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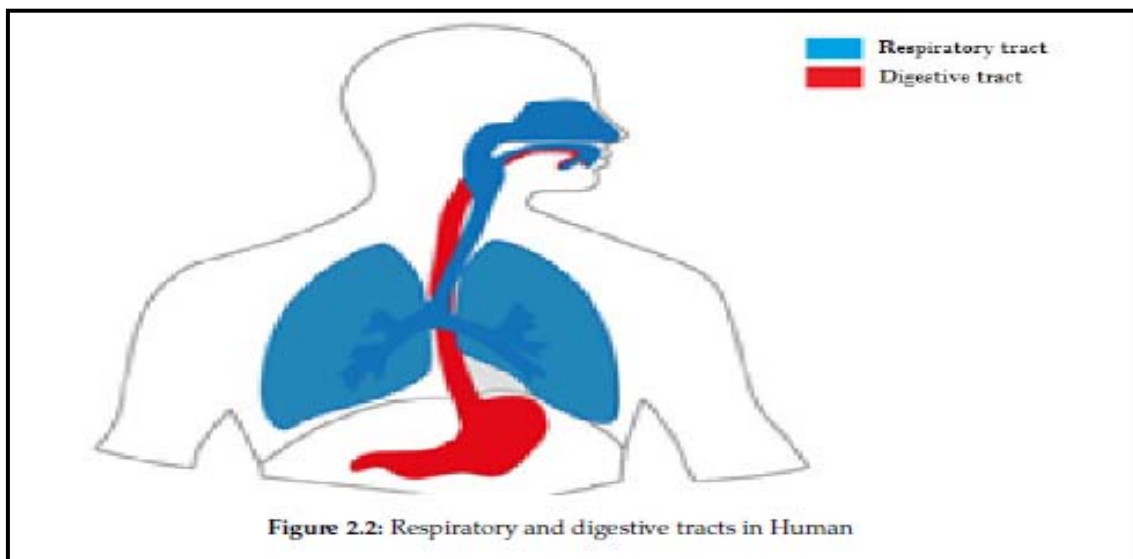
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Par Hajer KHLAIFI

Preliminary study for detection and classification of swallowing sound

Thèse présentée
pour l'obtention du grade
de Docteur de l'UTC



Soutenue le 21 mai 2019

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DOCTORAL THESIS

Spécialité :

Bio-ingénierie et Sciences et Technologies de l'Information et des Systèmes

Preliminary study for detection and classification of swallowing sound

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for the degree of Bioengineering, Information Science and Technology and systems*

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To mum and dad...

To my dear brother Anis who is always by my side.....

Abstract

The diseases affecting and altering the swallowing process are multi-faceted, affecting the patient's quality of life and ability to perform well in society. The exact nature and severity of the pre/post-treatment changes depend on the location of the anomaly. Effective swallowing rehabilitation, clinically depends on the inclusion of a video-fluoroscopic evaluation of the patient's swallowing in the post-treatment evaluation. There are other available means such as endoscopic optical fibre. The drawback of these evaluation approaches is that they are very invasive. However, these methods make it possible to observe the swallowing process and identify areas of dysfunction during the process with high accuracy.

"Prevention is better than cure" is the fundamental principle of medicine in general. In this context, this thesis focuses on remote monitoring of patients and more specifically monitoring the functional evolution of the swallowing process of people at risk of dysphagia, whether at home or in medical institutions, using the minimum number of non-invasive sensors. This has motivated the monitoring of the swallowing process based on the capturing only the acoustic signature of the process and modeling the process as a sequence of acoustic events occurring within a specific time frame.

The main problem of such acoustic signal processing is the automatic detection of the relevant sound signals, a crucial step in the automatic classification of sounds during food intake for automatic monitoring. The detection of relevant signal reduces the complexity of the subsequent analysis and characterisation of a particular swallowing process. The-state-of-the-art algorithms processing the detection of the swallowing sounds as distinguished from environmental noise were not sufficiently accurate. Hence, the idea occurred of using an adaptive threshold on the signal resulting from wavelet decomposition.

The issues related to the classification of sounds in general and swallowing sounds in particular are addressed in this work with a hierarchical analysis that aims to first identify the swallowing sound segments and then to decompose them into three

characteristic sounds, consistent with the physiology of the process. The coupling between detection and classification is also addressed in this work.

The real-time implementation of the detection algorithm has been carried out. However, clinical use of the classification is discussed with a plan for its staged deployment subject to normal processes of clinical approval.

Keywords: Wavelet decomposition, signal processing, detection, classification, GMM, HMM...

Résumé

Les maladies altérant le processus de la déglutition sont multiples, affectant la qualité de vie du patient et sa capacité de fonctionner en société. La nature exacte et la gravité des changements post/pré-traitement dépendent de la localisation de l'anomalie. Une réadaptation efficace de la déglutition, cliniquement parlant, dépend généralement de l'inclusion d'une évaluation vidéo-fluoroscopique de la déglutition du patient dans l'évaluation post-traitement des patients en risque de fausse route. La restriction de cette utilisation est due au fait qu'elle est très invasive, comme d'autres moyens disponibles, tels que la fibre optique endoscopique. Ces méthodes permettent d'observer le déroulement de la déglutition et d'identifier les lieux de dysfonctionnement, durant ce processus, avec une précision élevée.

"Mieux vaut prévenir que guérir" est le principe de base de la médecine en général. C'est dans ce contexte que se situe ce travail de thèse pour la télésurveillance des malades et plus spécifiquement pour suivre l'évolution fonctionnelle du processus de la déglutition chez des personnes à risques dysphagiques, que ce soit à domicile ou bien en institution, en utilisant le minimum de capteurs non-invasifs. C'est pourquoi le principal signal traité dans ce travail est le son.

La principale problématique du traitement du signal sonore est la détection automatique du signal utile du son, étape cruciale pour la classification automatique de sons durant la prise alimentaire, en vue de la surveillance automatique. L'étape de la détection du signal utile permet de réduire la complexité du système d'analyse sonore. Les algorithmes issus de l'état de l'art traitant la détection du son de la déglutition dans le bruit environnemental n'ont pas montré une bonne performance. D'où l'idée d'utiliser un seuil adaptatif sur le signal, résultant de la décomposition en ondelettes.

Les problématiques liées à la classification des sons en général et des sons de

la déglutition en particulier sont abordées dans ce travail avec une analyse hiérarchique, qui vise à identifier dans un premier temps les segments de sons de la déglutition, puis à le décomposer en trois sons caractéristiques, ce qui correspond parfaitement à la physiologie du processus. Le couplage est également abordé dans ce travail.

L'implémentation en temps réel de l'algorithme de détection a été réalisée. Cependant, celle de l'algorithme de classification reste en perspective. Son utilisation en clinique est prévue.

Mots-clés : Déglutition, sons déglutitoires, décomposition en ondelettes, traitement de signal, détection, classification, GMM, HMM.

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List of Abbreviations

ANR	National Research Agency NRA
BTS	Bolus Transit Sound
CA	Cervical Auscultation
DREES	Directorate of Research, Studies, Evaluation and Statistics
DWT	Discrete Wavelet Transform
ECPFR	Echelles Cliniques Prédicatives de Fausse Route
EGG	Electroglottography
EM	Expectation Maximisation
EMG	Electromyography
ENMG	Electroneuromyogram
FAR	False Alarm Rate
FDS	Final Discrete Sound
FEES	Fiberoptic Endoscopic Evaluation Swallowing
FFT	Fast Fourier Transform
GMM	Gaussian Mixture Model
GUSS	Gugging Swallowing Screen
HMMs	Hidden Markov Models
ICT	Information an Communication Technologies
IDS	Initial Discrete Sound
IESEI	Inspiration Expiration Swallowing Expiration Inspiration
IESI	Inspiration Expiration Swallowing Inspiration
ISEI	Inspiration Swallowing Expiration Inspiration
IMU	Inertial Measurement Unit
INED	National Institute for Demographic Studies
INSEE	National Institute of Statistics and Economic Studies
KNN	K-Nearest Neighbours
LDA	Linear Discriminant Analysis
LES	Lower Esophageal Sphincter

LFCC	Linear Frequency Cepstral Coefficients
LIRA	Limited Receptive Area
MEBD	Modified Evan's Blue Dye
MER	Missed Event Rate
MFCC	Mel Frequency Cepstral Coefficients
MsFS	Mel-scale Fourier Spectrum
ORR	Overall Recognition Rate
PASS	Practical Aspiration Screening Schema
PER	Partial Event Rate
RIP	Respiratory Inductance Plethysmography
sEMG	Surface Electromyography
STFT	Short Time Fourier Transform
SVM	Support Vector Machine
TOR-BSST	Toronto Bedside Swallowing Screening Test
UES	Upper Oesophageal Sphincter
VER	Validated Event Rate
VFSS	Videofluoroscopic Swallowing Study
WDT	Waveform Dimension Trajectory
WFD	Waveform Fractal Dimension
WHO	World Health Organization
WPD	Wavelet Packet Decomposition

Chapter 1

Introduction

Breathing, drinking, eating, protection from cold and heat are among the essential elements for survival. Some primary needs are met by nature, including breathing, but the majority of them are not and require voluntary action by the individual. Among them, swallowing is one of these needs. Swallowing is a complex and vital process in humans. It provides two vital functions at once: nutrition and protection of the respiratory tract. Swallowing, defined as a voluntary act, enables transport of substance, saliva or liquid or chewed solids, from the oral cavity to the stomach passing through the pharynx, oesophagus while ensuring the airways security. Swallowing is a repetitive act that occurs 300 times per hour during a meal and is estimated to occur about 600 to 2000 times a day in healthy people Amft and Troster (2006). Eating and drinking are physiological necessities, but also a source of individual and social pleasure. Indeed, to eat is to gather, to share, to desire, to see, to smell, to salivate, to taste, and so on. If eating is a necessity for everyone, a pleasure for many, a sin for some, it is also a danger for others. Difficulties in swallowing, disorders are known as dysphagia. Dysphagia can occur at any age, but it is more common in older adults in general and their management requires a multidisciplinary approach to recognise, characterise and propose rehabilitation measures. However, in France, the number of practitioners is decreasing across the healthcare professions including general practitioners, specialised doctors or medical auxiliaries.

1.1 Ageing of the population

Dysphagia in the elderly is called presbyphagia. It can be divided into two categories: (i) Primary presbyphagia which refers to the effects of normal ageing on the organs involved in swallowing and (ii) Secondary presbyphagia which refers to the

accumulation of normal aging and related changes to diseases which can lead to severe dysphagia such as stroke and Parkinson's disease. McComas, Upton, and Sica (1974) found that there is a little loss of functioning motoneurons before the age of 60 years but there is a striking and progressive depletion subsequently with age, by applying electrical stimuli of low, gradually increasing intensity, to single motor units.

As a world phenomenon, the ageing populations effects both developed and emerging countries. The French population like other European peoples is also ageing. People aged 65 and over increased from 13.9% in 1990 to 18.8% in 2016. The challenge will be to adapt the capacities of the structures caring the loss of autonomy so that they accompany this important increase. By 2050, according to the population projections calculated by Eurostat, the number of people aged 65 and over would be 27.2% which is a significant and increasing demographic trend.

Swallowing disorders are common in the elderly, from 9% for those aged 65 to 74 living at home to 28% after 85 years Audrey (2013). Previous studies estimate that the prevalence of dysphagia after stroke ranges from 33% to 73% Mann, Hanky, and Cameron (2000) and Paciaroni et al. (2004). In another study, cited by various authors, Greuillet and Couturier estimate a prevalence ranging from 12% to 68% among institutionalised elderly populations. For home-stay patients, a questionnaire study found that 10% to 16% had symptoms of dysphagia Audrey (2013). In institutions, dysphagia reaches 30% to 60%. According to the Nestlé Institute of Health Science Science (2016), 40% of people over 75 have swallowing disorders. Up to 66% of those affected are residents of a Medico-Social Institution.

As the world's population ages, these statistics will increase. In France, the percentage of people living alone in their homes between 65 and 79 years is 27.1% whereas for people aged 80 or over is 48.8% according to the National Institute of Statistics and Economic studies (INSEE). The higher risks associated with dysphagia for those living alone, make for an alarming situation given that a significant percentage of dysphagic elderly live in institutions and at home.

Ageing, according to Stedman's Medical Dictionary (26th edition, p 38) is "the gradual deterioration of a mature organism from time-dependent irreversible changes in structure that are intrinsic to the particular species, and that eventually lead to a decreased ability to cope with the stresses of the environment, thereby increasing

the probability of death." The effects of ageing result in changes in the mouth, pharynx and oesophagus which is called presbyphagia. Studies have shown a decrease in tongue mass in elderly patients Ney et al. (2009). This phenomenon of decreased skeletal muscle is well known in elderly as sarcopenia. As a result, tongue position and movements are often altered in the elderly Baum and Bodner (1983) and lingual pressure decreases with age Robbins et al. (1995) causing prolonged oral phase Nicosia et al. (2000). Studies have also shown that the pharyngeal phase of swallowing is significantly prolonged in the elderly Ney et al. (2009) and Rofes et al. (2011). Changes in lip posture may also cause drooling of saliva which is common in older persons Cook and Kahrilas (1999). A radiological study has shown that 90% of 90-year-olds had impaired oesophageal motility with one third having complete loss of the primary peristaltic waves responsible for transport of feed Zboralske, Amberg, and Soergel (1964). Similar observations have been obtained by a nanometric study which examined the effect of the age on secondary oesophageal peristalsis Ren et al. (1995); frequency of secondary peristalsis and lower esophageal sphincter relaxation in response to air distention was significantly lower in the elderly than in the young. With advancing age, loss of teeth reduces masticatory performance and increases duration for chewing. Influence of masticatory behavior on muscle compensations during the oral phase of swallowing of smokers was proposed by Silva et al. (2019). A study on the influence of food thickeners on the size of bolus particles swallowed was also the focus of study proposed by Yamaguchi et al. (2019)

1.2 Dysphagia consequences

The consequences of dysphagia are highly variable, ranging from no discernible effect to airway obstruction or severe aspiration pneumonia.

1.2.1 Epidemiology of dysphagia

Incidence of pneumonia is estimated to be around one-third of person with stroke, and increases mortality by three Hilker et al. (2003). It is associated with a quarter of deaths in the first month after stroke Worp and Kappelle (1998); 27% to 37% of dysphagic patients die within 3 to 6 months Singh and Hamdy (2006). In a study conducted by Zhou, among 70 patients with stroke recruited, 6 patients (8.6%) had pneumonia within 1.7 ± 2.4 days (end: 0 ~ 6 days) compared to the occurring instant

of stroke. In a retrospective study of 40 dysphagic patients in the geriatric category, Croghan et al. (1994) described the occurrence of pneumonia in 43% within one year compared to the first videoradioscopic examination of swallowing and at 30% of deaths related to these pneumonias.

Dysphagia is responsible for about 4000 deaths per year in France Audrey (2013). According to the National Institute for Demographic Studies (INED), the mortality rate in France in general population in relation to suffocation by swallowing disorder is 5.99 per 100000 for men, and 6.1 per 100000 for women.

The consequences of dysphagia are multiple, ranging from a deterioration in a patient's quality of life to death. The medical management of dysphagia for rehabilitation purposes requires multidisciplinary care to ensure rehabilitation and good practice of swallowing and to avoid any incidence of dysphagia.

1.2.2 Multidisciplinary care of dysphagia

The objective of the management of swallowing disorders is to ensure a feeding modality that guarantees the safest possible nutritional state with regard to respiratory function and respects the person's quality of life as much as possible, whether in terms of reducing the discomfort caused by the dysphagia experienced or in terms of eating pleasure. For populations at risk of swallowing disorders, the prevention of complications of this disorder leads to the development of screening tests based on care protocols. For a patient for whom the diagnosis of dysphagia has been confirmed, the clinician must understand the cause of the disorder and how well it is tolerated.

Following a swallowing complication, the diagnosis of dysphagia begins with a simple questioning of the patient and his or her relatives. Clinical examination is essential for the diagnosis of dysphagia, but it is not effective in detecting and preventing cases of food choking, which are often silent. The treatment of dysphagia is mainly etiological. Videoradiography is the gold standard for determining the mechanism of dysphagia and the modalities of symptomatic treatment. Rehabilitation and adaptation of food textures Ross et al. (2019) to the mechanisms of dysphagia can help preserve oral nutrition. In addition to enteral nutrition, maintaining an oral diet is important to preserve the patient's quality of life Professionnelles (2007) and Audrey (2013). This involves multidisciplinary follow-up.

The therapeutic aspect is essentially based on multidisciplinary care that requires cooperation between medical staff (doctors, the nursing staff), the patient, their family or the members of the institution where they reside. Rehabilitation and dietary management techniques are the most widespread.

The nurse ensures the good practice of medical and logopedic instructions and tracks the warning signs encountered during food intake.

Otorhinolaryngology physicians perform a detailed clinical assessment such as screening test with replenishment such as the "3 Oz Water Swallow Test" validated by DePippo, Holas, and Reding (1993), which is considered perfectly adapted to stroke victim population Bassols and Puech (2011), and also, the functional ability test of swallowing by Guatterie and Lozano (2005). In addition, the no-feedback test is presented as predictive aspiration clinical scales ECPFR (Echelles Cliniques Prédictives de Fausse Route). Practical Aspiration Screening Schema (PASS) Zhou (2009) combines the ECPFR and the 3 Oz Water Swallow Test.

There is also the Videofluoroscopic Swallowing Study (VFSS), which is a technique used to observe and film radiographic swallowing to follow the food bolus coated with a product that allows contrast. Videofluoroscopy makes the entire swallowing process visible. In case of an aspiration, it enables quite precisely, the determination as to how much material has entered the airways, at what level, when and how the patient responds Martin-Harris and Jones (2008). VFSS enables the to determination of the effect of various behavioural and sensory interventions on the physiological function of the swallowing mechanism. However, these techniques are invasive and uncomfortable requiring an active patient participation, and are therefore not always applicable in the elderly.

After a detailed clinical assessment, the therapist identifies appropriate strategies in order to re-educate the deficit phase. The physiotherapist manages the respiratory function by using various techniques. The ergotherapist ensures the optimal use of rehabilitative skills in the management of daily life activities or the compensation of deficits by use of appropriate technical aids. The dietician adapts the diet in relation to medical and logopedic instructions, but also to the taste of the patient and realises the feasibility of these recommendations in an institution. The psychologist detects a possible depressive reaction syndrome, ensures the acceptance of the disease and the integration of the patient in their environment.

1.3 Medical desertification

Today, in France, few territories in the regions still escape medical desertification. According to statistics published by the Directorate of Research, Studies, Evaluation and Statistics (DREES), otolaryngologists and head and neck surgery physicians and physiotherapists are not evenly distributed across the territory. However, there are disparities between regions. Figures 1.1 and 1.2 show the distribution of otolaryngologists and physiotherapists on French territory. Overall, the otolaryngology has a density of 4.6 otolaryngologists per 100 000 inhabitants. Thus, the Ile-de-France have privileged access to this medical service with a density of 6.6 otolaryngologists per 100 000 inhabitants. According to the Demography of Physiotherapists report (Situation on 31 August 2017), the average French number of physiotherapists per 10 000 inhabitants is 12.6. This Figure can be described as low compared to other European countries such as Belgium which have 25.8 physiotherapists per 10 000 inhabitants.

Also, the management of dysphagia must, in order to be effective, be carried out in collaboration with the family and staff of the institution in which the person resides. This could not be the case according to the large number of people living alone. Clear and accurate information must be provided so that the evolution of the disorder and its possible complications can be understood, Allepaerts, Delcourt, and Petermans (2008). Access to care in good conditions, participation in the choices that concern them; continuing to have confidence in their health system: these are the expectations of patients and users, especially patients at risk.

The complexity and compartmentalization of the current system often enable the patient to coordinate the different professionals themselves. A complexity that professionals feel every day and that patients perceive in their daily lives. Social difficulties such as ageing, increased health spending and medical deserts are also relevant.

The reforms to be undertaken to overcome these difficulties can only be envisaged in a global approach including the hospital and the medico-social sector. This transformation must aim to improve all subjects: access to care, prevention, quality of care, regulation of health insurance expenditure, but also the medico-social link, the transformation of the hospital and the modernisation of medicine. It is the entire health system that must be challenged to meet today's challenges and prepare

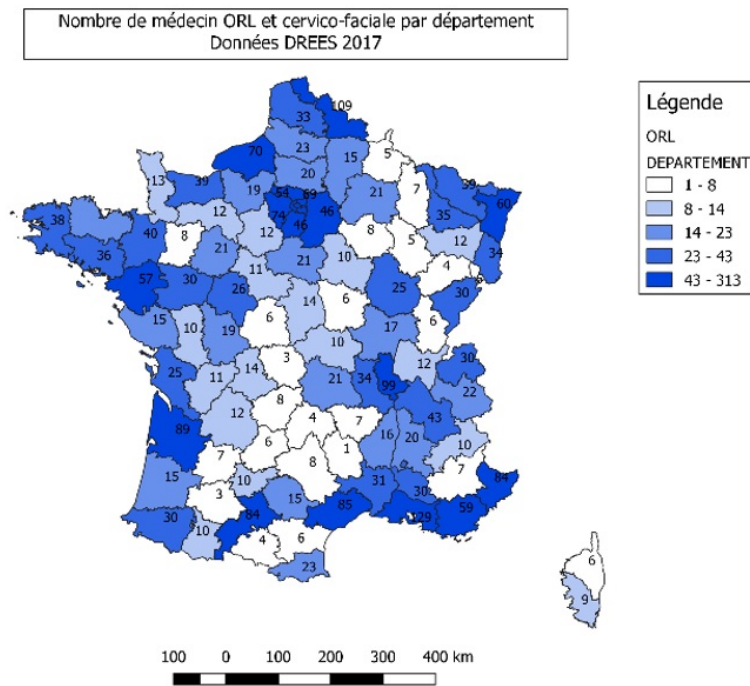


Figure 1.1: Distributions of otolaryngologists on French territory

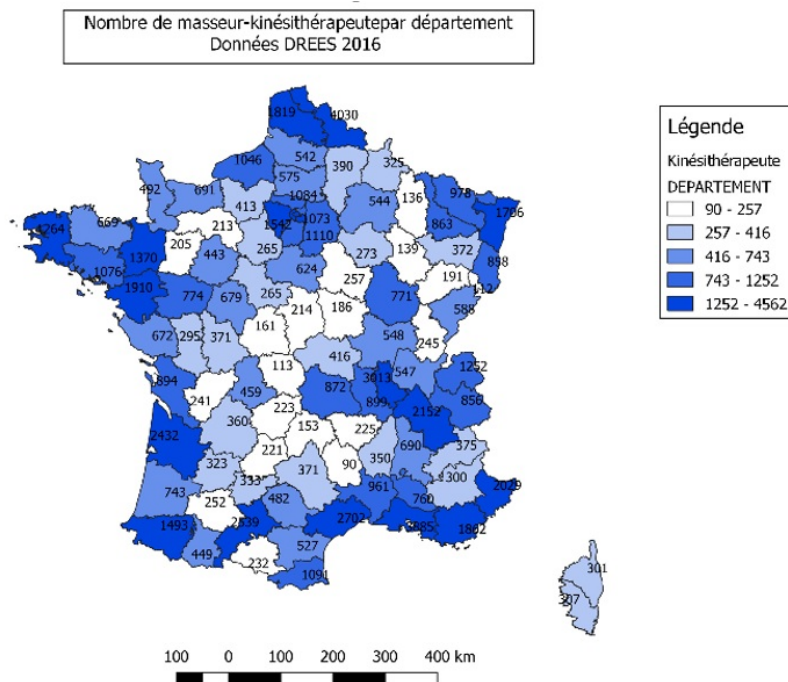


Figure 1.2: Distributions of physiotherapists on French territory

for tomorrow's health system. To do so, the patient must more than ever be at the centre of future thinking and developments. From this point of view, medicine is evolving and starting on "e-health".

e-health is a multi-disciplinary domain which involves many stakeholders, including clinicians, researchers and scientists with a wide range of expertise in healthcare and engineering. Digital health is the convergence of digital technologies with healthcare, living, and society to enhance the efficiency of healthcare delivery and make medicine more personalised and precise. It involves the use of information and communication technologies to help to address the health problems and challenges faced by patients. These technologies include both hardware and software solutions and services, including telemedicine.

1.4 Telemedicine

Telemedicine is the performance of a remote medical procedure. Telemedicine brings together medical practices permitted or facilitated by telecommunications. It is an exercise in medicine by use of telecommunications and technologies that enables distance health benefits and the exchange of medical information related to it. Different in application, telemedicine has to provide a rapid medical response to a patient's problem. It makes it possible to establish a preventive follow-up or a post-therapeutic follow-up for patients at risk. Already in 2016, the World Health Organisation (WHO-Organisation Mondiale de la Santé OMS) reported on e-health in Europe encouraged the deployment of national health policies on telemedicine. Delivering e-health, i.e. the use of information and communication technologies (ICT) for health is a relatively recent healthcare practice dating back to at least 1999 Mea (2001). e-health is considered as the death of telemedicine; "e-health can be considered to be the health industry equivalent of e-commerce:". e-health is deemed to be a fashionable name for telemedicine. It includes electronic/digital processes in health, namely health applications. Telemedicine has four components:

- **Tele-consultation:** which is a remote consultation,
- **Tele-regulation:** which takes the form of a service that puts a person in touch with an operator if there is a problem at home,
- **Tele-expertise:** when doctors consult each other between them, and
- **Tele-monitoring** which is a remote monitoring of a patient by transmission of medical data between patients and different medical staffs.

Telemedicine was born in medical practice in the 1970s in rural America and northern Norway. It has also been tested very early independently in 1966 in USA, Russia and France with telephonic transmission of ECGs. It has been said that it originated in January 1905 in Netherlands, when W. Einthoven's assistant transmitted a ECG record via a telephone line from the hospital of Leyden to his laboratory located 1.5 kms away. Telemedicine aims to optimise the care of the patient upstream of his care path, giving him access to a general practitioner through a videoconference consultation. Telemedicine uses signals obtained from different sensors, installed in the patient's home or in intelligent socio-medical institutions, in order to extract information needed for diagnosis. This first step enable direct orientation according to their situation, for a physical consultation or referral to a specialist. It is the birth of a hybrid model that alternates physical and remote consultations between a doctor and his patient. Above all, it provides the patient with a panel of specialists who can follow him at regular intervals, overcoming the obstacle of distance. Beyond the remote consultation, the monitoring of physiological parameters can be carried out in real time or in a delayed manner if the data are stored. The surveillance is willing to follow the progress of a patient at risk which in some cases becomes vital. This aspect is very important in the case of patients at risk of dysphagia that can lead to dramatic consequences even the death of the patient if intervention is not timely. Therefore, telemedicine opens up new opportunities and better access to health care, particularly for emergencies where a diagnosis must be made quickly. These technologies can significantly improve access to health care, especially in medical deserts.

In Europe, telemedicine is developing rapidly. In France, it has been included in the Public Health Code since 2010, and is governed by the HSPT law (hospital, health, patients, territory). Since January 2019, the teleconsultation act has been recognised and reimbursed by the national health insurance fund. Doctors are in favour of the evolution of this technology. Already today, 84% of them use smartphones or digital tablets in their work. Telemedicine is a recent phenomenon in the health field consisting of the use of services that allow clinicians and patients to come into direct contact, almost instantaneously, through the use of new technologies.

The work of this thesis is part of the telemedicine and it is presented as a telemonitoring application. It is based on the processing of sound signals acquired during food intake.

1.5 e-SwallHome project

The work of this thesis is part of the e-SwallHome (Déglutition & Respiration : Modélisation et e-Santé à domicile) project. e-SwallHome, funded by National Research Agency (ANR), aims to explain the normal behaviour of three coupled functions in humans; swallowing, breathing and phonation, to better understand the mechanisms underlying dysphagic, dysphonic and dyspnoeic pathological behaviours, following in particular a stroke. To do so, it works on a set of protocols for diagnosis, home monitoring, education and rehabilitation in subjects at risk of death by aspiration, asphyxiation or fall without the possibility of voicing any oral expressions as warning signals.

The theme of e-SwallHome is e-health which brings all applications of Information and Communication Technologies (ICT) in the field of health, with a wider scope than telemedicine. This discipline aims at the use of distance medicine aiming at well-being on topics related to medicine but without medical constraints. Thus focus on, home-based tele-accompaniment, combining technological innovation in health and contributing, through a better acceptability on the part of the patient, to the improvement of adherence to therapeutic recommendations and rehabilitation protocols (by speech therapists and physiotherapists), and thus to prevent the complications induced by chronic dyspnoea / dysphagia / dysphonia disorders related to the initial stroke.

The target population in the e-SwallHome project is healthy subjects and patients who have suffered from stroke. Healthy subjects included in this study must be aged between 18 and 40 years, raised in a monolingual French-speaking environment and not presenting language, neurological and/or psychiatric disorders. Volunteers signed an informed consent form. The inclusion criteria for stroke patients included in this project were to be more than 18 years of age, first cerebral infraction and confirmed by MRI \leq 15 days, absence of severe leukoaraiosis, swallowing disorders identified by a GUSS scale less than 20, identified neurological deficit and the patient has to be able to cooperate.

This thesis is part of the research project e-SwallHome. In revising the initial assumption of inclusion criteria of patients, has been reoriented to include only healthy subjects due to lack of access to patient's medical records. So, it was proposed to work only with healthy subjects while keeping the same objectives of e-SwallHome

project to be used subsequently for evaluating pathological signals in this study.

1.6 Objectives

The thesis subject, proposed as part of the diagnosis system described above, based on home telemonitoring, participates in the home monitoring of patients suffering from dysphagia, by proposing automatic monitoring methods and evaluation of functional rehabilitation. The end goal of this PhD is to develop a tool able to monitor swallowing in real time using the least invasive sensor, ambulatory, while ensuring the comfort and the good quality of the daily life of the person. Limited to data in healthy subjects, the proposed system has to be a part of a rehabilitation support that could be provided to the patient and clinicians.

This PhD study enables telemonitored patients to follow the progress of people at risk. More specifically, it concerns dysphagia in the elderly and seeks to identify automatically the specific characteristics that could be used in the assessment of the health status of patients at risk of dysphagia.

The analysis and extraction of information from the sound is an important aspect for medical telemonitoring of dysphagia. In this context, this thesis analyses and proposes solutions to the problems specific to sound processing for medical telemonitoring. In addition, breath signal analyses are also performed for the same purposes.

Among these problems, the automatic classification of sounds of swallowing in the context of everyday life has been little explored and a sound analysis system is proposed. This thesis sets out the problems and objectives of medical telemonitoring of dysphagia. The study of the sound signal must be able to highlight the various characteristics of the normal functional state of swallowing process and thus also the state of its malfunctioning.

Among the problems of telemonitoring that have been studied in this thesis are: signal quality, and adaptation of sound recognition techniques to the classification of sounds of swallowing in everyday life during food intake.

The quality of the signal influences the result of the recognition and signal processing systems. Taking into account the difficulties related to the quality of the signal, the work of this thesis focused on the signals with a sampling frequency of

16 kHz as well as its treatment by decomposing it in order to extract the most significant frequency bands as assessed to be adequate for the processing of swallowing events. This step must guarantee the best performance of the used algorithms in terms of the error rate, which is an important problem. The algorithms must ensure sufficient performance.

To be able to test, improve and validate the algorithms proposed in this thesis, a database was created as there was no access available to existing databases. An adaptation of sound recognition techniques has been carried out. The frequency characteristic of swallowing and those of other sound classes have differences and similarities, which requires finding suitable parameters to differentiate them.

1.7 Document organisation

The document starts with an introduction followed by a physiological description of the swallowing process and anatomy. Chapter 2 presents the etiology and semiology of dysphagia. Chapter 3 presents the state-of-the-art of the different methodologies for investigating the swallowing process and the different modalities used. Chapter 4 describes the different methodologies used and proposed in this work for the processing of sound and respiratory signals. Chapter 5 describes the data acquisition protocol followed, the sensors proposed and the procedure followed. The results of the methodology for performing the tests built to validate detection, classification and detection-classification coupling are presented in Chapter 6. The document concludes with conclusions and perspectives in Chapter 7 and the Appendices.

Chapter 2

Anatomy and Physiology

Swallowing is the set of coordinated acts that ensure the transfer of solid food or liquids from the mouth to the stomach, through the pharynx and oesophagus. According to Guatterie and Lozano (2005), dysphagia is the difficulty of performing the action of eating, to swallow with a feeling of discomfort or stop in the transit, painful or not, with possible misconceptions when swallowing food, liquids or saliva and, by extension, any abnormalities in the passage of food to the stomach. To be able to monitor the swallowing process, understanding the normal physiology and pathophysiology of swallowing is fundamental to evaluate the signs of the swallowing disorders and develop dysphagia rehabilitation programs.

2.1 Swallowing and breathing: fundamental couple

The oral cavity, larynx, pharynx and oesophagus are the structures used in swallowing. They are described by Bassols and Puech (2011), which will serve as the main reference for anatomy. Figure 2.1 shows the anatomy of the upper human digestive system.

