Submental MechanoMyoGraphy (MMG) to characterize the swallowing signature

Adrien Mialland[1], Bienvenu Kinsiklounon[1], Guibin Tian[1], Camille Noûs[2], Agnès Bonvilain[1]
[1] Univ. Grenoble Alpes, CNRS, Grenoble INP*, Gipsa-lab, 38000 Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP*, laboratoire Cogitamus, 38000 Grenoble, France
* Institute of Engineering and Management Univ. Grenoble Alpes
agnes.bonvilain@univ-grenoble-alpes.fr

Abstract

Objectives: currently, only tracheostomy is available for people who have had a total laryngectomy, and no solution exist for people with swallowing disorders. Yet, muscles activity produces measurable vibrations, known as MechanoMyoGraphy (MMG), and is regarded as the mechanical counterpart of electromyography. Besides, we have already shown the possibility to control an artificial urinary sphincter with the MMG signal measured in the abdomen [1]. Therefore, the goal of this long-term work is to use this method to allow to predict a deglutition and command an active artificial larynx. So, the present paper analyses the MMG signal acquired in the submental area, which contains anterior suprahyoid (SH) muscles and the floor of the tongue. Indeed, one function of SH muscles is to support the tongue, which in turn is highly involved in the propulsive phase of swallowing and follow a relatively stereotypical pattern. Lastly, the localization of the bolus is of prime interest to defines the ultimate and available detection times. Thus, the swallowing sound was also recorded on the throat, as it has been shown to allow to locate the bolus.
Material and methods: we recorded MMG and swallowing sound signals with tow accelerometers in submental area and the throat of 39 people. Each participant completed water, saliva and solid food swallow, seated on a chair, and was asked to remain still. Four benchmarks were place in the signals to differentiate swallowing phases and signal's components and timings. We also looked for any influence of age, height and weight in corresponding timings.
Results: a characteristic pattern has been registered in most of recordings. The benchmarks allowed to display a minimum average available time of 0.324 sec (0.125 - 0.786). Age and weight had a noticeable impact on the timings.
Conclusion: these findings hint toward the possible detection of swallowing via MMG signals from submental area.

Keywords: mechanomyography, swallowing signal, active implantable medical device, submental

I.1 - Introduction

We swallow an average of thousand times a day to carry saliva, water and any other liquid or solid food in the stomach. During a swallowing, the bolus passes from the mouth to the stomach in different stages, following the intervention of more than thirty pairs of muscles. The crucial step, performed by the larynx, is to direct the bowl to the esophagus and close the trachea so that nothing enters in the lungs.
The primary role of the larynx is to ensure the passage of the air to the lungs during breathing, and to close automatically during swallowing. It is also generator of sounds allowing the phonation. The larynx is a highly complex mechanism under mostly neurological control. When the larynx is removed or damaged (in cases of cancer), the failure of laryngeal functions has never been properly resolved. Its disruption leads to food residues in the lungs, which is a source of significant morbidity and mortality. However, many people are affected by these laryngeal dysfunctions, many millions per year worldwide.

To overcome this problem, the only technological solutions proposed aim to restore the voice. There is currently no technology worldwide focusing on the resolution of swallowing disorders.

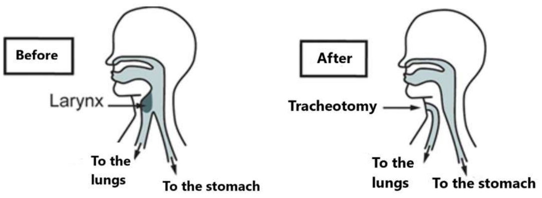
Our long-term work aim is to restore swallowing in the most faithful way as possible, as we are going to present in this paper.

I.2 - Current practices

In the practice of surgery, different solutions exist according in the patient's cases. It is necessary to distinguish the cases where the larynx is dysfunctional and the cases where the larynx is totally removed (total laryngectomy) [2]. These two cases are described below.

