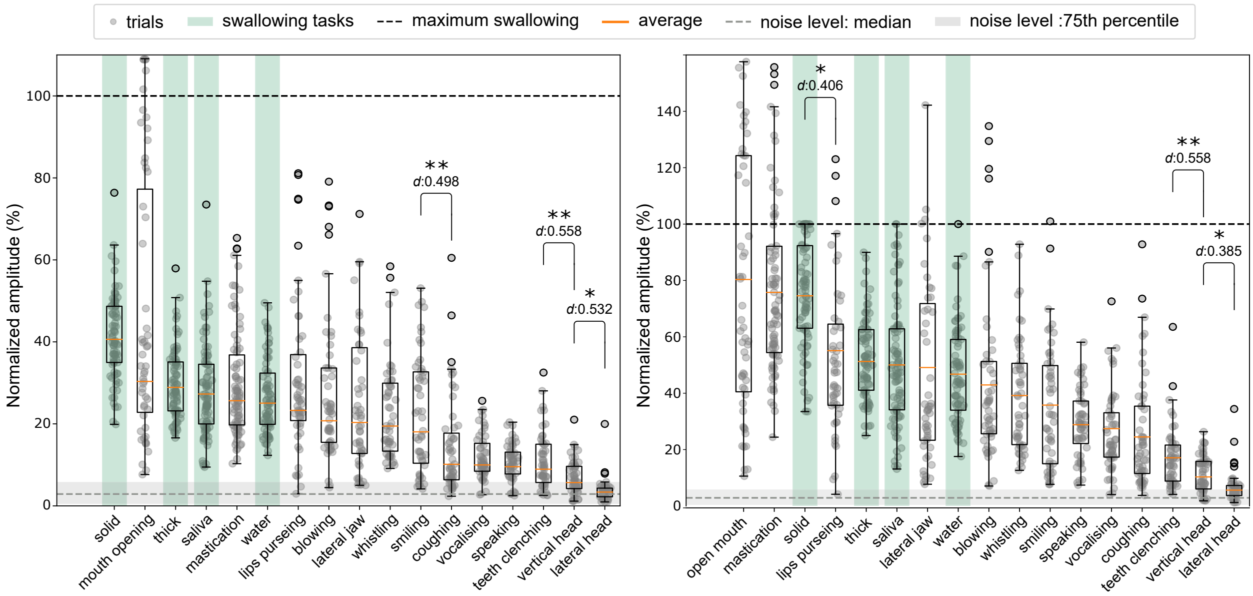


Figure 4: Tasks comparison: mean and maximum RMS-amplitude within the posterior digastric muscle. The tasks are ordered by their corresponding value from highest to smaller, from Table 2.

the SH muscle was particularly dedicated to the swallowing tasks, which the exception of mastication (Figure 3). Then, the PD muscle was not as dedicated as the SH muscle but still showed a predominant activation for the oral preparatory and pharyngeal stage of swallowing (Figure 4). In comparison, the SM muscles exhibited no clear tendency and were activated for almost all tasks (Figure 5). Finally, ICC from each channel suggests that a large variation in RMS-amplitude can be accounted for the participants, with the SH muscle being the most stable between participant.

So far, EMG-based approaches have shown limited performances with regard to our requirements for a swallowing to be detected as soon as possible with no detection failure. These approaches have primarily favored the easily measurable superficial muscles with surface EMG, but our results show that more thoroughly selected muscles measured with intramuscular EMG could provide improved swallowing data. The reported strategies have essentially focused on swallowing detection for a clinical practice [18] with no constraint of implantability, which has likely restricted the search to muscles that do not require invasive measurements. However, while deeper muscles probably do not systematically provide improved data, we argue that superficial muscles known to activate during swallowing, such as the SM muscles, should be carefully considered before inclusion. Indeed, while the SM muscles have long been considered the primary contributor to laryngeal elevation, recent evidences provided a more nuanced interpretation, showing the significant contribution that the SH and PD muscles also have [25–27]. Their synergistic contraction with other muscles has a great potential in hyoid bone elevation [26], which is considered to adopt a circular-like trajectory, starting upward and then forward [24]. So, our results confirm their importance and suggest that the short and early contraction of the PD muscle participates in the first elevation of the hyoid bone, while the SH muscle is engaged in its sustained elevation throughout the whole swallowing.

Thus, in the case of a real-time detection of swallowing for an implantable active artificial larynx following total laryngectomy, both the SH and PD muscles represent a suitable alternative and each has a clear advantage in terms of dedication and stability to swallowing, and earliness of activation, respectively. In addition, recent investigations on pigs [7] found comparable results for the SH muscle, where the authors investigated a large set of muscles with fine wire EMG. The electrodes were duplicated to evaluate the spatial recruitment of each muscle and they observed little variability in the temporal and spatial activity of the SH muscle. Besides, even though the peak activity of the SH muscle arises around the UES bolus flow (Figure 2a), its mean RMS-amplitude was still among the highest amplitude (Fig-



(a) Submental: mean RMS-amplitude per task

(b) Submental: maximum RMS-amplitude per task

Figure 5: Tasks comparison: mean and maximum RMS-amplitude within the submental muscles. The tasks are ordered by their corresponding value from highest to smaller, from Table 2.

ure 3) and could provide relevant data before it. The PD muscle would therefore introduce crucial temporal aspects (Figure 2a), potentially allowing for discrimination between swallowing activities before and after the UES bolus flow, which could significantly improve any algorithm's capacity to detect a swallowing around its beginning. Indeed, modern classifiers allow for complex combinations of channels [1, 6] that can extract relevant information from both muscles' relationships. And even though some tasks showed strong activation along with swallowing, such as mastication and open mouth, these algorithms are still able to produce complex representations of their content and maximize the differences. But whether or not this would lead to satisfactory results with regard to our requirement is still an open question and investigations are currently ongoing. In any case, given the perspective of this study, the SM muscles did not show particular advantages and should probably be considered last for the extraction of data representative of swallowing (Figure 5).

