Swallowing Onset Detection: Comparison of Endoscopy- and Accelerometry-Based Estimations

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Abstract. The swallowing process involves the coordinated activation of several muscles to ensure the transfer of nutrients from the mouth to the stomach. A proper segmentation of swallowing into its constituent phases is relevant to obtain a quantitative biomechanical and electrophysiological description of this sensorimotor task.

The aim of the study was to design a non-invasive measurement framework integrating electromyographic and acceleration measurements to detect the swallowing onset and event-related muscular symmetry indexes during the oropharyngeal phase. Therefore, the experimental protocol included: surface electromyography (sEMG), accelerometry and Fiberoptic Endoscopic Examination of Swallowing (FEES) as a clinical gold standard. A comparative study on five healthy subjects was performed in order to evaluate the results of the accelerometer-based segmentation with respect to those obtained through the gold standard.

Results showed that the accelerometer-based method consistently underestimated the swallowing onset (204 ± 192 ms, mean and standard deviation). Despite this bias towards the onset estimation, sEMG symmetry indexes computed from the accelerometer- and FEES-based onset exhibited comparable values.

These preliminary results suggest that the observed underestimation is not relevant in order to study symmetry differences in swallowing muscular activation. Thus, the acceleration measurements can provide a possible non-invasive alternative to the FEES-based segmentation for the extraction of event-related symmetry indexes during the oropharyngeal phase of swallowing.

Keywords: Swallowing muscles · Accelerometry · FEES · sEMG · Symmetry indexes

1   Introduction

Swallowing is a neuromuscular process consisting of a complex sequence of events aimed at moving nutrients from the mouth to the stomach passing through pharynx and esophagus [1]. This sensorimotor task includes the voluntary and reflexive activation of several muscles to produce a highly coordinated movement [2]. There are three swallowing phases: oral, pharyngeal and esophageal. The oral phase involves the voluntary activation of many muscles aimed at the manipulation and propulsion of the bolus. In this phase, the bolus volume and density are factors affecting the degree and timing of muscle activation. The pharyngeal phase includes the reflexive activation of two muscular groups: submental and infrahyoid. The former allows the beginning of the swallow by elevating the hyolaringeal complex in the antero-superior direction, the latter stabilizes the complex and depresses it at the end of the swallow [1]. The last esophageal phase is governed by the peristaltic wave pushing the bolus into the stomach [3].

An objective assessment of the swallowing process is clinically relevant not only to understand the pathophysiology of the swallowing impairment (referred to as dysphagia), but also to target its treatment and quantitatively follow its evolution [4]. The assessment of muscle activation is usually performed through the analysis of left-right symmetry in surface electromyographic (sEMG) activation patterns [5]. To the best of our knowledge, however, the symmetry indexes are computed without performing any temporal segmentation (i.e. considering both the oral and pharyngeal phases of the swallowing). This provides a global symmetry indication that includes the voluntary activation of the oral phase and may mask short-time asymmetries associated with the pharyngeal phase. An assessment of sEMG asymmetries would require the identification of the swallowing phases. Although the oral and pharyngeal phases are highly interrelated and the distinction between them is often unclear [6], specific events can be used to separate them. Their identification could be possible by using the Fiberoptic Endoscopic Examination of Swallowing (FEES), an invasive technique allowing to visualize the transit of the bolus in the oropharyngeal cavity. Although this technique is a clinical standard, due to its invasiveness, alternative approaches have been developed in recent years. Zoratto et al. [7], for instance, investigated the possibility of quantifying the hyolaringeal excursion through accelerometry to perform a biomechanical evaluation of swallowing.

The aim of this study was to design a measurement framework integrating electromyographic and acceleration measurements to: (i) provide a non-invasive method to identify the swallowing onset, (ii) compute event-related muscular symmetry indexes. To this end, a comparison between the accelerometer- and the FEES-based segmentation was initially performed.

2 Methods

2.1 Subjects

Five participants (three males and two females, age range: 31–42 years), with no history of swallowing impairments were recruited. The study was approved by the ethical committee of the Casa di Cura Privata del Policlinico di Milano (Local Ethical Committee: Milano Area 2; Resolution 718_2019; ID 1112). The study was conducted in accordance with the Declaration of Helsinki and written informed consent was obtained from all participants after having received detailed explanation of the study procedure.