2.1.1 Anatomy

The oral cavity is composed of several structures which are involved in swallowing: The lips close the oral cavity and maintain the food between the cheeks and teeth during chewing. The tongue with a mobile front is connected to the pharynx and the edge of the epiglottis by the glossoepiglottic fold on each side of which are located the valleys. The soft palate forms with its front and rear pillars and the palatal tonsils, the isthmus of the throat, passage between the oral cavity and the oropharynx. The mandible is mobilised by muscular activity in all three planes to crush the food with

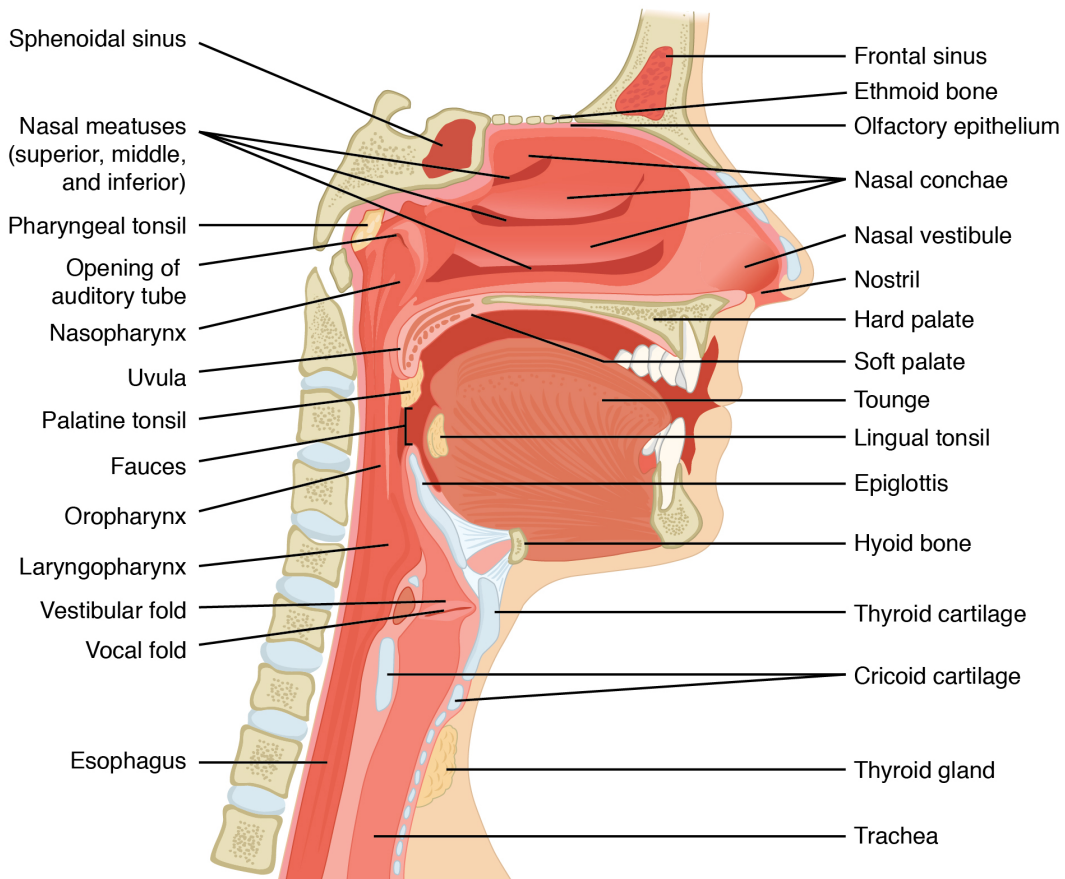


Figure 2.1: Anatomy of human superior digestive system BCCampus (<https://opentextbc.ca/anatomyandphysiology/2303-anatomy-of-nose-pharynx-mouth-larynx/>)

the teeth before swallowing: the pieces decrease in size and are unsalivated. The mouth floor is made up of three of the suprahyoid muscles that connect the mandible with hyoid bone: digastric, mylo-hyoid and geniohyoid.

The larynx is located at the front of the neck, it is moored at the top to the base of the tongue and bone hyoid, below it extends into the trachea. This musculocartilaginous duct communicates with the pharynx backwards. The larynx performs the functions of breathing, swallowing and phonation and can be considered as a valve that opens and closes the glottis. The larynx is divided into three levels. The supraglottic stage, or vestibule, is located above the vocal cords and includes the ventricular bands. The glottic layer corresponds to the plane of the vocal cords. The subglottic layer, located under the vocal cords, extends from the lower part of the vocal folds to the lower edge of the cricoid cartilage. The laryngeal skeleton consists of cartilage, among which two important joints can be mentioned. The crico-thyroid joint enables the thyroid cartilage to shift from the thyroid cartilage to the cricoid

cartilage, and thus to put the vocal cords under tension. The crico-arytenoid joint enables the arytenoid cartilage to shift in or out the cricoid cartilage to bring the strings closer or further apart, as well as a forward or backward shift to change their length. The larynx consists of two categories of muscles. The intrinsic muscles enable adduction or abduction movements, as well as tension or relaxation of the vocal cords. The constrictor and tightening muscles bring the vocal folds closer together in order to close the glottis when swallowing, and the dilators open the glottis for breathing. The extrinsic muscles ensure the suspension and mobility of the larynx in the neck. Some are subhyoidal and lower the larynx and hyoid bone, others are suprahyoids and elevators of the larynx and hyoid bone.

The pharynx is located behind the oral, nasal and laryngeal cavities, this conduit musculomembranous consists of constrictor muscles, responsible for pharyngeal peristalsis, and elevating muscles. It is divided into three floors. The rinopharynx is located behind the nasal passages; its role is respiratory and it is closed by the velopharyngeal sphincter during the oral time of swallowing. The oropharynx, behind the oral cavity, is the crossroads of the aerodigestive pathways: the swallowed food bolus and the breathed air circulate through it. It contains the pillars anterior and posterior of the soft palate, the tongue base, the valleculae and the lingual epiglottis. The hypopharynx circles the larynx backwards and sideways and ends at the bottom with the oesophagus. It contains the piriform sinuses which are a depression of the mucous membrane between the larynx and pharynx forming two cavities through which the food bolus passes during swallowing.

The oesophagus is a muscular tube connecting the pharynx with the stomach. The oesophagus is lined by moist pink tissue called mucosa. The upper oesophageal sphincter (UES) is a bundle of muscles at the top of the oesophagus. The muscles of the UES are under conscious control, used when breathing and eating and keep food and secretions from going down the trachea. The lower oesophageal sphincter (LES) is a bundle of muscles at the low end of the oesophagus, where it meets the stomach. The LES muscles are not under voluntary control.

As acknowledged, swallowing and breathing are a paradoxical couple because of the common structure involved in both functions. The breathing air passes through the mouth or nose, pharynx, larynx and trachea. The air of phonation uses the larynx, pharynx, mouth and nose. The swallowed food passes through the mouth, pharynx and oesophagus. Breathing, phonation and swallowing therefore share a

common crossroads: the mouth and pharynx. Figure 2.2 shows simultaneously the respiratory and digestive tracts.

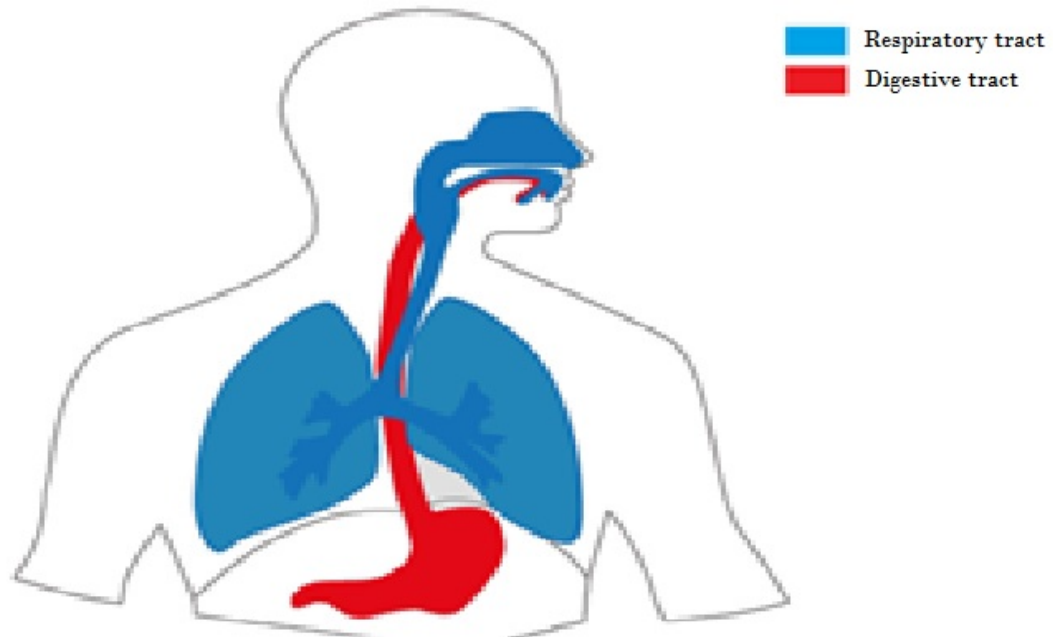


Figure 2.2: Respiratory and digestive tracts in Human

2.1.2 Physiology

Swallowing is a process resulting from muscle contraction under nervous control. Swallowing is initiated by the sensory impulses transmitted as a result of the stimulation of receptors on the tongue, soft palate and posterior pharyngeal wall. Then, sensory impulses reach the brainstem first through the VII, IX and Xth cranial nerves, while the efferent function is mediated through the IX, X and XIIth cranial nerves. Then, the fact that the bolus reaches the posterior pharyngeal wall triggers the relaxation and the opening of the cricopharyngeal sphincter which is reflexive.

The Aero-digestive junction is an area with complex but vital anatomy and functions. The aero-digestive junction is the crossroads of the airways that enables the passage of air between the outside of our body and the lungs and digestive tract that enables us to feed. Swallowing refers to the placement of food in the mouth, its mastication if necessary, prior to initiate swallow when the bolus is propelled backward by the tongue to the pharynx and to the œsophagus through the upper œsophagus sphincter.

Classically, swallowing is described in three phases: oral, pharyngeal and œsophageal. Swallowing is initiated by the introduction of the food into the oral cavity and its preparation by the process of mastication and insalivation. Once the bolus is formed and is ready to be expelled to the pharynx, the tip of the tongue is raised up and applied against the alveolar ridge of the upper incisors and the tongue takes the form of a spoon where the bolus slips and forms a single mass. The latter moves backwards by the moving tongue which gradually applies to the palate from front to back. At this moment, the soft palate realises the closure of the oropharynx and prevents the penetration of the bolus into the pharynx, however, the larynx is still open. By the time the bolus penetrates the throat isthmus, the oral time (voluntary time) is over. The back of the tongue moves forward and forms an inclination allowing the bolus to move towards the oropharyngeal cavity. Thus, the pharyngeal phase is triggered by the contact of the bolus with the sensory receptors of the throat isthmus and of the oropharynx.

The pharyngeal process is a continuous phenomenon in time, considered as a reflex accompanied simultaneously by the velopharyngeal closure by the velum, by the laryngeal occlusion assured by the elevation of the larynx, and by the retreat of the tongue's base, the movement at the bottom of the epiglottis, the pharyngeal peristalsis and finally the opening of the upper sphincter of the œsophagus allows the passage of the food bolus into the œsophagus. This phase lasts less than one second. The opening of the upper sphincter of the œsophagus is initiated by the arrival of the pharyngeal peristalsis and passage through the esophagus is ensured by the continuity between the pharyngeal and the œsophageal peristalsis.

The pharyngeal stage triggered by the end of the oral stage becomes involuntary and is called the swallowing reflex. Velum is raised to close the nasal cavities and avoids any passage of food into the nose and facilitates the passage of the bolus downwards towards the œsophagus through the pharynx. Precisely at this moment, the passage of food into the trachea is avoided. The larynx opens during chewing, to allow breathing, and is closed as soon as the bolus arrives on the base of the tongue. At the same time, the vocal cords are embracing to ensure airway closure, the moving cartilages of the larynx (arytenoids) swing forward in the laryngeal vestibule, covered by the rocking of the epiglottis. The larynx is pulled up and down by the hyoid muscles, which place it under the protection of the base of the tongue.

As a result, breathing is interrupted and at the same time the last stage of swallowing begins with the introduction of the bolus into the oesophagus and its progression through the oesophageal peristaltic waves (muscle contractions) to the stomach. The oesophagus is indeed a muscular tube, the two extremities of which are sphincter zones, the upper oesophageal sphincter and the lower oesophageal sphincter act as a valve preventing reflux of food or acidity from the stomach.

The pharyngeal and oesophageal phases constitute the reflex of swallowing, without voluntary control Bassols and Puech (2011), Guatterie and Lozano (2005), and Jones (2012). The swallowing reflex is the result of the laryngopharyngeal activity, which is triggered by intrapharyngeal and sometimes laryngeal stimuli and is introduced in humans during the fourth month of intrauterine life and observed by ultrasound from the 6th month Guatterie and Lozano (2005) in order to protect airways from any passage of food.

The functions associated (breathing and phonation) with swallowing are important in an evaluation of the swallowing since they involve the same neuro-anatomical structures. During the preparation of the food bolus, breathing continues through the nasal passages. Once the food bolus is prepared, it is time to propel it to the pharynx by back. First, the mandible closes and the food bowl is gathered on the back, from the tongue to the palatal vault. The apex is supported by the alveolar ridges, and the floor of the mouth contracts. The tongue exerts pressure by a movement anteroposterior and from bottom to top against the palate. The velopharyngeal sphincter closes (the palate veil rises and hardens until it comes into contact with the oropharyngeal wall) to avoid leakage of the food bolus to the nasal cavities, and therefore to the pharynx while the airways are still open. Finally, the tongue base contracts, and the food bolus slides to the pillars of the veil. The patient must strongly block their breathing before swallowing, which produces an early adduction of the vocal cords before swallowing.

An unchanging coordination is well defined in order to avoid choking of the element being swallowed the wrong way (Figure 2.3 everydayhealth (2017)).

2.2 Dysphagia

Dysphagia or swallowing disorder is a defect of protection of the airway during the passage of the alimentary bolus towards the oesophagus. It results in a swallowing

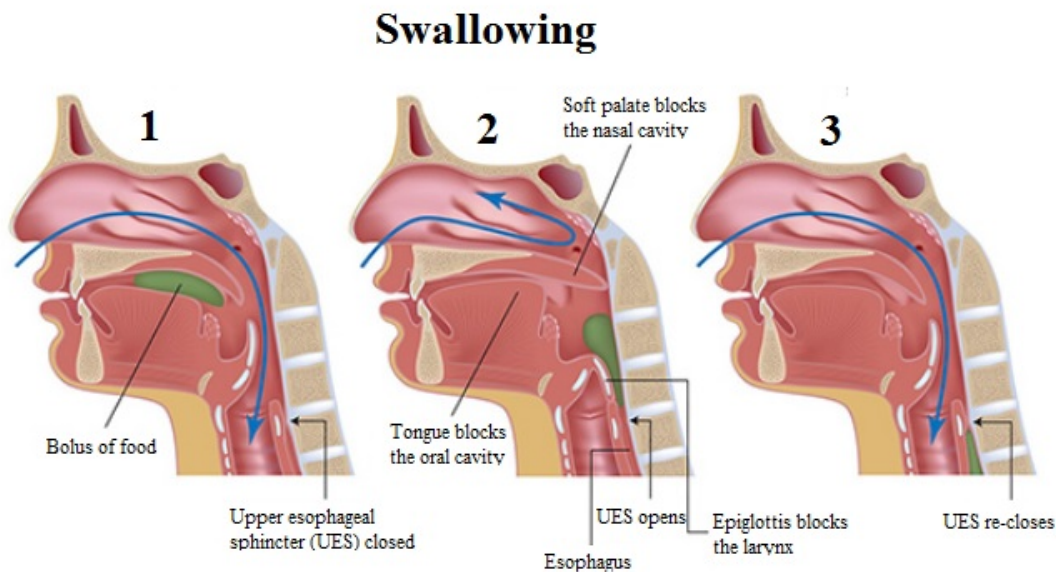


Figure 2.3: Lateral view of bolus propulsion during swallowing

choking incident or inhalation of food in the airway, and a disorder of the transit of the alimentary bolus towards the oesophagus, leaving residues in the pharynx, which can lead to a secondary swallow choking incident. Dysphagia can be also manifested by difficulties of transport of the bolus into the oesophagus. The etiology of swallowing disorders is very varied insofar as any damage to the anatomical structures of the aerodigestive junction or structures allowing the neurological control of swallowing can be involved. The etiology of dysphagia is dominated by neurological and tumoral pathologies of aerodigestive tract or brain tumors affecting swallowing functionality.

Two types of dysphagia are distinguished; oropharyngeal and oesophageal dysphagia. Oropharyngeal dysphagia is defined as the difficulty of transferring the bolus from the mouth to the pharynx and the oesophagus. As for oesophageal dysphagia, this occurs during the third phase of the swallowing process whereby there is difficulty in passage of the bolus along the oesophagus to the stomach. Dysphagia can manifest in the form of a blockage to the passage of foods (stasis), a slowing down in the progression of the food bolus or in a lack of coordination of breathing and swallowing. In all these cases, aspiration can occur.

There are four different types of aspiration:

1. the aspiration before swallowing when the bolus passes before the swallowing reflex is triggered and this results in the absence of the swallowing reflex

(when the bolus slides on the base of the tongue, but the absence of swallowing reflex does not trigger the closure of the larynx, which remains open, and therefore the respiratory function is active, and the aspiration occurs after accumulations of food in the pharynx). This absence of swallowing reflex results in neuromotive disorganisation of this reflex. The aspiration can also occur due to a delayed swallowing reflex. In such cases, the swallowing reflex is slow to trigger, the bolus has time to flow on the base of the tongue and fill the bottom of the pharynx before swallowing is triggered.

2. Aspiration during swallowing when laryngeal protective structures are deficient.
3. Aspiration after swallowing (secondary or indirect aspiration) that occurs upon resumption of breathing, leading to food stasis in the trachea or nasal fossa.
4. Eventually, the most dangerous of aspiration is the silent one, which can occur before, during or after swallowing and does not cause reflex coughing. 71% of silent aspiration were found in elderly patients hospitalized in a long stay with acquired community pneumonia, compared to 10% for control population without pneumonia in a control study Marik and Kaplan (2003).

Among the clinical signs of the aspiration is the reflex cough that may be absent (as in the case of silent aspiration), only coincidental and not very effective in clearing the channel if blocked. The alteration of the voice too can be a sign of aspiration. In addition, pain during food intake, vomiting, weight loss and recurrent pneumopathies. Short-term complications can result in aspiration, respiratory complications, suffocation and severe lung infection. In the long term, the person expresses his disinterest and anxiety about the meal and its duration, which may be longer than normal DePippo, Holas, and Reding (1994) and Deborah J. C. Ramsey and Kalra (2003), which causes chronic malnutrition and inflammation of the lungs. Swallowing disorders in a chronic context may be related to chronic diseases such as stroke, degenerative diseases such as Alzheimer's and Parkinson's, Oto-Rhino-Laryngology surgery, drugs and aging structures and functions (presbyphagia).

Occasional difficulty in swallowing, which may occur when a person eats too fast or does not chew the food well is not a cause for concern. However, when it is persistent, it may indicate a serious medical condition requiring treatment and functional

rehabilitation. Persistent swallowing disorders cause many inconveniences, ranging from the deterioration of the quality of life of the patient to the risk of death Schmidt et al. (1994). The majority of dysphagic cases often remain undiagnosed and are therefore not treated. An undetected, untreated or inadequate swallowing disorder definitely leads to malnutrition and/or dehydration, the consequences of which pose a risk of serious harm to the person. In fact, when swallowing is no longer safe, the person experiences the pain of physical and social disability response to the loss of the pleasure of eating and drinking, and anorexia. The person may also have anxiousness associated with meals for themselves and for their relatives because of, for example, the drooling during food intake which consequently leads to social isolation.

2.2.1 Etiology of Dysphagia

The etiologies of swallowing disorders are numerous and its treatment depends on the cause. Dysphagia can result from a wide variety of diseases and disorders listed below.

Oral pathologies

Pathology affecting teeth, such as infection or caries, can also affect mastication of food. A congenital anomaly can also be one cause of dysphagia such as the malformation of the oesophagus, Leflot et al. (2005), cleft lip and palate Tanaka et al. (2012) causing food and fluids drooling and reflux into nasal fossae when swallowing and the formation of bolus is also impaired. Upper oesophageal sphincter (UES) dysfunction is the leading cause of pharyngeal dysphagia such as failure of UES relaxation which is a motor disorder Cook (2006).

Xerostomia is also known as a cause of abnormally low volume of saliva which causes dysphagia. Furthermore, it causes the loss of the antibacterial protection that saliva affords. A person with xerostomia is more at risk of aspiration pneumonia if aspiration occurs due to a higher oral bacterial load Rofes et al. (2011).

Obstructions and diverticula

Obstructions, which can be caused by different conditions such as tumours of the head and/or neck, can cause swallowing difficulties since tumours can affect the

motility of structures involved in swallowing Logemann et al. (2006). Directly, if there exists a tumour in the neck in the form of obstructions blocking the tract of the bolus through the oral cavity or/and the pharynx. Indirectly, if there exists a tumour in the head causing damage to the nerves of oral cavity or pharynx Pauloski et al. (2000). Diverticula of the pharyngeal and oesophagus mucosa, pouches that protrude outward in a weak portion of the pharynx or oesophageal lining, are also a cause of dysphagia, namely Zenker's diverticulum Sasegbon and Hamdy (2017), which is located just above the cricopharyngeal muscle causing complications that include aspiration and pneumonia Bergeron, Long, and Chhetri (2012) and Jonathan M. Bock and Blumin (2012).

Medications

Medications can be the origin of dysphagia. A recent study showed that up to 64% of patients with xerostomia take medications which cause this xerostomia Guggenheimer and MOORE (2003). Chemical radiotherapy of head and neck cancers often results in delayed swallowing, decreased pharyngeal transport, and inefficient laryngeal protection Eisbruch et al. (2002) and Grobbelaar et al. (2004). In 2007, Elting et al. (2007) presented their study on a group of 204 patients receiving radiotherapy (RT) to head and neck primary cancers and showed that 91% of these patients developed oral mucositis, which is manifested by a painful swelling of the mucous membranes lining the digestive tract, which can lead to a different form of swallowing difficulties during mastication or the different stages of swallowing. Also, 50% of the general elderly population use at least one anticholinergic medication Mulsant et al. (2003) which is well recognised as a common cause of xerostomia Bostock and McDonald (2016). Another study showed that dysphagia in Parkinson's patients is induced by some medications Leopold (1996) causing abnormalities during all swallowing stages.

Neurological diseases

Neurological conditions that cause damage to the brain and nervous system can cause dysphagia, such as Parkinson's disease and dementia Easterling and Robbins (2008) and Coates and Bakheit (1997), Huntington disease, Alzheimer's dementia Secil et al. (2016), cerebral tumours Frank et al. (1989), stroke Paciaroni et al. (2004), cranial pairs damages and some sequelae of neurological interventions. Kalf and al.

Kalf et al. (2011) showed that the presence of oropharyngeal disease after stroke can be as high as 82%. Stroke is also known as the most common cause of oropharyngeal disease of acute onset Daniels (2006).

The most common cause of dysphagia is stroke. In France, one stroke occurs every 4 minutes, which implies 13 000 hospitalisations per year. Stroke causes severe sequelae. It represents the first cause of acquired handicap of the adult Santé (2012). Previous studies have suggested that complications in hospitalised stroke patients are frequent ranging from 40% to 96% of patients Langhorne et al. (2000). Dysphagia are frequent and are estimated at 42 to 76% following an acute stroke Group (1999) and Zhou (2009). Many studies have attempted to establish the incidence of dysphagia after stroke with values ranging from 23% to 50% Singh and Hamdy (2006). Available statistics differ from one study to another, but their frequency seems high. In terms of economics, the hospitalisation of stroke patients is very expensive for health insurance-social security because the stroke is 100% covered by social security from the moment it is considered debilitating.

Swallowing is a complex process which requires the intervention of several muscles and cranial nerves with a very precise temporal coordination.

2.2.2 Semiology of dysphagia

Semiology is the study of the signs of diseases and so helps guide the diagnosis. For dysphagia, there is a specific semiology determining the physio-pathological mechanisms of the swallowing disorder. Swallowing disorder or dysphagia is defined as difficulty of synchronisation between the progression of the alimentary bolus to the oesophagus and the protection of the airways, or / and mastication disorder.

Dysphagia is common in human pathology and can be caused by a variety of diseases affecting neural, motor and/or sensory systems that contribute to the swallowing function. It is due in a large number of cases to neurological damage Mann, Hankey, and Cameron (2000) and Counter and Ong (2018). Swallowing disorders can be described chronologically by classifying the various mechanisms according to airways protection defects and bolus transportation defects. Below are described the pathophysiological mechanisms present chronologically Bassols and Puech (2011):

- During the preparatory phase
 - Defect of contention:

- * Forward: default of lip closure,
 - * Backward: default of oropharyngeal closure
- Insalivation disorders
- Chewing disorders
- During the oral transport phase
 - Disorders of initiation of oral time
 - Failure to close the oral cavity:
 - * Anterior
 - * Posterior
 - Bolus control defects in the oral cavity
 - Bolus propulsion default
 - Default of initiation of pharyngeal time
 - Failure to trigger pharyngeal time
- During the pharyngeal phase
 - Failure to protect the airways
 - * Upper = Default of velopharyngeal closure
 - * Lower =
 - Default of laryngeal closure
 - Default of expulsion mechanisms
 - Pharyngeal transport defects:
 - * Failure of pharyngeal peristalsis
 - * Default of basi-lingual decline
 - Dysfunction of the sphincter of the oesophagus
- During oesophageal time
 - Default of expulsion mechanisms

Swallowing disorders include several symptoms such as coughing, voice modification and prolonged mealtimes. Dysphagia may not be accompanied by cough in many cases but is silent. Signs suggestive of swallowing disorder may be listed using a swallowing disorders scorecard (Annex 1) Desport et al. (2011).

Drooling of food or liquids can be at the level of the mouth, for example due to insufficient labial closure, or by the nose. When the patient cannot keep the food bolus long enough in the mouth, the bolus can slip into the oropharynx prematurely before triggering the swallowing reflex. Food residues may persist in the mouth after swallowing and then the already swallowed bolus may sometimes regurgitate from the oesophagus to the mouth. The duration of the meal or mastication may be prolonged and a change in the voice may occur during swallowing. Other signs may give evidence of swallowing disorders such as alteration of breathing rhythm or coughing during a meal, and also a progressive change in the type of texture accepted by the patient.

As mentioned above, swallowing is the transport of food from the oral cavity to the stomach. Knowledge of the anatomical structures involved and their physiology is necessary for the assessment and management of swallowing disorders caused mainly by neurological disorders. To study and monitor the swallowing process, several studies have been proposed by processing different signals, several of which are presented in the following chapter.

Chapter 3

State-of-the-art

The state-of-the-art of this thesis is multidisciplinary because the monitoring of swallowing can be made using several modalities. First, the clinical screening modalities of dysphagia will be presented continuing with the state-of-the-art in the technical field. Thereafter, more detail on the state-of-the-art of sound recognition and the analysis of the breathing signal will be set because these are the two modalities used in this work.

3.1 Screening for dysphagia

The clinical dysphagia examination demonstrates multiple abnormalities including slowed, laboured feeding, inefficient mastication and impaired lingual motility Leopold and Kagel (1996), Bushmann et al. (1989), and Athlin et al. (1989).

The material being swallowed is a critical factor in determining the type of swallow. Increased volume to be swallowed has an impact on the duration and width of opening of the upper oesophageal sphincter as well as the duration of airways closure increase Logemann (2007). Dividing the liquid into two or more segments or piecemeal deglutition was observed in normal subjects after 20 ml volume of water. However, patients with neurogenic dysphagia are obliged to divide the bolus into two or more swallows successively, below the 20 ml volume of drinking water Ertekin and Aydogdu (2003).

Swallowing assessment can be carried out in different ways in order to identify any sign of dysphagia, including careful questioning and physical examination. There are three types of clinical tests: tests with food intake, tests with no food intake which are generally a food choking predictive score and others combining tests with

and without food intake. The general clinical examination, guided by the interrogation, will begin looking for a pathology of the cardiorespiratory, cervico-thoracic or neurological sphere. Particular attention will be paid to the examination of the oro-facial sphere. Thus, the following will be evaluated successively: oral hygiene, salivation, motor skills and the sensitivity of the bucco-facial sphere, oral and facial praxies and the possibility of performing voluntary actions such as swallowing saliva or coughing. If necessary, an observation of the patient during a meal or during a swallowing attempt may complete the assessment.

The interview with the patient and / or the companion/carer of the patient is fundamental and crucial. It is the clinical non-instrumental evaluation of the dysphagic patient which is called also "bedside examination". It facilitates the understanding and identifying of the signs of swallowing disorders. Anamnesis by means of questionnaire obtaining all relevant information from the patient and his entourage about the history of the disorders or the circumstances that preceded it. A simple grid (Annex) was proposed by Desport et al. (2011) which contains different questions to ask the patient such as: with which food(s) do you encounter difficulties? Are there foods you avoid? Do you ever choke on food? How much time do you take to eat your meal? Do you lose weight? Do you have frequent lung infections? By this questions doctors can notice the texture causing swallowing disorders, characteristics of altered voice and some features related to food intake such as meal duration, food choking location, food reflux, head posture during meal, etc. . .

In the clinic, standard swallowing screening is set up using instrumental methods. Clinical examination is to record the physical signs. The primary tool for swallowing assessment is Cervical Auscultation (CA). CA is noninvasive tool that uses a stethoscope to detect cervical sounds during swallowing or breathing sounds. CA is adopted by dysphagia clinicians as a tool for swallowing evaluation. It enables estimation of some dysphagic conditions such as aspiration Takahashi, Groher, and Michi (1994b) and Takahashi, Groher, and Michi (1994a). Sensitivities and specificities of CA in detecting dysphagic conditions varied widely among several studies. A sensitivity varying from 23% to 94% and a specificity varying from 50% to 74% Lagarde, Kamalski, and Engel-Hoek (2015) and Nozue et al. (2017). These wide variations among the CA studies are caused by the differences of targeted sounds. CA is a technique which assesses the sounds of swallowing and swallowing related breathing. Some studies focused on expiratory sounds before and after swallow Zenner,

Losinski, and Mills (1995) and HIRANO et al. (2001). Other researchers have focused just on the swallowing sound Bergstrom, Svensson, and Hartelius (2013), Stroud, Lawrie, and Wiles (2002), and Santamato et al. (2009). Fiberoptic Endoscopic Evaluation of Swallowing (FEES) Langmore, Schatz, and Olsen (1988) and Nacci et al. (2008) is another method used for studying swallowing disorders enabling the examination of the motor and sensory functions of swallowing. It is a method which involves the passing of a thin flexible scope through the nose to the pharynx. FEES is an invasive tool and it can result in some complications such as discomfort of patient, vomiting and in some cases laryngospasm Aviv et al. (2000).

The instrumental method currently considered as the “gold standard” for studying swallowing is videofluoroscopy Palmer et al. (1993). Videofluoroscopy enables the observation and filming in real-time of the swallowing process using X-ray in order to follow the bolus coated with a barium that enables its outlines to become visible during the phases of swallowing as it is viewed by this process. Videofluoroscopy makes the entire swallowing process visible. Videofluoroscopy Swallowing Study (VFSS) is widely used in the field of dysphagia management. It is very effective in diagnosing dysphagia in order to decrease the risk of aspiration and food choking. In case of difficult swallowing, it allows to determine quite precisely the cause of the dysphagia and in case of penetration of food in airways, it allows to determine how much material has entered the airways, at what level, when, and how the patient reacts Martin-Harris and Jones (2008). It makes it possible to detect silent choking food and to test textures and positions. VFSS is an invasive examination with radiation exposure to the patients through fluoroscopic procedures however it allows the diagnosis of the swallowing process in the presence of the patient and the responsible medical staff.

Different screening tests for swallowing disorders have been developed including the 3 Oz Water Swallow Test, the swallowing test of 50 ml of water, validated by Depippo in the context of stroke DePippo, Holas, and Reding (1993). The 3 Oz Water Swallow Test is considered perfectly adapted to the post-stroke population Bassols and Puech (2011). Gordon, Hewer, and Wade (1987) have defined dysphagic individuals as those who could not drink 50ml of water or who coughed more than once after completion of the water swallow test, in a study of patients in the acute phase of stroke. They found that 45% of patients were dysphagic on admission. Many other tests have been developed in order to improve the Depippo test DePippo, Holas, and

Reding (1993) by examining the validity of volume used, the proposed texture and the effectiveness of the indicators of mis-routed bolus false road including food stasis for example. Many other tests have been developed in order to answer these questions e.g. the Gugging Swallowing Screen (GUSS) Trapl-Grundschober et al. (2007) and John and Berger (2015) as developed in 2006 at the Landeskrankenhaus Donau-Region Gugging in cooperation with the Department for Clinical Neurosciences and Preventive Medicine of the Danube University Krems in Austria. The test starts with saliva swallowing followed by swallowing of semiliquid, fluid and solid textures. The GUSS is divided into 2 parts; the preliminary assessment or indirect swallowing test, subset 1, and the direct swallowing test which consists of 3 subsets. Sequentially performed, in the indirect swallowing test, saliva swallow has been realised because most patients are often unable to sense such a small amount of water. Patients who are unable to produce enough saliva because of dry mouth are given saliva spray as a substitute. Vigilance, voluntary cough, throat clearing, and saliva swallowing are assessed. This subset is set up according to most swallowing tests and, researchers start with a specified quantity of water, the smallest used volume is 1 ml in the bedside test of Logemann, Veis, and Colangelo (1999) and Daniels et al. (1998). In the indirect swallowing test, swallowing is sequentially performed starting by semiliquid, then liquid and finally solid textures. During the four subsets, vigilance, voluntary and/or involuntary cough, drooling and voice change are assessed. The evaluation is based on a point system and, for each subset a maximum of 5 points can be reached. Twenty points are the highest score that a patient can reach and indicate the swallowing ability without a choking food risk. Then, four levels of severity can be determined as follows: i) 0-9 points: severe dysphagia and high risk of aspiration, ii) 10-14 points: moderate dysphagia and moderate risk of aspiration, iii) 15-19 points: mild dysphagia and mild risk of aspiration, iv) 20 points: normal swallowing ability. According to the test result, different diet recommendations are given.

