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## 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 transit 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. An experimental study on five healthy subjects was performed to compare the accelerometer-based swallowing segmentation with that obtained through the clinical standard (fiberoptic endoscopic examination of swallowing, FEES). The comparison was performed in terms of: (i) swallowing onset detection and (ii) event-related symmetry indexes computed on surface electromyograms (sEMG) during the oropharyngeal phase. Results from different swallowing tasks showed that the swallowing onset identified through the accelerometer preceded that identified by FEES of  $204 \pm 192$  ms (mean and standard deviation), regardless the type or volume of bolus. Despite the bias in onset estimation, sEMG symmetry indexes computed within a 1.5s epoch from the accelerometer- and FEES-based onset, exhibited comparable values. This result suggests that the observed underestimation was not relevant in order to study symmetry differences in swallowing muscular activation. Although preliminary, these results suggest that accelerometric measures 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 hyolaryngeal complex in the antero-superior direction, the latter depresses the mandible and the hyoid bone 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 swallowing impairment (referred to as dysphagia), but also to target its treatment and quantitatively follow its evolution [4]. In this regard, 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 EMG 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. This can be performed through the fiberoptic endoscopic examination of swallowing (FEES), an invasive technique that allows 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 hyolaryngeal excursion through accelerometry to perform a biomechanical evaluation of swallowing.

In this study we designed a non-invasive measurement framework integrating accelerometric and electromyographic measures to obtain event-related muscular symmetry indexes. The specific aim was the comparison of the accelerometer-based segmentation with that obtained through the clinical standard (FEES) in terms of (i) swallowing onset detection and (ii) muscular activation symmetry during the oropharyngeal phase of swallowing.

## 2. Methods

### 2.1 Subjects

Five participants (three males and two female, 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 receiving detailed explanation of the study procedure.

### 2.2 Protocol

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

*Accelerometer recordings.* Laryngeal elevation was monitored by an ultracompact linear tri-axis accelerometer with a selected full scale of  $\pm 2g$  (LIS344ALH, STMicroelectronics, Netherland) 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 2048Hz and A/D converted with 16-bit resolution through a wireless system (DueBio, OT Bioelettronica, Torino, Italy).

*Videoendoscopic recordings.* The clinical evaluation of swallowing was performed by introducing a flexible fiber optic, transnasally (Optomic, Madrid, Spain). The correct placement of the fiber optic was ensured by an expert speech pathologist. Videos were acquired synchronously with accelerometer and sEMG recordings with a frame rate of 25fps and stored in a personal computer for further analyses.

*sEMG recordings.* Muscle activity was recorded using high-density sEMG technique, i.e. with two grids of 32 electrodes (4 rows by 8 columns with an inter-electrode distance (IED) of 10mm - 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. Electromyographic signals were detected in monopolar derivation (referred to a reference electrode placed behind the ear), amplified, band-pass filtered (10–500 Hz), sampled at 2048Hz and A/D converted with 16-bit resolution through a miniaturized EMG acquisition system (MEACS, LISiN, Politecnico di Torino, Turin, Italy [11] ).

