An Accurate Fiducial Marker for Aligning EMG signals with Swallow Onset*

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Abstract— **Swallowing involves the precise coordination of a large number of muscles. This coordination can be quantified non-invasively by electromyographic (EMG) time-series analysis of swallowing events. The temporal alignment of swallow events is critical for defining coordination patterns. Here, a new framework was developed to use the acoustic signal associated with the opening of the Eustachian tube as a fiducial marker to align EMG signals with swallowing. To investigate its accuracy, manometry, audio from the Eustachian tube, and EMG were simultaneously recorded from two participants while performing different swallowing maneuvers. Eustachian tube opening consistently occurred alongside EMG activations and within 0.025 ± 0.022 s of the gold standard manometry-determined functional swallowing onset. A comparison with two traditional EMG alignment methods based on the integrated and rectified EMG signals was then performed over eight participants. Discrepancies of between 0.2 to 0.3 s were found between the initiation of swallowing and the onset or peak EMG activity. Eustachian tube opening served as a more accurate fiducial marker for temporal data alignment, compared to the traditional EMG alignment methods that were based on EMG parameters.**

Clinical Relevance— **The proposed method will allow EMG recordings to be directly associated with the functional onset of swallowing. This provides a more accurate foundation for time-series analysis of muscle coordination and thus the identification of EMG biomarkers associated with healthy and dysphagic swallowing.**

I. Introduction

Swallowing is a critical function that requires precise, sequential, neuromuscular processes involving the contraction of over 32 pairs of muscles and the activation of 6 cranial nerves [1]. It is not only responsible for passing food and liquid through the oral and pharyngeal passage into the esophagus but also ensures the airways remain unobstructed. Swallowing is regulated by a central pattern generator located in the brainstem. This generator manages sensory reflexes and motor control synergies to ensure a coordinated response [2], [3]. Motor control synergies represent a common neuromuscular activation pattern for a specific task, forming temporary, flexible coupling between muscles groups [4]. However, the timing and force of the muscle activation may vary due to cortical modulation of the response [5]. Failure to effectively coordinate the muscular contractions involved in swallowing leads to a disorder known as dysphagia. Dysphagia can occur as a result of a variety of disorders such as stroke, neurodegenerative diseases, or head and neck cancers [6]. Dysphagia is associated with serious health outcomes and is the primary reason behind the development of aspiration pneumonia, a common cause of death in these patient groups. The prevalence of dysphagia ranges between 12-13% in hospitalized patients and significantly increases healthcare utilization and cost [7], [8]. Current diagnostic methods utilize invasive tools, such as fluoroscopy and manometry, which focus on the biomechanics of swallowing, neglecting the underlying electrophysiology responsible for muscle activation and coordination. This limited scope has led to a lack of understanding of the pathophysiologic mechanisms underlying dysphagic swallowing [9], [10].

Electromyography (EMG) can non-invasively assess neuromuscular activations using electrodes located on the surface of the skin. Recent studies have demonstrated the ability to identify unique spatial activation patterns when swallowing different bolus volumes, bolus viscosities, and maneuvers [11]–[13]. Further investigation into the temporal development of these spatial patterns can provide insights into the neuromuscular coordination of both healthy and dysphagic swallowing [14]–[16]. An important consideration when performing EMG coordination analysis is the alignment of the EMG signals with the different task events or between recording sessions. This process involves identifying a specific point within the rectified, integrated myoelectrical signal, such as the onset, offset, or peak activation time, of each muscle and aligning the events from that fiducial point [17]–[20].

An alternative approach to align EMG swallow events is to identify a functional time point that relates the EMG response to the functional swallowing sequence. A recent study used an accelerometer placed on the hyoid bone to time-lock EMG swallow events to the onset of hyolaryngeal excursion [21]. Another potential time-locking event is the opening of the Eustachian tube. The contraction of the tensor veli palatini muscle, which tenses the soft palate, has been linked with the onset of the pharyngeal phase of swallowing [22]. This muscle contraction results in the opening of the Eustachian tube, allowing air pressure to equalize, and creates a distinctive acoustic signature [23], [24].

In this study, a framework was established that incorporates the acoustic signal produced by the opening of the Eustachian tube as a fiducial marker for swallow onset. To assess accuracy, simultaneous recordings of manometry, Eustachian tube audio, and EMG were performed across different swallowing maneuvers. The study also investigated temporal

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differences between swallow onset and two traditional data alignment methods based on the integrated rectified EMG.