The Toronto Bedside Swallowing Screening Test (TOR-BSST) is also a dysphagia screening tool. It is a psychometric study published by Martino et al. (2008). The TOR-BSST was tested on 311 stroke patients which demonstrated a validity with sensitivity at 91.3% and negative predictive values at 93.3% in acute and 89.5% in rehabilitation settings. TOR-BSST contains 5 items including test of voice, lingual

motricity and sensitivity of the posterior wall of the throat, following by water intake; the patient is asked to swallow ten boluses of 5ml of water in a teaspoon followed by a sip from a cup. The patient is asked to say “ah” after each swallow. If any voice alteration or coughing occurs, test is immediately stopped for the patient’s safety.

Another screening test for dysphagia has been developed: the timed swallow test Nathadwarawala, Nicklin, and Wiles (1992). The test was designed for use in patients with neurologic dysphagia. In regard to calculating swallowing speed (ml/s), it has been demonstrated that it is independent of flavour or temperature. Swallowing speed ≤ 10 mm/s is considered as an index of abnormal swallowing. The swallowing speed test had a sensitivity of 96% and a specificity of 69%. During this test, the subject was asked to drink 150 ml of cold tap water from a standard glass. Patients who have swallowing difficulties receive less water. The subject is asked to drink the water as quickly as possible, but to stop immediately if difficulties arise.

Incidence of aspiration in patients with tracheostomies or endotracheal tube in place was studied using the Evans blue dye test G (1977) and Cameron, Reynolds, and Zuidema (1973). This test applies 4 drops of 1% solution of Evans blue dye on the tongue every 4 hours with tracheal suctioning at set intervals. The presence of the dye upon suctioning was considered as an evidence of aspiration. This procedure was modified by mixing foods and liquids with the dye, giving the modified Evan’s Blue Dye (MEBD) Thompson-Henry and Braddock (1995).

Another model of food choking screening, is the Practical Aspiration Screening Schema (PASS), was proposed by Zhou (2009); this requires 3-oz water to be Swallowed DePippo, Holas, and Reding (1993). The test was presented as a predictive clinical scale for food choking (Echelles Cliniques Prédictives de Fausse Route (ECPFR)), which includes primitive reflexes, voluntary swallowing, laryngeal blocking and a total score ranging from 0 to 42 points (Annex) Guinvarc’h et al. (1998). It makes it possible to detect food choking incidents with a high sensitivity of 89% and accurate rate of specificity of 81%.

All the tests cited below are used as a diagnostic tool to identify dysphagic patients who are aspirating and who need further clinical assessment. Strategies include different dietary patterns that can be distinguished according to their modalities which are non-invasive methods through viscosity, volume and consistency of foods and liquids Bisch et al. (1994), Reimers-Neils, Logemann, and Larson (1994),

Raut, McKee, and Johnston (2001), and Steele et al. (2014), postural adaptation Alghadir et al. (2017), Md et al. (2011), Bisch et al. (1994), and Welch et al. (1993) and, invasive methods as the non-oral nutrition using a nasogastric tube or a gastrostomy Pearce and Duncan (2002).

Screening tests for swallowing disorders vary from one study to another, ranging from a simple questionnaire to a real medical diagnosis with or without food intake. The questionnaires proposed in some studies give an idea of the presence or not of a swallowing problem, but they are not precise. The tests with food intake are controlled (volumes, textures), which are not as varied as the typical range and amount of daily food intake in real life. Medical means are precise, but they can not be used at home for continuous monitoring of the swallowing process. These modalities have not the potential to prevent food choking in real life. Then, the scientific community has been interested in physiological signals using several sensors.

3.2 Swallowing Monitoring Modalities

The use of physiological signals such as sounds, EMG, videos, radiography, etc..., is widespread in the field of dysphagia. The literature is dense with measurement methods and studies used to establish a strong understanding of the nature of swallowing disorders and estimate the degree of abnormalities.

Cook et al. (1989) proposed to evaluate and quantify the timing of events associated with the oral and pharyngeal phases of liquid swallows using video-radiographic, electromyographic and manometric methods. The study, through healthy subjects, finds that there are two types of swallow according to the localisation of the bolus relative to the position of the *tongue tip* and the *tongue base* movement as well as superior *hyoid* movement and *mylohyoid* myoelectric activity during swallowing triggering. The common “incisor-type” swallow starts with the bolus positioned on the tongue with the *tongue tip* pressed against the *upper incisors* and *maxillary alveolar ridge*. The “dipper-type” swallow corresponds to a bolus located beneath the *anterior tongue* and the *tongue tip* scooping the bolus to a supralingual location. Timing of events during the oral and pharyngeal phases of swallowing for graded bolus volumes shows an increasing time for both types of swallow. A timing of glottic closure during swallowing was also studied by Daele et al. (2005) through an electromyographic and endoscopic analysis. It was noticed that arytenoid movement

consistently preceded full glottis closure and was associated with the cessation of activity of the posterior *cricothyroid* muscle. An early closure of vocal folds occurs during super-supraglottic swallow. The use of video radiography is considered as a reference in relation to electromyographic and manometric signals, which are considered more or less invasive.

Using simultaneously electrocardiogram signals and swallowing movements with a thin wallet rubber capsule fixed on the neck above the *thyroid cartilage*, Sherozia, Ermishkin, and Lukoshkova (2003) showed that swallowing induced tachycardiac responses, a marked increase in heart rate. Signals were acquired in 23 healthy subjects. Deglutition tachycardia was clearly observed in 21 subjects. In the two remaining subjects, tachycardia induced by the first swallow was masked by respiratory arrhythmia. However, even with this case, heart rate changes associated with swallowing were successfully revealed. Swallowing is considered then as a stimulus which disturbs the autonomic regulation of the heart for a short time, but, are there other mechanisms generating the same effect such as movement ?

A study conducted in 1986 by Armstrong, McMillan, and Simon (1985) investigated the link between swallowing and syncope assuming that swallowing is in some cases the cause of syncope. They presented five cases through patients having a spectrum of gastrointestinal tract or cardiovascular disease. For each presented case, there was a clear association between swallowing and syncope. The different electrocardiograms showed a period of asystole during swallowing. ECG showed complete atrioventricular block with 4.5 seconds period of asystole while the patient (58-year-old woman presented with an 8-year history of a "seizure disorder") was drinking hot water. The same interpretation was seen with a 53-year-old man suffering from myocardial infarction complicated by ventricular fibrillation and atrioventricular block; the cardiograph showed 7 seconds of asystole and a high-degree atrioventricular block, while drinking ice water during near syncope. Medical observations of the cardiac behaviour of different cases during swallowing are strongly linked, but there is no explanation of the neurological process. This hypothesis has not been investigated from a signal processing and comparison point of view between healthy and patient subjects. For unhealthy subjects this may lead to another way of identifying the source of the disease. Cardiac behaviour can be monitored. Today, there are mobile sensors capable of continuously recording cardiac signals such as the "eMotion mobile FAROS sensor".

Dynamic swallowing MRI has been used to visualize anatomical details, soft tissues and their movements as well as the path of the food bolus. Its temporal resolution is less interesting than in videofluoroscopy. On the other hand, this examination can be non-irradiating. Its application to the analysis of physiology and the pathophysiology of swallowing has been the subject of work for some twenty years DM et al. (2003).

Maniere-Ezvan, Duval, and Darnault (1993) examined the *tongue* muscle structure using real time ultrasound performed using the *sub-hyoid* approach. The study was performed on 30 subjects. It consists of scanning the *tongue* at rest and swallowing mechanism with and without a liquid bolus. Examining static and dynamic ultrasound images, they can differentiate between different structures. They find that the movement of the *tongue* is variable in form and amplitude depending on the subject. Synthetic analysis shows that the *tongue* changes shape and gives successive pushes to the bolus from pressing *tongue tip* against the palate to changing the form of the lingual base to push the bolus into the *oropharynx*.

Using the same technique, real time ultrasound, Shawker et al. (1983) showed swallowing in eight healthy subjects and one neurologically impaired patient with dysphagia and chronic aspiration. Initially, the subject was asked to keep his *tongue* on the floor of the mouth and keep it motionless for 10 seconds followed by a single swallow of 5 cc of water after holding it in the front of the mouth. Resting mid-tongue thickness and timing of events during single swallow was then studied and compared between healthy and pathologic patients. Average length of the *tongue* in normal patients was 7.3 ± 0.2 cm and the height and length of the bolus in the midtongue position in five healthy volunteers was 1.3 cm and 1.9 cm respectively. However, in three normal subjects the *tongue* margins were not visible enough for adequate measurement. For normal subjects, the bolus velocity was 15.1 cm/sec. the time in which the bolus reached the back of the *tongue* and the posterior *tongue* went back to its normal configuration averaged 0.72 seconds for normal subjects. In the patient who had 12th cranial nerve weakness, there was complete absence of normal tongue activity and no midtongue bolus formation or transmission. In both cases of rest and during swallowing, the *tongue* appeared generally thick. Contrary to the normal case, the *hyoid* was visible in the scanning plan during rest and during swallowing which suggests an abnormal elevation. Also the swallowing process

was markedly prolonged. Using real time ultrasound, Stone and Shawker (1986) focused on *tongue* movement during swallowing. They calculated *tongue* length during swallowing with six female adults aged between 20 and 40 years old. To do this, they fixed a pellet 4.5 cm back on the protruded *tongue* and they added the posterior *tongue* length to get total *tongue* length. Distances were obtained through ultrasound scanner in the midsagittal plane. The movement of the pellet was divided into four stages according to its path: forward, upward, steady and downward. A large variability of swallowing patterns was observed through these experiments. Average *hyoid* timing of 24 swallows was calculated: ascending movement time was about 500 ms, *hyoid* in elevated position time duration was about 300 ms and *hyoid* descending movement was about 350 ms.

Ultrasound imaging shows good observations of the sequential movements of the *tongue* and its shape during swallowing. The static images recorded by the ultrasound scanner in real time can be analysed sequentially by the doctor responsible for monitoring the patient at risk of food choking. The intervention for the reading and interpretation of ultrasound images requires expertise for the best positioning of the probe which should be held very precisely and positioned at a well-defined location to be able to view the structures involved in the swallowing process. Ultrasound is non-invasive, but there are no automatic image analysis methods nowadays. In addition to the subjects, there is a great variability in the deformation of the *tongue* and its shape, however it is important to know if the patients studied by ultrasound had a normal or atypical swallowing mechanism.

Bulow, Olsson, and Ekberg (2002) evaluated the impact of supraglottic swallow, effortful swallow and *chin* tuck on the intrabolus pressure using simultaneously videoradiography and solid state manometry in 8 patients with different levels of pharyngeal dysfunction. Videofluoroscopic image and the manometric registration were simultaneously acquired. Three swallows were registered for each type of swallow. Supraglottic swallow, effortful swallow and *chin* tuck did not alter the peak intrabolus or duration of this pressure when measured at the level of the inferior pharyngeal constrictor. Using manometry is too invasive compared to other modalities because sensors were fixed in the food path.

Electromyography (EMG) or electroneuromyogram (ENMG) is a medical techniques used for a long time to study the function of nerves and muscles. Taking into account that muscles are controlled by a peripheral nerve ensuring the propagation

of nerve impulses, EMG enables the study of the quality of muscle contraction. It is used also to understand the swallowing process. Sochaniwskyj et al. (1987) have studied the frequency of swallowing and drooling in normal children and in children with cerebral palsy. Twelve subjects were taken from each group. For each subject, five sessions were undertaken. For each session, two phases were designed in order to determine the frequency of swallowing while the child sat quietly and watched a pre-taped television program for 15 minutes to one-half hour according to the child's attention span. The proposed tasks were i) sitting, ii) one distinct sip of 5ml of juice from a cup followed by a swallow, iii) three distinct sips of approximately 5ml of juice from a total of 15 ml, each sip followed by a swallow and iv) continuous drinking of 75ml of juice. *Infrahyoid* muscle group EMG was recorded during this period. Electromyography activity of three orofacial groups: *masseter*, *orbicularis oris* and *infrahyoid group* of muscles, was recorded via three Beckman electrode channels. Swallowing frequency was determined by a software peak detection. Drooling saliva were collected simultaneously with EMG. The correlation between the frequency of swallowing and the rate of drooling in cerebral palsy children suggests that drool is caused by both ineffective and infrequent swallowing.

In 2013, Yu et al. (2013) investigated the feasibility of surface electromyography (sEMG) as a new approach for continuously visualising muscle activity of normal swallowing. The dynamic sEMG of swallowing was recorded from three subjects without any history of swallowing disorders. A 16x6 (96 electrodes) mono-polar electromyographic electrodes grid was placed at the neck and a reference electrode placed on the right wrist. Three healthy subjects aged 23-25 were the volunteers for data acquisition. During acquisition session, the subjects were seated comfortably. First, an acquisition of sEMG signals was performed without swallowing for normalisation. Subsequently, three different swallowing exercises were performed for each subject: dry swallowing (saliva), single swallowing of 5ml of water from an open cup and single swallowing of 15ml from an open cup. Each subject carries out each exercise three times. For the swallowing of the water, the volunteer was asked to hold the water in their mouth for a while, then they swallowed it normally by holding their head forward and avoiding any movement of the head. EMG signals analysis were based on sEMG RMS calculated through a sliding window of 100ms. Figure 3.1 shows the typical sEMG RMS maps during a normal swallowing of 15ml

of water. It shows the dynamics of swallowing and the corresponding muscle contraction. Two symmetric EMG activities were located at the top of maps near the palate at the beginning of swallowing and then moved downward and the intensity of EMG activities were gradually increasing along the swallowing progress. The intensity of EMG activities was weakening gradually until it disappeared at frame 20. During swallowing 5ml of water, the location of high intensity was moving down gradually from the upper edge to the centre of the map and then disappeared. Unlike swallowing 5ml of water, dry swallow was marked by a long-lasting high intensity sEMG activity during the final stage. Variability of swallowing patterns between subjects was not too high.

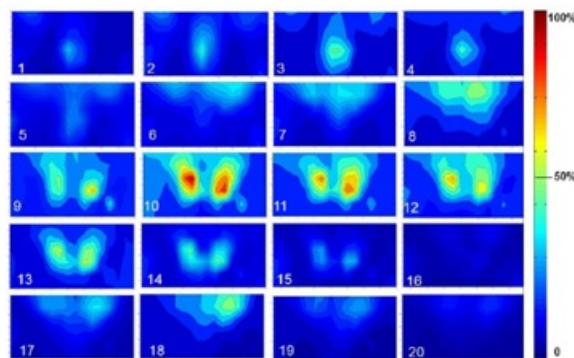


Figure 3.1: Dynamic sEMG topography in a swallowing process

In 2008, Amft and Troster (2008) studied dietary food activity using different sensors for the recognition, at once, of arm movements, chewing cycle and swallowing cycle. For arm movements, they used an inertial sensor containing an accelerometer, gyroscope and compass sensor. For chewing cycle recognition, they used an ear microphone and finally for swallowing process recognition, he used both the stethoscope and electromyographic electrodes (EMG) attached at the *infrahyoid throat* position. The approach for the detection and classification of food activities is based on three main steps: an explicit segmentation of signals to define the search limits, an event detection using an algorithm extraction similarity characteristics, defining dynamically the size of the observation, and a selective fusion of detection results using independent sources of error to filter false positives and obtain a classification of events. After processing, they concluded from first trials that EMG is disrupted by different muscles activations, regardless of swallowing, as the muscle studied (*hyoid muscle*) is covered by several muscle layers. Thus, they preferred simple activity detection using time domain characteristics such as signal peaks. Their findings report

high accuracy for body movements and chewing sound identification but swallowing requires more investigation. Sample recognition rates were 79% for movements, 86% for chewing and 70% for swallowing. The recognition rate of swallowing was 68% for the fusion approach of EMG and sound versus 75% for EMG alone and 66% for sound alone.

In their previous work of 2006, Amft and Troster (2006) proposed almost the same investigation on the detection and classification of normal swallowing from muscle activation and sound acquired respectively by electromyography and a microphone posed on the sternal head (sternal fork). They compare methods for detecting an individual event of swallowing in order to separate swallowing events from the sound of the sensor used and the daily activities and various functions of the *pharynx*. In addition, they present a comparison of the classifiers (Linear Discriminant Analysis (LDA), K-nearest Neighbour (KNN) and Hidden Markov Models (HMMs)) of the properties of the deglutition event: volume and viscosity. They recorded sEMG to capture the variability of volume viscosity and sound to analyse volume variability and pharyngeal density. Two classes of low and high volume as well as viscosity were considered because of the weak performance obtained when using three classes of each. The classification revealed that the sound provides important discrimination for the volume as well as for the viscosity. But the classification result from EMG was weak for both and best result was achieved using fusion data EMG and sound.

The surface electromyography method in swallowing study has some limitations. The swallowing mechanism involves the coordination of a surface and deep muscles group. This method does not record the electrical activities of the deep muscles, which is also a major criterion in the choice of muscles considered in the studies. The use of surface EMG can also lead to signal cancellation. In fact, a part of the EMG signal is lost leading to an underestimation of muscle electrical activity Farina, Merletti, and Enoka (2004) and Keenan et al. (2005).

Huckabee et al. (2005) and Huckabee and Steele (2006) evaluated the forced swallowing manœuvre on pharyngeal pressure and surface electromyographic amplitude under the *chin* by studying the influence of the *tongue* on the contractions of the *chin* muscles and the oral and pharyngeal pressure. They used three pressure sensors placed at the level of the *oesophagus* with a manometric catheter and a pair of bipolar surface electrodes at the molars under the mandible. Forced deglutition is

applied according to two strategies. The first consists of applying force with the neck during swallowing (“as you swallow, I want you to squeeze hard with the muscles of your throat, but do not use your *tongue* to generate extra strength”) this is called the Mendelson’s manoeuvre. The second strategy consists to apply force with the *tongue* against the *soft palate* (“as you swallow push really hard with your tongue”). Forced swallowing is a compensatory technique and a therapeutic technique for the management of swallowing disorders such as the Mendelson maneuver which consists of maintaining the *larynx* for a few seconds at the highest position in the neck by voluntary muscular contractions. Maintaining the *larynx* at the upper level simultaneously means a wider opening of the *upper oesophageal sphincter*. For experimental editing of data acquisition, there were finally three exercises; the first was normal swallow swallowing, the second was forced swallowing of saliva by applying a force from the base of the *tongue* to the *soft palate* during swallowing, and the last was Mendelson’s manoeuvre. Data collection is performed during two sessions per participant (for forced swallowing) to account for intersessional variability. The effortless swallowing of saliva is considered as a reference exercise in this study. No significant statistical difference was observed in the intersessional pressure (amplitudes) between the different positions (mid-pharyngeal, post-pharyngeal and upper oesophageal sphincter (UES)) for non-forced swallowing. To evaluate the effect of the two strategies of forced swallowing (applying basilingual force and applying the Mendelson’s manoeuvre), they used the general ANOVA model. In fact, there was a statistically significant effect for five variables (Surface Electromyography, Midline Pressure, Posterior Tongue Pressure, Upper Pharyngeal Pressure, Lower Pharyngeal Pressure). In any case, the strategy of force applied by the *tongue* against the *soft palate* produces a significant change in normal swallowing pressure. Electromyographic recordings were also significantly higher during the Forced Tongue Palate strategy, which confirms that the activity detected by electromyography is not specific to the muscles of the sub-chin guard but also includes intrinsic lingual activity.

In the same approximation, Ding et al. (2002) studied the difference between two types of swallowing, normal and forced, using the Mendelson’s manoeuvre, in healthy subjects. The signals studied were acquired via electromyography and electroglottography (EGG) in order to record laryngeal displacement and muscle activity respectively. Electromyography was measured from five groups of muscles (upper and lower *orbicularis*, *masseter*, *submental* and *hyoid* muscles). As a result, they

found that there is a temporal relationship between *submental* muscle activity and laryngeal elevation measured non-invasively by EGG. During normal swallowing, the maximum laryngeal elevation is approximately 0.5 sec (0.25-0.33 sec), while the Mendelson's manoeuvre is extended and the *cricopharyngeal* opening is at its widest. The limits of each EMG activity of each muscle group and the EGG were manually established on the signals. The relevant EMG variables are: the maximum amplitude of each electrode during swallowing, the average amplitude of EMG activity at each electrode location and the duration of EMG activity at each electrode location. ANOVA analysis of variance was carried out for the measurements of the different retained variables of the EMG of the different groups of muscles.

Lapatki et al. (2004) developed a small sEMG electrode mounted on a thin flexible electrode grid that can be easily attached to the skin. In 2005, they conducted a study Lapatki et al. (2006) to characterise the motor activity of the *chin musculature* by an analysis of the action potential of the motor unit by selective contractions via a grid of 120 electromyographic electrodes. The analysis of the acquired data was based on spatio-temporal amplitude characteristics. In addition, in their 2010 study Lapatki et al. (2009), suggested optimal locations for bipolar electrodes in the lower facial muscles. The optimal position for a bipolar electrode was the location on the muscle where the sEMG signal with the maximal amplitude was registered. The recommended position of a bipolar electrode is in the upper portion of the *depressor anguli oris*. Note that the studies of Lapatki et al. (2004), Lapatki et al. (2006), and Lapatki et al. (2009) did not aim to study in particular the problem of swallowing, but rather to evaluate the sEMG material that he designed on the facial musculature. Similarly, Guzman-Venegas, Biotti, and Rosa (2015) showed that the *masseter* activity is organised into three functional compartments anterior, middle anterior and posterior, three positions relative to the location of the EMG grid.

Stepp (2012) presented a comprehensive study of the system of swallowing and speech using sEMG, a non-invasive method providing real-time muscle activation information. The sEMG signal is often referred to as an interference signal presenting the overall activity of the muscles and containing a variety of parameters (amplitude, frequency, etc.), that can be estimated from the raw signal commonly used to obtain more reliable information on specific functions like speech and swallowing.

Ertekin and Aydogdu (2003) presented a revue of studies dedicated to the neurophysiology of oropharyngeal swallowing. The sequential and orderly activation

of the muscles of the swallowing can be recorded during swallowing. The *masseter* muscle is the first activated in EMG during the oral phase Murray, Larson, and Logemann (1998). In fact, in normal subjects, *orbicularis oris* and *buccinators* muscles firmly close the mouth to prevent drooling. Then, the *submental* muscles are subsequently activated while the *larynx* is being raised by the *hyoid* bone with the contraction of the *submental/suprahyoid* muscles. It was observed that *perioral* muscle activity is ended just before the pharyngeal phase of swallowing. However, *masseter* activity can continue or reappear during the pharyngeal phase Stepp (2012).

In 2014, Imtiaz et al. (2014) proposed a system comprised of an Inertial Measurement Unit¹ (IMU) and an electromyography sensor able to measure the head-neck posture and the activity of the *submental* muscles during swallowing. Four healthy male subjects were included in this study. The IMU used in this investigation contained a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer. Two IMUs were used; one of which was fixed on the back of the head with a Velcro band and the second one was fixed over the seventh cervical vertebra. In addition, an EMG sensor was attached underneath the subject's *chin*, over the *suprahyoid* muscle using medical grade tape (Fig. 2.3). Five repetitions of three 10ml water swallowing actions were made at different head-neck angles. During the three trials, subjects were asked to: i) keep the head at a neural rest position facing forward, ii) rotate the head upwards to a *chin* up position and iii) rotate the head downwards to a *chin* tuck position. Orientation quaternion was calculated and converted into a rotation matrix from the IMU sensor. Then, a relative rotation matrix between both IMU sensors was converted into Tait-Bryan angles of XYZ convention, the roll, pitch and yaw angles. Acceleration norm and jerk norm were also considered. Averaged RMS error of Roll, Pitch and Yawn were calculated for all sessions and EMG RMS signals were used to identify swallowing events.

Another system has been proposed by Pehlivan et al. (1996), "Digital Phagometer", a portable electronic system. This device is composed of a piezoelectric sensor and a digital event counter/recorder. It is able to detect any upward and downward movement of the *Larynx* produced by spontaneous movements. The specially designed sensor was placed at the *coniotomy* area between *thyroid* and *cricoid* in order to control movements. For the evaluation of the deglutition frequency

¹Inertial sensor or Inertial Measurement Unit (IMU) is an electronic device that measures specific force ratios of a body, angular velocity, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, and sometimes magnetometers.

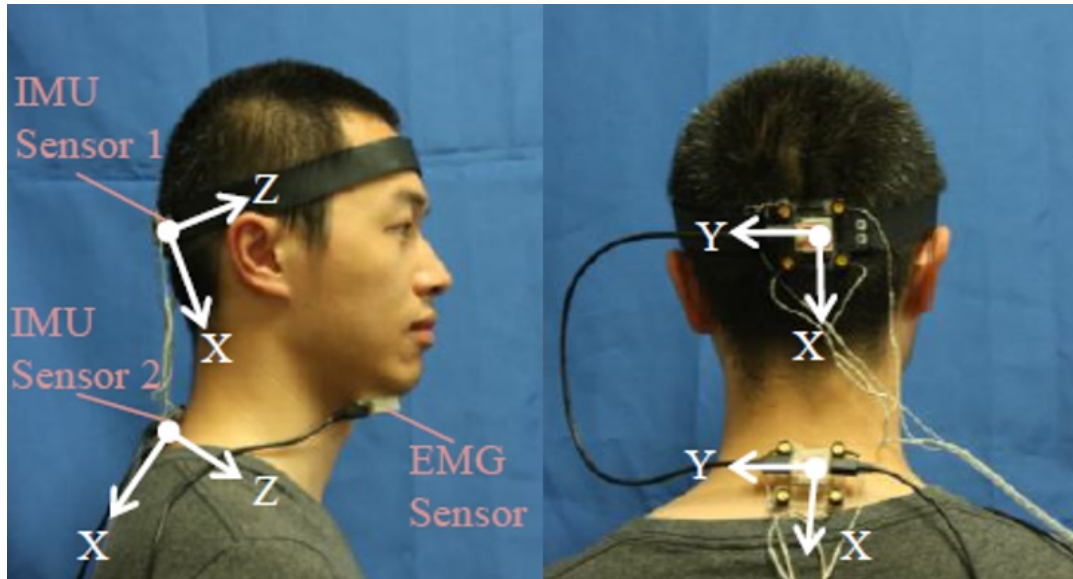


Figure 3.2: Sensor placement on the body and Frame axes

and duration, two different populations were present in this study: healthy people and Parkinsonian patients. Mean frequency of spontaneous swallow was about 1.22 ± 0.11 (mean \pm standard error mean) swallow/minute during 1 hour of awaking period. For Parkinson patients, whether complaining or not of dysphagia, mean frequency of spontaneous swallowing was significantly lower, about 0.92 ± 0.12 swallow/min. Unlike healthy subjects, Parkinson patients have been marked by a long time duration to swallow 200 ml of water.

3.3 Sound Recognition Domain

A considerable number of studies have been carried out on the sounds of swallowing thanks to its diagnostic potential. Acoustic analysis seems to be a non-invasive promising way to develop an objective measure of different swallowing sounds characteristics in order to identify swallowing events and to say if it is a normal or dysphagic swallow.

Movahedi et al. (2017) compared microphone signals and a matrix axial accelerometer in 72 patients with and without stroke, which support fluoroscopic examination. Temporal and frequency characteristics were extracted from the swallowing signal of thick liquids of different consistencies. They found that swallowing sounds had higher values for vibration frequency domain characteristics than sounds. In addition, Lempel-Ziv complexity was more effective at swallowing vibrations than at

swallowing sounds and swallowing sounds had higher deurtosis values than swallowing vibrations.

Taveira et al. (2018) evaluated the diagnostic validity of different methods for evaluating swallowing noise compared to the videofluoroscopic swallowing study for oropharyngeal dysphagia. They showed that Doppler has excellent diagnostic accuracy on the discrimination of swallowing sounds, while the microphone reported good sensitivity for the discrimination of swallowing sounds of dysphasic patients and the stethoscope showed the best screening test on the discrimination of swallowing sounds.

Anaya (2017) conducted a study in Colombia to determine the time and noise of swallowing in 306 people aged 20 to 50 years. A recording of the swallowing noise was made using a neck auscultation. The average ingestion time in this study was 0.387 second.

Hsu, Chen, and Chiu (2013) proposed a system for discriminating the severity of dysphagia for patients with myasthenia gravis. They recorded the sound of swallowing water using a non-invasive Adam's apple microphone and surface electromyography. They discriminate in severity, which makes it possible to evaluate the severity levels of dysphagia by determining the degree of severity of the pharyngeal phase disruption according to the characteristics of each swallowing phase and the onset of cough. Experimental results show that the system can provide concrete features that allow clinicians to diagnose dysphagia.

Takahashi, Groher, and Michi (1994b) attempted to provide a benchmark methodology for administering cervical auscultation. They provided information about the acoustic detector unit best suited to pick up swallowing sounds and the best cervical site to place it on the neck. Using the same site for cervical auscultation, Cichero and Murdoch (2002) provided the feasibility and the ability of cervical auscultation for the diagnosis of dysphagia. Belie, Sivertsvik, and Baerdemaeker (2003) studied the differences in chewing sounds of dry-crisps snacks by multivariate data analysis. They used foods of different textures emitted sounds were recorded using a microphone placed over the ear canal. They showed that the spectral power obtained from the chewing sounds was able to distinguish the different food textures. The best recognition rate was about 86%. Vickers (1985) showed that auditory sensations are sufficient to evaluate crispness and crunchiness. They led a study for bite sounds and chew sounds for both crispness and crunchiness. It was proved that

crispness scores were higher for bite sounds than for the chew sounds. The correlation between eating manner and individual food sounds was highly significant for both crispness and crunchiness scores.

Lazareck and Moussavi (2004b) and Lazareck and Moussavi (2004a) proposed a non-invasive and acoustic based method able to differentiate between individuals with and without dysphagia. Sounds were recorded using an accelerometer over the suprasternal notch of the trachea. 15 subjects with no history of swallowing disorders and 11 patients with different degrees of swallow disorders were included in this study. Volunteers participated in one of the two recording sessions, videofluoroscopic swallow or audiorecording session. Subjects were fed with food having three textures, "semisolid," "thick liquid," and "thin liquid" corresponding respectively to pudding, diluted pudding with milk and fruit juice. Manually annotating the beginning and end of each segment, swallowing sounds were extracted from each recording. Segmentation of swallowing segments were made using Waveform Dimension Trajectory (WDT), in which significant changes mark the boundaries of characteristic segments of the swallowing sound. Then, opening and transmission sections were identified. The opening section corresponds to the bolus entering the pharynx (the opening of the crico-pharyngeus muscle). The transmission section corresponds with the bolus traveling down the oesophagus and the return of the epiglottis. Results show that durations of opening, transmission and total sections were significantly longer for abnormal than for normal swallowing sounds, for both semisolid and thick liquid textures. Same research team, Aboofazeli and Moussavi (2004) developed an automated method based on multilayer feed forward neural networks able to decompose tracheal sound into swallowing and respiratory segments. Temporal and frequency characteristics were used as input to the neural network model such as root mean square of the signal, the average power extracted from the frequency band 150-450 Hz and waveform fractal dimension. Applying the method on 18 tracheal sound recordings obtained from seven healthy volunteers shows 91.7% of well detected swallows.

The studies above treat the swallowing sound signal as a single, undecomposed event. In 2005, as first team, Moussavi (2005) developed a method based on the Hidden Markov Model (HMM) in order to investigate different stages in swallowing sounds. In fact, they showed that a normal swallowing sound may be divided into three distinct characteristic sounds : Initial discrete sound (IDS), Bolus Transit

Sound (BTS) and Final Discrete Sound (FDS) corresponding each to a physiological swallowing step which are oral, pharyngeal and œsophageal Aboofazeli and Moussavi (2004). In Moussavi (2005), proposed automatically extracting the limits of each phase using Hidden Markov Models since swallowing sounds are non-stationary and stochastic signals. The assumptions for this model were :

- The consideration of three states similar to physiology, oral, pharyngeal and œsophageal stages,
- The current state depends only on the precedent state and not on the others,
- The transition probabilities are stationary,
- The observations are independent of past values and states.

Using the fact that Waveform Dimension Trajectory (WDT) is the best feature for classification between normal and dysphagic swallows, it was used to train the Hidden Markov Model by the initial guesses detailed above. The Viterbi algorithm was used to find the most likely states. Results show three states for all swallowing sounds of different subjects with different textures. Two years later, Aboofazeli and Moussavi (2008) presented the same Hidden Markov Model (HMM) for segmentation and classification of swallowing sounds with the same assumptions. They compared different features among Waveform Dimension Trajectory (WDT) which show the best performance in the HMM-based classification of swallowing sounds. They also tested different number of states of the HMM from 3 to 8. For the segmentation step, estimated sequences have been found applying the Viterbi algorithm. The estimated boundaries of the states were compared to the manually detected sequences; in the majority of cases using different features, the delay in detection of the beginning of the Initial Discrete Sound (IDS) occurs before the manually detected boundary. For the classification step, HMM parameters were set through the EM algorithm. Considering the entire range of swallowing sound signals, the accuracy of classification hardly reached 60%. Classification using BTS segments did not make a difference and classification using IDS segments improved the accuracy up to 84%. As a second stage of classification, classification of normal and dysphagic subjects was been set up. The subject was considered normal if more than 50% of his swallowing record was classified as normal. Otherwise he was considered as being at risk of dysphagia. All normal subjects were correctly classified except only one

healthy subject when using RMS as a characteristic feature of swallowing sounds and 8 states. When WFD or MSP1 was used, the number of misclassified raised to two.