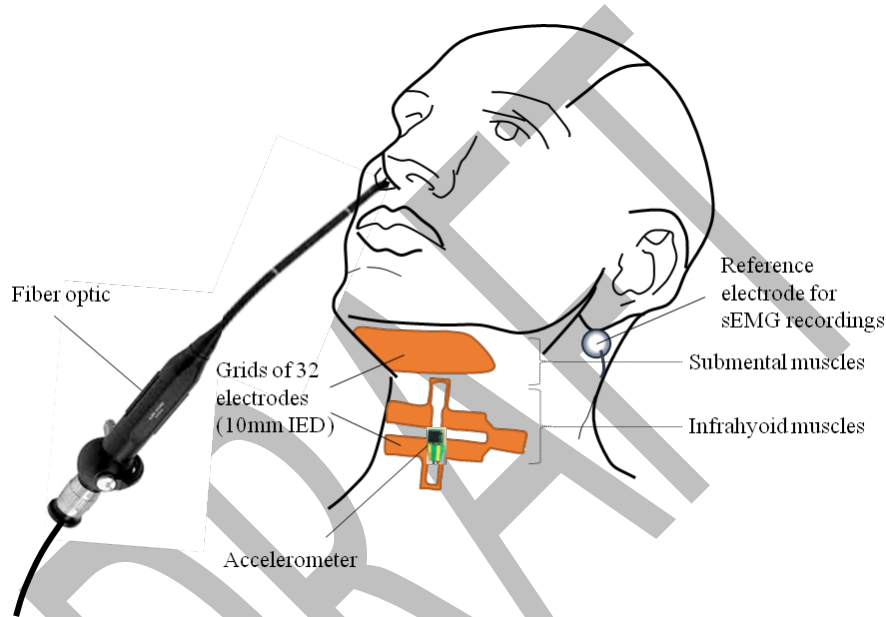


Figure 1 – Schematic representation of the proposed experimental setup: accelerometry and endoscopy for the mechanical evaluation of swallowing and HD-sEMG systems for the electrophysiological evaluation of submental and infrahyoid muscles.

**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), 3ml and 10ml of water, 3ml and 10ml 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 and the end of the video FEES acquisition on 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 hyolaryngeal excursion was obtained through the analysis of accelerometer signals as shown in Figure 2. After low pass filtering the raw signal at 4Hz (4<sup>th</sup> order, zero-lag Butterworth filter), a threshold was set at three standard deviations of the baseline estimated over a 1.5s epoch in the rest phase before the swallowing. The accelerometer-based swallowing onset ( $t_{ACC}$ ) was identified as the time instant corresponding to the first sample of the filtered signal crossing the threshold. 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.

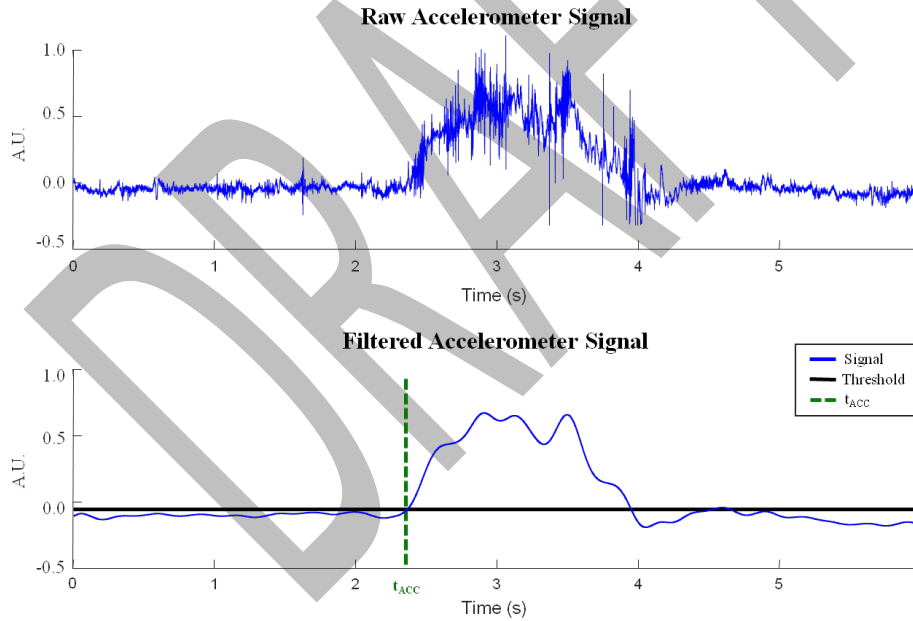


Figure 2 – Accelerometer signal of a representative subject performing a single task (swallowing of 3ml of water). The dashed green line shows the swallowing onset ( $t_{ACC}$ ) identified using an amplitude threshold of 3 standard deviations of the baseline (black horizontal line).