2.2 Protocol

Experimental Setup. The proposed experimental setup involved: (i) accelerometry to achieve a temporal segmentation of the swallowing event based on hyolaringeal excursion, (ii) FEES technique to obtain reference values for the comparison with accelerometry results, (iii) sEMG detection to evaluate the electrical muscular activity (Fig. 1).
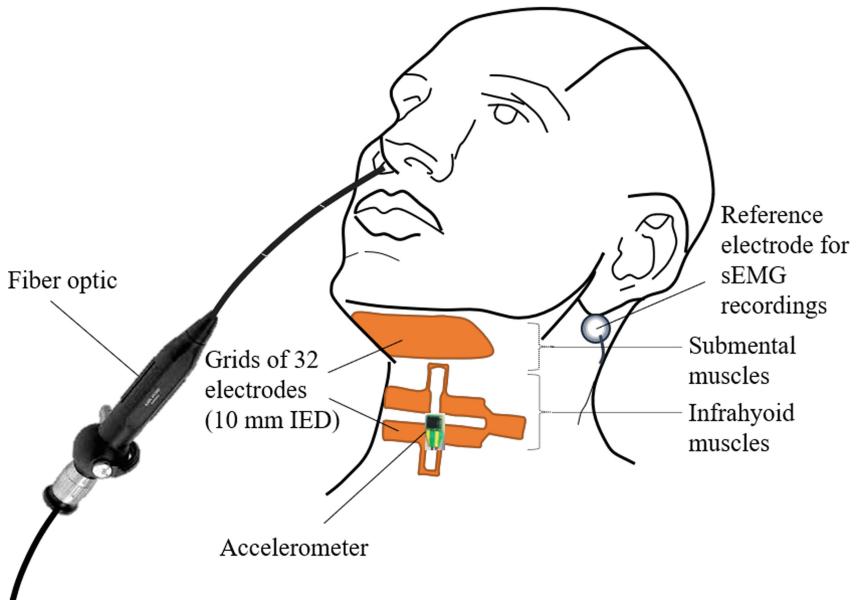

Fig. 1. Schematic representation of the experimental setup: accelerometry and endoscopy for the mechanical evaluation of swallowing; HD-sEMG systems for the electrophysiological evaluation of submental and infrahyoid muscles.

Accelerometer Recordings. Laryngeal elevation was monitored by an ultracompact linear tri-axis accelerometer (LIS344ALH, STMicroelectronics, Netherland) with a selected full scale of ± 2 g and 60 µg resolution, placed on the skin at the level of the cricothyroid space. Anatomical landmarks (Thyroid and Cricoid cartilages) were used to ensure the correct placement of the accelerometer. Only vibrations along the antero-posterior direction were considered, as suggested by previous studies [7–9]. Accelerometer signals were amplified, sampled at 2048 Hz and A/D converted with 16-bit resolution through a wireless general purpose acquisition system (DueBio, OT Bioelettronica, Torino, Italy).

Videoendoscopic Recordings. The clinical evaluation of swallowing was performed by introducing a flexible fiber optic (Optomic, Madrid, Spain), trans-nasally. Videos were acquired with a frame rate of 25 frames per second and synchronized with accelerometer and sEMG recordings. Finally, videoendoscopic images were stored in a personal computer for further analyses.

sEMG Recordings. Muscle activity was recorded through High-Density sEMG technique, using two grids of 32 electrodes (4 rows by 8 columns with an inter-electrode distance (IED) of 10 mm - LISiN, Politecnico di Torino, Torino, Italy). Electrodes grids were taped on the skin using a double-sided adhesive tape and placed above the region of interest after an appropriate skin preparation [10]. Both submental and infrahyoid muscular activities were recorded. The former muscular group was covered by a grid of electrodes positioned with the smaller symmetry axis lying on the sagittal plane of the subject. The latter was inspected through a custom-made cross-shaped grid of electrodes, specifically designed to allow the positioning of the accelerometer over the skin. Monopolar EMG signals were detected, conditioned (Bandwidth 10–500 Hz, Gain 46 dB), and sampled at 2048 Hz with 16-bit resolution through a miniaturized EMG acquisition system [11] (MEACS, LISiN, Politecnico di Torino, Turin, Italy and OT Bioelettronica, Turin, Italy).