II. Methods

A. Experimental Protocol

Ethical approval was provided by the Auckland Health Research Ethics Committee and Human Ethics Committee of the University of Canterbury. All participants provided informed consent.

Eight healthy participants (6 females, 2 males 24-38 years) with no swallowing or neuromuscular disorders were recruited. All participants performed simultaneous EMG and Eustachian tube audio recordings. Additionally, two of the participants had simultaneous manometry recordings, which was subsequently followed up with x-ray imaging to estimate the location of the manometry sensors. After positioning of all recording devices, a 3–4 minute adjustment period was allowed before triggering all devices to record simultaneously. Participants performed a series of standardized swallowing tasks (saliva swallow, non-effortful 10 ml water swallow, and effortful 10 ml water swallow). Each task was repeated 5 times.

B. Manometry Data

A subset of participants (n=2) had simultaneous manometry recordings. The manometry recording was performed using a PowerLab C digital data acquisition device (ADInstruments, New Zealand) at a frequency of 1,000 Hz. Before removal of the manometry catheter, a sagittal x-ray was taken to confirm the location of the sensors.

The functional onset of swallowing was determined from the manometry recording by a speech-language pathologist and treated as the gold standard. This involved identifying the time point at which one of the pressure sensors located in the oropharynx (sensors 1-3) showed a value above baseline.

C. Eustachian Tube Data

A lavalier microphone (RØDE, California, USA) was placed in the concha of the ear and directed inwards towards the ear canal. The recording was performed using audacity audio editor V3.2.3 (Muse Group, Limassol, Cyprus) at a frequency of 16 kHz.

The functional fiducial marker was determined based on the acoustic signal produced by the opening of the Eustachian tube. This corresponds to a large sharp deflection in the audio data. The event was isolated using a Hampel filter (parameters: $k = 0.5$ s and $\sigma = 20$, where k is the time on either side of the assessment window and σ is the number of median absolute deviations by which a sample must differ to be classified as an outlier).

D. EMG Data

The methods used for this EMG recording have been presented in a preliminary study [13]. In brief, at the start of each recording session, the surface of the skin was cleaned with alcohol. Flexible printed circuit EMG arrays were prepared with a thin layer of conductive paste (Ten20, Aurora, USA). The electrode arrays were then placed carefully onto