In the case of damaged larynx (in cancer, neurodegenerative diseases or stroke), swallowing functions are impaired, which could lead to food aspiration (part of the food bowl enters in the lungs). The only solution in these cases is gastric tube (nasally or through a digestive stoma). Nevertheless, not all patients are eligible for these solutions, and these practices are not risk-free, and complicated to manage on a daily basis (because it requires the intervention of a nurse). Therefore, when a gastric tube cannot be placed, the patient can be fed intravenously or intramuscularly. But these are not long-term solutions; this is why it is a source of significant mortality.

In the field of total laryngectomy (in case of cancer), the solution is the tracheostomy. It consists of the creation of two distinct ways, one for feeding, and one for breathing (Fig. 1 (a) and (b)). In this case, the patient loses his nasal functions (humidification, filtration, warming and olfaction), but the phonation can be restored [2]. Tracheostomy also leads to the inability to lift a load, to breathe, eat and talk normally and thus lead a normal life.



(a) (b)

Figure 1: Diagram of the larynx before (a) and after total laryngectomy and tracheostomy (b)

The state of the art in the field of artificial larynx mentions only a very few successful works. Many patents have emerged for several decades. These patents mention the loss of only one of the functions of the larynx, the phonation. Unfortunately, a very large majority of these patents have remained unfulfilled.

Note that it is starting to be a question of carrying out transplants [3], but these are still only one-off tests, so we will not mention them more.

The most significant work today around the world is the work that was carried out by the team of Pr Debry from Strasbourg (France), who developed laryngeal implants in biocompatible porous titanium, irremovable, replacing laryngeal cartilages [4]. This part has been associated with a removable biofunctional part replacing the sphincteric functions of the larynx. Experiments were conducted on patients, for whom the removable part was tested only under medical supervision. This device, exclusively mechanical, requires the maintenance of tracheostomy, because food residues are found inside the lungs after swallowing during in vivo tests [5].

I.3 - Previous works

In previous work, we have developed an implantable active artificial urinary sphincter. This device uses the abdominal MechanoMyoGraphy (MMG) signal to measure the activity of the patient and adapt the pressure of the sphincter on the urethra. It allows a better adaptation to the patient, but also avoid the disadvantages of the passive urinary sphincter [1,6]. This work led to the creation of the start-up UroMems [7].

The results of this work allowed us to explore the MechanoMyoGraphy (MMG) signal of the tongue from the submental area, in order to allow the development of an implantable active artificial larynx and to overcome the disadvantages of the passive artificial larynx developed by the Strasbourg team [4,5]. We have worked with them in a part of this study.

In a first step, we studied the physiological and anatomical (Fig. 2) aspect of the laryngeal region, in order to determine the most suitable position for MMG measures of the swallowing. In addition, swallowing should be detected as early as possible, in order to allow time for the artificial larynx closure, before the passage of the bolus.

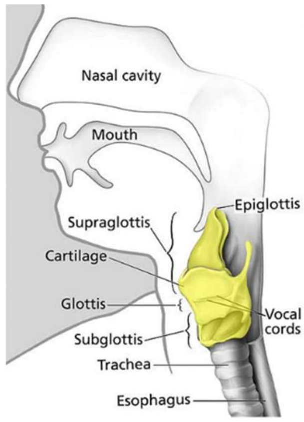


Figure 2: Sagittal section of the laryngeal region

The larynx [8] is located in the anterior compartment of the neck, suspended from the hyoid bone, and spanning between C3 and C6 (Fig. 2). It continuous inferiorly with the trachea, and opens superiorly into the laryngeal part of the pharynx. It is covered anteriorly by the infrahyoid muscles, and laterally by the lobes of the thyroid gland. The larynx is also closely related to the major blood vessels of neck, which ascend laterally to it. Posterior to the larynx is the oesophagus.