Rempel and Moussavi (2005) investigated the effect of swallowing pudding and liquid on the breath-swallow pattern in individuals with cerebral palsy. Acoustical signals of swallow and breath were acquired. During feeding, the airflow signal was also recorded using nasal cannulae attached to a Fleisch pneumotachograph and a Validyne differential pressure transducer. Two accelerometers were attached to intercostal space in the midclavicular line to record breathing sounds and deglutition apnoea. They confirm their assumption, thirteen normal subjects aged 13-30 years without any history of swallowing disorders or lower respiratory tract infection were included in the study as controls. In addition, eight subjects aged 15-25 years affected by cerebral palsy were also included in this study. These subjects were all wheelchair users with good head control but no independent sitting ability. Three common swallow patterns in relation to the respiratory cycle were observed:

1. Inspiration– Swallow–Expiration–Inspiration (ISEI)
2. Inspiration–Expiration–Swallow–Expiration–Inspiration (IESEI)
3. Inspiration–Expiration–Swallow– Inspiration (IESI)

Occasionally, other patterns such as ISESI and ISI were observed and were considered as belonging to only one class. Results show that subjects with cerebral palsy had a significantly higher rate of post swallow inspiration than controls during the drinking of thin liquid. Furthermore, duration of deglutition apnoea was greater in cerebral palsy subjects than in controls.

In 2006, Aboofazeli and Moussavi (2006) presented an automated method for extraction of swallowing sounds in a record of the tracheal breathing and swallowing sounds. Considering the non-stationary nature of swallowing sounds compared to breath sound, a wavelet transform based filter was applied to the sound signal in which a multiresolution decomposition reconstruction process filtered the signal. The signal is decomposed into band limited components and broken into many lower resolution components. Multiresolution decomposition of the sound was made at levels 6 using Daubechies-5. Swallowing sounds were detected in the filtered signal. Fifteen healthy and 11 dysphagic subjects were included in this

study. The results were validated manually by visual inspection using airflow measurement and spectrogram of the sounds as well as auditory means. The proposed filtering method is not able to separate the two swallowing and breath sounds with accurate boundaries.

In 2007, Makeyev et al. (2007) proposed a swallowing sound recognition technique based on the limited receptive area (LIRA) neural classifier. Recognition of swallowing sounds using continuous wavelet transform in combination with the LIRA neural classifier was compared with the same approach using short time Fourier transform. Twenty sound instances were recorded for each of three classes of sounds: swallow, talking and head movement, with a commercially available miniature throat microphone (IASUS NT, IASUS Concepts Ltd.) located over the laryngopharynx on a healthy subject without any history of swallowing disorder, eating or nutrition problems, or lower respiratory tract infection. Useful signals (swallowing, head movements and speech sounds) were extracted from the recordings using an empiric algorithm which looks for the beginning and end of each sound using a threshold set above the background noise level. Then, a scalogram of sound instances was calculated using Morlet mother wavelet with a wave-number of 6, 7 octaves and 16 sub-octaves. Results were better with a continuous wavelet transform in the different case of Test/Validation size compared to short time Fourier transform.

Amft, Kusserow, and Troster (2007) proposed an automated methodology to extract occurrences of similar chewing instances from chewing sound recordings. Four volunteers without a known chewing or swallowing abnormality were included in this study. Participants were asked to eat potato chips (25 pieces), meat lasagne (250 gm), one apple (100 gm) and 12 pieces of chocolate (40 gm). Chewing sound was recorded using a miniature microphone (Knowles, TM-24546) embedded in an ear-pad. The surface EMG from left and right side of masseter muscle was recorded. Chewing cycles were annotated based on an EMG recording. Then time domain features and spectral features were calculated. The assumption used consists of considering a complete sequence of chewing cycle as a set of successive phases described as a set of successive sequences of food. Non-supervised Sorting Genetic algorithm II was applied in order to select appropriate features followed by induction step in which hierarchical clustering on chewing observations was applied. The results led to the hypothesis that a sequential structure can be found in chewing sounds from brittle or rigid foods.

In 2009, Santamato et al. (2009) tested the predictive value of a pathological pattern of swallowing sounds. 60 healthy subjects and 15 patients affected by various neurological diseases were included in their study. Characteristics of dysphagia level were marked by the mean duration of the swallowing sound and post swallowing apnoea duration. The mean duration of swallowing sounds for a liquid of 10 ml water was significantly different between healthy subjects and patients with dysphagia disorders.

Huq and Moussavi (2010) presented a method based on several parameters derived from the phase duration from tracheal breath sound able to differentiate between breath phases, inspiration and expiration. Breath sounds were recorded using a Sony condenser microphone, and airflow was measured using a Biopac transducer/flowmeter. Both signals were acquired from 6 healthy volunteer non smokers. The flow signal was used as a reference to annotate the respiratory phases. Logarithm of variance was calculated from the filtered sound signal (band-pass filtered between 150 and 800Hz) using a sliding window of 25 ms with 50% overlap. Five parameters were derived from the breath sounds as the phase index, sound intensity in each phase, the duration parameter of the phase measured in seconds, pseudo-volume parameters and falling gradient of each breath phase. Then, a decision matrix was calculated based on the individual votes of the five parameters. The proposed method shows an accuracy of 93.1% for breath phase identification.

Sazonov et al. (2010) studied two methods of acoustical swallowing detection from sounds contaminated by motion artefacts, speech and external noise. Data signals were acquired from 20 volunteers of whom seven had body mass index greater than 30 (obese). Each subject participated in four visits, each of which consisted of a 20 minute resting period followed by a meal, followed by another 20 minutes resting period. The duration of the acquired dataset was about 64 hours with a total of 9966 swallows. Swallowing sounds detection was tested by a method based on mel-scale Fourier spectrum (msFS) and wavelet packet decomposition (WPD) for time-frequency representation and support vector machine (SVM) for automatic recognition of characteristic sounds of swallowing. Average automatic detection of swallowing sound rate was 84.7%.

In 2011, Fontana, Melo, and Sazonov (2011) made a comparison in detection of swallowing sounds by sonic (20- 2500 Hz) and subsonic (≤ 5 Hz) frequencies.

Two microphones were used including ambient microphone and swallowing microphone. Swallowing sounds in the sonic range were detected by a piezoelectric microphone placed over the laryngopharynx and swallowing sounds in the subsonic range were detected by a condenser microphone placed on the throat at the level of the thyroid cartilage. Data signals were acquired from seven healthy subjects who participated in a single session consisting on registering 5 minutes of resting where the subject is sitting quietly followed by 5 minutes of reading aloud, followed by a meal time where the subject repeats talking for 20 seconds period, followed by a single bite-chewing-swallow phase. The protocol has been conceived by the way to ensure presence of speech during meal. Hence, arises the interest of using two microphones recording signals on different band frequencies. The ambient microphone registers intrinsic speech, but not swallowing sounds. This allows the identification of the voice frequency intervals and then, its removal from the required throat signal to detect swallowing. Talking intervals were removed from the swallowing sounds signal by replacing their values by zeros in the same time interval. Resulting signal was smoothed using a moving average filter and a threshold level to detect swallows. A swallowing event was detected when the amplitude of the smoothed signal was higher than the threshold level for a period longer than 0.6 seconds, the minimum duration to cover a complete swallow. Their proposed method was able to achieve an accuracy of 68.2% averaged across all subjects and food items.

In the same research focus, Nagae and Suzuki (2011) proposed a wearable interface for sensing swallowing activities by an acoustical sensor mounted on the back of the neck giving a real time information reading swallowing movements. Method based on wavelet transform analysis with Gaussian window was used. The device used both frequency and amplitude characteristics to discriminate between the swallowing sound, vocalising and coughing. The device presents also LEDs to give feedback information consisting of three possible patterns: a blue light indicating the start of measurement, a green light indicating that swallowing is normal and red light indicating that an abnormal sound was detected or that the swallowing sound was longer than usual. Comparing to young group and older group, they conclude that the duration of swallowing action has a tendency to decrease with age. Feature considered for this conclusion was the ratio of the total length of the swallowing action and the time from the start of the swallowing until the bolus passes through the oesophagus. Phases are delimited as shown in the Figure 3.3. Limit of the device

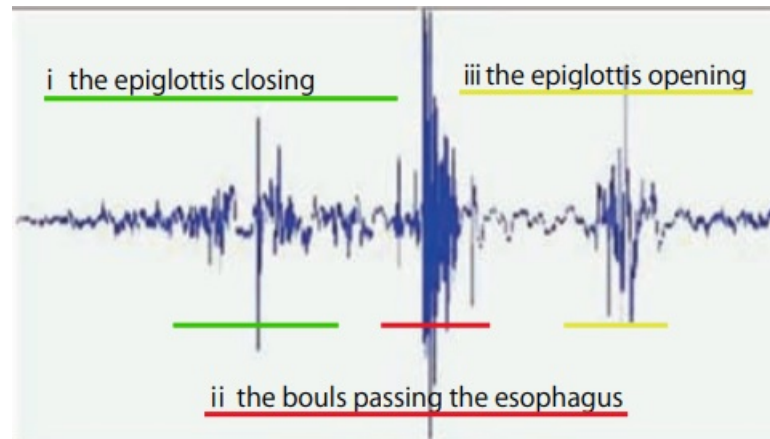


Figure 3.3: Characteristics of the swallowing sound wave

was the detection of several false positives when the subject coughed or vocalized.

Walker and Bhatia (2011) presented a swallowing sound analysis and a comparison was made with various other noises captured from a throat mounted microphone in order to manage obesity. A throat Microphone System used to record tracheal sound was placed around the throat over the laryngeal prominence. Experiments consisted of recording swallows, of liquid, solid and no substance, vocal cord activation, clearing of the throat and coughing. Data were acquired from two male subjects. Fourier analysis in the form of the Short Time Fourier Transform (STFT) indicates that swallow sounds have a strong presence in the upper frequencies when compared with the other sounds. To get higher temporal resolution, wavelet decomposition was applied in the form of the Discrete Wavelet Transform (DWT). Interesting frequency interval was covered by the first two levels of wavelet decomposition. The resulting signal was compared to a single digital filter based on ideal high-pass half-band filter. The first method for detection consisted of calculating the energy by using a sliding window and a simple thresholding to detect an event. The second event detection method consisted of analysing the maximum of the absolute value of the signal using a sliding window. At each detected maximum over each sliding window, if the value of the signal was also the maximum attained over the duration of the next time window, this value was labelled and recorded as such. Comparison between wavelet decomposition and a single high-pass filter showed similar results.

In 2012, Dong and Biswas (2012) presented their conception for a wearable swallow monitoring system in the form of wearable piezo-respiratory chest-belt detecting breathing sound. The system works based on the swallowing apnoea; the person

is not able to breath during swallow. Makeyev et al. (2012) presented an automatic food intake detection methodology based on a wearable non-invasive swallowing sensor. The method involves two stages: swallowing sounds detection based on mel-scale Fourier spectrum features and classification using a support vector machine. 21 healthy volunteers with different degrees of adiposity were included in this study. Results show average accuracies of 80% and 75% successively with intra-subject and inter-subject models. Shirazi and Moussavi (2012) presented an acoustical analysis in order to detect silent aspiration. Tracheal sounds were recorded using a Sony microphone ECM-88B placed over the suprasternal notch of the trachea simultaneously with fiberoptic endoscopic evaluation of swallowing from 10 adult patients suffering from stroke or acquired brain injury presenting silent aspiration during swallowing. Comparing the Power spectral densities of the breath signals and swallow signals, showed higher magnitude at low frequencies for the breath sounds following an aspiration. Therefore, they divided the frequency below 300 Hz into three frequency sub-bands over which they calculated the average power used for the classification. The classification based on the fuzzy k-means unsupervised classification method aims at clustering data into two groups of aspirated and non-aspirated signals. Results show 82.3% of accuracy in detecting swallows with silent aspiration.

In 2013, Tanaka et al. (2013) examined the swallowing frequency in 20 elderly people and compared it to 15 healthy young people. Swallowing frequency was measured using a swallowing frequency measurement device, a swallowing frequency meter, consisting of a laryngeal microphone and digital voice recorder. Different textures were used in this study: saliva, rice, tea. Tasks of vertical and horizontal movements of the head and neck, phonation and coughing were also recorded. The elderly group was divided into two groups according to the degree of activity in daily life. The group consisted of bedridden people and semi-bedridden elderly. The mean swallowing frequency per hour was 11.9 ± 5.1 in the semi-bedridden group which is significantly higher in the bedridden group (6.8 ± 3.3). However, the mean swallowing frequency per hour was significantly lower in the elderly group compared to the healthy adult control group.

In 2014, Staderini (2014) designed a proper instrument for cervical auscultation destined for people with dysphagia. The sensor consisted of a microphone and a

MP3 recorder for use in an ambulatory way. Yagi et al. (2014) proposed a non-invasive swallow-monitoring system using acoustic analysis. They recorded swallowing sounds using a sensor fixed on the neck and breath signals using a nasal cannula. Three approaches are presented in this study where Approach 1 extracts swallowing sound with frequency analysis. Approach 2 extracts swallowing event only from breathing information. The approach 3 takes into account both, frequency analysis and breathing information. Frequency analysis uses Fast Fourier Transform (FFT). Breathing information is based on the physiology of paradoxal couple breathing and swallowing apnoea, which is necessary to drive food safely to the oesophagus. Frequency analysis shows an increase in high frequency band power during swallowing. Of the three approaches, Approach 3 performed the highest specificity of 86.36%.

Table 3.1: State-of-the-art summary

Research topics	Important references	Criticisms
<p>Screening tests</p> <ul style="list-style-type: none"> • Questionnaire/interview • Tests with food intake • Mixing interrogation and food intake 	<ul style="list-style-type: none"> • Desport, J. C. et al. (2011). • DePippo, K. L. et al. (Jan. 1993). • Trapl-Grundschober, M. et al. (Dec. 2007). • Martino, R. et al. (Dec. 2008). 	<ul style="list-style-type: none"> • The questions allow him to identify the presence or absence of problems during swallowing with low accuracy. • All Tests with food intake are controlled and are carried out under well-defined conditions in term of texture, volume, temperature and the way we swallow. It doesn't seem like what is really happening. The swallowing proposed in the tests is performed in a unique way. Despite advice and instructions for patients at risk of food choking, the swallowing process can take the form of a single swallow or a succession of several swallows. In such case, the methods and models proposed in different studies will not be effective in all cases.
<ul style="list-style-type: none"> • Videofluoroscopy • Video-radiography • Fiberoptic endoscopy • Electromyography • Manometry • Electrocardiogram • Ultrasound 	<ul style="list-style-type: none"> • Palmer, J. et al. (Feb. 1993). • Cook, I. et al. (Mar. 1989). • Maniere-Ezvan, A. et al. (Feb. 1993). 	<ul style="list-style-type: none"> • Videofluoroscopy, video-radiography and Fibroptic endoscopy focus on the swallowing process with a very clear vision on the anomaly and the dysfunction site during food intake in order to define the appropriate rehabilitation measures. They are also very powerful in detecting silent aspiration. However, their application requires medical expertise and they are highly invasive. • Electromyography allows to acquire the activity of the surface muscles involved in the swallowing process such as masseter, throat... But, it does not allow the observation of deep muscle activity. In addition, it is very sensitive to movement.
<p>Swallowing Monitoring modalities</p> <ul style="list-style-type: none"> • Cervical auscultation • Accelerometer • <u>Microphone</u> 	<ul style="list-style-type: none"> • Amft, O. et al. (Nov. 2006). • Shuzo, M. et al. (Oct. 2009). • Aboofazeli, M. et al. (Aug. 2006). • Takahashi, K. et al. (Dec. 1994). 	<p>Previous studies on the assessment of swallowing noise can be classified as follows:</p> <ul style="list-style-type: none"> • Studies focused on the acoustic analysis of swallowing sounds, • Studies focused on evaluating physiological events associated with swallowing function: <ul style="list-style-type: none"> • Studies focusing on the evaluation of eating habits in relation to respiratory function, • Studies focusing on the frequency of swallowing • Studies focusing on oral-physiological events that use swallowing sound as a time marker. • Although the acquisition of swallowing sounds was an essential element of the swallowing sound processing, the methodology for detecting swallowing sounds was not examined in all studies. The optimal signal has not been studied either in terms of the characteristics of the amplitude acquired or in terms of the relationship between the signal and noise. The optimal location and method of installation of the detector has been reported in a few studies without empirical evidence. • Automatic detection is not too precise. Indeed, the beginning and end of each swallowing event is not precise and contains noise on both sides or there is the case of signal loss in the case of delayed detection of the beginning or early detection of the end.

3.4 Breathing monitoring

Breathing is inseparable from the swallowing process, both processes being dependent and necessary for the person's survival. Dysphagic people present risks of choking, malnutrition, dehydration and in extreme cases death. These health risks reveal the essential need to understand the mechanism of swallowing in relation to breathing. In fact, many studies evaluate the swallowing process by analysing the coordination between breathing and swallowing Zenner, Losinski, and Mills (1995), HIRANO et al. (2001), Rempel and Moussavi (2005), Aboofazeli and Mousavi (2006), and Huq and Moussavi (2010). In recent developments, involving the estimation of the acoustic air flow rate Moussavi, Leopando, and Rempel (1998) and Yap and Moussavi (2002), reveal the need to detect swallowing segments and automatically extract them from the breathing segments.

In 1989, Benchetrit et al. (1989) evaluated the breathing pattern in healthy adult subjects to test whether their resting pattern of breathing was reproducible over time. To do so, they measured several respiratory features such as inspiratory time, expiratory time, total breath time and the shape of the entire airflow profile. After a statistical study, they concluded that the breathing pattern is maintained over a long period despite changes which can affect breathing, like smoking habits and respiratory diseases.

The coordination of breathing and swallowing have been investigated over a long period of time. In 1981, Wilson et al. (1981) studied spontaneous swallowing during sleep and awakening in nine premature infants using pharyngeal pressure, submental electromyography and respiratory airflow as characteristics. During swallowing, a decrease in pharyngeal or oesophageal pressure produced an outward movement of the oesophagus or pharynx. Swallowing signals were recorded framed by respiratory signal, inspiration or expiration. The duration of airway closure during swallowing was independent of the respiratory rate. A brief "swallow-breath" was associated with swallow onset in most instances.

In the same context, through a study carried out by Smith et al. (1989), authors studied the coordination of swallowing and breathing in adults using respiratory inductive plethysmography for breathing signal and submental electromyogram for swallowing recordings. They concluded that swallowing is almost exclusively an expiratory activity which is consistent with the observation of Wilson et al. (1981)

and which is a protective role in preventing aspiration. The breathing pattern becomes increasingly irregular during meals, by recording respiration and swallowing simultaneously successively by inductance plethysmography, submental electromyography and a throat microphone in healthy subjects. The same observation of a brief swallow apnoea associated with swallows were noted in a paper by Preiksaitis and Mills (1996). In this study, expiration before and after the swallow apnoea was the preferred pattern with all swallowing tasks. A breathing pattern associated with single bolus swallow is different with distinct textures and volume which cannot remain the same with regular eating and drinking behaviour associated with successive swallowing events.

In 2018, Huff et al. (2018) studied the effect of incremental ascent on swallow pattern and swallowing-breathing coordination in healthy adults. Signals were acquired using submental surface electromyograms and spirometry for breathing. Tasks were carried out using saliva and water. Saliva swallows were with ascent. Water swallows showed a decrease in submental duration activity and a shift in submental activity with respect to earlier in the swallow-apnoea period. Therefore, swallow-breathing pattern is also affected by ascent.

Swallow-breathing coordination was also studied in chronic obstructive pulmonary disease Gross et al. (2009). Respiratory inductance plethysmography and nasal thermistry were used simultaneously to track respiratory signals in 25 patients with chronic obstructive pulmonary disease. Swallow events were referred using the submental surface electromyography. Tasks were random and spontaneous swallowing solids and semi-solids. The first remarkable observation comparing to healthy subject is that swallowing of solid food in patients occurs during inspiration frequently and significant differences in deglutitive apnoea durations were also found.

Rempel and Moussavi (2005) investigated the effect of different viscosities on the breath-swallow pattern in patient with cerebral palsy. A high rate of post-swallow inspiration was noted during thin liquid swallowing. Subjects with cerebral palsy had greater variability and duration of deglutition apnoea than controls.

In 2016, Fontecave-Jallon and Baconnier (2016) showed different swallow-breathing patterns observed on respiratory inductive plethysmography signal acquired from 11 healthy subjects. The first pattern was represented by swallows occurring during inspiration and followed by expiration. The second pattern is presented by swallows occurring during the expiratory phase which ends with the end of the swallow. The

latest swallow-breathing pattern is presented by swallowing in expiration which is followed by an active expiration, which decreases the respiratory volume under the Functional Residual Volume.

Yap and Moussavi (2002) proposed a parametric exponential model to estimate airflow from the sound of breathing. The model parameters were derived from each breathing phase (inspiration and expiration) separately, because the average power of the two phases is different. The tracheal sound was recorded by accelerometers placed at the chest and the air flow was measured by a pneumotachograph.

Moreau-Gaudry et al. (2005a) and Moreau-Gaudry et al. (2005b) focused on the Respiratory Inductance Plethysmography (RIP) signal with the aim to automatically detect swallowings events from respiratory records. During swallowing, the airflow is interrupted by the closure of the larynx. This results in zero values in the airflow signal curve. During the time-marked swallow, the airflow signal varies about zero non monotonously. Using a statistical test on a threshold calculated on the airflow signal, segments of swallow and breathing without swallow are identified. Results shown a sensitivity of 91.37% and a specificity was of 87.20%. They were not very precise in terms of border detection.

Moussavi, Leopando, and Rempel (1998) proposed an acoustical method able to automatically detect respiratory phases. Respiratory sounds were acquired using an accelerometer placed over trachea in 11 healthy children and 6 healthy adults. Airflow was simultaneously recorded. The average power spectra of inspiratory and expiratory phases were calculated separately for each signal. The average power was compared within different frequency bands. The best of which was given by the one who gave the greatest difference in power between inspiration and expiration phases.

3.5 Conclusion

Early detection of dysphagia is the key to reduce the risks of untreated dysphagia, such as malnutrition, dehydration or respiratory complications. Several studies have shown that a screening tool can significantly reduce the risk of complications Cichero, Heaton, and Bassett (2009). Currently, many screening measures are available. All share the common point of being able to divide patients into two categories: those at risk of choking food and in need of an accurate diagnosis for swallowing

and those who normally swallow without risk. Several types of tests are available, ranging from questionnaires to screening tests with food intake cited above used to observe and interpret the swallowing process. Swallowing process was studied using several modalities ranging from more to less invasive.

The objective of our study is to monitor the process of swallowing at home non invasively and using the minimum of sensors which are considered comfortable and do not modify the person's quality of life but rather improve it. This is why we did not choose to study MRI images for example which are very good for the diagnosis but it is not possible for a home monitoring. Analysis of the interactions between swallowing and breathing in patients could improve understanding and thus prevent inhalation risks. Then, we chose to record the breathing and sound of the swallowing with tools that can be easily installed at home following a well-defined protocol: microphone and Visuresp vest described in Chapter 5.

The following chapter describes the system proposed for processing the recorded; sound and respiratory signals.

Chapter 4

Proposed system

This work aims to detect useful signals from continuous audio flow analysis in real time. For the acoustical method, the first step is dedicated to automatically detect sounds event from the recording. For this purpose an algorithm based on wavelet decomposition was proposed. Once the stage of the automatic detection of the useful signals is validated, a sound classification was made based on the Gaussian Mixture Model (GMM) through Expectation Maximisation (EM) algorithm (improved under the name of CEM by Celeux and Govaert between 1990 and 1994 Celeux and Govaert (1992) and Gilles and Gérard (1994)) on three hierarchical levels. On the first level of the classification step, it was proposed to classify sounds through three specific classes representing respectively swallowing, speech and environmental sounds among which were coughing, yawning and all the other sounds that could be recorded during the recording session. Next, the sounds of swallowing were classified according to textures. Finally, the specific sounds from the different phases of swallowing were classified still using the GMM model and the detection of the boundaries of each phase of the sound of swallowing were searched for by applying two different methods, the first of which was based on the Hidden Markov Model (HMM) and the second took the form of a peak search algorithm in a single swallowing sound containing a single swallowing event. The global algorithm for the proposed system is presented in Figure 4.1 below:

4.1 The proposed Automatic Detection Algorithm

Recently, the analysis of swallowing sounds has received a particular attention Lazareck and Moussavi (2002), Aboofazeli and Moussavi (2004), Shuzo et al. (2009), and Amft and Troster (2006), whereby swallowing sounds were recorded using microphones

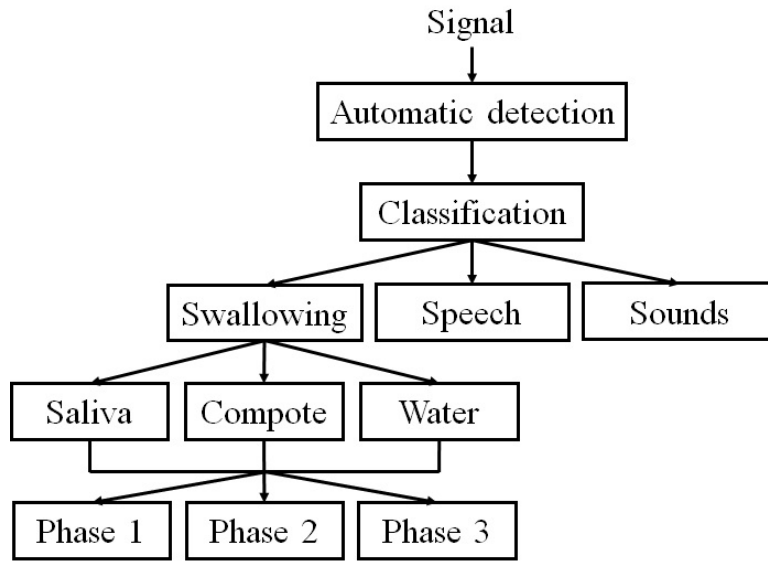


Figure 4.1: Global Proposed System

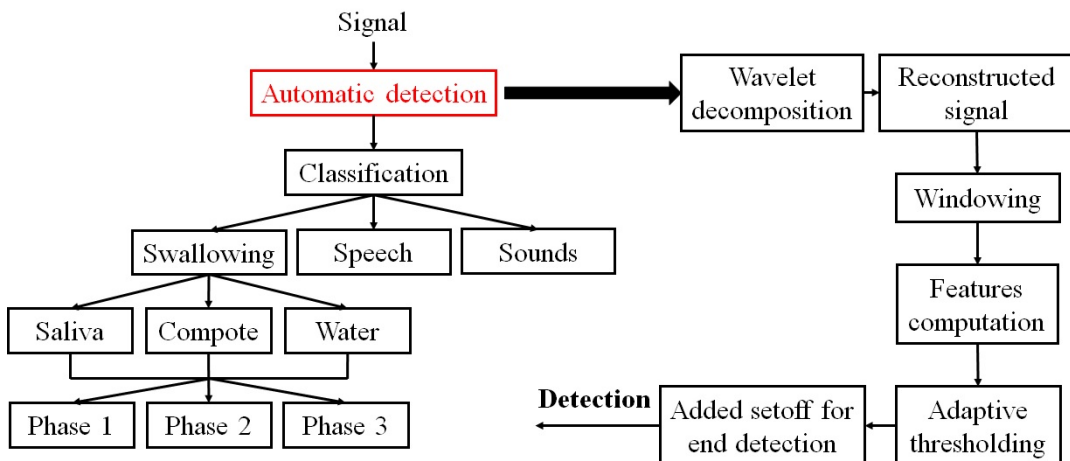


Figure 4.2: Diagram of the automatic detection algorithm

and accelerometers. The algorithms developed (Figure 4.2) enabled the automatic detection of swallowing related to sounds from a mixed stream of acoustic input as acquired through the neck worm microphone positioned as described above. Frequency domain analysis enabled the determination of the frequency band associated with the swallowing related process chain; within this band, relative prominence of frequencies varied according to the texture of the food being ingested. The analysis established that swallowing of liquid as well as food such as compote was associated with a frequency signature with an upper range of 3617 Hz; whereas swallowing water was associated with a frequency signature below 2300 Hz and for saliva

the corresponding maximum frequency component remained below a maximum of 200 Hz. To distinguish between the different frequency bands, it was decided to apply for processing wavelet decomposition and not the Fourier transform which is explained by the extremely short signals in time which are positioned at a precise moment in the sound recording signal. That is why a time and frequency analysis is required. In time-frequency analysis, slippery Fourier transform was carried out. Considering that the signals are very short, it is the wavelet transform that better matches the analysis of the signals. Wavelet decomposition was then achieved using symlet wavelets at level 12. After comparison of different combinations of wavelet detail coefficients and considering the frequency band of the different sounds of swallowed textures, details 5, 6 and 7 were selected for optimal decomposition and resolution of the swallowing related sounds corresponding respectively to the frequency bands 500-1000 Hz, 250-500 Hz and 125-250 Hz as shown in Figure 4.3.

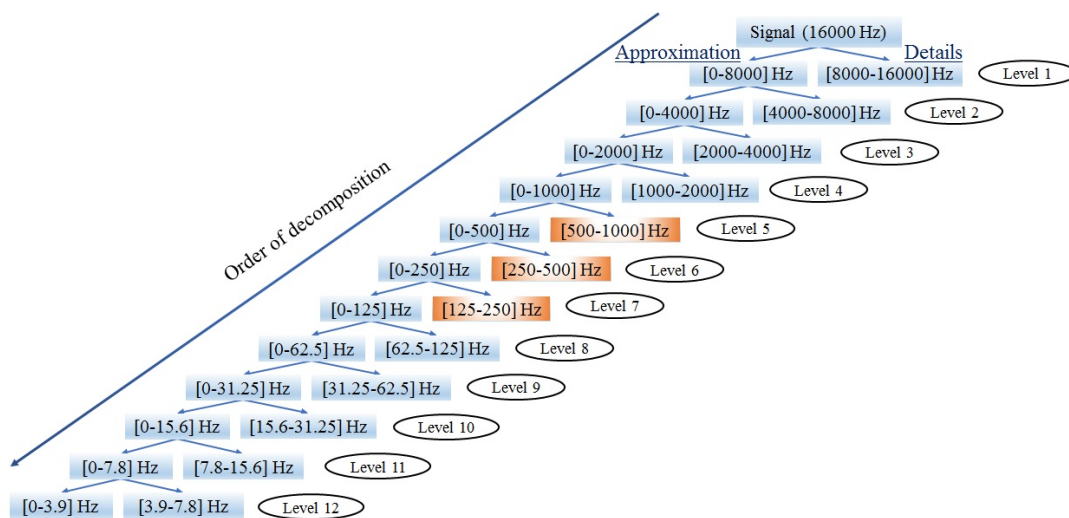


Figure 4.3: Wavelet decomposition into 12 levels

Accordingly, a new signal was reconstituted as the linear combination of the swallowing related sounds thus recovered, as shown in Figure 4.4.

Sound signals were resampled to 16 KHz. Frequency band associated with swallowing, according to textures, was studied. The Roll-off point was calculated for different swallowing segments. The Roll-off point is the frequency below which a percentage of the signal energy is located. It was calculated for 90%, 95% and 99% respectively. The results obtained are summarised in table 4.1.

Swallowing with the same texture was associated with high variability of the frequency signature excluding the sounds of saliva. Swallowing water and compote

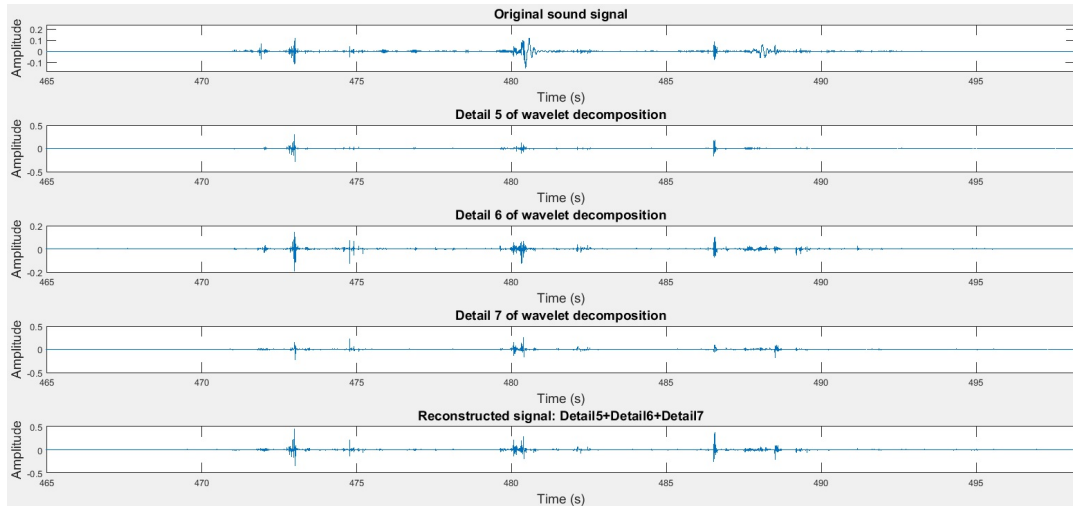


Figure 4.4: Reconstructed Signal as linear combination of selected details

S

Table 4.1: Roll-off point calculated according to textures (*Comp=Compote)

Frequency Analysis							
Compote							
	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6	Mean_freq
Freq_90%	861	172	1894	172	172	1550	803
Freq_95%	1378	172	2067	689	172	2239	1119
Freq_99%	2067	172	3273	1722	172	3617	1837
Water							
	Water 1	Water 2	Water 3	Water 4	Water 5	Water 6	Mean_freq
Freq_90%	172	861	172	172	172	172	287
Freq_95%	172	1378	172	172	172	172	373
Freq_99%	172	2239	172	516	172	172	574
Saliva							
	Saliva 1	Saliva 2	Saliva 3	Saliva 4	Saliva 5	Saliva 6	Mean_freq
Freq_90%	172	172	172	172	172	172	172
Freq_95%	172	172	172	172	172	172	172
Freq_99%	172	172	172	172	172	172	172

were associated with a frequency signature below 2300 Hz and for saliva the corresponding maximum frequency component remained below a maximum of 200 Hz. Next, analysis was performed on this reconstituted signal. The different features, shown in Figure 4.5 were calculated using a sliding window along the signal with an overlap of 50%. The blue line refers to the energy calculated as the average energy of preceding windows of the current one. Accordingly, a threshold for the start and end of each event was established presented by green line. Using only this threshold,

event detections were very short in such a way as to detect just the peaks. So, events were not correctly and quickly detected. For this reason the threshold was modified by adding an offset to the end-point detected (red line). Thus, the decision is made based on this modified threshold. The start point is detected when the energy exceeds the modified threshold. The end-point is not detected when energy becomes lower than the modified threshold, but a pause is taken during the added offset and, if there is a new detection, detection is continued if not end-point is marked by the end of the added offset.