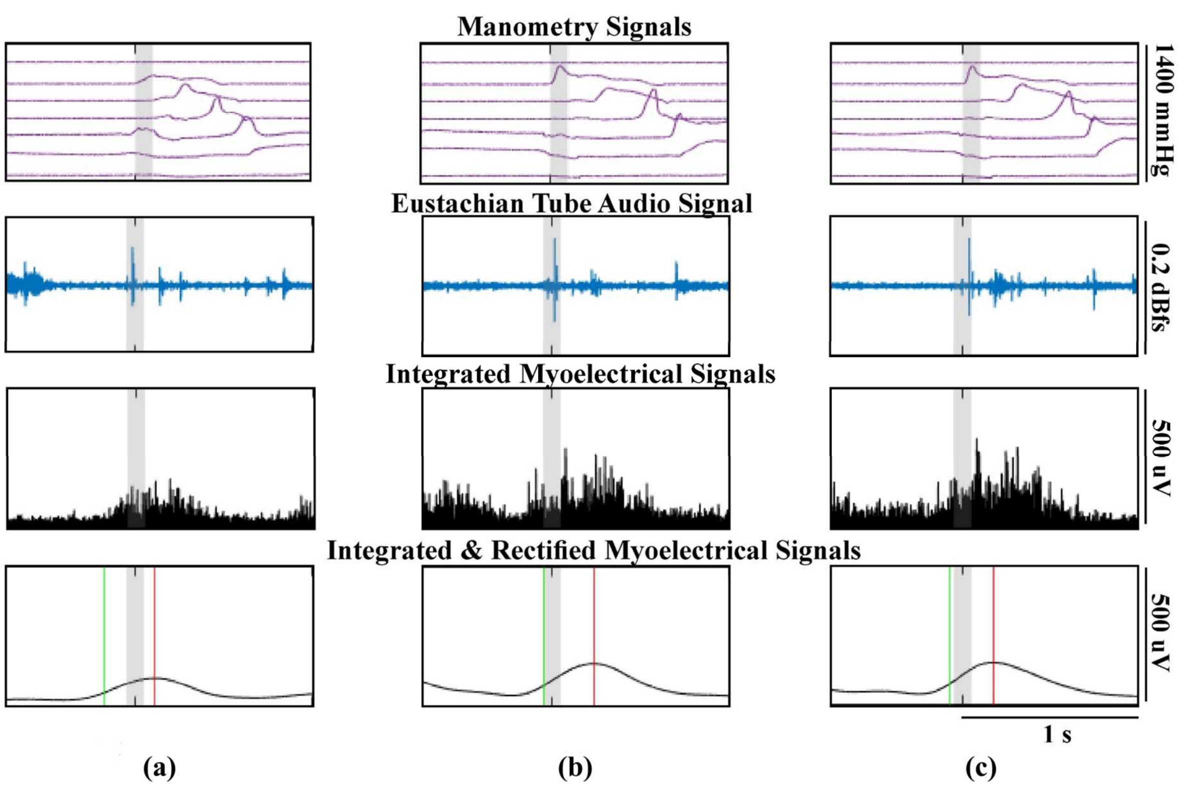

Figure 1. Simultaneously recorded manometry, Eustachian tube audio and EMG across three different swallowing maneuvers: (a) saliva, (b) non-effortful 10 ml water and (c) effortful 10 ml water. The grey highlight represents the functional onset of swallow determined from the manometric pressure profile. The EMG signals have been integrated, rectified and enveloped (black). The onset of EMG activity (green line) and peak EMG activity (red line) have been identified.

the neck and submental region of the participant and held in place with an adhesive film dressing (Tegaderm, 3M, USA). Reference electrodes were placed on the collar bone and the back of the neck. The electrodes were connected to an ActiveTwo bioamplifer (BioSemi, the Netherlands). Monopolar recordings were acquired at a sampling frequency of 2,048 Hz.

The recorded EMG signals were bandpass filtered using a zero-phase digital filter (4th order Butterworth filter with cut-off frequencies of 40 and 400 Hz), and then integrated and rectified. The correlation of two EMG parameters (onset of EMG activity and peak EMG activity) to swallowing onset as determined by manometry and Eustachian tube opening were investigated. EMG parameters were calculated from the integrated, rectified, and enveloped signal with a 15 ms interval separation. The peak amplitude determined the maximum EMG activity, while the onset of EMG activity was defined as when the signal crossed a threshold of 50% of the peak signal.

III. Results

The sound associated with the opening of the Eustachian tube was evident through a large instantaneous deflection in the audio signal and a duration of approximately 25 ms (see Fig. 1), in agreement with previously recorded responses [23]. The Hampel filter effectively identified the timing of the opening of the Eustachian tube in the audio signal. The synchronicity between the opening of the Eustachian tube, the onset of manometric pressure, and EMG activation was 100%, accurately predicting swallowing onset in the 30 recorded events (Fig. 1). The mean difference between the two measures, calculated across 30 swallow events, showed that the Eustachian tube opening occurred almost simultaneously with the functional onset of swallowing, with 0.025 ± 0.022 s difference (Table 1).

Using the Eustachian tube opening as a fiducial marker for swallowing onset, the correlation with the traditional EMG based alignment parameters was investigated. Fig. 1 illustrates the extraction of the onset EMG activity and maximum EMG activity from the integrated rectified EMG signal. The timing of EMG parameters varied with respect to the onset of swallowing across different participants (Fig. 2). Between participants, the onset of EMG activity and peak EMG activity was variable (standard deviations of 0.247 s and 0.331 s respectively) Fig. 3 shows the variability of three types of swallows from participants 4 and 7 which had lower variability.