The larynx is formed by a cartilaginous skeleton, which is held together by ligaments and membranes. The laryngeal muscles act to move the components of the larynx for phonation and breathing.
Anatomically, the internal cavity of the larynx can be divided into three sections:

- Supraglottis – From the inferior surface of the epiglottis to the vestibular folds (false vocal cords),
- Glottis – Contains vocal cords,
- Subglottis – From inferior border of the glottis to the inferior border of the cricoid cartilage.

In the process of swallowing, the larynx plays an important role in the direction of food into the esophagus. Apart from a swallowing, the epiglottis resides in an upright position just anterior to the lumen of the larynx. In this position, it allows air to pass freely through the larynx during inhalation and exhalation. When food or liquid happens to enter the oropharynx, a mostly reflex swallow response is initiated. The larynx moves superiorly and anteriorly which opens the Upper Esophageal Sphincter (UES) and causes the posterior inversion of the epiglottis over the laryngeal lumen, which seals the airways. In addition, the vocal folds close as well to definitely block the swallowed substances from entering the larynx. The food is then safely guided to the esophagus by the pharyngeal constrictor muscles following the tail of the food bowl. Finally, the whole structure gets back to its resting position.
In normal conditions, the food enters the oropharynx when the tongue propel the bolus posteriorly. This propulsion movement follows the erratic motion of the tongue during chewing and is thought to follow a typical pattern [9]. At first, the tongue slightly goes downward and adopts a wave-like shape to guide the bolus posteriorly. Then, when the bolus reaches the base of the tongue, a rapid elevation of the tongue toward the soft palate propel the bolus in the oropharynx and close the nasopharynx. Initiating the reflex response we described.

Our preliminary investigation thus focuses on the submental area. Not only it could make the propelling movement of the tongue measurable in the early swallowing stage, but it also contains several supra-hyoid muscles that could enrich the recorded MMG signal. Indeed, MMG measures the vibrations produced by muscles during contractions and has widely been used as an electromyographic (EMG) mechanical counterpart [10].

A practical study was then carried out. The objective was to verify the theoretical conclusions, but also to compare different swallowing on different healthy subjects, to determine if the swallowing signal has a specific signature, and this, whatever the type of food swallowed (water, saliva, solid food).
This practical study was conducted on three healthy subjects (one woman and two men, people of the laboratory), performing several swallowing of water and solid food (because swallowing of water is most quick than solid food), in the sitting position. During the MMG recordings, we asked the subjects to cough, sing, speak and chew, always with the aim of verifying the specific signature of the swallowing in a recording signal.

To conduct this study, in addition to the submental MMG signal, we placed a second accelerometer on the neck, near the trachea under the cricoid cartilage (Fig. 3), to measure the swallowing sound [11,12]. Indeed, it has been shown that, using either an accelerometer or a microphone, it is possible to record the sound produced by the bolus with a reproducible pattern [11]. Three main components have latter been shown to contain information about the location of the bolus and the anatomical part involved in the swallowing [11].

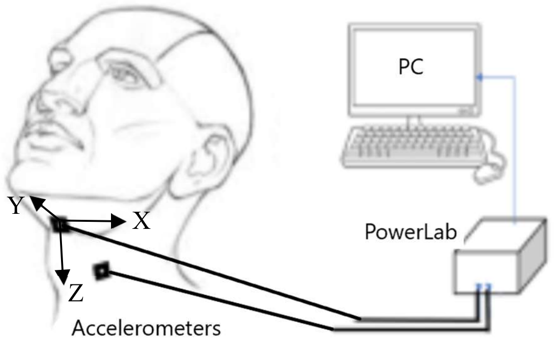


Figure 3: Schematic of the experimental setup

The three axis accelerometers are connected to the PowerLab which is an analogic to digital converter. The signals from the PowerLab are recorded on a PC via LabChart software as shown on figure 3. The three axis accelerometers are MMA7361 [13].
PowerLab is a reliable product, offering a simple and flexible solution for almost all types of physiological data acquisition. It is capable of recording at speeds of up to 400,000 samples per second continuously, and is compatible with instruments, signal conditioners, and transducers of many leading brands [14].
LabChart data analysis software [15] creates a platform for all of recording devices, allowing to acquire biological signals from multiple sources