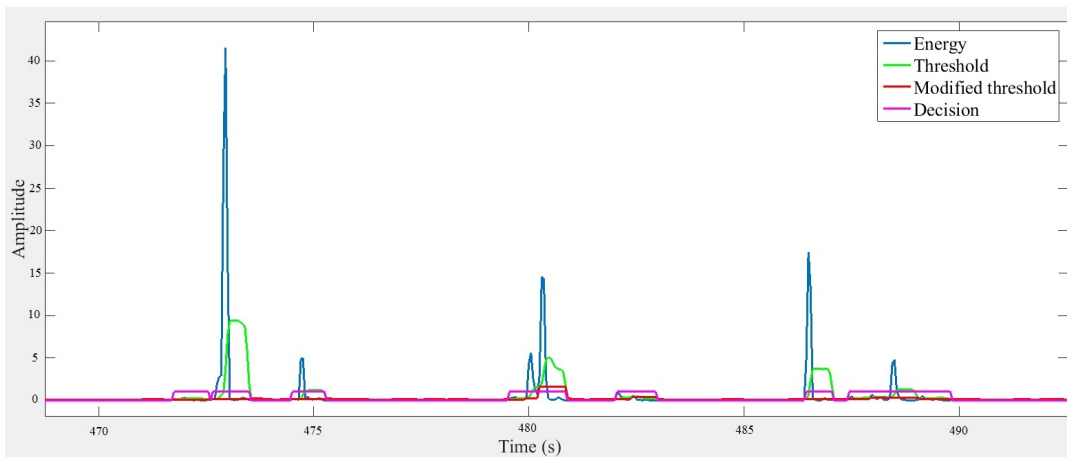


Figure 4.5: Procedure of detection algorithm with different calculated features

The combination of the selected details was analysed using a sliding window running along the signal with an overlap of 50%. For each position of the current sliding window, simultaneously, an associated energy criterion was initially computed as the average energy of the ten preceding windows and accordingly, a threshold for the start and end points of swallowing related sounds was established. This threshold was calculated as a function of the average energy as follows:

$$Threshold_i = \epsilon * APW_i + \alpha \quad (4.1)$$

where APW_i corresponds to an average of the n preceding windows of each position (position i). Thus, following this framework, the starting point of a swallowing related signal would be detected when the value of its associated energy as calculated according to the above method, exceeded the threshold and its end-point would be detected when the associated energy decrease below the threshold level

of the energy. However, experiments showed the application of the above associated energy criterion to result in significant start-end detection errors as the extreme peaks of the signal still affected the start-end points detection disproportionately. Accordingly, it was proposed to not stop detection of swallowing related sounds at the position where the associated energy falls below the threshold computed as described above, but to continue detecting and validating through a two-pass process whereby validated start-end points were ultimately established.

4.1.1 The Gaussian mixture model

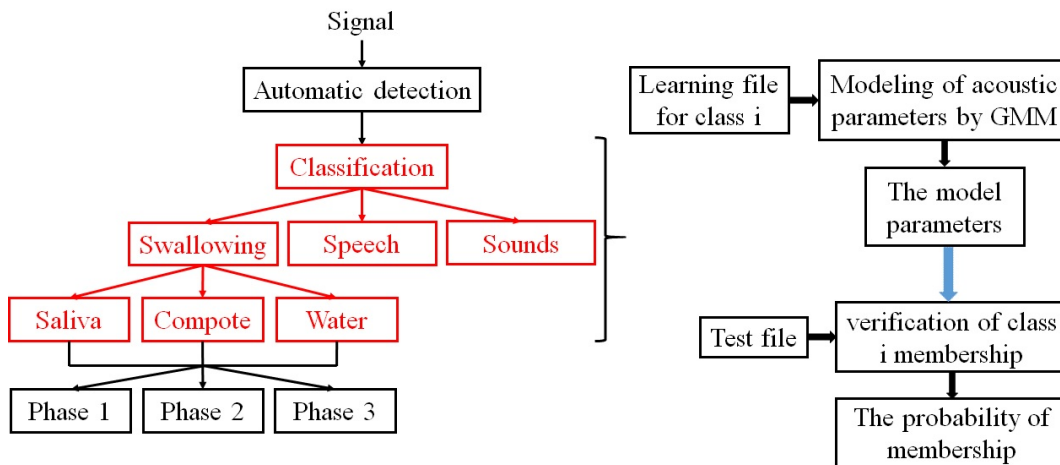
GMM was used to model the different sounds. According to previous work, proposed for sound classification, GMM has given good results Istrate (2003) and Sehili (2013). The combination of gaussian mixture model with support-vector machines has not improved the performance of the classification system proposed for the recognition of environmental sounds in a home control context by Sehili (2013). However, random-forest and support-vector machines combined, gives a good Fish Sounds classification rate Malfante et al. (2018). GMM involves two stages of learning and testing. The training step with the Expectation Maximisation algorithm was used for classification of the three types of sounds in the input stream mixed as set out previously: the swallowing-related, the speech and the ambient noise signal components. The EM algorithm is robust to random initialization and provides equal or comparable performance compared to Kmeans Sarkar and Barras (2013). The signal to be classified cannot be used directly because the information it contains is in its raw state with a lot of redundancy. By transforming the time signal into a collection of acoustic parameters the amount of information is reduced. Several parameters were tested in this section such as the Cepstre at the outlet of a Mel scale filter bank, the Mel Frequency Cepstral Coefficients (MFCC) and in the linear scale, the Linear Frequency Cepstral Coefficients (LFCC), and their delta and delta-delta, differences between coefficients obtained from one analysis window to another, to include the signal temporal variations. In order to take into consideration the swallowing-related frequency band, only 14 coefficients were chosen through 24 filters in order to consider only coefficients contained in the 2000 Hz frequency band. The time window for calculating the acoustic parameters was chosen to be 16 ms with a 50% overlap. Knowing that speech is stationary over 16 ms and that swallowing sounds are also human sounds, it is considered that sounds in a 16 ms

Table 4.2: Correspondence of the coefficients in mel and frequency scales for each coefficient using 24 filters

Coefficient	1	2	3	4	5	6	7	8	9	10
Mel scale	0	113.6	227.2	340.8	454.4	568	681.6	795.2	908.8	1022.4
Frequency (Hz)	0	74.2	156.3	247.1	347.6	458.7	581.6	717.5	867.8	1034.1
Coefficient	11	12	13	14	15	16	17	18	19	20
Mel scale	1136	1249.6	1363.2	1476.8	1590.4	1704	1817.6	1931.2	2044.8	2158.4
Frequency (Hz)	1218	1421.5	1646.5	1895.3	2170.6	2475	2811.8	3184.2	3596.2	4051.8
Coefficient	21	22	23	24						
Mel scale	2272	2385.6	2499.2	2612.8						
Frequency (Hz)	4555.8	5113.2	5729.7	6411.6						

window are also stationary. Table 4.2 below shows the correspondence between the coefficients in mel and frequency scales for each coefficient:

The first step in the calculations is to determine the GMM model from all the files of a sound class. Then, each of the files to be tested is evaluated according to each GMM model calculated previously. The average likelihood rate is calculated on the total duration of the sound to be classified which is finally allocated to the class for which there exists the highest average, as shown in Figure 4.6.

**Figure 4.6:** Recognition process

The model is applied at two levels. Firstly, it is used for the recognition of sounds by assuming that there are three global classes represented by swallowing sounds, speech and environmental sounds that may exist during food intake such as coughing and sneezing, etc.. Secondly, it is then used to recognise swallowed textures: water, saliva and compote.

4.1.2 Hidden Markov Model (HMM)

The Hidden Markov Model (HMM) was used, in which the number of hidden states was set to three representing the swallowing sound phases. The state sequence must begin in state 1. For this reason, the initial state probabilities are given by $\pi_i = \{1 \text{ if } i = 1; 0 \text{ if } i \neq 1\}$. Since the number of swallowing sounds was not large enough to randomly divide the swallowing sounds into training and testing data sets, a leave-one-out approach was used in which one swallow sound from the data set was removed for testing and the HMM model was trained using the rest of the data step for which the sequences of sound signal features and sequences of manually annotated states were used. A trained HMM model was used for segmentation of the swallow sound which had been removed. A discrete HMM model was used to model the different sound phases. Different temporal and frequency characteristics (such as LFCC, MFCC, Skewness, etc...) were calculated on the different sound segments and used as input to the model for learning step. For recognition step, the hidden realisation are restored using bayesian methods to calculate the joint distribution $P(Y|X)$, where Y is the Markov sequence and X is the observed sequence. Once the HMM model was trained, the Viterbi algorithm was used to find the most likely state sequence and therefore, the boundaries of the states assigned by HMM were compared to those annotated manually.

HMM steps are presented in Figure 4.7 below. The evaluation was carried out by comparing the resulting sequence of the HMM with the reference sequence (manually annotated) state by state.

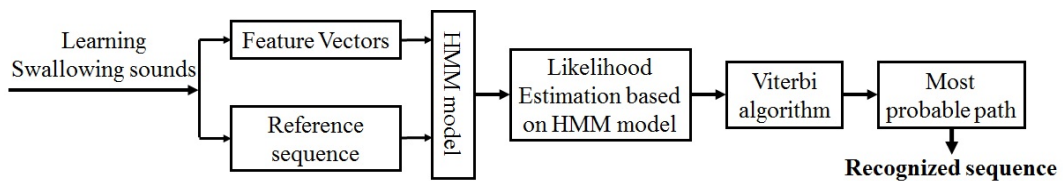


Figure 4.7: Hidden Markov Model algorithm

4.1.3 Local maximum detection algorithm

Based on the fact that the swallowing sound is characteristic of three specific sounds: Initial discrete sound (IDS), Bolus Transit Sound (BTS) and Final Discrete Sound (FDS) corresponding each to one of the physiological swallowing steps which are

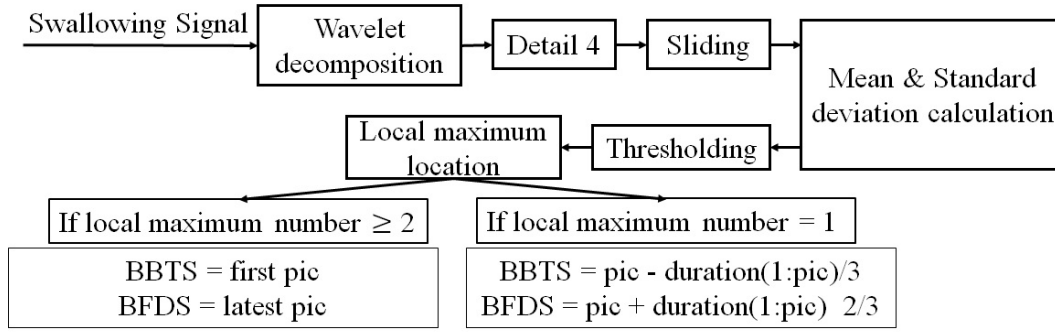


Figure 4.8: Local maximum detection algorithm

oral, pharyngeal and œsophageal Aboofazeli and Moussavi (2004) and Vice et al. (1990). The IDS sound corresponds to the opening of the cricopharyngeal sphincter, in order to enable the bolus to pass from the pharynx into the œsophagus. The BTS sound corresponds to the gurgle sounds generated by bolus transmission into the œsophagus during the pharyngeal phase. The FDS sound immediately precedes the respiratory sound, which follows the swallowing sounds. According to the observations, the FDS are not always present in the swallowing sounds. The idea of the algorithm (Figure 4.8) is to look for the location of the local maxima of the signal by imposing a minimal distance between two peaks. The signal chosen for this search is the detail 4 obtained from the wavelet decomposition using symlet wavelets at level 5 from which the mean and standard deviation are calculated using a sliding window of 16 ms duration. Then, a new signal is obtained corresponding to the sum of the mean and the standard deviation on which values that are below a certain threshold, defined according to the overall signals, are reset. Then, the maxima is looked for. According to the local maximum number found, the boundaries of each phase are decided.

- If the number of local maximum number ≥ 2 : the beginning of the BTS sound is taken as the first peak and the beginning of the FDS sound is taken as the latest detected peak.

$$B_{BTS} = \text{first pic} \quad (4.2)$$

where B_{BTS} corresponds to the beginning of the BTS sound and

$$B_{FDS} = \text{latest pic} \quad (4.3)$$

where B_{FDS} corresponds to the beginning of the FDS sound.

- If the number of local maximum number = 1: the beginning of the BTS sound is defined following the equation below:

$$B_{BTS} = pic - duration(1 : pic) / 3 \quad (4.4)$$

where $duration(1 : pic)$ corresponds to duration of the segment preceding the peak, and

$$B_{FDS} = pic + duration(1 : pic) * 2/3 \quad (4.5)$$

4.1.4 Classification types

For the classification step, first swallowing events regardless of the texture swallowed were classified. Secondly, swallowing events based on the texture swallowed were defined. Then, the different phases of a single swallow by detecting the boundaries of each phase were classified. Below, the description of each step is given.

Classification: Deglutition-Speech-Sounds

For this purpose, it was proposed to classify three different sound classes using the GMM model through the EM algorithm. For each sound class, a model was made during the training step using files supposedly representative of this sound class. Subsequently, the step of checking the membership of any sound to this class was performed. During the learning phase of the model, the statistical modelling of the acoustic parameters of the sound was carried out and the distribution of acoustic parameters of a sound class was modelled by a sum of Gaussian probability densities. Practically, for an analysis window (16 ms), the system evaluates the acoustic parameters corresponding to the sound signal. To estimate the likelihood ratio of a sound file (acoustic vector), the observation distribution belonging to the same sound class by a weighted sum of K Gaussian distributions was modelled. For the test step, the signal to be tested was transformed into an acoustic vector X . It will most likely belong to the class i for which $p(x | \Theta_i)$ is maximum:

$$p(x | \Theta_i) = \max_{k=1}^K (p(x | \Theta_k)) \quad (4.6)$$

Textures

For the classification of different textures, for each texture a specific GMM model (saliva, water and compote) was created and in the same way as that described above in a) for the test step, the likelihood ratio versus each model is calculated and related to the class that has the maximum likelihood.

Swallowing Phases

For the classification of swallowing phases and identification of the boundaries of the different characteristics of sounds (phases) of a swallowing process, two methods were tested. First, HMM was applied in order to generate sequences of observations. The number of hidden states of HMM model was set to three representing the swallowing sound phases, i.e., the oral, pharyngeal and esophageal phases in swallowing sounds. A state sequence must begin in state 1. For this reason, the initial state probabilities $\pi_i = \{1 \text{ if } i = 1; 0 \text{ if } i \neq 1\}$. The next state follows only after the current state, and therefore it is dependent only on the current state and not on the others. The second assumption for this model is that transmission probabilities are stationary, that is to say that the probability from the state i to j at time t_1 is the same as that at time t_2 :

$$p(x_{t_1+1} = j | x_{t_1+1} = i) = p(x_{t_2+1} = j | x_{t_2+1} = i), \forall t_1, t_2 \quad (4.7)$$

The last assumption of the model is that the observations are independent of past values and states, which means that the probability that pharyngeal sound for example will be produced at time t depends only on the current state and it is conditionnaly independent of the past. In this study several acoustic features were tested. Each feature of swallowing sounds with HMM were modeled in two steps of training and secondly calculating the most likely states using Viterbi algorithm. Initial values for the transmission probability were taken the same as in the study of Aboofazeli and Moussavi (2008):

$$T_{initial} = \begin{bmatrix} 0.5 & 0.5 & 0 \\ 0 & 0.5 & 0.5 \\ 0 & 0 & 1 \end{bmatrix} \quad (4.8)$$

Since the number of swallowing sounds was not large enough for randomly dividing the swallowing sounds into training and testing data sets, the leave-one-out approach was used in which one swallow sound from the data set was removed for test and the HMM model was trained using the rest of data, step for which, the sequences of sound signal features and sequences of manually annotated states were used. Trained HMM model was used for segmentation of the swallow sound which had been removed. Once the HMM model was trained, the Viterbi algorithm was used to find the most likely state sequences and therefore the boundaries of the states assigned by HMM were compared to those annotated manually.

4.2 Methods for breath analysis

Respiration and swallowing have been studied in healthy subjects Guatterie and Lozano (2005), Preiksaitis and Mills (1996), Smith et al. (1989), and Nishino, Yonezawa, and Honda (1986) and the elderly using several methods Hirst et al. (2002) and Benchetrit et al. (1989). During swallowing, breathing is inhibited.

In this work, the respiratory signal was acquired via the Visuresp vest of which the measuring principle is based on the Plethysmography by inductance. The system enables the acquisition of thoracic and abdominal respiratory volumes and their display with the respiratory volume and flow calculated from the Thorax and Abdomen signals. The calculated flow was used for processing where convex curve refers to expiratory phase and concave curve refers to inspiration phase. Figure 4.9 shows the interface of the sensor. In this work, the reconstituted flow rate of the respiratory volume (Débit Rec) was measured in litres/second, which is calculated as a function of the thoracic and abdominal volume.

The observation of swallowing in the recordings made shows that the most frequent dominated swallowing-breathing pattern was presented by swallows occurring during expiratory phase which takes its end after the end of the swallow. Based on this assumption, in the first step of processing, the automatic detection of the respiratory phase inspiration and expiration was important. For this purpose, an algorithm was developed for automatically detecting the boundaries of each respiratory phases.

The idea was based on fixing a threshold on the reconstituted flow rate of the respiratory volume such that any value below this threshold was reset to zero. Then,

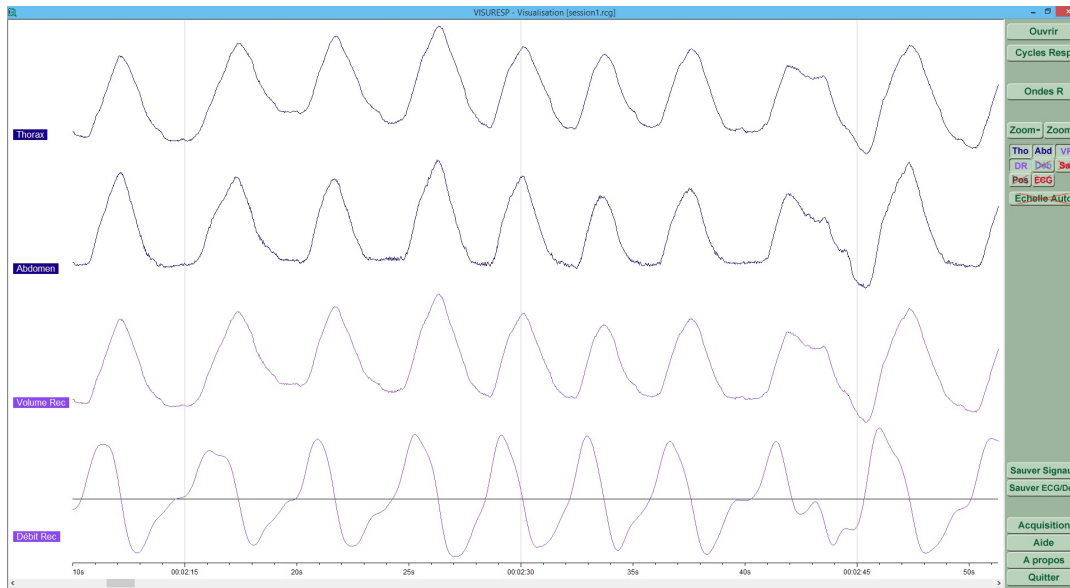


Figure 4.9: The Visuresp interface

based on this signal, the transition points from/to zero to/from positive values were detected. The detected point was considered as the beginning of the inspiratory phase if it was a transition from zero to a positive value. The point at the end of the inspiratory phase or at the beginning of the expiratory phase was identified as the transition from a positive value to zero.

Based on the observation that swallowing occurred during expiratory phase, the possibility of automatically detect expiratory segments containing swallowing was studied. The hypothesis that has been put forward is that the duration of the exhalation is longer than that at rest, for this reason, the average duration of each recording, was from the three minutes of rest at the beginning of each recording (for each subject). Detected expiration which has a shorter duration than a fixed threshold was merged with the cycles before and after the phase concerned. So, the end of the preceding phase and the start of the next phase were deleted. Then, for each recording (each subject), a threshold was defined and, whether an expiration contains events (swallowing, speech, cough,...) or not was considered.

4.3 Conclusion

The methods of resolution of the swallowing sound are detailed in this chapter in addition to a brief description of the methodology used to process breathing signals. For automatic detection of useful sounds, a method based on wavelet decomposition

was applied in order to use only signals in frequency band that that interest us. Wavelet decomposition is one type of filtering bu signal de-noising step can lead also to a filtered signal which can represent better or not events that we are looking for. To review whether or not some additional filtering types before wavelet decomposition will improve the results.

Gaussian Mixture Model (GMM) and Hidden Markov Model (HMM) are detailed in this section as in a supervised classification. So for each class, we learn first the considered sound classes. But what about sound classification in an unsupervised case? In the case of GMM, one gaussian component can not represent one sound class (considering three classes). In addition, I think that the short duration of such sounds (swallowing) will influence the performance of the classification. For HMM, still to be tested the unsupervised case.

For the proposed method of local maximum detection still a new strategy for signal segmentation, but the exploitation of the signal envelope remains a track to be explored.

The breathing signals should be re-examined and merged with the sound signal. In the next chapter, results are presented.

Chapter 5

Results

In this chapter, the different results obtained using methods described above are presented. First, the protocol and procedure for data acquisition and the equipment used are presented as well as the resulting database. Next, the recorded database and the different proposed patterns are set out according to the state-of-the-art. Then, the results of the automatic detection algorithm are presented followed by the results of classification, first, of manually annotated segments and then, by coupling a classification and automatic detection algorithm. Classification is made at different levels; first, different sounds are classified in order to distinguish swallowing sounds from speech and other sounds. Secondly, the result of textures classification is presented. Finally, the segmentation of a swallowing sound into three characteristic sounds is presented according to swallowing physiology and swallowing phases: oral, pharyngeal and œsophageal.

5.1 Recording protocol and swallowing monitoring database

This section is divided into two parts; first, the data acquisition protocol and materials are presented followed by the procedure and resulted database.

5.1.1 Data acquisition protocol

As part of the e-SwallHome project, a first step for the team was to develop the sequence of physiological signal acquisition sequences measured non-invasively in order to study the functions of spontaneous breathing, phonation and swallowing as well as their temporal organisations. The PRETA team (Physiologie cardio-Respiratoire Expérimentale Théorique et Appliquée) in TIMC-IMAG (Techniques de

l'Ingénierie Médicale et de la Complexité - Informatique, Mathématiques et Applications, Grenoble) laboratory has the necessary authorisations for the recording of physiological signals acquired non-invasively on healthy volunteers and patients with different degrees of swallowing disorders.

The clinical evaluation of swallowing disorders includes a certain number of tools the relevance of which are well-established Poudroux, Logemann, and Kahri-las (1996) and Tohara et al. (2003). Ventilatory system protection processes are evaluated by estimating ventilation control, ability to perform voluntary apnoea, and voluntary coughing. In stroke patients, it has been shown that the weakness of voluntary cough is correlated with the severity of the inhalation Hammond et al. (2001) and that a failure of the cough reflex (evaluated by an abnormal test using tartaric acid nebulisation) may increase the risk of developing pneumonia Addington et al. (1999). The water test consists of drinking water (quantity ranging from 50 to 100 ml) with successive boluses of 5 ml spoon McCullough et al. (2000) or free by glass Mari et al. (1997), Splaingard et al. (1988), DePippo, Holas, and Reding (1993), and Gottlieb et al. (1996) and is positive if the patient coughs or has an impaired voice. The advantage of the test is to be simple with a satisfactory predictive value of inhalations in neurological patients Mari et al. (1997), DePippo, Holas, and Reding (1993), and Splaingard et al. (1988) or with other pathologies Miyazaki, Arakawa, and Kizu (2002). However, it carries a risk of exposing the patient to choking on food. A test based on the same principle is this time to ask the patient to swallow various textures (liquid or gelled water and cream) while checking during and after each swallowing a number of parameters (voice, discomfort, movement of the lips, cough, etc ...).

There are other specialised methods of exploration. Endoscopic examination by an otolaryngologist provides an opportunity to see abnormal anatomical structures and gives information on the mobility of the components involved during swallowing. Videofluoroscopy, a dynamic functional analysis of swallowing based on a video recording of the patient's ingestion of a barium-based contrast medium, is considered as the gold standard for diagnosing dysphagia. Videomanometry (manometry associated with a videoradiography) makes it possible to study the pressure variations during swallowing and thus to quantify the forces exerted on the bolus during the pharyngeal phase of swallowing. Oropharyngeal videoscintigraphy enables a qualitative and quantitative study of the transit of the Technetium labelled

liquid bolus with a gamma-camera. Ultrasound can also be used to explore the movements of the tongue during the shaping and propulsion of the bolus, from the oral cavity to the oropharynx.

Other means of investigation are also widely used or explored in swallowing studies. The onset of surface electromyographic activity (sEMG) of the submental muscles, the onset of the electroglottograph signal (EGG), and the onset of the laryngeal swallow movement measured by videofluoroscopy have been shown to be nearly synchronised Perlman and Grayhack (1991), suggesting that EGG and sEMG could be used as an early indicator of pharyngeal swallowing Logemann (1994). Electroglottography measures impedance variations at the level of vocal folds (vibration, opening and closing of the glottis) and thus allows the dynamics and contact of the vocal folds to be monitored during phonation and swallowing. For this technique, the electrodes should be placed on the skin above the thyroid cartilage at the vocal folds level. The submental or hyoidal surface EMG is used as a means of recording swallowing Preiksaitis and Mills (1996) and Uysal et al. (2013) or proposed as a screening method for assessing dysphagia Vaiman and Eviatar (2009). Cervical auscultation of swallowing can be done either with a stethoscope Leslie et al. (2004), with a microphone or an accelerometer placed on the skin between the thyroid and cricoid cartilage or just beneath it. Indeed, swallowing produces sounds in the pharynx, larynx, upper musculature of the oesophagus and tongue. The recording of the acoustic signal by a microphone Preiksaitis and Mills (1996) and Golabbakhsh et al. (2014) or the recording of mechanical vibrations on the surface of the skin generated by these sounds by an accelerometer Camargo et al. (2010) makes it possible to study swallowing.

The sounds of speech are produced by the air coming from the lungs, which will then pass between the vocal folds. The sound is then emitted when the vocal folds vibrate during the exhalation, i.e., during the intermittent expulsion of the air with the opening and closing of the glottis.

In this study, the protocol followed, enabled the recording of events of breathing, swallowing, speech, apnoea, coughing and yawning in healthy volunteers. Each participant is asked to sign the consent form to confirm their agreement to participate in the study. The detailed protocol, consent and case report form are presented in the Appendix. The different tasks followed in this study are summarised as follows:

1. Make 8 seconds of voluntary apnoea,
2. Realise 3 minutes of rest (normal breathing) where spontaneous swallowing can be annotated,
3. Swallowing tasks:
 - (a) Swallowing induced saliva on command: 6 times every 30 seconds,
 - (b) Swallowing water free by glass (random proportions),
 - (c) Swallowing compote with a teaspoon (100 g),
4. Speech: Read aloud sentences in a paragraph phonetically balanced:
 - (a) Read 3 sentences, repeat twice,
 - (b) Read a sequence of sentences and then a text excerpt.
5. Make an apnoea of 3 seconds (repeat 3 times),
6. Make an apnoea of 8 seconds (repeat 3 times),
7. Make a volunteer cough (repeat 3 times),
8. Make a volunteer yawn (repeat 3 times),
9. Make a voluntary apnoea of 8 seconds.

5.1.2 Materials

In this project, non-invasive equipment was used to simultaneously record sounds associated with the swallowing process and other ambient sounds and also respiratory habits during food intake. Sounds were recorded using a discrete miniature omni-directional microphone capsule (Sennheiser-ME 102) with an IMG Stageline MPR1 microphone pre-amplifier, placed on the neck at a pre-studied position midway between the Jugular Notch and the Laryngeal Prominence optimised for the most effective acquisition of the swallowing related signals, marked in yellow in Figure 5.1. The microphone has been attached with an elastic band around the neck that does not harm the person.

Breathing is measured using a Visuresp Vest, RBI, France, using Induction Respiratory Plethysmography. Its principle is based on measuring, with the aid of an

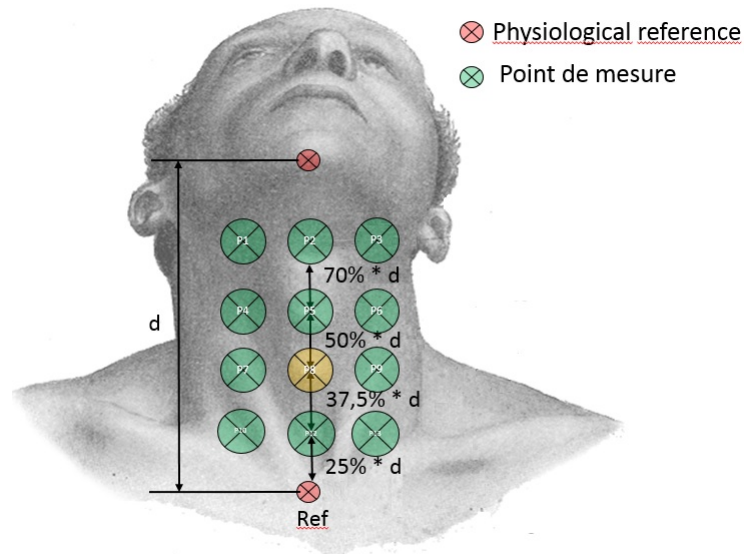


Figure 5.1: Best microphone position (in yellow)

elastic vest slipped over the subject's clothing, variations in the volume of the chest cage and the abdomen, from which the variations of the pulmonary volume are estimated (linear combination of thoracic and abdominal volumes).

5.1.3 Procedure and Database

The recording includes apnoea at the beginning and end of each recording session, followed by 3 minutes of spontaneous ventilation during which spontaneous swallowing will be annotated, then swallowing events will be induced in sequence by ingesting random volumes of different homogeneous textures (saliva, water and compote), sequences of reading aloud will then be recorded, followed by voluntary apnoea, voluntary coughs and voluntary yawning.

Regarding to sounds recordings, sounds were recorded at a 44.1 KHz sampling rate. The Signal was re-sampled at 16 KHz for the processing as required. Participants were seated comfortably on a chair. They were told that the equipment would record swallowing-related sounds. The baseline function of each participant's swallowing process for the most fluid-like foods was established by capturing the data from participants during the swallowing of water and saliva as was also the case when fed with compote in a teaspoon. Additionally, they were asked to read aloud phonologically balanced sentences and paragraphs. The sounds of their coughing and yawning were also recorded.

For the annotation of events, a free software named "TranscriberAG" was used Transcriber (<http://transag.sourceforge.net/>) which is designed for segmenting, labelling and transcribing events from a sound recording to enable the manual annotation of speech signals. It provides a user-friendly graphical user interface (GUI) for segmenting long duration speech recordings, transcribing them, labelling speech turns, topic changes and acoustic conditions. The different records were used to evaluate the detection and the classification algorithms and coupling between them. For speech segments, it was not too difficult to define their boundaries but that was not the case for swallowing sound which is drowned sometimes in the noise because of its low power. For this purpose, the events were manually segmented by listening and monitoring the swallowing signals in both time and frequency domains. In total, there were 39 records obtained in 27 healthy volunteers with a total duration of approximately 11 hours with 3493 manually annotated segments. The detailed database is described in the Table 5.1 below:

Table 5.1: Sound database

Classes	Number of files	Duration
3*Swallowing	Compote	3*1949567
	Water	647
	Saliva	735
Speech	705	1h 31 minutes
Sounds	839	29 minutes

The database contains two types of signals: sound signals and breathing signals. Below, first the sound signals and the associated interpretations used for segmentation are set out. Next, the respiratory signal and its relationships to the sound signal are presented.

5.1.4 Sound signals

In several studies, normal swallowing sound may be divided into three distinct characteristic sounds. According to the state-of-the-art, different patterns of swallowing sound segmentation were proposed. The researcher's team Aboofazeli and Mousavi (2008), Aboofazeli and Moussavi (2004), and Moussavi (2005) at the University of Manitoba considered that the swallowing sound can be divided into three distinct segments: Initial Discrete Sound (IDS), Bolus Transit Sound (BTS) and Final Discrete Sound (FDS) as shown in Figure 5.2. According to their observations, FDS may not be present all the time.