IV. Discussion

A novel approach to align EMG data was introduced in this study, to link the acoustic signal of the Eustachian tube

TABLE I. Consistency of Eustacian Tube Openning to Swallow Onset Determined by Manometry

Swallow Task	*Mean Difference (s)*
Saliva	0.015 ± 0.011
Non-effortful	0.027 ± 0.023
Effortful	0.032 ± 0.028
All	0.025 ± 0.022

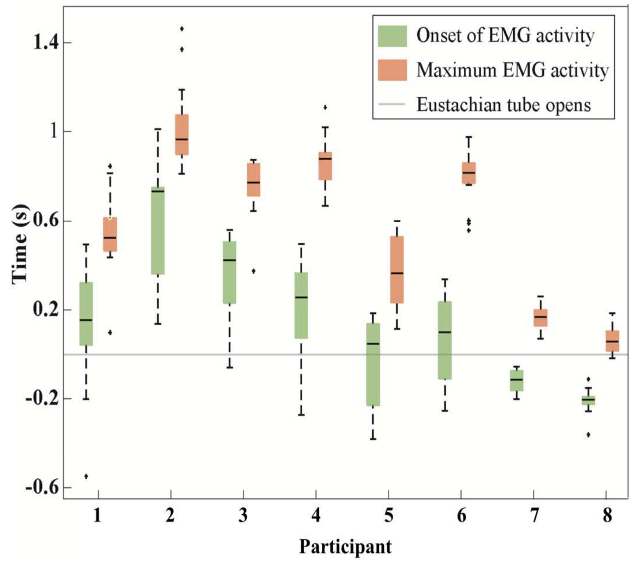

Figure 2. Temporal difference of the EMG parameters to the onset of swallowing across participants for EMG activation onset (green) and EMG peak activity (red), each for 15 swallows.

opening measured in the ear to the onset of oropharyngeal swallowing. The findings showed that the Eustachian tube opening consistently occurred within 0.025 ± 0.022 s of the gold standard functional swallow onset, as determined by manometry, and is more accurate than prior non-invasive functional measures. A previous study used the time-locking event of hyoid bone elevation, as measured by an accelerometer and endoscope, and found that accelerometer readings consistently underestimated swallow onset by 0.204 ± 0.192 s [21].

Traditional EMG data alignment methods can suffer from temporal fluctuations that would affect the accuracy of the coordination analysis. Relying on EMG parameters, such as the onset of activity or maximum activity, to align the EMG swallow events can lead to discrepancies between 0.2-0.3 s within a time–series analysis of swallowing coordination. This can be attributed to differences in the thickness of

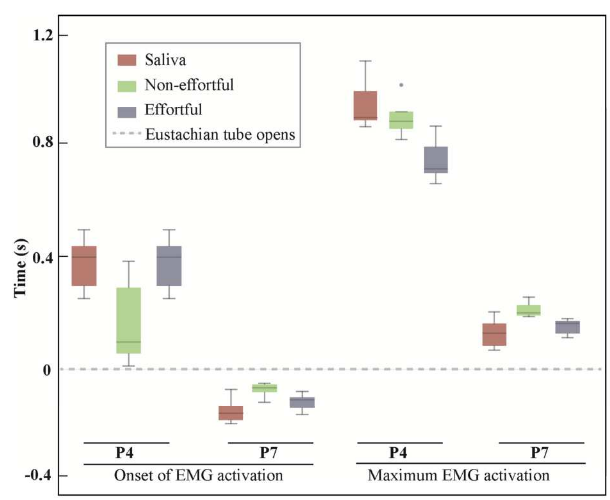

Figure 3. Temporal difference of EMG parameters across swallow maneuvers (saliva, non-effortful 10 ml and effortful 10 ml) for 5 repeated swallow events from participant 4 and 7.

subcutaneous tissue layers across participants, which impact the amplitude and frequency bandwidth of EMG signals [25].

The ingestion of boluses with varied sizes, consistencies, and temperatures can also result in changes to the EMG swallowing response and adjustments in the amplitude and duration of the EMG signal [5]. This can be seen in the EMG signals in Fig. 1, where the effortful and non-effortful 10 ml swallow EMG responses show more muscular pre-activations, causing a shift in the EMG parameters and a greater spread of the muscle activations. This highlights the importance of data alignment in EMG coordination studies. Using EMG parameters to align and compare functional changes is not an accurate method for analyzing EMG coordination patterns between swallowing tasks or individuals.

In the future, aligning EMG data using the Eustachian tube opening may allow for more accurate swallow coordination analysis and help bridge the gap between EMG coordination patterns and functional swallowing patterns associated with healthy and disordered coordination. However, this study is limited by its sample size, and future studies on more participants are required.

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