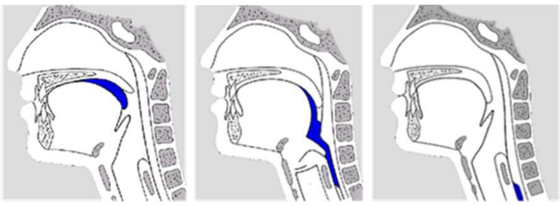
simultaneously and apply advanced calculations and plots as your experiment unfolds.

Swallowing is a phenomenon that can be decomposed into three phases like shown on figure 4 [16].

The first one is the **preparatory/oral phase**. The food is placed in the mouth, chewed and coated with saliva, thanks to the complex movements of the tongue. Then, the tongue propels the food posteriorly into the oropharynx, which initiate the second phase.

The second one is the **pharyngeal phase**. The airways close, man realize an apnea. The alimentary bolus is pushed towards the esophagus by the pharyngeal peristalsis. The UES opens. The third phase begins.

The third one is the **esophageal phase**. Esophageal peristalsis advances food to the stomach.



(a) (b) (c)

Figure 4: Diagram of the three phases of the swallowing: (a) oral phase, (b) pharyngeal phase, (c) esophageal phase

The recorded signals enabled us to highlight (Fig. 5 and 6):

- the signature of swallowing. Which does not look like any other signal recorded during the experiment.
- the different phases of swallowing in this signature.
- the timing of the different phases for swallowing of water and solid food.

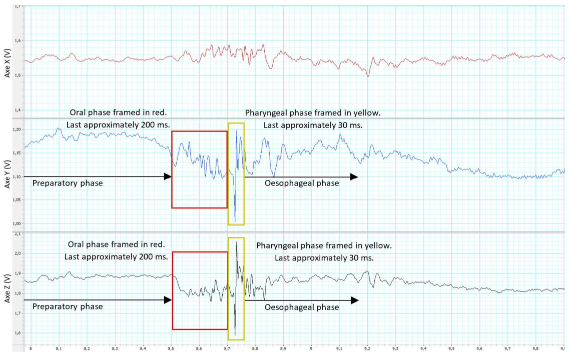


Figure 5: Signature of swallowing of water on the three axis with the different phases and their timing. On the vertical axis, the amplitude of the signal is done in volt, and on the horizontal axis, the time is done in second.

Indeed, the recorded signal closest to swallowing is that of coughing. The other like singing, speaking or chewing are very different. In the coughing signal, there is also three phases (inspiratory phase, blocking phase, expulsive phase), but they have a very different timing like shown on figure 7. In addition, the expected propelling pattern of the tongue is mostly visible in axis Z and Y (Fig. 5 and 6) as it mainly involves anterior-posterior and superior-inferior movement of the tongue to direct the bolus into the pharynx [9]. Therefore, leaving X axis with little to no activity, except residual noise and movements.

Thus, this preliminary work allowed us to show the specificity of the MMG signal of swallowing from the submental area, compared to other event such as coughing, and its association with the coarsely estimated swallowing phases and timings. These conclusions could be obtained regardless of the bolus type and density. However, it needs to be refined with further investigation. Therefore, we increased the study with more subjects within the framework of a more precise protocol that we will present below.

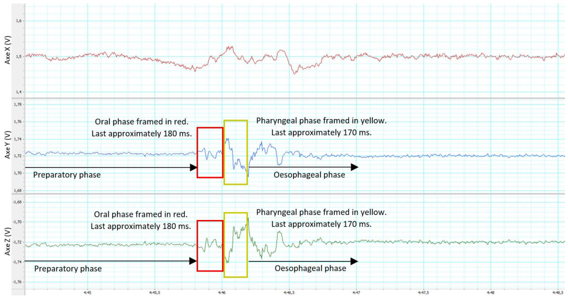


Figure 6: Signature of swallowing of solid food on the three axis with the different phases and their timing. On the vertical axis, the amplitude of the signal is done in volt, and on the horizontal axis, the time is done in second.