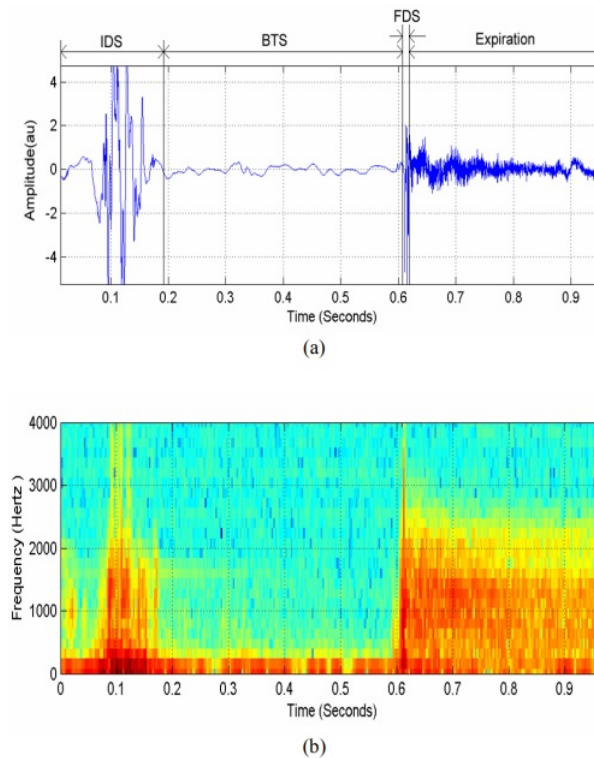


Figure 5.2: A typical swallowing sound (a) time-domain signal (b) the corresponding spectrogram. ('au' arbitrary units for normalised amplitude Aboofazeli and Moussavi (2004))

The same characteristic sounds were explored by Nagae and Suzuki (2011). The sounds correspond respectively to: the epiglottis closing, the bolus passing the œsophagus and the epiglottis opening as shown in Figure 3.3. The interpretation of the click that appears in the sound signal of the swallow is the same but the difference is on the shape of the two signals. The signal acquired by Aboofazeli and Moussavi (2004) are using two Siemens accelerometers (EMT25C) which were attached by double-sided adhesive tape rings to the skin over the trachea at the suprasternal notch to record breathing and swallowing sounds and at the left or right second intercostal space in the midclavicular line to record breath sounds. The typical pattern observed contains a first phase which is described as quiet followed by the second phase which is started by initial discrete sounds (IDS) corresponding to the opening of the cricopharyngeal sphincter during the pharyngeal phase. During the next phase, the third phase, a gurgle sound is heard due to the transmission of the bolus into the œsophagus named the Bolus Transfert Sound which does not necessarily have a peak. Another characteristic sound in the form of click occurs at the end of swallowing process known as the Final Discrete Sound (FDS) which is not present in all recorded segments. The swallowing process is followed by expiration which is

explained by the inhibition of inspiratory neuron activity during swallowing proved by Hukuhara and Okada (1956).

In the work of Nagae and Suzuki (2011), swallowing sounds were acquired using their own interface to detect swallowing sounds. The measurement device was not placed through the trachea. Based on a study of measurement location related to the frequency and intensity of the detected signal, the best location was fixed on either side of the central axis of the neck. The swallowing sound contains three characteristic sounds: the sound of the epiglottis closing, the sound of the bolus passing the oesophagus and the sound of the epiglottis opening. The three characteristic sounds have peaks in the signal unlike what was observed in the signal recorded in the Aboofazeli and Moussavi (2004) study, in which the second characteristic sound does not have a peak and takes a flat form.

The interpretations of the two models highlight two important aspects that influence the quality of the swallowing sound signal: the position of the sensor sensitive to the swallowing sound and the sensor itself. Accordingly, using an preamplified microphone, a matrix of 12 positions (4x3) was proposed on the neck with two reference positions to normalize measurements from one subject to another, located respectively at the sternal point and the tip of the chin protuberance (at the end of the chin) as shown in the Figure 5.1. Signal quality evaluation is performed by analysing the signal-to-noise ratio of the swallowing segments according to textures. The best value of signal-to-noise ratio is given by position 8 above the sternal point at about 37.5% of the distance between the two references points considered. So, for the next step, this position was chosen to be registered in the database. Once the recordings are obtained, the event annotations are also performed by listening and monitoring the sound signals in both time and frequency domains.

It should be noted that the swallowing segments include one or more successive swallows. Durations of the swallowing event presented below are calculated from segments containing a single swallowing event. The duration of a swallowing event without taking into account the texture is about $1.007 \pm 0.407s$ (*mean \pm standard deviation*). The duration of a single swallowing process according to texture did not show a significant difference between water and compote. However, the duration for saliva is slightly longer. Durations of different segments are presented in Tables 5.2 and 5.3:

Swallowing sounds are highly variable even if recorded from the same subject.

Table 5.2: Swallowing event duration

Swallowing	
Duration (s)	1.007 ± 0.407

Table 5.3: Swallowing event duration according to textures

	Compote	Water	Saliva
Duration (s)	0.990 ± 0.319	0.979 ± 0.276	1.095 ± 0.687

They do not have a unique temporal and durational pattern. The swallowing sound signal is a not-stationary signal. In physiological terms and according to the state-of-the-art, swallowing occurs in three phases: oral, pharyngeal and oesophageal. The sound thus recorded is generated by the various movements of the bolus during the swallowing process. A different interpretation of the swallowing sound is presented here. The waveform of a typical swallowing sound signal of water and its three phases are shown in Figure 5.3. Considering always that swallowing sounds contain three characteristic peaks, the first characteristic sound corresponding to the first peak is represented on Figure 5.3. This sound corresponds to the opening of the cricopharyngeal sphincter and the closing of the epiglottis referenced in Figure 5.3 by the IDS segment. The second phase BTS can be divided into two subphases. The first subphase noted by BTS1 in the Figure 5.3 is in accordance with what was presented in the work of Aboofazeli and Moussavi (2004), which corresponds to the bolus transmission sounds (BTS) which are due to the transmission of the bolus from the oropharynx into the oesophagus during the pharyngeal phase. Otherwise, it is assumed that the BTS2 segment, which takes the form of a flat wave, corresponds to the propulsion of the bolus at the upper part of the oesophagus and finishes with the opening of the epiglottis referring to the third characteristic sound FDS.

Another microphone position used was fixed on the Visuresp vest (Figure 5.4). Swallowing sounds were approximately 188 samples with a duration of 100 seconds in total. They were recorded from 10 persons (5 females and 5 males) aged between 23 and 34 years. Participants were seated comfortably on a chair. They were told that the equipment would record swallowing sounds and respiration signals. During the test, all of them were asked to drink or eat freely to promote an ambient environment. They were fed with thick liquid (compote-100 grams) using teaspoon and a glass of water (200 ml).

In addition to the databases belonging to the team, two other databases were

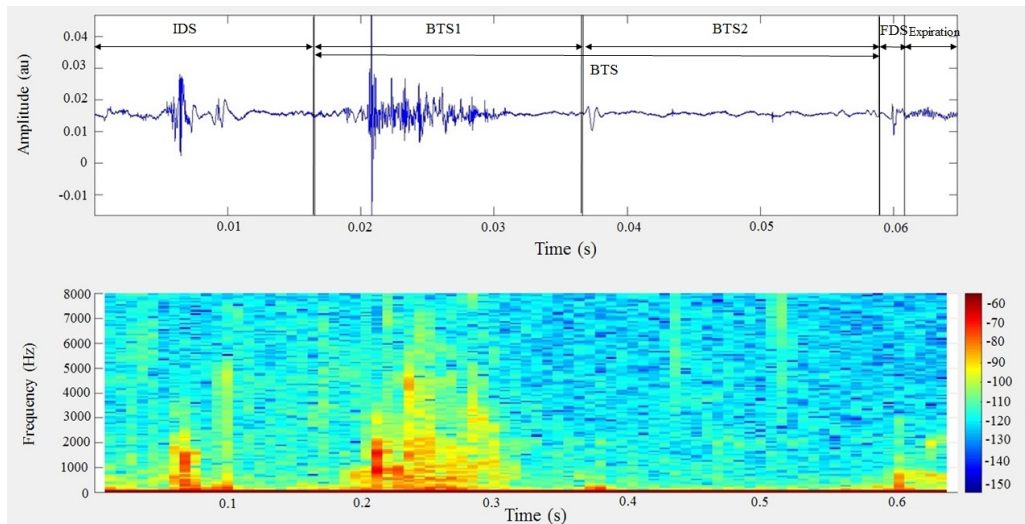


Figure 5.3: A typical swallowing sound of water in time-domain signal and its corresponding spectrogram



Figure 5.4: Microphone position on Visuresp gilet

used. The first one contains sounds signals including swallowing and phonation which were recorded in Grenoble in TIMC-IMAG laboratory by PRETA team using the microphone of the electroglottograph equipment which is a device that makes it possible to obtain an image of the joining and the opening of the vocal cords by means of the measurement of the electrical impedance between two electrodes placed on each side of the larynx. Signals were recorded at 10 KHz sampling rate. TIMC-IMAG database is described in Table 5.4 below:

The second database was used previously by Sehili (2013) during his thesis (described in Table 5.5). Sounds include non physiological data, but includes sounds that can be detected during food intake which makes it possible to reach the goal which is recognition of swallowing sounds in an environment likely to have other

Table 5.4: Grenoble’s database (acquired as part of the e-SwallHome project by Calabrese et al. (1998))

Sounds	Number of samples	Total Duration (s)
Swallowing	923	1538.6
Speech	351	2047.6
Sounds	126	166.2

types of ambient sounds (i.e. noise).

Table 5.5: Sehili’s database

Sounds	Number of samples	Total Duration (s)
Breathing	50	106.44
Cough	62	181.69
Yawn	20	95.87
Dishes	98	03.77
Glass breaking	101	99.52
Keys	36	166.33
Laugh	49	166.33
Sneeze	32	51.67
Water	54	84.72

5.1.5 Breathing signals

In this study, ventilation is monitored using respiratory inductive plethysmography via the Visuresp vest. The system enables the measurement of the thoracic and abdominal respiratory volumes, but also, it enables the derivation of two other signals: the respiratory volume and flow calculated from the Thorax and Abdomen signals (Figure 4.9). In this work, the reconstituted flow rate was used as it was considered to be more representative of respiratory variation by the team that designed the vest.

The annotations are considered to be the same as those obtained from sound. This is why the synchronisation of sound and respiratory signals is required. The apnoea sequences at the beginning and end of each recording play a crucial role in synchronisation. Apnea is characterised by a flat signal in the respiratory records, as shown in Figure 5.5, but not in the sound signal. For this reason, at the beginning

and end of each recording session, "TOP" is said aloud indicating the beginning and end of the recording.

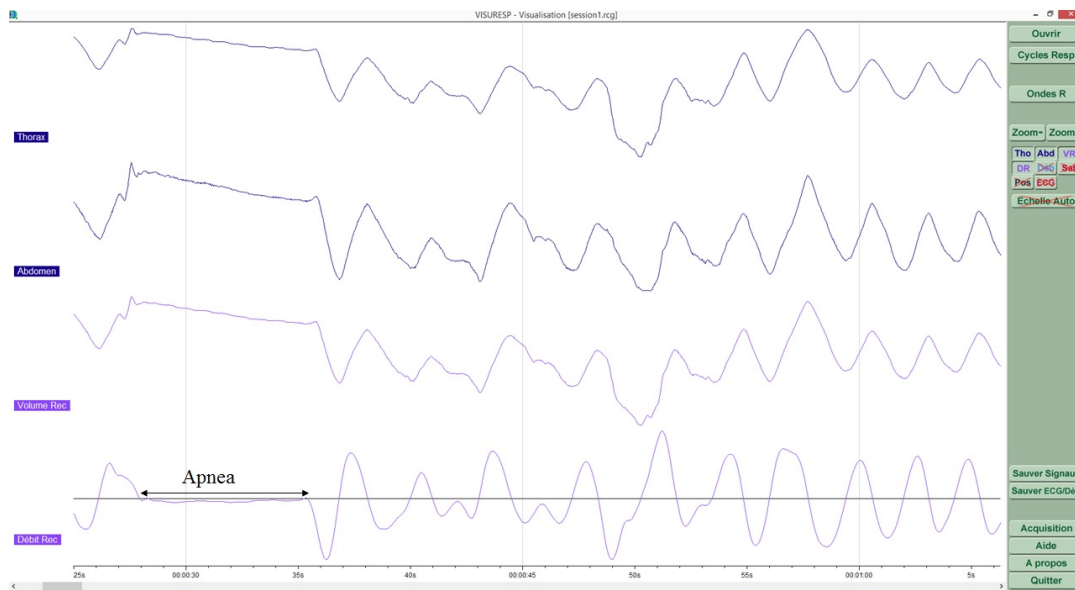


Figure 5.5: Respiratory signals and the corresponding apnea segment

The following presents the results obtained from the automatic detection algorithm in both signals and the result obtained from the coupling of the two signals.

5.2 Automatic detection algorithm results

The aim of the proposed algorithm is to automatically detect a useful signal from noise. Particularly, swallowing sounds from recording signals. The automatic detection of target signals in the study will enable, in future work, the monitoring in real time of the situation of the subject in relation to their swallowing process. It favours the study of segments recognised as the sound of swallowing and then to say after processing if it is a normal swallowing or if disorders are suspected during the course of the monitoring.

The developed algorithm is based on wavelet decomposition and on the calculation of an adaptative threshold on the selected signal. Using a sliding window along the signal with an overlap of 50%, features are calculated. The energy is calculated as the average energy of ten preceding windows of the current one. The choice of ten windows is based on experimentation. By looking at the length of the signals and taking into account the minimum limit for a good average energy, 10 is the optimal number of windows.

An example of results obtained in one signal is presented in Figure 5.9, where the green panels indicate validated detections and the light grey panels indicate partial detections and the dark grey panels indicate false alarms.

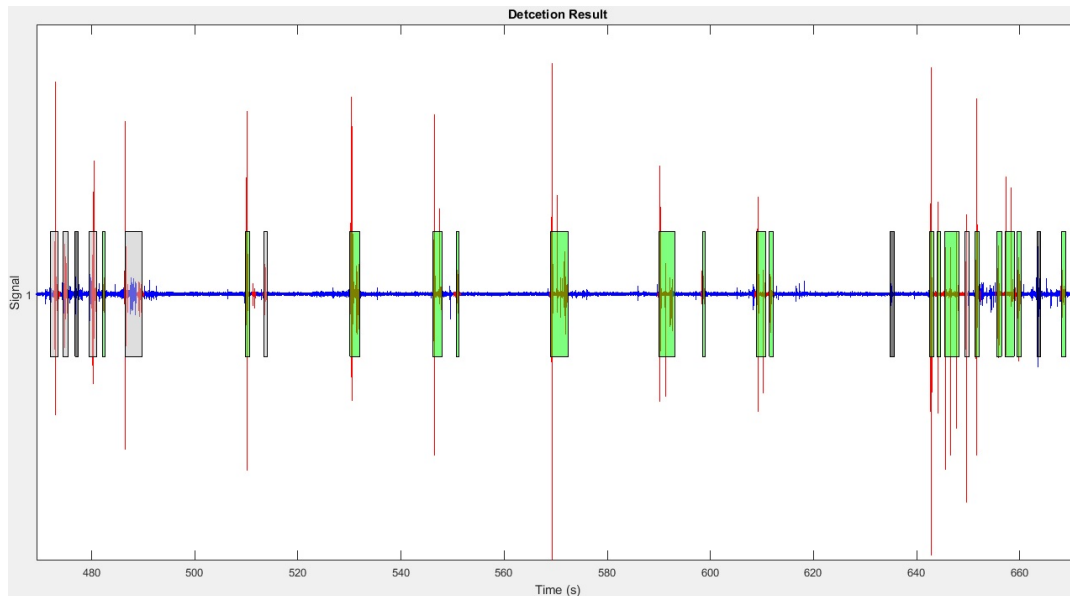


Figure 5.6: Result of the proposed automatic detection algorithm

5.2.1 Evaluation methodology

For the evaluation, a reference is considered as validated if its percentage of recovery by one or more events is $\geq 80\%$. A detection is considered validated if its percentage of overlap with a reference is $\geq 80\%$. Furthermore, partial detection was characterised when the associated energy falls below 80% of the above reference and a false alarm corresponds to a detection when the associated energy did not correspond to any annotated event. The different cases that can be obtained with this algorithm are described in Figure 5.7.

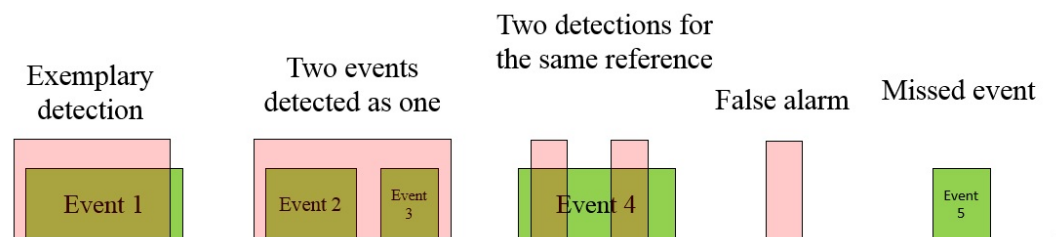


Figure 5.7: Some examples of automatic detection and errors that can be validated by the detection algorithm where green panels refer to reference event and pink panels refer to detections

The false alarm rate (FAR) is calculated as shown in equation 5.1:

$$FAR = \frac{\text{Number of false alarms}}{\text{Number of false alarms} + \text{Number of references to be detected}} \quad (5.1)$$

Validated event rate (VER) is calculated in equation 5.2:

$$VER = \frac{\text{Number of validated references}}{\text{Number of references to be detected}} \quad (5.2)$$

Partial event rate (PER) is calculated in equation 5.3:

$$PER = \frac{\text{Number of partial references}}{\text{Number of references to be detected}} \quad (5.3)$$

Missed event rate (MER) is calculated in equation 5.4:

$$MER = \frac{\text{Number of missed references}}{\text{Number of references to be detected}} \quad (5.4)$$

5.2.2 Developed detection application

The algorithms were integrated into an application developed through Matlab which enables the acquisition and detection of useful signals in real time. The graphical interface (Figure 5.8) of the application contains two panels. The first of which corresponds to the place where the curve of the signal acquired in real time will be presented. The second panel corresponds to the options available in the form of two push-buttons corresponding respectively to the beginning of the recording and the end of the recording. The black line shows the sound acquired in real time and the red line refers to the decision indicating the start point shown by the red curve going from zero to one. The end-point is shown in the red curve going from one to zero. The sound signal was recorded by the microphone positioned on the pre-studied position on the neck. The microphone has been connected to the computer through a signal amplifier (Img Stage Line Microphone Preamplifier), which is connected to an external DeLOCK sound card in the form of a sound box connected to the PC via a USB 2.0 cable. A signal is required with a sample rate of 16 kHz with an analysing window of 0.08 second.

Results showed an overall rate of validated events of 86.14% of which 22.19% were validated events and 63.95% were partial events. The rate of missed events

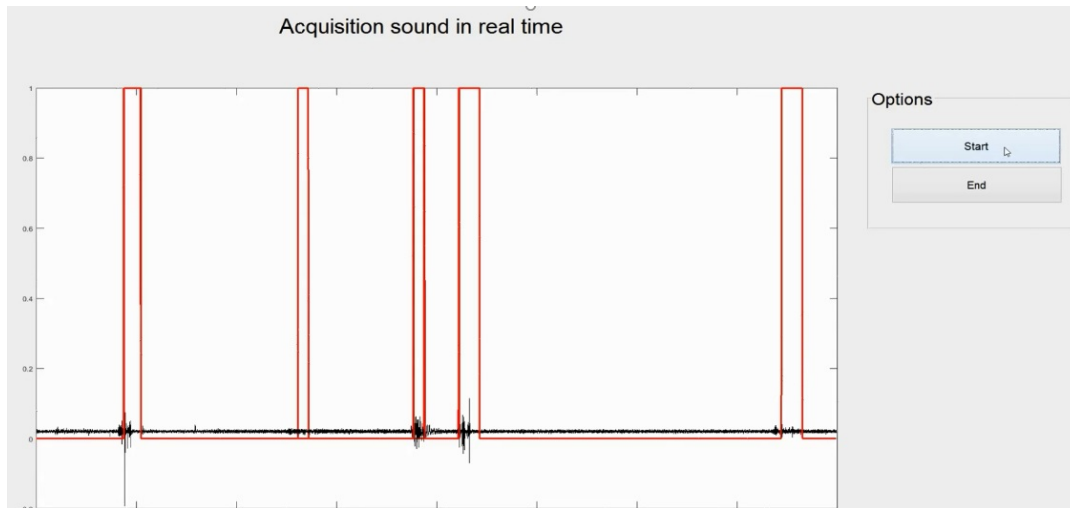


Figure 5.8: Graphical interface of the recording and detection application in real time

is about 13.85%. The false alarm rate is about 24.92%. Results are summarised in Figure 5.9 and Table F.1 below.

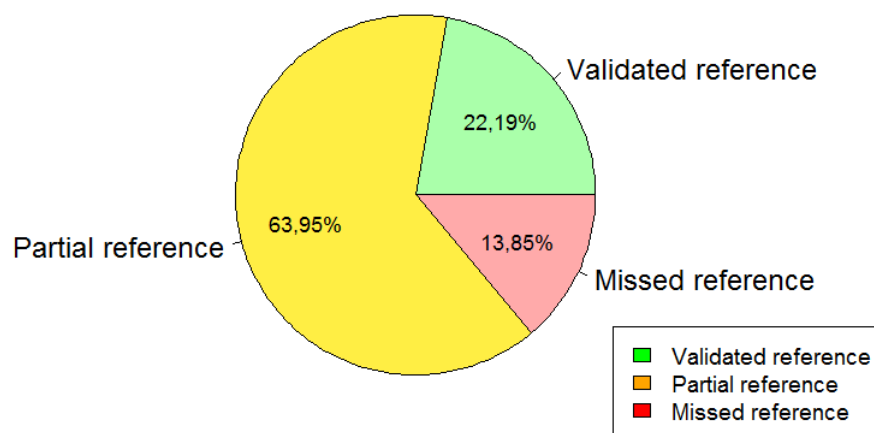


Figure 5.9: Detection results

Once the results of the automatic detection algorithm have been validated, the next step is to classify a new sound among the different sound classes.

Table 5.6: Automatic detection results

Number of references to be detected = 3501			
Events		References	
Number of Validated Events	67.55%	Number of Validated References	22.19%
Number of Partial Events	30.13%	Number of Partial references	63.95%
Number of False Alarms	24.92%	Number of Missed References	13.85%

5.3 Classification results

In this section, the results of classification algorithms are presented in order to identify firstly swallowing sounds from other sounds. Secondly, the results for the classification of textures are presented. Finally, the results obtained to identify the boundaries of the different characteristic sounds from the sound of the single swallow are set out.

5.3.1 Evaluation methodology

For classification evaluation, a large corpora is needed for training the models and also a large (in order to have good statistics) corpora for testing. If sufficient data are available, usually, the corpora are divided into 2/3 for training and 1/3 for testing. If the corpora size is not sufficient, the a k-folds method was used.

The k -folds method consists of randomly splitting the database into k equal parts and then removing part of the learning and using it as a test, then repeating this manoeuvre for each part. The k -fold cross-validation divides the original sample of size n into k sub-samples, then selects $k - 1$ sub-samples as learning set and the last sample serves as validation set. Since there was not enough data, the leave-one-out cross validation approach was used, a particular case of k -fold cross validation for $k = 1$. Practically, the first observation was used as a validation sample and the $n - 1$ remaining observations as a learning set. Then, this procedure was repeated n times by choosing as validation observation the 1st, 2nd, 3^d etc..., the last one, and taking each time the other observations as learning set. The leave-one-out method is a particular case which is only used for test data set-up.

The choice of leave-one-out cross validation approach (5.10) minimises the interdependence between samples and thus comes as close as possible to the effective accuracy of the evaluated system.

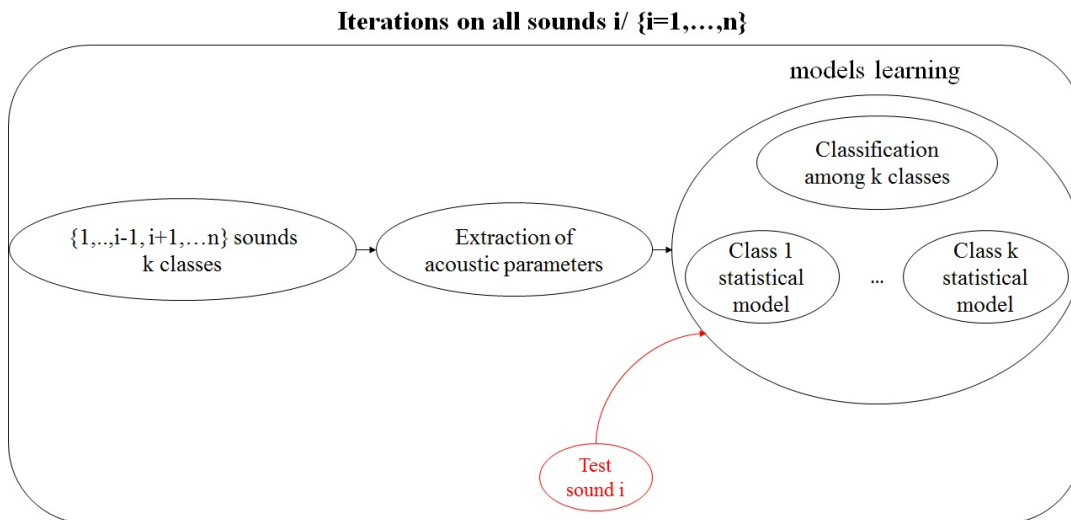


Figure 5.10: Classification evaluation process with leave-one-out approach

5.3.2 Classification

The first intention, while respecting the initial goal of the project, is to be able to recognise the sounds of swallowing from other sounds. To do this, three sound classes were worked on; representing swallowing sounds, speech sounds and other sounds such as coughing, yawning and breathing. For this purpose a Gaussian Mixture Model (GMM) through the EM algorithm was used. For each sound class, a model was made using the fourteen LFCCs and their first and second derivatives calculated for each sound using a sliding window of 16 ms with an overlap of 50%. For the test step, the membership of each sound was checked for each model created previously during the learning phase by taking the maximum of the log-likelihood. The evaluation process is presented here with the leave-one-out approach evaluation process result obtained using the database described in Table 5.1. First, the results obtained using the manually annotated segments are presented (ideal case) followed by the coupling of the automatic detection results and classification.

Optimization of Gaussian numbers for the GMM model

In practice, automatic learning implies the optimization of a performance criterion. It was then that the Gaussian number to be used for the model of each sound class was optimized. Two scenarios are displayed: an optimization of the number of Gaussian for the classification taking into account three sound classes representing

swallowing, speech and environmental sounds respectively. And other optimisation step for classification of swallowing sounds according to the swallowed texture. following steps for training and testing, by varying the number of gaussian components in each studied case. By consulting the confusion matrix for each case, the optimal number of Gaussian is 8 in the case of the classification of sounds considering swallowing, speech and all other sounds. And in the case of classification of the sound of swallowing according to the swallowed texture: saliva, water and compote, the optimal number of gaussian components is 4.

Swallowing-Speech-Sounds classification of manually annotated sounds

For the manually annotated segments, an overall recognition rate (ORR) was obtained of 95.49% with a recognition rate of 100% for swallowing sounds. The results are presented in Table 5.7. The good recognition rates corresponding to each sound class are presented in Figure 5.11. The recognition rate for speech is 91.49% and for sounds 94.98%. The risk of confusion with the class of speech and sounds is low; 8.51% of speech are recognised as sounds and 5.02% of sounds are recognised as speech.

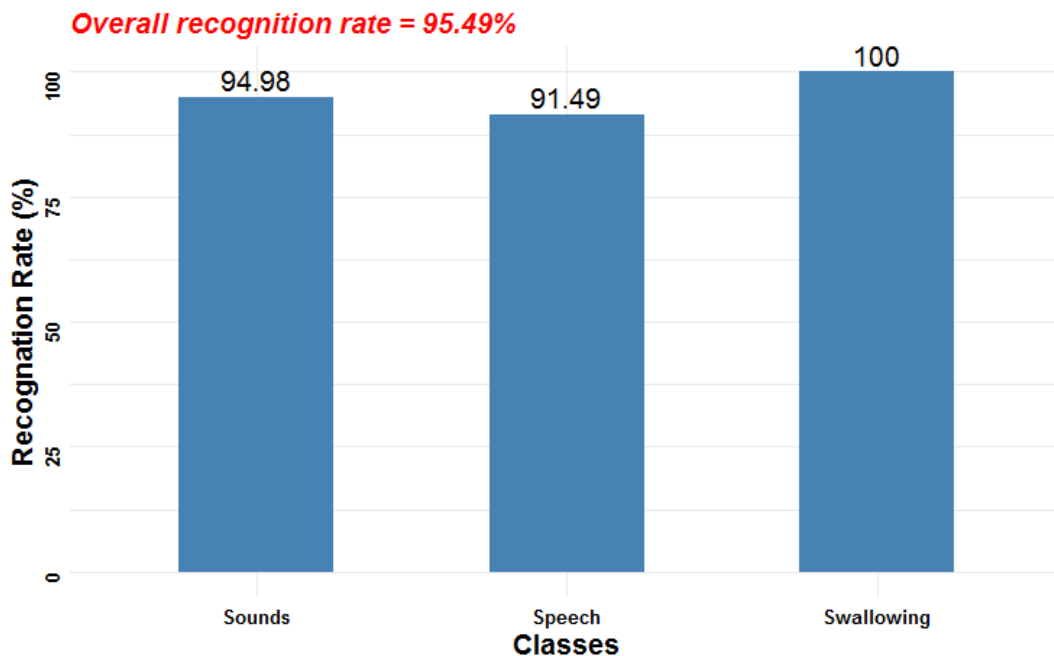


Figure 5.11: Good recognition rate per class using manually annotated segments

Table 5.7: Confusion matrix of the classification of manually annotated segments

ORR = 95.49%	SwallowingSpeechSounds		
Swallowing	100%	0	0
Speech	0	91.49%	8.51%
Sounds	0	5.02%	94.98%

Swallowing-Speech-Sounds classification-Comparison with other databases

This sub-section presents a comparison of the results of the detection algorithm and classification applied using different databases other than the database used here (Tables 5.4 and 5.5).

Results of the automatic detection algorithm, applied on the sounds obtained from the microphone attached to the vest, show a global rate of good detection of 87.31% among the different events of swallowing, speech and sounds as shown in Table 5.8 and a global rate of false detection of 36.49%. Then to show the impact of partial detection in the classification system, the detections that contain more than 50% of the reference event are observed, which represent 82.9% of global good automatic detections.

Table 5.8: Automatic Detection Algorithm results for data obtained from microphone attached to the vest

Rate of good detection 87.31%	Swallowing 90.11%	Automatic detections containing +50% of reference event	Swallowing 76.83%
	Speech 80%		Speech 80%
	Sounds 100%		Sounds 66.67%

Figure 5.12 shows the confusion matrix using just the UTC database using GMM trained through the Expectation Maximisation (EM) algorithm and leave-one-out approach. It shows a good rate of recognition of 84.57% for swallowing events and 75% and 70.57% respectively for speech and sounds events. On other hand, results show a false positive rate of swallowing events of 4.26% and 11.17% classified respectively in speech and sounds events which means that some swallowing events will be missed. Also, sounds events are sometimes misclassified as swallowing events which means false alarm of swallowing event. This result is obtained using segments manually annotated and extracted. The same test has been applied to the Grenoble database. The results in Figure 5.13 show a good rate of recognition for three classes Swallowing, Speech and Sounds respectively of 95.94%, 98.92% and 67.46%.