Experimental Procedure. Subjects were comfortably seated on a chair and were required to keep the same position of the head during the entire protocol. Different swallowing tasks were performed: saliva (dry swallow), 3 ml and 10 ml of water, 3 ml and 10 ml of gelled water (Resource Aqua+, Nestlè, Switzerland). Three trials were performed for each task. Before starting the recording, subjects held the bolus in the oral cavity until the instruction to swallow given by the experimenter. An external synchronizing trigger was used to identify the start of the video FEES acquisition on both accelerometer and EMG signals.

2.3   Data Analysis

All recorded data were processed in Matlab (R2019b, The MathWorks Inc., MA, USA).

Accelerometry and Videoendoscopic Data. The swallowing onset based on hyo-laryngeal excursion was obtained through the analysis of accelerometer signals as shown in Fig. 2. A 4th order, zero-lag Butterworth low-pass filter with 4 Hz cutoff frequency was used to filter the raw accelerometer signals. The accelerometer-based

swallowing onset (t_{ACC}) was identified as the time instant corresponding to the first sample of the filtered signal crossing a specific threshold. The threshold was set at three standard deviations of the baseline, estimated over a 1.5 s epoch in the rest phase before the swallowing. A visual inspection was necessary to verify the correctness of the automatically-identified time onsets and to exclude spurious onsets due to noise or artifact-related threshold crossing.
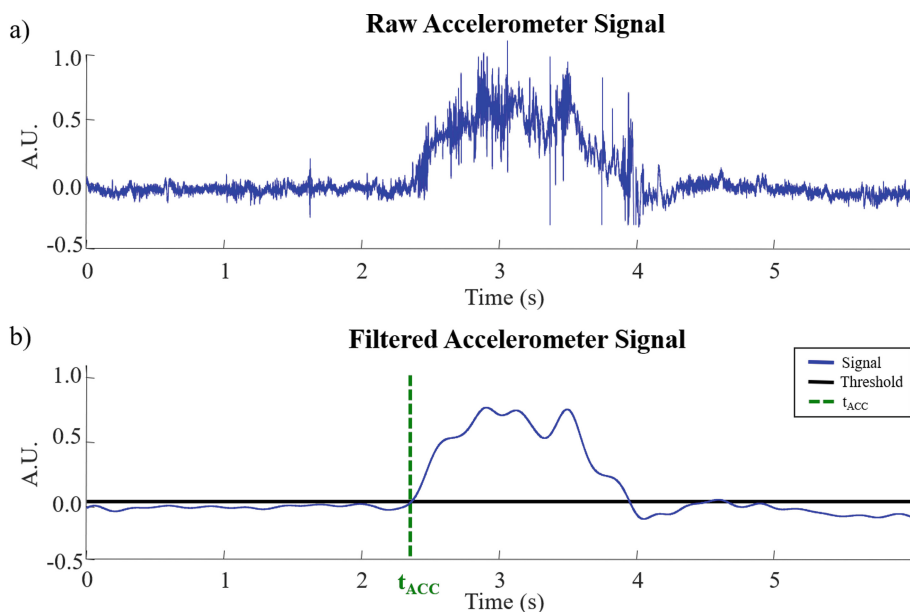
a) **Raw Accelerometer Signal**

b) **Filtered Accelerometer Signal**

Fig. 2. Raw (a) and filtered (b) accelerometer signal of a representative subject performing a single task (swallowing of 3 ml of water). The dashed green line shows the swallowing onset (t_{ACC}) identified using an amplitude threshold (black horizontal line) computed as 3 standard deviations of the baseline.

Video recordings from FEES were visually inspected through a frame by frame analysis. The identification of the swallowing onset (t_{FEES}) was performed by isolating the time instant relative to the first "white frame" (video whiteout), as shown in Fig. 3 [12]. The video whiteout frame is generally produced by the obliteration of the tip of the endoscope due to the pharyngeal restriction [13].

The effects of the method (accelerometer vs FEES) and of the type of bolus on the swallowing onset estimations were tested separately through a Friedman's ANOVA. The extracted swallowing onsets (t_{FEES} and t_{ACC}) were used to compare accelerometry and FEES methodologies. Statistical analyses were thus carried out on the time differences between t_{ACC} and t_{FEES}, for each trial.