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

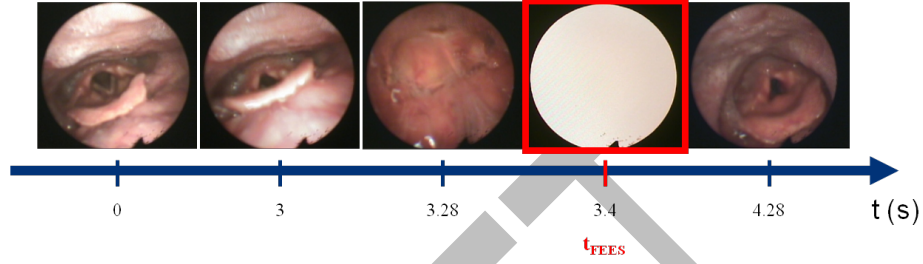


Figure 3 – FEES frames of interest of a representative subject during a single task (swallowing of 3 ml of water). From left to right: rest condition, retraction of the tongue, epiglottis tilting, whiteout, end of the swallow. The squared red frame refers to the swallowing onset extracted from the video recordings ( $t_{FEES}$ ).

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. To this end, statistical analyses were carried out on the time differences between  $t_{ACC}$  and  $t_{FEES}$ , for each trial.

**Surface EMG signals.** Raw signals were band-pass filtered in the 20-400Hz frequency band (4th order, zero-lag, Butterworth filter). For quantitative analyses, bipolar signals were estimated from the HD-sEMG recordings for both submental and infrahyoid muscles. For each side of the grids (left and right with respect to the two halves) we differentiated two of monopolar signals 2cm 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, we selected those located in the muscle region with the highest monopolar activity.

The swallowing onsets identified through accelerometer and FEES ( $t_{ACC}$  and  $t_{FEES}$ ) were used to segment sEMG signals. Specifically, an epoch of 1.5s 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 LRI =

$$\left(1 - \frac{\sum |RMS_{left} - RMS_{right}|}{\sum (RMS_{left} + RMS_{right})}\right) * 100 \quad \text{Eq. 1.}$$



$$LRI = \left( 1 - \frac{\sum |RMS_{left} - RMS_{right}|}{\sum (RMS_{left} + RMS_{right})} \right) * 100 \quad \text{Eq. 1}$$

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 all the requested tasks without reporting problems or excessive discomfort due to FEES procedures. The quality of the acquired videos was sufficient to clearly identify the whiteout frame in every recording. As regards the accelerometer-based swallowing onset, only the 10 signals out of 75 acquisitions were excluded after the visual cross-checking of automatically detected onsets.

Statistical analysis showed no statistically significant effect of the bolus type on the swallowing onset estimation. On the other hand, statistically significant differences ( $p < 0.05$ ) were found between the swallowing onset identified with the two methods (accelerometry and FEES). In fact, the swallowing onset identified through the accelerometer preceded that identified by FEES of  $204 \pm 192$  ms (mean and standard deviation across subjects, bolus type and trials), Figure 4.