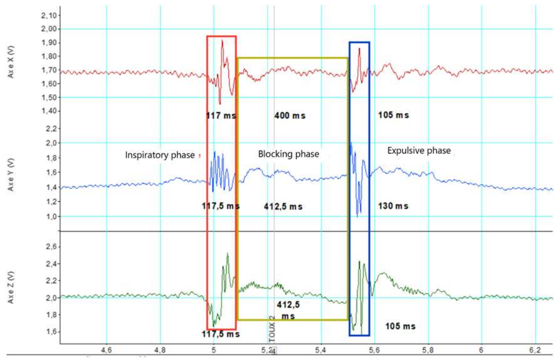


Figure 7: Signature of coughing on the three axis with the different phases and their timing. On the vertical axis, the amplitude of the signal is done in volt, and on the horizontal axis, the time is done in second.

II – Material and Methods

II.1 – Context of the measures

The following recordings were made on healthy volunteers; all adults (more than eighteen years old). We recorded MMG signals on 39 people (20 women and 19 men) of different age and body size to observe the swallowing signals. These three parameters (gender, age and Body Mass Index (BMI)) seemed to us the most likely to generate variations on the swallowing signature. A protocol and an observation book were written in order to unify the records.

II.2 – Volunteers

Each volunteer gives his informed consent to participate in the study, by signing a document specifying the terms of the study. Each volunteer will be anonymous and will thus be assigned a number. Each volunteer gave his age (45 ± 10), height (172.2 ± 8.4) and weight (70.2 ± 13.6), to allow us to calculate their BMI. Tow accelerometer are placed according to figure 3: a first one is placed on the submental area to measure MMG signal, and a second one on the neck near the trachea under the cricoid cartilage, to measure the swallowing sound and locate the position of the bolus [11, 12]. Figure 8 and 9 picture a subject wearing those sensors. In a first time, tests were done so that the volunteer could understand what was asked of him. The person was asked to sit comfortably and not move too much. In a second time, a small training was carried out, in order to be well prepared for the exercises, which consisted of nine swallowing of saliva, fifteen swallowing of water and five swallowing of solid food.

Figure 8: photo of a volunteer during the exercise

Figure 9: photo of the registered signals

II.3 – Equipment

The recordings were carried out with a PowerLab [14], associated with the LabChart software [15], like in our first experiments (Fig. 9).
The acquisition of tongue movements during swallowing is done using the ADXL327 [17] analog accelerometer mounted on an evaluation board. The accelerometer has three axis with a sensitivity of 420 mV/g and a noise spectral density of 250 µg / √Hz. The bandwidth of the X and Y axis is 1600 Hz and 550 Hz on the Z axis. The evaluation board is connected to the acquisition box by a cable at the end of which are three 8-way DIN connectors. This accelerometer is placed directly on the submental area, with the wires facing forward, the Z axis pointing down.
Acquisition of the signal of swallowing is done using a one-axis pulse transducer TN1012/ST of AD Instrument [18] (Fig. 8) and having a bandwidth of 1600 Hz. Although microphone seems to provide a better signal-to-noise (SNR) ratio, accelerometer has also proven their reliability in swallowing sound acquisition [12]. Which will be sufficient to delineate the swallowing patterns acquired with the first accelerometer. In addition, the vast majority of the frequency band of the sound components fall within the chosen accelerometer band [19]. It is thus sufficient to acquire information related to swallowing sound. This accelerometer is placed on the edge of the trachea, directly under the cricoid.
The PowerLab uses channels 1 to 3 for the X, Y and Z axis of swallowing respectively. Axis 4 is used for the signals of swallowing. Each PowerLab channel is low pass filtered with a cutoff frequency of 2 KHz. The signal is then sampled at 4 KHz to avoid aliasing.