Surface EMG Signals. Raw signals were digitally band-pass filtered in the 20-400 Hz frequency band (4th order, zero-lag, Butterworth filter). Bipolar signals were estimated from the HD-sEMG recordings for both submental and infrahyoid muscles. For each
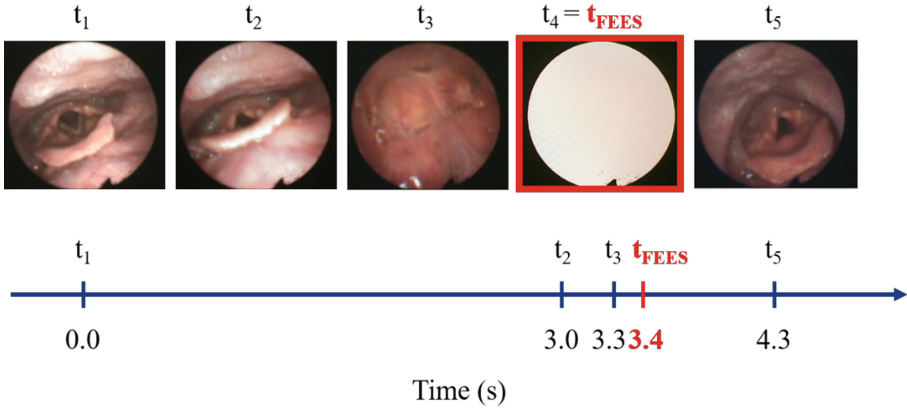
Fig. 3. FEES frames of interest of a representative subject during a single task (swallowing of 3 ml of water). From left to right: rest condition (t_1), retraction of the tongue (t_2), epiglottis tilting (t_3), whiteout (t_{FEES}), end of the swallow (t_5). The squared red frame refers to the swallowing onset extracted from the video recordings (t_{FEES}).

side of the grids (left and right with respect to the two halves) two monopolar signals were differentiated 2 cm apart to obtain one bipolar channel mimicking a conventional sEMG detection [14]. For each side of the grid, 8 pairs of electrodes could be used for this purpose. Among all, those located in the muscle region with the highest monopolar activity were selected.

The swallowing onsets identified through accelerometer and FEES (t_{ACC} and t_{FEES}) were used to segment sEMG signals. Specifically, an epoch of 1.5 s after each swallowing onset was considered and the signals of this epoch was used to compute the left/right symmetry index (LRI), according to the following formula of Eq. 1.

$$\text{LRI} = \left(1 - \frac{\sum \left|\text{RMS}_{\text{left}} - \text{RMS}_{\text{right}}\right|}{\sum \left(\text{RMS}_{\text{left}} + \text{RMS}_{\text{right}}\right)}\right) * 100 \tag{1}$$

LRI of all the trials were averaged separately for each subject. The effect of the segmentation method on the muscular activation symmetry evaluation (LRI) was analyzed using the Friedman's ANOVA.

3   Results

3.1   Swallowing Onset Estimation

Recruited subjects completed the requested tasks without reporting problems or excessive discomfort due to the FEES procedure. Whiteout video frames were clearly identified for each recording. As regards the accelerometer-based swallowing onset, 10 signals out of 75 acquisitions were excluded after the visual cross-checking of automatically detected onsets.

No statistically significant effect of the bolus type on the swallowing onset estimation resulted from the statistical analysis ($p > 0.05$). On the other hand, statistically significant differences ($p < 0.05$) were found between the swallowing onset identified with the two methods (accelerometry and FEES). Swallowing onsets identified through the accelerometer anticipates that identified by FEES of 204 ± 192 ms (mean and standard deviation across subjects, bolus types and trials), as shown in Fig. 4.
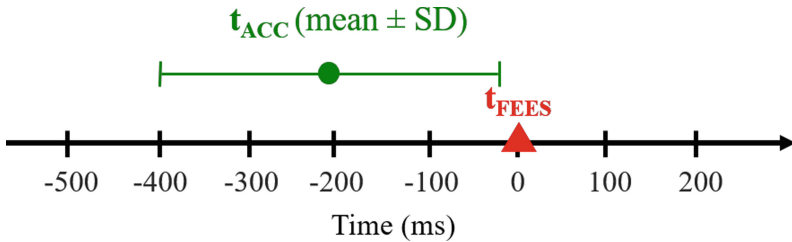

Fig. 4. Time differences between the accelerometer-based and the FEES-based swallowing onset (mean and standard deviation (SD) across subjects, bolus types and trials). Positive and negative values on time axis refer respectively to late and beforehand t_{ACC} with respect to t_{FEES} ($t = 0$ ms).