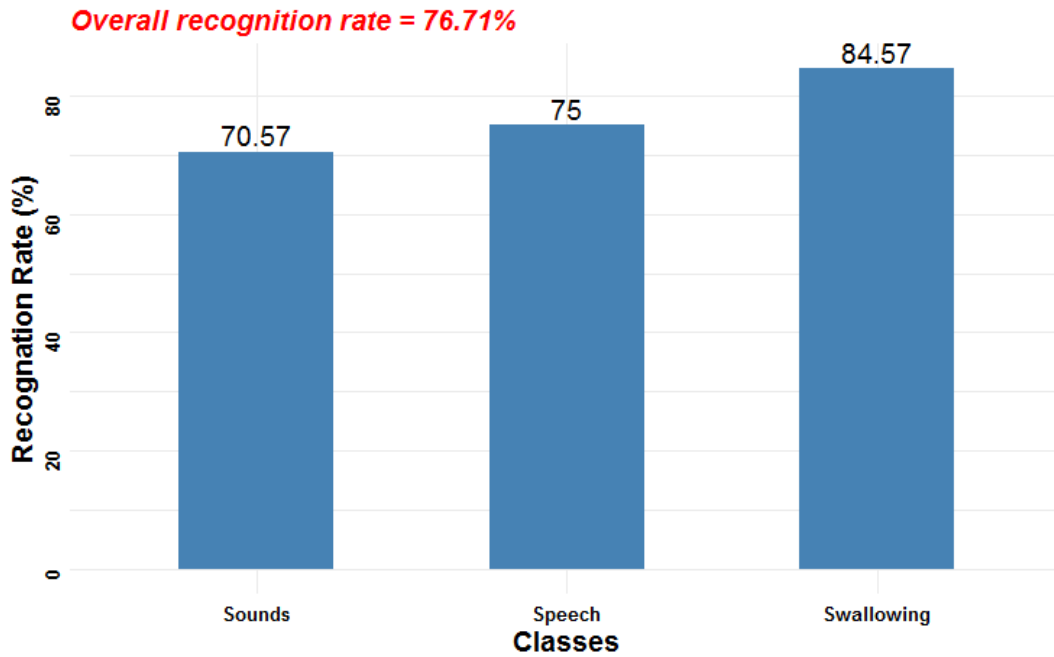


Figure 5.12: Good recognition rate per class using sounds obtained from microphone fixed on the vest

Table 5.9: Confusion matrix using sounds obtained from microphone fixed on the vest

	Swallowing Speech Sounds		
Swallowing	84.57%	4.26%	11.17%
Speech	0%	75%	25%
Sounds	14.96%	14.46%	70.57%

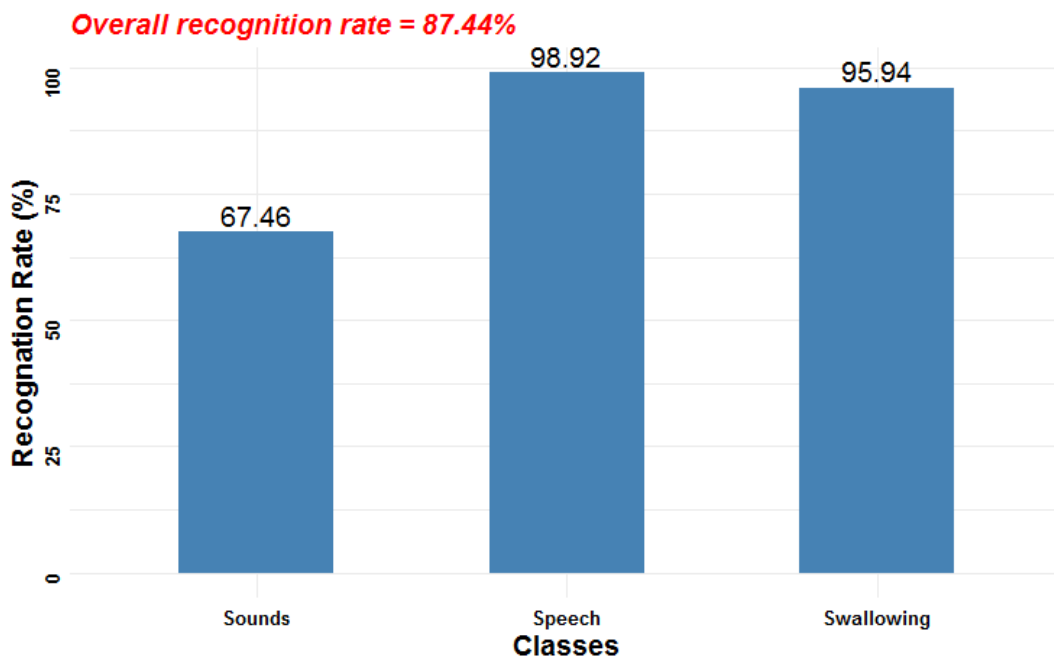
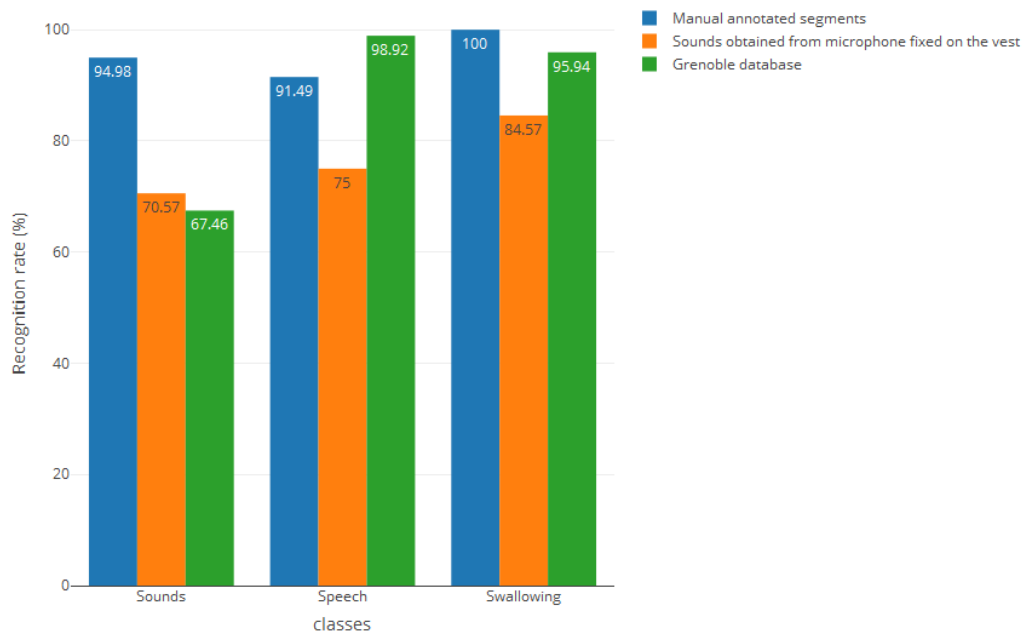


Figure 5.13: Good recognition rate per class using Grenoble database

Table 5.10: Confusion matrix of Grenoble database

	Swallowing Speech Sounds		
Swallowing	95.94%	1.22%	2.85%
Speech	1.08%	98.92%	0%
Sounds	11.11%	21.43%	67.46%

Results of classification have produced comparable results but the best recognition rate was obtained using sounds recorded with a microphone fixed in a controlled and pre-studied position on the neck. It shows the importance of the position of the used microphone. The results also show that sound recognition depends on the quality of the signal and therefore indirectly on the type of microphone used for recording and its position. The comparison between the results, shown in the Figure 5.14 below, shows good results when using the preamplified microphone with a pre-studied position.

**Figure 5.14:** Good recognition rate per class using different data

Moreover, we also would like to test classification using different data. So, models were trained using UTC data and test with Grenoble data. Obviously the results deteriorate because signals were not recorded in the same environmental conditions and were acquired with different sensors. To remedy this degradation, in future work it is intended to apply a GMM and MAP (Maximum a Posteriori) adaptation approach.

Unlike the recognition of manually annotated swallowing sounds, the recognition of swallowing sounds according to the swallowed texture is not well recognised and the risk of confusion between the three classes is very high. This is explained by the similarity intra-subjects of the sound components of the swallowing sounds independently of the textures and their great variability inter-subjects. Below, examples are shown of the sound signals referring to the different textures of swallowing sounds and their corresponding spectrograms (Figure 5.15, 5.16 and 5.17).

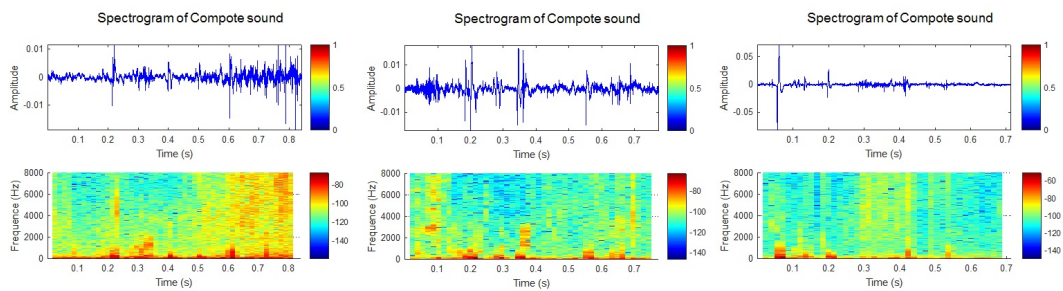


Figure 5.15: Spectrograms of the sounds of compote swallowing

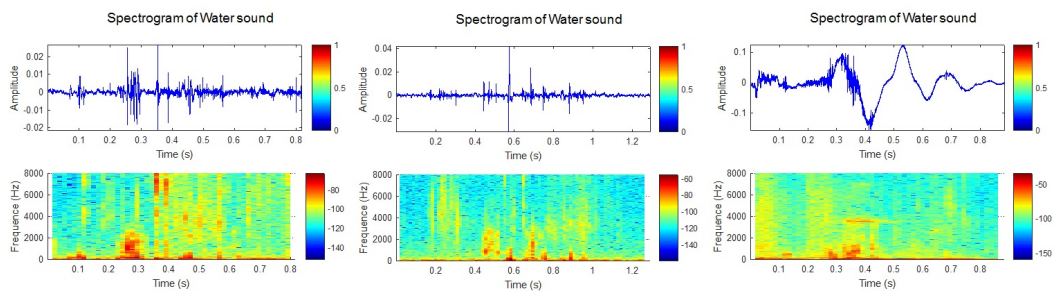


Figure 5.16: Spectrograms of the sounds of water swallowing

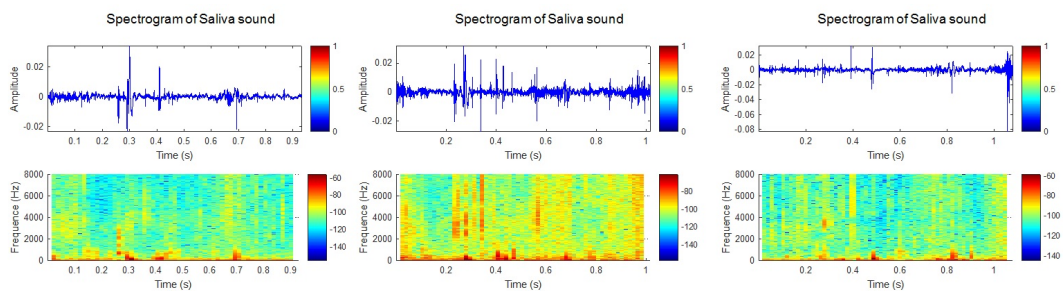


Figure 5.17: Spectrograms of the sounds of saliva swallowing

Textures classification of manually annotated sounds

In this section, it was proposed to classify textures using GMM. To do so, models were created for each sound class of texture according to the swallowed textures of compote, water and saliva respectively. Good recognition rates for each considered class are given in Figure 5.18. The detailed results are summarised in Table 5.11. Good recognition rate for each considered texture are presented in Figure 5.18

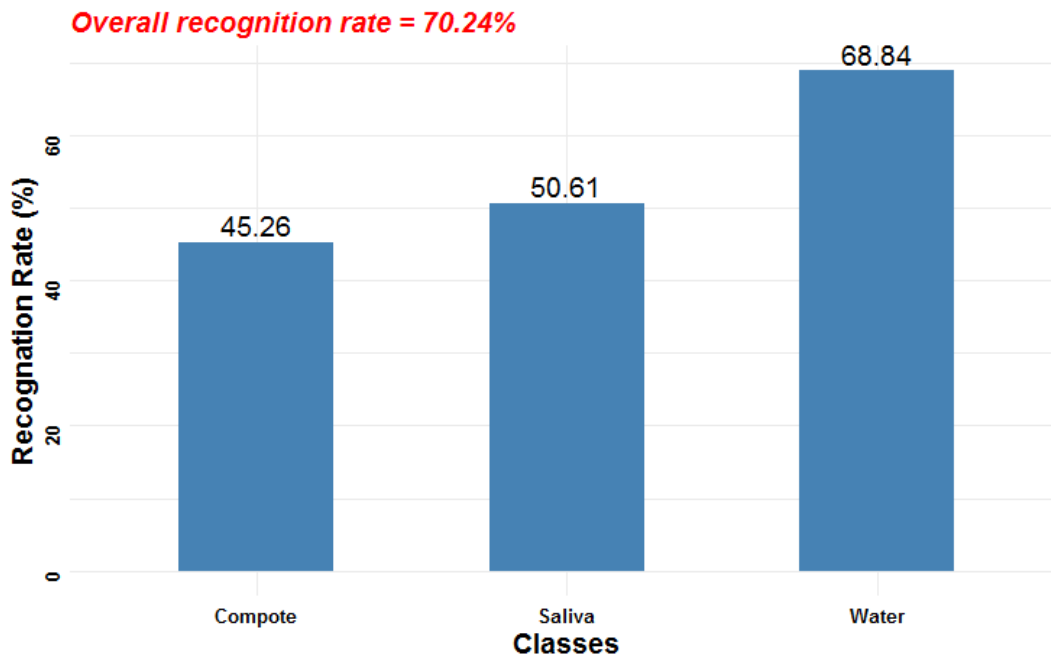


Figure 5.18: Good recognition rate per class using manual annotated swallowing sounds according to textures

Table 5.11: Confusion matrix of the classification of manually annotated swallowing sounds according to textures

ORR = 70.24%	Compote	Water	Saliva
Compote	45.26%	30%	24.74%
Water	19.07%	68.84%	12.09%
Saliva	23.27%	26.12%	50.61%

Coupling between detection and classification

This section presents the results of the coupling between the sound event detection system and the sound classification system. The detection of a sound event consists of determining the time of appearance and end detection of a signal, after which the classification system is activated in order to identify the event. The critical point affecting the coupling between classification and detection is the performance of the

algorithm for automatic detection of useful signals. In other words, the detection of the beginning and end of the detected signals. Among the possible failures are:

- Early detection of the signal or the start is detected before the actual start of the signal and the cost part of the detected signal contains only noise (same remark for the detection of the end after the actual end of the signal),
- Delayed detection of the signal or the start is detected after the actual start of the signal and therefore part of the useful signal is not taken into account (same remark for the detection of the end before the actual end of the signal),
- Detection that merges several events, i.e. the detected signal contains both useful signals and noise. This does not pose a problem for classification if the merged events are of the same nature, for example swallowing-deglutition, but for example in the case of merging swallowing and speech, the segment will be attracted to one of the two classes. It should be noted that the classification of automatically detected signals containing or not noise does not influence the classification that is carried out with a GMM system that does not take into account the time evolution of the signal,
- Detection of false alarms that do not correspond to any useful signal.

The detection algorithm based on the wavelet transform, proposed in Chapter 4, has good detection performance and good accuracy in determining the time of signal start and end. But it also has constraints in the form of event merging, delayed detection of the beginning and end of each event, and detection of false alarms.

Three global sound classes are obtained from the algorithm of automatic detection: validated detections, partial detections and false alarms. The same procedure of classification is done using GMM model using the automatically detected sounds.

Taking into account all the outputs of the detection, an additional class has been added to the system previously proposed. The classification based on GMM models was performed using the leave one out approach. Each class is learned at each iteration from the validated segments. The results of the classification are summarised in the Table 5.12. The overall recognition rate of the system is 88.87% with a good recognition rate of swallowing sounds of 87.10%. False alarm sounds are all well recognised (100%). However, the risk of confusion between classes is almost important for sounds of which 25.44% is recognised as swallowing, which can be explained

by the similarity between the segments of the swallow and those of the automatically detected sounds caused by the noise contained in the detected segments.

Table 5.12: Confusion matrix of the classification of automatically detected sounds

ORR = 88.87%	Swallowing	Speech	Sounds	False alarm
Swallowing	87.10%	12.58%	0.32%	0%
Speech	3.46%	95.60%	0.94%	0%
Sounds	25.44%	1.78%	72.78%	0%
False alarm	0%	0%	0%	100%

The same interpretation for the classification of textures for automatically detected swallowing sounds, the risk of confusion between classes is remarkably high as shown in table 5.13.

Table 5.13: Confusion matrix of the classification of automatically detected swallowing sounds according to textures

ORR = 62.55%	Compote	Water	Saliva
Compote	33.33%	58.02%	0%
Water	15.15%	67.42%	1.52%
Saliva	13.40%	68.04%	6.19%

5.3.3 Assessment of Swallowing Sounds Stages

As described above, single swallowing sounds were manually segmented into three phases by visual aids such as spectrogram and auditory means (by listening to the sounds repeatedly). Figure 5.19 shows examples of decomposition of swallowing sounds for swallowing of water and compote into three phases.

The duration of each swallowing phase in healthy subjects is presented in Tables 5.15 and 5.14 below:

Table 5.14: Swallowing phases duration for Water sounds

	Phase 1	Phase 2	Phase 3
Duration (s)	0.240 ± 0.109	0.439 ± 0.149	0.299 ± 0.137

Table 5.15: Swallowing phases duration for Compote sounds

	Phase 1	Phase 2	Phase 3
Duration (s)	0.222 ± 0.111	0.461 ± 0.167	0.308 ± 0.128

To automatically identify the boundaries of each phase of the swallowing phases described above, it was proposed to apply two algorithms.

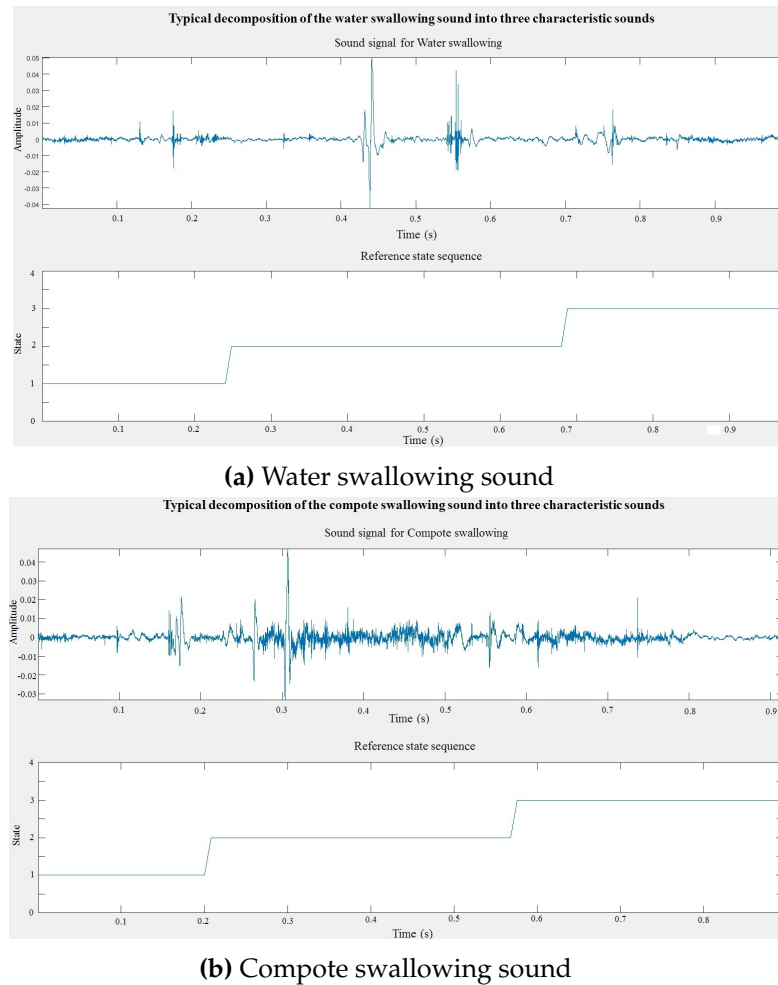


Figure 5.19: Typical decomposition of the swallowing sound into three characteristic sounds

Assessment of Swallowing Sounds Stages with HMM

Several features were tested as inputs for each swallowing sound: LFCCs, MFCCs, mean, standard deviation, mean frequency, mean power, root mean square, variance, waveform fractal dimension (WFD), skewness and kurtosis measures. Table 5.16 shows the mean and standard deviation for delays in the detection of boundaries of swallowing sound phases among all tested data. Negative values in the delays mean that the boundary detected by the Vitervi algorithm occurs before the manually annotated boundary.

Based on the results shown in Table 5.16, the best results were achieved using LFCC_2 and 8LFCC where LFCC_2 refers to the second coefficient of LFCCs and 8LFCC refers to the first eight LFCCs coefficients. It was expected at the beginning that the best result would be obtained from WFD as was the case in the study of Moussavi (2005), but the model does not change state for all the segments tested.

Table 5.16: Mean \pm standard deviation for delay in detection of boundaries of swallowing sound phases obtained by HMM

Features	Delay in detection of the beginning of IDS (ms)	Delay in detection of the beginning of BTS (ms)
LFCC_2	13.56 \pm 40.67	-0.44 \pm 39.15
8LFCC	2.67 \pm 38.70	-0,64 \pm 63.76
8MFCC	22.32 \pm 51.67	-56.91 \pm 53.33
MFCC_2	16.23 \pm 38.13	-39.31 \pm 44.54
Mean	-9.98 \pm 39.77	-88 \pm 55.38
Standard deviation	-34.13 \pm 18.22	-127.62 \pm 56.75
Mean frequency	17.37 \pm 52.48	-72.38 \pm 51.39
Mean power	-36.50 \pm 16.72	-102.48 \pm 65.73
Root Mean Square	-34.13 \pm 18.22	-137.37 \pm 51.03
Variance	-36.50 \pm 16.72	-144.84 \pm 40.26
Waveform fractal dimension	X	X
Skewness	7.31 \pm 46.88	-68.11 \pm 65.68
Kurtosis	9.22 \pm 50.75	-35.81 \pm 64.39

It could be explained by the quality of the signal which is acquired using different sensors, compared to this study. In the following, the results obtained are presented separately with the sounds of water and compote using parameter LFCC_2 that gave the best results. Table 5.17 shows the confusion matrix of the classification of water sounds, which shows that the first phase is the best recognised phase unlike phase 2 and phase 3 which is consistent with what was found by Moussavi (2005). The classification using IDS segment improves the accuracy up to 73%. Delays of detection boundaries are shown in Table 5.18.

Table 5.17: Confusion matrix of the classification of water sounds of the swallowing phases using HMM

ORR = 52.83%	Phase 1	Phase 2	Phase 3
Phase 1	73.35%	20.62%	6.03%
Phase 2	41.96%	37.29%	20.74%
Phase 3	18.40%	36.74%	44.86%

Table 5.18: Delays in detection boundaries of swallowing phases in water sounds (ms)

Detection delays of IDS	Detection delays of BTS
6.49 \pm 55.11ms	-49.15 \pm 68.98 ms

Results using HMM were almost similar for the compote sounds, always using LFCC_2 as input feature for HMM, as shown in Table 5.19 with a delay of detection IDS of 16.10 \pm 60.12ms, and detection of BTS boundaries are well in advance of what it was annotated manually (Table 5.20).

Table 5.19: Confusion matrix of the classification of compote sounds of the swallowing phases using HMM

ORR = 46.29%	Phase 1	Phase 2	Phase 3
Phase 1	72.36%	19.15%	8.49%
Phase 2	48.16%	29.36%	22.47%
Phase 3	28.60%	34.24%	37.15%

Table 5.20: Delays in detection boundaries of swallowing phases in compote sounds (ms)

Detection delays of IDS	Detection delays of BTS
16.10 ± 60.12ms	-43.04 ± 68.76 ms

The accuracy of classification by HMM hardly reached 52%. In the next section, the results obtained by the algorithm based on the detection of local maxima described in section 4 are presented.

Local maximum detection algorithm results

Assuming that a single swallowing sound contains three specific sounds characterised by three peaks, the main idea is to look at the location of the local maxima of the signal by imposing a minimal distance between two peaks. Accordingly, the boundaries of each phase are determined according to the number of local maxima detected. Results showed good results for recognition of phases with an overall rate recognition of 80.27% for water and 70.95% for compote as shown in Tables 5.21 and 5.22.

Table 5.21: Confusion matrix of the classification of water sounds of the swallowing phases using local maximum algorithm

ORR = 80.27%	Phase 1	Phase 2	Phase 3
Phase 1	93.60%	6.40%	0%
Phase 2	19.81%	71.11%	9.09%
Phase 3	0%	23.89%	76.11%

Table 5.22: Confusion matrix of the classification of compote sounds of the swallowing phases using local maximum algorithm

ORR = 70.95%	Phase 1	Phase 2	Phase 3
Phase 1	73.11%	26.76%	0.14%
Phase 2	11.36%	81.16%	7.48%
Phase 3	0%	41.43%	58.57%

Detection of boundary of IDS is always delayed compared to manual annotation by $13.49 \pm 20.42ms$ for water and $0.71 \pm 29.68ms$ for compote. Delay for detection of

the BTS boundary also occurs in advance compared to manual annotation for water sounds indicated by the negative values in Tables 5.23 unlike delay for detection of BTS boundary for compote.

Table 5.23: Delays in detection boundaries of swallowing phases in water sounds (ms)

Detection delays of IDS	Detection delays of BTS
$13.49 \pm 20.42ms$	$-0.61 \pm 30.45ms$

Table 5.24: Delays in detection boundaries of swallowing phases in compote sounds (ms)

Detection delays of IDS	Detection delays of BTS
$0.71 \pm 29.68ms$	$19.69 \pm 36.25ms$

Considering feature sequences as the features of the entire swallowing sound signals considered as one segment of a single swallowing process, the accuracy of classification by the proposed algorithm of looking for pics reached an overall good recognition rate of 80.27% with a good recognition rate of 93.60% considering only the IDS segment and around 71% and 76% for BTS and FDS segments for water. For compote, results are deteriorating with an overall recognition rate of 70.95%.

The proposed algorithm gives good results for identifying the boundaries of each swallowing phase that enables the comparison of the duration of normal swallowing phases with those of pathological swallowing.

5.4 Breathing analysis results

As described in chapter 4, the dominated swallowing-breathing pattern is reported by swallowing process occurring during expiratory phase. Hence, the idea consists of detecting the beginning and end of each respiratory phase. Below, the Figure 5.20 shows the respiratory flow signal reconstructed at the beginning and end of each detected respiratory phase. Red star refers to the beginning of inspiratory phase (or the end of expiratory phase) and green star refers to the end of inspiratory phase (or the beginning of expiratory phase).

Detecting boundaries of the respiratory phases enables the identification of the exhalation segments, during which swallowing can occur. Based on the duration of the expiratory phase, by imposing a threshold from which it is considered that the identified phase does not only include exhalation, but also swallowing. Figure 5.21

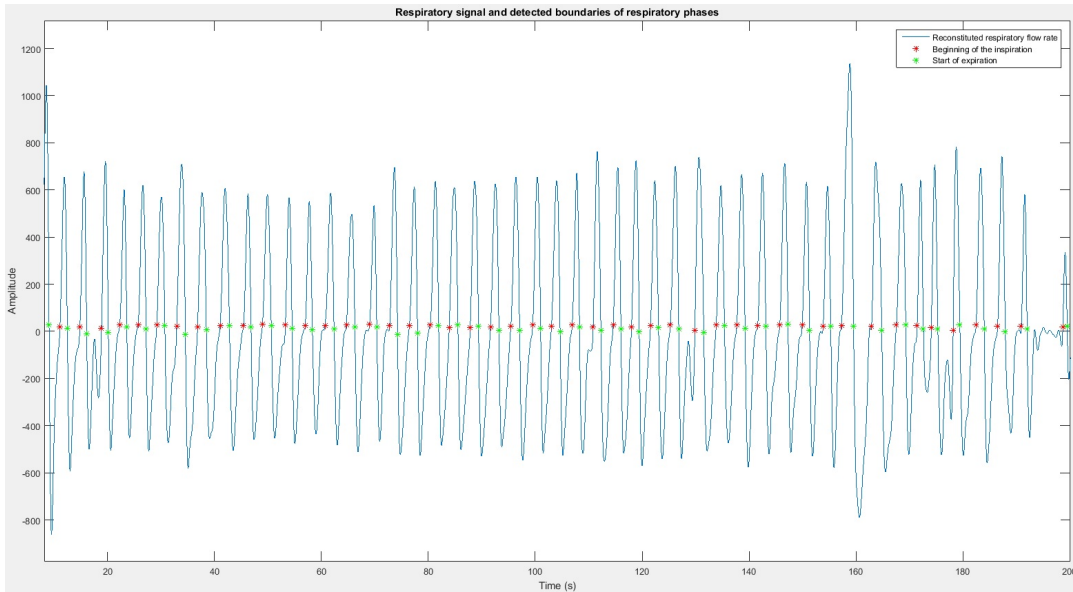


Figure 5.20: Respiratory signal and detected boundaries of respiratory phases (inspiration and expiration) during the subject's rest

shows the detection results obtained on both the sound signal and the respiratory signal. It can be seen that the majority of the detected expiratory phases merge several reference events as shown in the Figure 5.21 with the segments marked by green arrows. In other examples, missed events were noticed, indicated by arrows and red circles on the same Figure below, where events of swallowing take place at the transition inspiration-expiration as it is impossible that it will occur during the inspiration phase Hukuhara and Okada (1956) and they are of a very short duration.

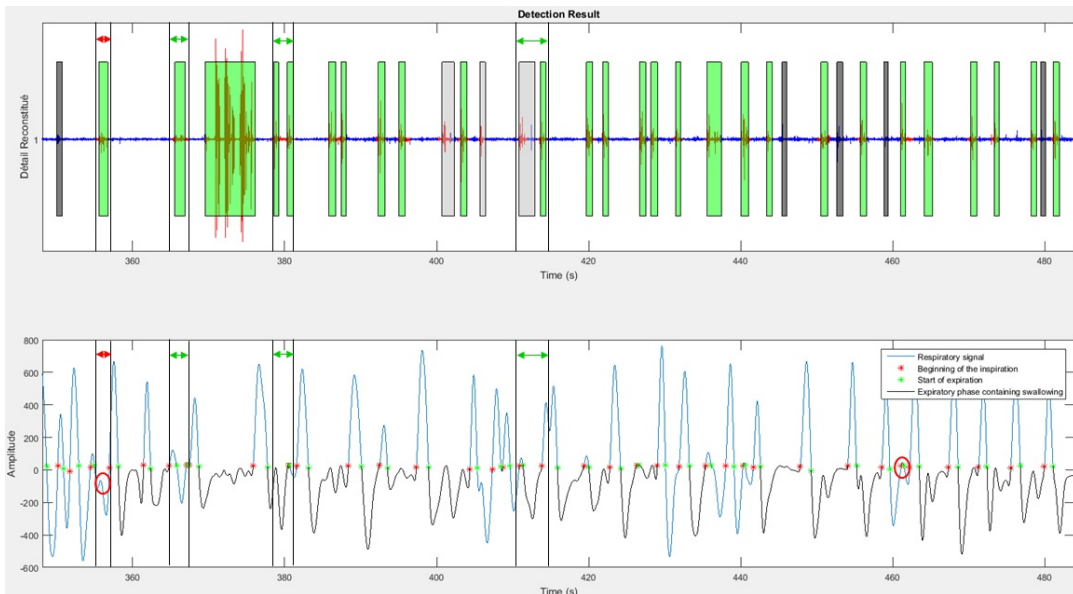


Figure 5.21: Results of automatic detection on the synchronized sound and respiratory signals

At this stage, the breathing signal was processed for data fusion with the swallowing signal as obtained. Accordingly it was possible to detect respiratory phases and swallowing apnoea segments characterised by a flat shape fluctuating around zero. Apnoea can indicate a distress situation for the subject if the duration exceeds a certain defined threshold. A thorough investigation was necessary to accurately identify the segments of swallowing on the respiratory signal.

5.4.1 Discussion

The first part of the proposed system concerns the detection of useful sound, regardless of its nature, from a sound recording. In this regard, I proposed an algorithm based on wavelet decomposition, a method that allows the signal to be analyzed in specific frequency bands. This allows us to study in particular the frequency band of the swallowing sound, the sound that is of specific interest to us. The analysis of the algorithm's performance shows good results, but there are still imperfections to be reviewed and improved in the next work. Among these imperfections are early or delayed detections of the beginning and/or end of the desired signal. The more we detect that the desired signal, the more we avoid processing the sound noise that contains no events. Including noise in the sound segments automatically detect reduces the performance of the next steps in the system, such as classification.

The second part of the proposed system concerns noise classification. The latter was present in three levels; first, we chose to recognize the sounds of the swallowing of any other sound event. Once the swallowing event has been well recognized, the swallowed texture can either be recognized or segmented directly into three characteristic phases.

In order to achieve optimal system performance, it was decided to process the manually annotated sound segments. This resulted in a 95.49% overall good recognition rate. But once we move on to the detection-classification coupling, the results deteriorate. For the recognition of the sound segments of swallowing among the others, three classes have been established: swallowing, speech and sounds. The GMM were thus exploited in a supervised way and therefore a learning step of each sound class was performed before assigning the test sound files to the most likely class. For the learning of a sound class, while assuming the three classes mentioned above, an experimental study was carried out to determine the optimal number of Gaussian components. Thus, Gaussian model was learned for each class. It was not possible

to use a single model with three Gaussian components representing the three fixed classes because a single component is not sufficient to model the different sounds sufficiently diversified within the same class. The choice of the number of the class and their nature is quite critical. We have both human and non-human sounds. An in-depth study should be carried out on the number of classes and their nature to be more appropriate with the isolation of each sound class.

Results on average are good for all considered classes: swallowing, speech, sounds and false alarm. The worst recognition rate was obtained with the sounds class which is largely (about 25%) recognized as swallowing sounds. This could be explained by the very short duration of the detected sounds, which are similar to swallowing sounds using the chosen acoustic features. Furthermore, The differentiation of the swallowed texture is not well established but the segmentation into three phases characteristic of the sound of swallowing has given promising results allowing in the presence of pathological signals to determine the abnormal phase of swallowing.

For the segmentation of the swallowing sound into three characteristic sounds, two methodologies were used, the first based on Markovian models and the second based on the search for peaks limiting the different phases. The same spirit of application was used for the classification of the different states using HMM. A new approach was also applied to the segmentation of the sound of swallowing. It is based on the detection of peaks characteristic of phase boundaries. This approach has yielded good results and an overall rate of good phase recognition of = 80.27%.

The processing of breathing signals requires a thorough study and, if necessary, a fusion with the results of the sound signal in order to improve the performance of the system based on both sound and breathing.

Chapter 6

Conclusions and perspectives

For several years, the processing of physiological signals of the swallowing process has been enhanced in order to meet the needs of patients suffering from pathologies affecting the normal conduct of swallowing. The signals and informations useful for processing the swallowing process used in the various studies come from a variety of invasive and non-invasive sources such as video-fluoroscopy, microphone or questionnaires, with varying degrees of accuracy. The main objective of this thesis according to the initial objective of the e-SwallHome project is to develop a tool able to process swallowing signals in real time using the least non-invasive ambulatory sensors that do not interfere with the person's quality of life. For this reason, it has been proposed to use mainly the sound of swallowing because of its potential for the diagnosis of dysphagia.