II.4 – Signal processing and data analysis

With each swallowing, the volunteer is asked to sit upright and still in a chair. Three types of swallowing are performed: saliva, water and a consistent food (milk bread). For water and consistent food, volunteer is also asked to sip or bite a comfortable amount, to represent the inherent subject variability. The bowl is then prepared in the mouth with a chewing phase if necessary. A time of about two seconds without moving is observed and then swallowing is performed. A second time of two seconds without moving is respected after swallowing. This makes it possible to obtain swallowing patterns as much as possible devoid of body movement to better characterize them. The behavior of each MMG axis and swallowing sound signal is described and shown (Fig. 10) below.

The X axis (first graph on fig. 10): transverse axis, it is of little interest since the movements of the tongue are almost nonexistent in this direction. The movements captured are mostly related to the body than to the tongue.

The Y axis (second graph on fig. 10): It captures the anterior-posterior movements of the tongue when propelling the bowl. However, a specific pattern could be found but it was hardly repeatable, and exhibit a wide variability among subjects. Surely due to the position of the sensor, the nature of the food bolus and the variation of swallowing among people.

The Z axis (third graph on fig. 10): It captures the superior-inferior movement of the tongue. A decrease in signal amplitude means a rise in the tongue, and vice versa. We find here a repeatable and reliable behavior specific to the movement described in part I.3.

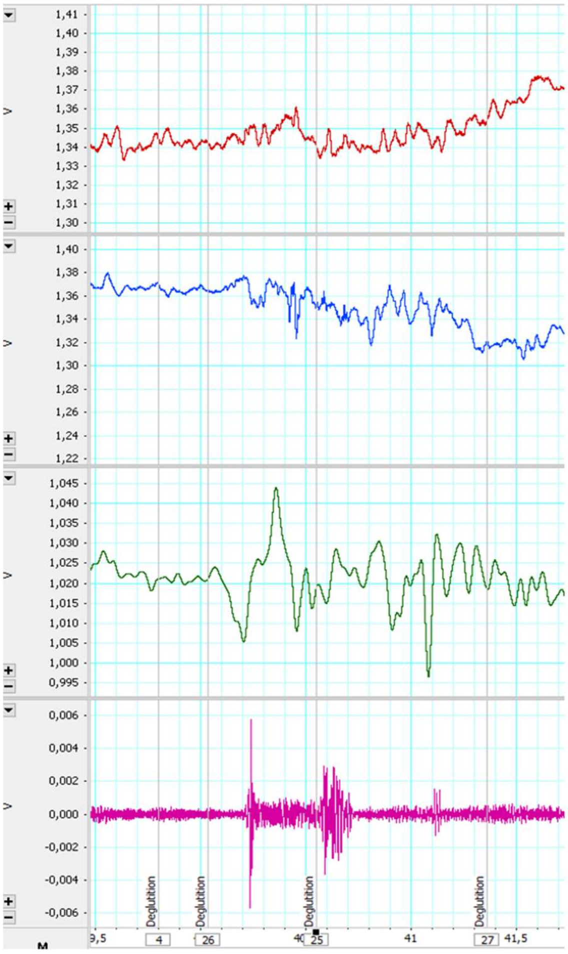


Figure 10: X, Y and Z axis, and the sound signal. On the vertical axis, the amplitude of the signal is done in volt, and on the horizontal axis, the time is done in second.

The swallowing sound (fourth graph on fig. 10): each component allows to locate the bolus in the throat. Although most often described as three in number, they are sometimes accompanied by additional components or significant noise. Nevertheless, the pattern shown here were found to be easily repeatable with a strong predominance of the second component.