3.2 Muscular Activation Symmetry Evaluation

The symmetry indexes computed from bipolar sEMG signals are reported in Fig. 5. Averaged LRI across trials, separately for each subject, were always higher than 85% for both muscular regions under investigation. High LRI values were in line with expectations since participants were healthy subjects. Both muscular regions and segmentation methods showed a LRI value across all the participants of $93\% \pm 3\%$. Results showed no statistically significant differences ($p > 0.05$) between LRI values computed after segmenting the sEMG signals with the two methodologies: FEES or accelerometry.

4 Discussion

As compared to the clinical standard (FEES), accelerometry revealed a systematic bias towards an underestimation of the swallowing onset, regardless of the bolus type or volume. It is worthy to note that the time uncertainty, considering the possible delay among recording systems, the video frame rate and the electromechanical delay of anatomical structure movements is about dozens of milliseconds. As a result, the identified time instants could be shifted of this quantity on time axis. Nevertheless, since the LRI values were not statistically different when estimated with the two methodologies (accelerometry and FEES), the observed underestimation suggested to be not relevant in terms of sEMG-based symmetry estimation. These findings suggested the use of accelerometer traces as a possible and non-invasive method for the
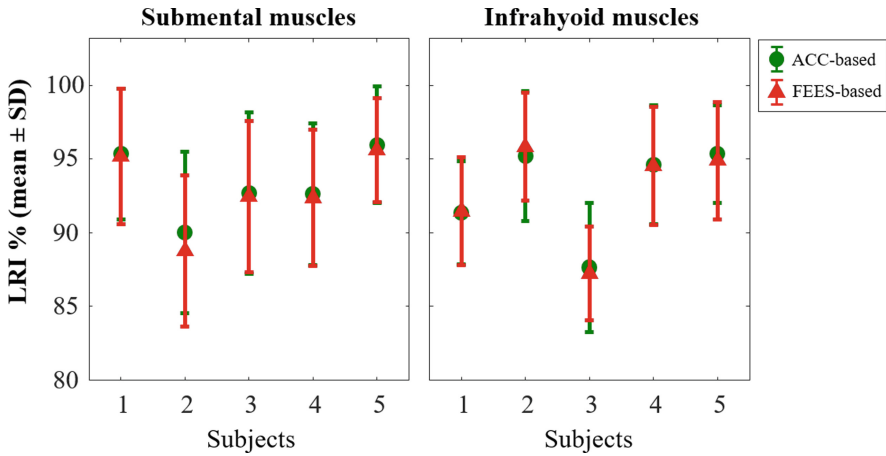
Fig. 5. Left/Right Indexes (LRI) computed on bipolar sEMG signals in a 1.5 s epoch starting from swallowing onset estimations based on FEES (red) and accelerometer (green). Data from both submental (left panel) and infrahyoid muscles (right panel) are reported in terms of mean and standard deviation (SD).

swallowing onset identification as far as measures are aimed at finding symmetry differences in swallowing muscular activation.

5   Conclusions

The main goal of this study was to design a non-invasive measurement framework integrating electromyographic and acceleration measurements to detect swallowing onset and muscular activation symmetry during the oropharyngeal phase of swallowing. This approach was sought to improve the global symmetry analysis used in literature.

An experimental protocol aimed at the validation of accelerometer-based swallowing segmentation was carried out. The comparison with the standard FEES-based segmentation showed that the accelerometer-based identification method consistently underestimates the swallowing onset. Nevertheless, this underestimation did not seem to affect the sEMG evaluation outcomes. Indeed, event-related symmetry indexes revealed to be comparable when performed with the two segmentation techniques. Although preliminary, these results suggest that acceleration measurements can provide a possible alternative to the invasive FEES-based segmentation for the extraction of event-related symmetry indexes during the oropharyngeal phase of swallowing.

Considering the positive methodological improvements on the assessment of the swallowing function on healthy subjects, the integrated experimental framework proposed in this study is ready for a validation on a larger sample population, including also pathological subjects.

Conflict of Interest. The authors report no conflicts of interest.

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