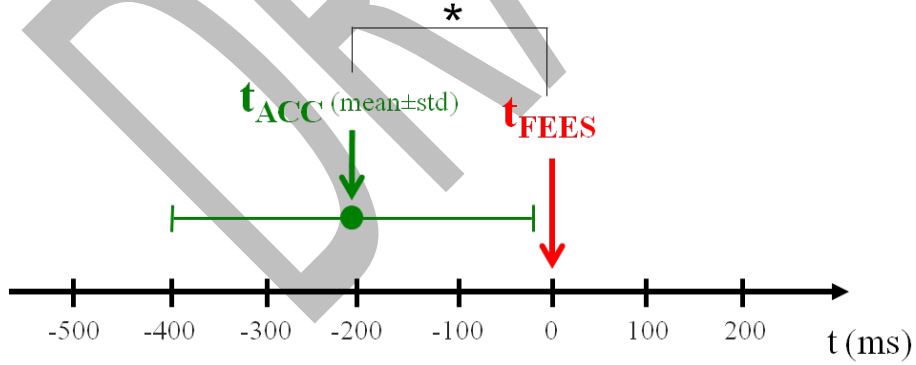


Figure 4 – Time differences between the accelerometer-based and the FEES-based swallowing onset. Positive and negative values refer respectively to late and beforehand  $t_{ACC}$  with respect to  $t_{FEES}$  ( $t = 0$ ms). Mean and standard deviation refer to all trials and bolus for all subjects (\*  $p < 0.05$ ).

### 3.2 Muscular activation symmetry evaluation

Results of symmetry indexes of bipolar EMG signals are reported in Figure 5. Averaged LRI across trials, separately for each subject, were always higher than 85% for both muscular regions under investigation. The mean LRI value across all the participants was of  $93 \pm 3\%$  (mean $\pm$ std) for both muscular regions and segmentation methods. 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.

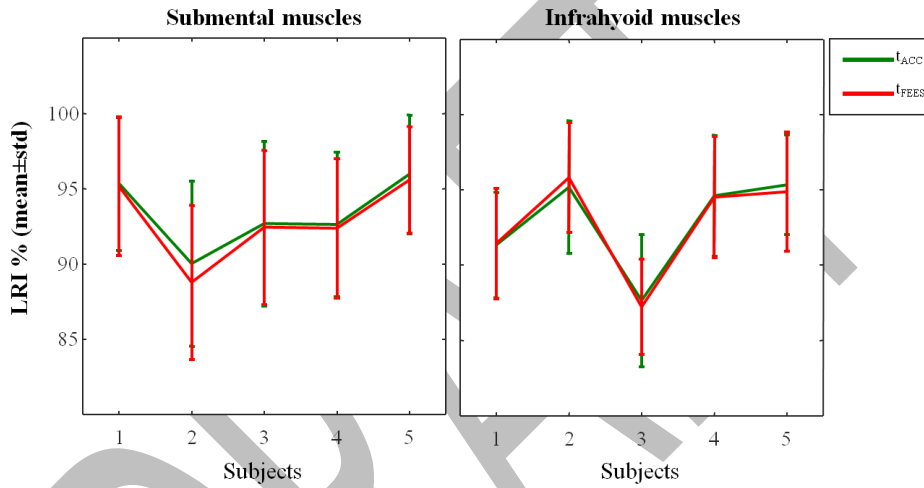


Figure 5 – Left/Right Indexes (LRI) computed on bipolar sEMG signals in a 1.5s epoch starting from swallowing onset estimations based on FEES (red traces) and accelerometer (green traces). Data from submental (left panel) and infrahyoid muscles (right panel) are reported.

### 4. Discussion

As compared to the clinical standard (FEES), accelerometry revealed a systematic bias towards an underestimation of the swallowing onset, regardless to 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 ms. 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 is suggested to be not relevant in terms of sEMG-based symmetry estimation. As a result, this findings

suggested the use of accelerometer traces as a possible method for the swallowing onset identification as far as measures are aimed at finding symmetry differences in swallowing muscular activation.

Finally, high LRI values were in line with expectations since participants were healthy subjects. Event-related LRI were not compared to global ones (i.e. including portions of the signal before the hyolaryngeal excursion) since the standardization of the oral phase of our experimental protocol.

## 5. Conclusions

The main goal of this study was to design an experimental setup integrating biomechanical and electrophysiological measures to: (i) provide an alternative, non-invasive method to identify the swallowing onset, (ii) compute event-related symmetry indexes. 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 accelerometry consistently underestimated 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 accelerometric measures 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.

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