The spectral density of the MMG signals shows that the vast majority of them (>99%) is below 30Hz while the swallowing sound range all the way through the sensor frequency band (1600Hz). The MMG is thus low-pass filtered at 32Hz so that the 50Hz line interference falls into a zero. The swallowing sound is then high-pass filtered at 80Hz to get rid of the line interference as well, the body movement and the unwanted pulse. The SNR will also be calculated to compare the effectivity of the filtering.

III – Results and discussion

The swallowing sound signature has been shown to be made up of three main components [18]:

- the first occurs during the rise of tongue and the hyoid bone, when the bolus starts its journey through the oropharynx,
- the second occurs when the UES opens and the bolus passes through,
- the third occurs when the larynx move back to its resting position and opens.

The amplitude of these components is variable, there is regularly one more or less and they are often accompanied by noise. However, the second one has shown to always be present [18] and represents the limit from which a recognition of the swallowing must be made. We thus wanted to quantify the available timings to make sure that there is enough time for a swallowing detection. To do this, 4 benchmarks have been positioned for post-processing (Fig. 11):

- the first: it was asked to the volunteer to press a button at the initiation of the swallowing. It is thus roughly related to the start of the tongue motion.
- the second: first peak downward and therefore the rise of the tongue. It is placed manually to mark the beginning of relevant activities.
- the third: maximum time at which the detection must be made. It is also manually place according to the swallowing sound second component.
- the fourth: end of the movements linked to swallowing. It is place manually according to the axis activity.

It should be noted that the second and third benchmarks are the most robustly placed and their time difference represent the available timing for a detection. The two others, even though being subjectively placed, allow for an approximation of the time when an artificial larynx may open in case of, say, a time-out security to forbid any too long artificial larynx closure.

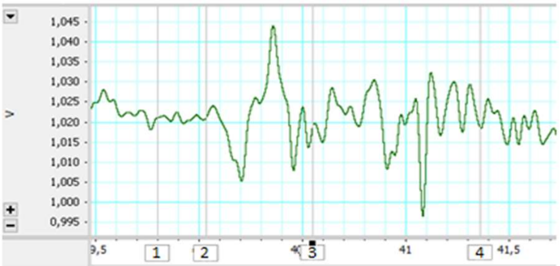


Figure 11: swallowing signal with the four benchmarks

But first, the signals show some variability that makes some of them unusable. They have thus been classified into 4 different categories:

- C1: exploitable and delimitable,
- C2: exploitable and imprecise,
- C3: exploitable and indistinct,
- C4: cannot be used.

Exploitable / Unexploitable: the swallowing pattern is visible on the Z axis although its shape is not necessarily as expected.
Delimitable / Imprecise / Indistinct: the pattern can be bounded or not using the Z axis if it stands out distinctly from the rest.
We chose to exclude from our study the swallowing of categories 3 and 4 (table 1):

type / category	saliva	water	solid food	total
C1	227	425	99	751
C2	54	73	25	152
C3	9	6	7	24
C4	101	101	93	295
$\frac{C1+C2}{C1+C2+C3+C4}$	0.719	0.823	0.554	0.739

Table 1: number of swallowing per category

Then, we are interested here in the interval 1 - 2, 1 - 3, 1 - 4 and 2 – 3 to quantify the swallowing pattern. We see that the distribution of the random variable "time" does not follow a normal law.
Note that the distribution is not symmetrical. It is therefore necessary to find an asymmetric law which best meets these different distributions. After a short study, it is the log-normal distribution that seems appropriate since it preserves the vertex and the right and left parts. This is verifiable on the other intervals.

Before proceeding to the study of the different swallowing, we compared the averages of category 1 and 2. Here, category 1 is considered representative, because it represents the easily identifiable patterns and includes the greatest number of swallowing. It was necessary to ensure that the averages were not statistically different, to ensure that category 2 was not to be excluded.