Concerning previous work on human, the literature provides very few studies that analyzed the PD and SH muscles in swallowing and non-swallowing tasks. Moreover, none allowed simultaneous and independent measurements so far. Therefore, our study fills that gap and we sought to fuse most of the tasks that were previously used, with additional ones, to provide a comprehensive comparison. With regard to the PD muscle, Widmalm et al. [31] investigated its activity on healthy participants with fine wire intramuscular EMG, following an insertion procedure they developed on cadavers. Mouth opening task generated the highest amplitude in comparison to every other tasks, while swallowing and lateral jaw movements tasks still markedly activated the PD muscle. Lateral head movements and teeth clenching were considered inactive or negligible. Besides, they also emphasized the specific pattern of swallowing, which was characterized by short and high bursts of activity, with no precision on the bolus type. So, our results mostly agreed with these observations, but with few discrepancies (Figure 4). First off, mouth opening was still among the tasks that generated the highest amplitude, but it was not significantly different than adjacent tasks and showed a large variation. Also, we found opposite results on teeth clenching, which markedly activated the PD muscle in our study and is actually in line with former results [20]. Regarding additional tasks, we found that mastication highly activates the PD muscle, which is likely to be partly explained by the various and complex jaw movements it involves. Besides, we confirm the short and high amplitude generated by swallowing tasks (Figure 2a) but also found significant differences between boluses (Figure 2b), which have not been previously compared.

But more recent investigations are also available on the SH and PD muscles, studied as a whole *STH-PD* complex. Specifically, Kurt et al. [12] reported the complex to be mainly mouth opener, while still being significantly activated during saliva swallowing and mastication. Smiling, whistling, and blowing were considered insignificant. These later tasks involved facial muscles, that are innervated by the facial nerve, just like the SH and PD muscles. Therefore, the authors investigated their relation in innervation and their differences in task recruitment, with electrical stimulation of various nerves. This allowed them to evaluate to what muscles the complex is more similar. They argue that the *STH-PD* complex has no relation to mimicry but similar functions to the submental muscles, even though being innervated by the facial nerves. Yet, the study we report in the current paper allows to differentiate the SH and PD muscles activity, and our findings suggest that the results of Kurt et al. [12] are more akin to the PD muscle. Indeed, we showed that the PD muscle has limited to negligible activity for the tasks that are not involved in the oral preparatory phase and the pharyngeal phase of swallowing, which are the bolus manipulation and breakdown initial step, and the actual transportation of the bolus down the pharynx, respectively. Conversely, marked to high activity were found for the tasks involved in both these phases (Figure 4). In comparison, the SH muscle showed a strong implication in swallowing and mastication, with little to negligible activity for the remaining tasks (Figure 3). Therefore, our results allow to refine the findings of Kurt et al. [12] but also to support their conclusion that the STH-PD complex tends to predominantly activate for swallowing.

So, while our results are in line with previous studies and showed promising outcomes, a few additional considerations emphasize the suitability of the SH and PD muscles. First off, they have the added benefit to be easily accessible during the total laryngectomy, which would not require further impairment of the neck during any sensor placement [18]. Also, while the surgery impairs various neck areas, the SH and PD muscles are only separated from the hyoid bone at the level of their insertion and left in place with no damage. Their contraction activity could then be accessed by a detection system. However, one could argue about the disrupted interaction between the sensory inputs and the complex sequencing of the muscles that occurs during swallowing, which could reduce their benefit. But post-surgery analysis of swallowing does not encourage this idea, as unaltered neck areas show little to no impairment in their function, especially the upper part of the neck where the SH and PD muscles are located [15, 18]. Finally, while the SH and PD muscles show promising results, the feasibility of a real-time detection of swallowing, to be run continuously, on a daily basis, in various conditions, and within an implantable system cannot be guaranteed on the sole basis of the current study. Especially, a final detection system should probably access data of various types to ensure more flexibility and robustness, but the current paper provides valuable muscles that can effectively contribute to such a system.

5. Conclusion

This paper evaluated the recruitment pattern of the stylohyoid and posterior digastric muscles to assess their suitability for the development of a real-time and implantable swallowing detection system, to enable the development of an implantable active artificial larynx. We found a strong implication of the stylohyoid toward swallowing and mastication, and the posterior digastric showed a clear tendency towards swallow-related tasks including oral preparation's tasks. Also, both muscles provided significant data at around the beginning of swallowing, before an increased risk of aspiration defined by the passage of the bolus through the UES. In comparison, the commonly used submental muscles showed no clear tendency and was activated for almost all of the 17 tasks considered. These elements make the stylohyoid and posterior digastric muscles a suitable choice for a real-time, implantable, and timely constrained detection algorithm. So, even though the submental muscles are easily accessible and known to activate during swallowing, other muscles can prove to be more reliable for swallowing identification, and muscles selection should be thoroughly considered. Finally, further investigations are ongoing to determine whether or not the remaining variations in both studied muscles can be addressed by modern detection algorithms.

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