The literature [20, 9] provides us the duration of the different stages of swallowing. Both agree on a total duration of around 1 to 2 seconds. Which is consistent with our results. We also notice a relatively large time on interval 2 - 3 (the one that interests us first for a detection), despite a weak lower limit. This should allow sufficient time for swallowing detection, but still limits the calculation time. Knowing that eventually it will be necessary to take into account the time of obstruction of the airways. Regarding the amplitude variations, this agrees with the first tests.

We studied the influence of the characteristics of the volunteer on the durations. Each swallowing exhibits a behavior in term of duration in agreement with studies, in particular [20, 9]. Regarding the different types, water is the fastest, followed by saliva and finally solid food. For pattern recognition, it is necessary to have sufficient time to perform calculations and obstruct the airways. Although on average this time is sufficient over the interval 2 - 3 (propulsion of the food bolus into the pharynx by the rise of the tongue, which sticks to the palate), the minimum values limit the calculation time. The interval 1 - 2 (sends bolus of food to the back of the tongue by lowering the tongue) may possibly lengthen this time. However, the amplitudes over the interval 1 - 2 are small (bad SNR) and the associated pattern is not always present. One possible explanation is that the bolus is sometimes far enough behind the tongue that it does not need to first get the bolus posteriorly.

We present in table 2 the durations of the different phases of the swallowing for saliva, water, and solid foods.

duration(s) / benchmark	water	saliva	Solid food
1-2	0.154 (0.016-0.929)	0.186 (0.015-1.333)	0.161 (0.018-0.945)
1-3	0.478 (0.206-1.02)	0.571 (0.181-1.58)	0.515 (0.223-1.101)
1-4	1.141 (0.693-1.831)	1.256 (0.667-2.269)	1.182 (0.682-1.984)
2-3	0.324 (0.125-0.786)	0.385 (0.125-1.01)	0.354 (0.143-0.812)

Table 2: duration of the benchmark intervals for the different swallowing with the 3σ confidence intervals and averages.

Regarding the influence of the characteristics of the volunteers, age and weight showed some influence over other characteristics. Age acts mainly on the interval 2 - 3 but on all types of swallowing [21]. Weight acts on most saliva and water swallowing intervals, but not on solid food. However, we have seen the latter type of swallowing exhibited higher amplitudes, allowing better detection if we consider that overweight affects the measurement. However, these influences remain minimal since the linear correlation line has a rather weak slope and the absolute value of the correlation coefficient | R | does not exceed 0.253 for age and 0.325 for weight.

In general, men tend to have higher extremes than those of women, but nothing significant. In fact, the characteristics of the volunteers are not decisive factors in swallowing, possibly due to the weight, which may hinder detection during a significant overweight (For an external measurement considering the framework of this study).

So, these findings hint toward the possible detection of swallowing via MMG signals from submental area. Indeed, the specific swallowing pattern along with a relatively comfortable timing may allow for an embedded system to perform the detection. Weather one or more axis would necessary remains to be investigated. As the whole system has to be implemented, an accelerometer placed under the skin may provide richer information. Finally, one may argue about the lack of higher frequency in MMG signals (<30Hz). It has been shown that the weight of the accelerometer could act as a low-pass filter [22]. So, further investigation should take a closer look on the impact of it for swallowing detection.

IV - Conclusion

A post-acquisition analysis has been carried out finally to analyze the following parameters:
• Search for possible repeatability between volunteers
• Look for possible variations according to age, gender, weight or size.
• Search for identifiable reasons.
• Look for any differences between the swallowed types (saliva, water, solid food).
• Temporal characterization of waveforms related to swallowing:
  - Duration of different events
  - Total durations

We have shown in this study that swallowing presents a specific signature in the MMG signal, for the different people recorded. We have given also the timing of the swallowing, and the influence of parameters such as age, gender and BMI on this timing.

V - Funding sources

This work was supported by the Carnot institute Software and Intelligent Systems (Institut Carnot LSI, Grenoble) and the Rhône Alpes region through the research ambition pack [CALADSP].

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