This PhD study has been conducted within the overall framework of telemedicine and telemonitoring applications research. In this context, the focus of this study has been to exploit acoustic signal processing deployed in the detection and analysis of swallowing process acoustic signatures during food intake for medical monitoring.

An important issue in monitoring the swallowing process that has been covered in this work is the detection of sound events from a recording acquired in real time or not. The performance of this proposed algorithm is essential to the next step in sound recognition during food intake. Signal quality also has a significant role to play in the performance of the algorithm. It depends on the sensor used and its position. Therefore, a study of the best position for the sensor was carried out.

The adaptation of methods for recognizing different sounds was also an issue addressed in this work. To do so, a search was performed for the acoustic parameters the best adapted to the sounds of swallowing. The work presented consists of two parts: the automatic detection of sound events and the classification of sounds.

The main contributions of this work are as follows:

Establishment of the sound database: A database was created to make up for the lack of an available swallowing sound database with a total duration of 2 hours and 40 minutes distributed in three global classes; swallowing sounds, speech sounds and other sounds consisting of breathing sounds, coughing sounds, yawning sounds, etc... The recording was performed using a data acquisition protocol to record swallowing of different textures (saliva, water and compote), speech, apnoea, coughing and yawning. The annotation of the various events was done using the free TranscriberAG software, which is designed for assisting manual annotation.

Detection of sound events: The detection of sound events is discussed in Chapter 4. The proposed algorithm is based on the wavelet transform of the signal helping to work on specific frequency bands on all types of sound events and more specifically on swallowing sounds which are characterised by low amplitudes and are sometimes drowned in noise. According to the observations, the strength of the swallowing signal depends on several factors including the persons themselves and the way they swallow.

The classification of sounds: The classification algorithms were used to classify sounds first to identify swallowing sounds, second to identify swallowed texture and finally to detect the boundaries of each phase in the swallowing sound. The choice of using the Gaussian Mixture Algorithm (GMM) is explained by the fact that a giant database is not required, unlike other models such as Deep Learning. For the application, several parameters were tested and those that gave the best performance were selected.

The identification of the swallowing segments was well achieved with a good recognition rate both for the ideal case on the manually annotated segments and with the proposed coupling system. However, the recognition of the swallowed texture did not give good results. For the segmentation of the swallowing sound into three characteristic sounds as described in Chapter 6, the hidden Markov models were adapted to recognise the state sequences. However, the accuracy of classification hardly reached 52%. Consequently, and based on the typical shape of the swallowing sound, which includes three characteristic peaks, an algorithm was developed based on the search for the positions of these peaks, deciding the limits of

each phase according to these positions. Evaluation shows a good recognition rate of 80.60% which enables an automatic measuring phase swallowing duration, which could be markers indicating dysphagic swallowing.

The detection-classification coupling: The coupling of automatic detection of useful signal and the classification is very critical. Indeed, its performance is fundamental to guarantee a better result for the final system namely for the classification step. The detection algorithm has a good rate, but with some failure described above. The main limitation of this algorithm is a fusion of events which can be of a similar nature, which is not a problem for the sound recognition but, if they are of different types, poses a problem for the classification, because the proposed algorithm processes the signal of a single swallowing. Then, it is necessary to adapt the algorithm to treat all the automatic detections recognised as swallowing.

Perspectives

Detection of sound events uses algorithm based on the wavelet transform, keeping only the details with frequency bands contained in the frequency band of 0-1000 Hz and using an adaptative thresholding for each analysis window. Temporal energy was measured to follow the temporal evolution of the signal under consideration. Using frequency parameters could allow a better detection accuracy. The improvement of the algorithm is crucial in order to typically detect the beginning and end of each event and guarantee a better performance for the classification stage. In the home monitoring application, one of the limitations of the algorithm is that it is not designed to detect sound even in the presence of environmental noise such as the presence of a television or radio set on during food intake.

For the classification step, the recognition of swallowing sounds performed with GMM model is good. However, for texture recognition, it does not obtain a good recognition rate and it may be that using another model may provide better results. The segmentation of a single swallow sound is made by two algorithms. The first one is HMM, which gave poor results and has barely reached 52%. The second algorithm is based on a signal processing method and not a statistical one but it shows a high recognition rate of the different phases. A statistical method may give better results.

The potential uses of the acoustic signature detection approach to monitor the swallowing process can be exploited to monitor patients with certain swallowing problems such as patients who have undergone long-term tracheal intubation or tracheostomy after the tracheal tube is removed (extubation) or in case of tracheotomy which could be permanent and require deflation of the tracheostomy cuff before eating or drinking.

The patency of the organs involved in the swallowing process, particularly the oesophageal canal, is essential for normal swallowing and it would be useful if there were a non-invasive method of monitoring the swallowing, especially after removal of the tracheal tube of tracheostomy and of course for patients with permanent tracheostomy who are subject to infections etc....

Speech processing before and after swallowing must be investigated in order to identify biomarkers from the sound and respiratory signals. The study must be carried out on healthy and pathological signals in order to compare, but no pathological signals were recorded to be able to properly evaluate the proposed methods.

Another extremely important point is also the collaboration with the medical staff in all the stages of the study, in particular the segmentation of the signals, which could have been more precise if it had been carried out with videofluoroscopy conducted by doctors.

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Appendix A

List of Publications

Journal Papers:

- Khlaifi H., Istrate D., Demongeot J., Malouche D., Swallowing Sound Recognition at Home Using GMM, IRBM, 39(6):407 - 412. JETSAN, Feb. 2018.
- Demongeot J., Istrate D., Khlaifi H., Mégret L., Taramasco C. and Thomas R., From conservative to dissipative non-linear differential systems. An application to the cardio-respiratory regulation, Discrete Continuous Dynamical Systems, Feb. 2019.

International Conferences:

- Hajer KHLAIFI, Atta BADII, Dan ISTRATE, Jacques DEMONGEOT, Automatic detection and recognition of swallowing sounds, 12th international conference on Health Conference, Feb, 2019.

National Conferences:

- Hajer Khlaifi, Dan Istrate, Jacques Demongeot, Jérôme Boudy, Dhafer Malouche, Swallowing Sound Recognition at Home Using GMM. Journées d'Etude sur la TéléSANTé, 6ème édition, May 2017, Bourges, France. (<https://hal.archives-ouvertes.fr/hal-01692422/document>)

Appendix B

Theory and Methods for signal processing and pattern recognition

In this section, the theory and different algorithms are described which are used by the proposed system (see Chapter 4). In the sound signal processing, there is pre-processing (different transform of the signal in order to focus on the interest characteristics) and statistical learning (GMM and HMM approach) in order to automatically recognise the swallowing sounds.

B.1 Fourier Decomposition

The Fourier transform diagonalises time-invariant convolution operators. It rules over linear time-invariant signal processing. The description below is extracted from Mallat and Peyré (2009)

B.1.1 Continuous Fourier transform

Fourier analysis represents any finite energy function $f(t)$ as a sum of sinusoidal waves $e^{i\omega t}$:

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}(\omega) e^{i\omega t} d\omega \quad (\text{B.1})$$

The amplitude $\hat{f}(\omega)$ of each sinusoidal wave $e^{i\omega t}$ is equal to its correlation with f , also called Fourier transform:

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} f(t) e^{i\omega t} dt \quad (\text{B.2})$$

The more regular $f(t)$, the faster the decay of the sinusoidal wave amplitude $|\hat{f}(\omega)|$ when frequency increases. When $f(t)$ is defined only on an interval, say $[0, 1]$,

then the Fourier transform becomes a decomposition in a Fourier orthonormal basis $e^{i2\pi mt}$, $m \in \mathbb{Z}$ of $L^2[0, 1]$. If $f(t)$ is uniformly regular, then its Fourier transform coefficients also have a fast decay when the frequency $2\pi m$ increases, so it can be easily approximated with few low-frequency Fourier coefficients. The Fourier transform therefore defines a sparse representation of uniformly regular functions.

Over discrete signals, the Fourier transform is a decomposition in a discrete orthogonal Fourier basis $e^{i2\pi kn/N}$, $0 \leq k \leq N-1$ of \mathbb{C}^N , which has properties similar to a Fourier transform on functions. Its embedded structure leads to fast Fourier transform (FFT) algorithms, which compute discrete Fourier coefficients with $O(N \log N)$ instead of N^2 . This FFT algorithm is a cornerstone of discrete signal processing.

B.1.2 Discrete Fourier Transform

The space of signals of period N is an Euclidean space of dimension N and the inner product of two such signals f and g is:

$$\langle f, g \rangle = \sum_{n=0}^{N-1} f[n]g^*[n] \quad (\text{B.3})$$

Any signal with period N can be decomposed as a sum of discrete sinusoidal waves. The family $e_k[n] = \exp\left(\frac{i2\pi kn}{N}\right)$, $0 \leq k \leq N-1$ is an orthogonal basis of the space of signals of period N . Since the space is of dimension N , any orthogonal family of N vectors is an orthogonal basis. Any signal f of period N can be decomposed on this basis:

$$f = \sum_{k=0}^{N-1} \frac{\langle f, e_k \rangle}{\|e_k\|^2} e_k \quad (\text{B.4})$$

By definition, the discrete Fourier transform (DFT) of f is:

$$\hat{f}[k] = \langle f, e_k \rangle = \sum_{n=0}^{N-1} f[n] \exp\left(\frac{-i2\pi kn}{N}\right) \quad (\text{B.5})$$

Since $\|e_k\|^2 = N$, B.4 gives an inverse discrete Fourier formula:

$$f[n] = \frac{1}{N} \sum_{k=0}^{N-1} \hat{f}[k] \exp\left(\frac{i2\pi kn}{N}\right) \quad (\text{B.6})$$

B.1.3 Fast Fourier transform

For a signal f of N points, a direct calculation of the N discrete Fourier sums

$$\hat{f}[k] = \sum_{n=0}^{N-1} f[n] \exp\left(\frac{-i2\pi kn}{N}\right), \text{ for } 0 \leq k \leq N, \quad (\text{B.7})$$

requires N^2 complex multiplications and additions. The FFT algorithm reduces the numerical complexity to $O(N \log_2 N)$ by reorganising the calculations.

When the frequency index is even, the terms n and $n + N/2$ are grouped:

$$\hat{f}[2k] = \sum_{n=0}^{N/2-1} (f[n] + f[n + N/2]) \exp\left(\frac{-i2\pi kn}{N/2}\right) \quad (\text{B.8})$$

When the frequency index is odd, the same grouping becomes:

$$\hat{f}[2k] = \sum_{n=0}^{N/2-1} \exp\left(\frac{i2\pi n}{N}\right) (f[n] + f[n + N/2]) \exp\left(\frac{i2\pi kn}{N/2}\right) \quad (\text{B.9})$$

Equation B.8 proves that even frequencies are obtained by calculating the DFT of the $N/2$ periodic signal:

$$f_e[n] = f[n] + f[n + N/2]. \quad (\text{B.10})$$

Odd frequencies are derived from by computing the Fourier transform of the $N/2$ periodic signal:

$$f_o[n] = \exp\left(\frac{i2\pi n}{N}\right) (f[n] - f[n + N/2]) \quad (\text{B.11})$$

A DFT of size N may thus be calculated with two discrete Fourier transforms of size $N/2$ plus $O(N)$ operations. The inverse FFT of \hat{f} is derived from the forward fast Fourier transform of its complex conjugate \hat{f}^* by observing that:

$$f^*[n] = \frac{1}{N} \sum_{k=0}^{N-1} \hat{f}^*[k] \exp\left(\frac{-i2\pi kn}{N}\right) \quad (\text{B.12})$$

B.2 Wavelet Decomposition

The wavelet transform makes it possible to analyse the local structures of a signal in time frequency domain, with a zoom that depends on the scale considered. This transform makes it possible to analyse signals by focusing on the desired frequencies with a precise resolution in time and frequency (which is not the case of Fourier transform). Simply, the signal is decomposed to better analyse it. There are two

types of wavelet transforms: continuous and discrete wavelet transform. The continuous is the theoretical one and the discrete is the transform applied on real discrete signals.

B.2.1 The Continuous Wavelet Transform

The wavelet transform is defined as follows:

$$\tilde{f}(a, b) = \int_{-\infty}^{\infty} f(t) \psi_{a,b}^*(t) dt \quad (\text{B.13})$$

where $\psi_{a,b}^* | a, b \in \mathbb{R}$ is the set of basic functions which are a discrete set of elementary wavelets. The star * represents the conjugate complex and a and b are continuously varying in \mathbb{R} as respectively shift and scale parameters. The wavelet family is generated from the dilation (a) and translation (b) of a reference wavelet $\psi(t)$ (like the Daubechies, Symlet, etc...), function that generates a multi-resolution orthogonal analysis. The wavelets $\psi_{a,b}$ are thus defined by:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \quad (\text{B.14})$$

so Equation (B.14) becomes:

$$\tilde{f}(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \psi^*\left(\frac{t-b}{a}\right) dt \quad (\text{B.15})$$

where ψ denotes the mother wavelet function whose dilated and translated versions are the bases of a wavelet analysis space on which the function $f(t)$ is projected. The wavelet transform is reversible, the analysis of a function to its reconstruction is reached by:

$$f(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{f}(a, b) \psi_{a,b}(t) \frac{da}{a^2} db \quad (\text{B.16})$$

Unlike the Fourier transform, the ψ function must satisfy a constraint of finitude of the integral:

$$\int_{-\infty}^{\infty} \frac{|\hat{\psi}(w)|^2}{|w|} dw < \infty \quad (\text{B.17})$$

where $\hat{\psi}$ is the Fourier transform of ψ . Moreover, $|\hat{\psi}(w)|^2 = 0$. So it can be said that the ψ function is a bandpass filter. This implies that $\int_0^\infty \psi(t)dt = 0$ and therefore ψ is zero average, it must oscillate and so ψ is a wave.

B.2.2 Discrete wavelet transform

The continuous wavelet transform is applied to signals theoretically defined for which there is an equation, but, it cannot be applied to real signals that for which it is not known how they are defined and whether they are stationary or not. In order to apply wavelet transformation to discrete signals (like digitalised sound signal), the ψ function should be described using discrete values. Therefore a grid of discrete values is imposed taken by the ψ function. Therefore, discrete wavelet transform is given by:

$$\tilde{f}(m, n) = a_0^{-\frac{m}{2}} \int_{-\infty}^{\infty} f(t) \psi(a_0^{-m}t - nb_0) dt \quad (\text{B.18})$$

where a_0 and $b_0 \in \mathbb{Z}$

At each level of decomposition, the approximation contains the low frequency part of the signal and the detail the high frequency part. The more the levels are lower, the more frequency bands are lower and the more signal is smoother. There are several types of mother wavelet functions: Morlet wavelet, Mexican hat, Daubechies, Symlet, etc... **B.1.** In this study, it was decided to decompose the signal by multiresolution analysis in 12 wavelet levels using as mother wavelet functions, Symlet through the detection step.

Once the detection is done, the classification can be performed but the sound signals cannot be used directly because they are redundant. The information contained therein must then be reduced by calculating various acoustic parameters which is described below.

B.2.3 Fast wavelet transform

A fast wavelet transform decomposes successively each approximation $P_{V_j}f$ into a coarser approximation $P_{V_{j+1}}f$, plus the wavelet coefficients carried by $P_{W_{j+1}}f$. In the other direction, the reconstruction from wavelet coefficients recovers each $P_{V_j}f$ from $P_{V_{j+1}}f$ and $P_{W_{j+1}}f$.

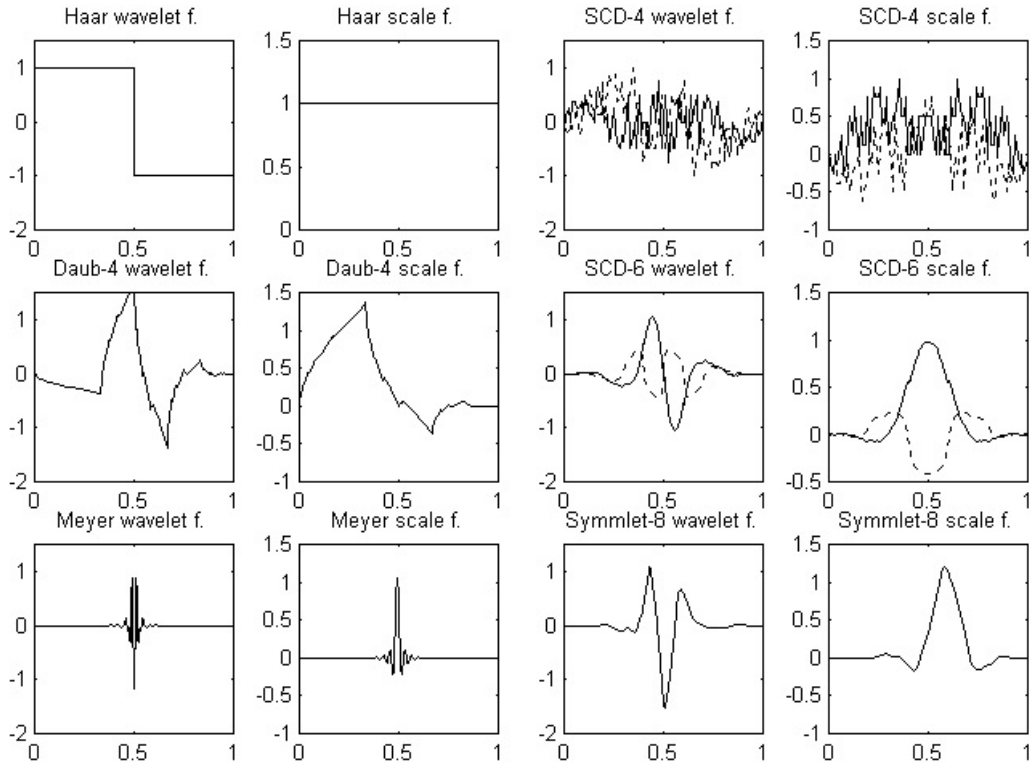


Figure B.1: Wavelet Functions Examples

Since $\phi_{j,n \in \mathbb{Z}}$ and $\psi_{j,n \in \mathbb{Z}}$ are orthonormal bases of V_j and W_j , the projection in these spaces is characterised by:

$$a_j[n] = \langle f, \phi_{j,n} \rangle \text{ and } d_j[n] = \langle f, \psi_{j,n} \rangle \quad (\text{B.19})$$

These coefficients are calculated with a cascade of discrete convolutions and subsamplings. $\bar{x}[n] = x[-n]$ and

$$\tilde{x} = \begin{cases} x[p] & \text{if } n = 2p \\ 0 & \text{if } n = 2p + 1 \end{cases}$$

At the decomposition

$$a_{j+1}[p] = \sum_{n=-\infty}^{\infty} h[n - 2p] a_j[n] = a_j \cdot \bar{h}[2p], \quad (\text{B.20})$$

$$d_{j+1}[p] = \sum_{n=-\infty}^{\infty} g[n - 2p] a_j[n] = a_j \cdot \bar{g}[2p], \quad (\text{B.21})$$

At the reconstruction

$$a_j[p] = \sum_{n=-\infty}^{\infty} h[p-2n]a_{j+1}[n] + \sum_{n=-\infty}^{\infty} g[p-2n]d_{j+1}[n] = \tilde{a}_{j+1} \cdot h[p] + \tilde{d}_{j+1} \cdot g[p] \quad (\text{B.22})$$

B.3 Acoustical features

Sound processing tasks need in first feature extraction for sound scene and event analysis. There are three types of features: temporal features (computed directly on the temporal waveform), spectral shape features (derived from frequency representations of a signal) and cepstral features (allowing the decomposition of the signal according to the source-filter model widely used to model speech production.).

- **Mel Frequency Cepstral Coefficients (MFCC):** MFCC coefficients are cepstral coefficients very often used in automatic speech recognition Davis and Mermelstein (1980). By definition, the Mel frequency scale is given by the equation:

$$M(\nu) = 2595 \log\left(1 + \frac{\nu}{700}\right) \quad (\text{B.23})$$

where ν represents the frequency in Hz. $M(\nu)$ is then a frequency in the Mel frequency scale. The calculation of the MFCC parameters uses a non-linear Mel-frequency scale. Figure B.3 presents the process of creating MFCC features. The first step consists of framing the signal into frames by applying a sliding window throughout the signal. The duration of the analysis window is of 16 millisecond duration all along this work. The reason for taking small sections of the signal is that it is considered as statistically stationary. The next step consists of the discrete Fourier transform of each frame. Let $x(t)$ ($1 \leq t \leq T$) denote the signal acquired in an observation window of length T . Then, the spectrum of the signal is filtered by triangular filters whose bandwidths are of a variable width in the frequency range Mel (Figure B.2). The boundary values B_m of the Mel frequency scale filters are calculated from the formula B.24:

$$B_m = B_1 + m \frac{B_h - B_l}{M + 1}; \text{ where } 0 \leq m \leq M + 1 \quad (\text{B.24})$$

where M corresponds to the number of filters, B_h corresponds to the highest

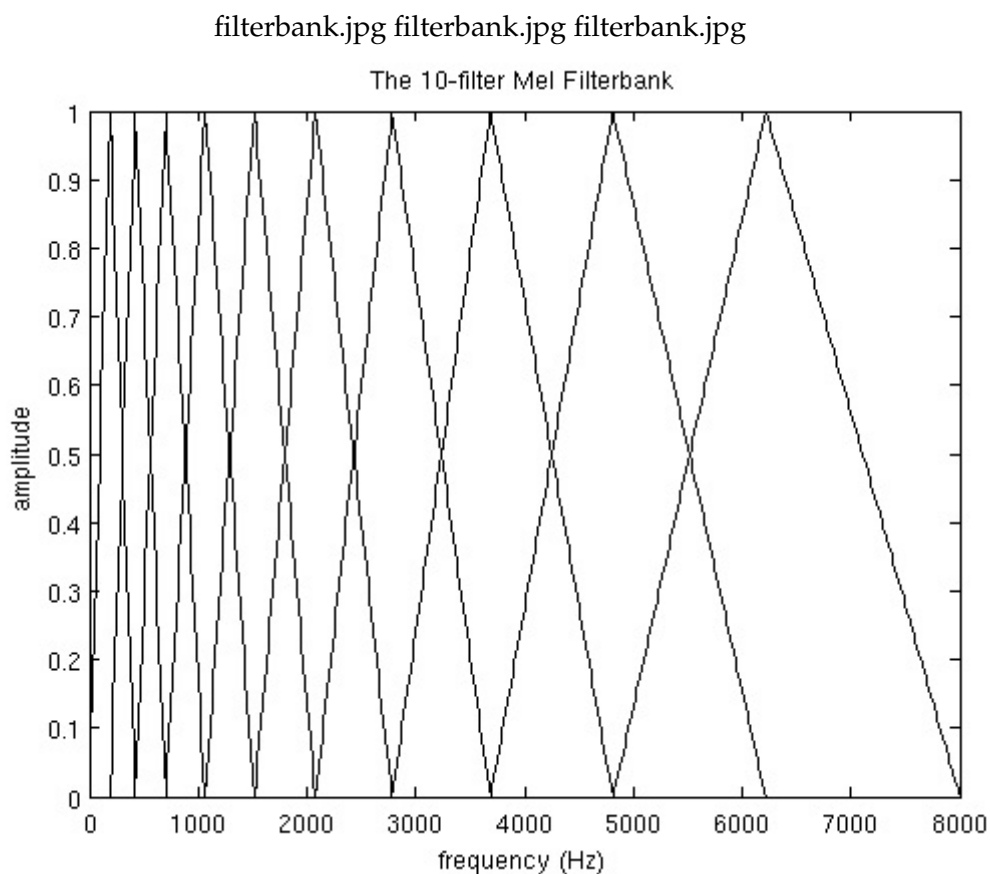


Figure B.2: Mel filter bank (containing 10 filters and starts at 0Hz and ends at 8000Hz)

frequency and B_l to the lowest frequency of the signal. In the frequency domain, the discrete frequency values f_m are calculated using the formula:

$$f_m = \left(\frac{T}{F_s}\right) B^{-1}\left(B_l + m \frac{B_h - B_l}{M + 1}\right) \quad (\text{B.25})$$

where $B^{-1}(f)$ refers to the frequency corresponding to the frequency f in the Mel scale. Then, the cepstral coefficients of frequency in Mel scale are obtained by a discrete inverse cosine transform.

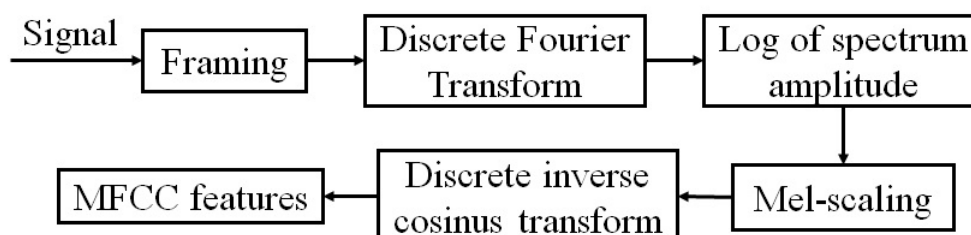


Figure B.3: Steps of MFCC features calculation

- **Linear Frequency Cepstral Coefficients (LFCC):** The LFCC coefficients are calculated in the same way as the MFCC, but the difference resides in that the frequencies of the filters are uniformly distributed on the linear scale of frequencies and no longer on a Mel scale.
- **The derivatives of the coefficients (Δ and $\Delta\Delta$):** To be able to take into account the variations in the time scale of the parameters, the derivative of the parameters enabling the measurement of their variations in time have been calculated. The approximations used for this purpose are as follows:

$$\Delta v_t = \frac{-(v_{t+2} - v_{t-2}) + 8.(v_{t+1} - v_{t-1})}{12} \quad (\text{B.26})$$

where v_t corresponds to the current value and $v_{t-2}, v_{t-1}, v_{t+1}$ and v_{t+2} correspond respectively to the two values preceding the current value and the next two values. The $\Delta\Delta$ is given by:

$$\Delta\Delta v_t = \frac{-(v_{t-2} - 16v_{t-1} + 30v_t - 16v_{t+1} + v_{t+2})}{12} \quad (\text{B.27})$$

- **The Roll-off point (RF):** is the frequency below which 95% of the signal energy is located. It can be considered as an index of the distribution of the signal power spectrum. It is calculated according to the formula B.28 with $Y = 0.95$.

$$RF = \alpha \text{ where } \sum_{k < \alpha} X(k) = Y \sum_k X(k) \quad (\text{B.28})$$

The different sound features calculated are tested and used as empirical statistical inputs of the models used in this work and described below.

B.4 The Gaussian mixture model

The Gaussian Mixture Model (GMM) is established as one of the most statistically mature methods for clustering Reynolds and Rose (1995). GMM has been deployed widely in acoustic signal processing such as speech recognition and music classification. Accordingly GMM is used to classify signals without a priori information about the generation process; this is conducted in two steps as required: a training step and a recognition step.

Multivariate Gaussian model is a flexible alternative for representing a set of clusters of size K in which each cluster is modeled by a Multidimensional Gaussian. The Gaussian clusters may overlap that is to say that each pattern may probabilistically belong to many Clusters. This method evolves in two steps: a training step and a recognition step:

- **Training step:** The training is initiated for each class w_k of signals and gives a model containing the characteristics of each Gaussian distribution of the class: the likelihood, the mean vector and the covariance matrix. These values are achieved after 20 iterations of an "EM" algorithm (Expectation Maximisation). The matrices are diagonal.
- **Recognition step:** The recognition step aims to calculate the likelihood of membership of a class w_k for each acoustical vector calculated on the signal, taking into account the parameters calculated during training step.

A Gaussian mixture model is a parametric probability density function represented as a weighted sum of M component Gaussian densities as given by the equation below :

$$p(x|\Theta) = \sum_{i=1}^M \pi_i f(x|\mu_i, \Sigma_i) \quad (\text{B.29})$$

where x is a d -dimensional continuous-valued data vector; in this case it represents feature acoustic vector, $\pi_i, i = 1, \dots, M$, are the mixture weights, and $f(x|\mu_i, \Sigma_i), i = 1, \dots, M$, are the component Gaussian densities. The mixture weights satisfy the constraint that $\sum_{i=1}^M \pi_i = 1$. Each component density is a d -variate Gaussian function which takes the form :

$$f(x|\mu_i, \Sigma_i) = \frac{1}{(2\pi)^{d/2} |\Sigma_i|^{1/2}} \exp -\frac{1}{2} (x - \mu_i)' \Sigma_i^{-1} (x - \mu_i) \quad (\text{B.30})$$

where μ_i is the mean vector and Σ_i is the covariance matrix. Gaussian Mixture Model is parametrised by the mean vector, covariance matrix and mixture weights denoted :

$$\Theta = (\pi_i, \mu_i, \Sigma_i) \quad (\text{B.31})$$

B.4.1 Expectation Maximisation (EM) algorithm

Given training acoustic vectors and an initial GMM configuration Θ , the aim is to estimate the parameters of the optimal GMM model which corresponds to the distribution of the training features vectors. There are several techniques to estimate model parameters. The well-established method is Expectation Maximisation (EM), an iterative algorithm which its basic idea is to start with the initial model to estimate a new model $\bar{\Theta}$ with maximum likelihood ($p(x|\bar{\Theta}) \geq p(x|\Theta)$). At each iteration, the new model is becoming the initial model. This step is repeated until a convergence threshold ϵ is reached which is expressed by the equation below:

$$L(\bar{\Theta}; x) - L(\theta; x) < \epsilon \quad (\text{B.32})$$

where L is the likelihood of the model. On each EM iteration, the re-estimation of parameters is done in the following way:

Gaussian Component Weights

$$\bar{\pi}_i = \frac{1}{T} \sum_{i=1}^T P(z|x_i, \Theta) \quad (\text{B.33})$$

Mean

$$\bar{\mu}_i = \frac{\sum_{i=1}^T P(z|x_i, \Theta) x_i}{\sum_{i=1}^T P(z|x_i, \Theta)} \quad (\text{B.34})$$

Variance

$$\bar{\Sigma}_i = \frac{\sum_{i=1}^T P(z|x_i, \Theta) (x_i - \bar{\mu}_i)(x_i - \bar{\mu}_i)'}{\sum_{i=1}^T P(z|x_i, \Theta)} \quad (\text{B.35})$$

where μ_i , x_i and Σ_i refer to the i^{th} elements of μ , X and Σ and z refers to the z^{th} component.

B.5 Markovian models

B.5.1 Markovian process

The Markovian character of the process corresponds to the independency of X_i with respect to all X'_j ($j < i$), except for $j = i - 1$: A discrete-time Markov process is a sequence of random variables X_1, \dots, X_n with values in the finite state space $\Omega = x_1, \dots, x_m$ that validate equation B.36. The different elements of the state space are called classes.

$$\forall k \in \{1, 2, \dots, n\} : P(X_k | X_1, X_2, \dots, X_{k-1}) = P(X_k | X_{k-1}) \quad (\text{B.36})$$

The description of the current state is done from the previous state, this corresponds to the models of order 1. Generalisation to k-order models is feasible, in which the current state is predicted using the last k states.

Being interested in discrete state Markov processes, of order 1, Markov Chain of order 1 is discussed.

The law of a Markov chain is defined by the law of X_0 and a transition matrix family giving the probabilities of passing from one state x_i to another state x_j . This probability is given by:

$$T_k(x_i, x_j) = P(X_{k+1} = x_j | X_k = x_i) \quad (\text{B.37})$$

I assume that the chain is homogeneous. The chain is homogeneous if the transition probability does not depend on n. This corresponds to its independence from time.

$$\forall (i, j) \in \{1, 2, \dots, m\}^2 : P(X_{k+1} = x_j | X_k = x_i) = T_{i,j}(x_i, x_j) \quad (\text{B.38})$$

Therefore, the probability of having observed the sequence: x_0, x_1, \dots, x_n is equal to:

$$P(x_0, x_1, \dots, x_n) = P(x_0)T(x_0, x_1) \dots T(x_{i-1}, x_i) \quad \forall i_j \in \{1, 2, \dots, m\} \quad (\text{B.39})$$

B.5.2 Hidden Markov Model (HMM)

A Hidden Markov Model (HMM) is a process composed of a double sequence of random variables (X, Y) , such that X is a Markov sequence, and the process Y is real. Each Y_i depends only on the corresponding state X_i . X and Y respectively will be called hidden variable (unobserved) and observed variable.

The law of an HMM is defined by the law of X which is a Markov sequence and the law Y conditionally to X . The law of X is defined by the original law $\pi = p(x_0)$ and the transition matrix $(x_i, x_j) = p(X_{n+1} = x_j | X_n = x_i)$. So, the sequence of observations x_0, x_1, \dots, x_n has a probability equal to:

$$p(x_0, x_1, \dots, x_n) = p(x_0)p(x_1|x_0)p(x_2|x_1)\dots p(x_n|x_{n-1}) \quad (\text{B.40})$$

Assuming that the random variables Y_n are conditionally independent of X , the law of Y conditional to X is defined as follows:

$$p(y|x) = p(y_0|x_0)\dots p(y_n|x_n) \quad (\text{B.41})$$

The law of Y_n conditional to X is equal to its law conditional to X_n :

$$p(Y_n|X = x) = p(Y_n|X_n = x_n) \quad (\text{B.42})$$

Based on the above definitions:

$$p(x, y) = p(x_0)p(x_1|x_0)\dots p(x_n|x_{n-1})p(y_0|x_0)p(y_n|x_n) \quad (\text{B.43})$$

B.5.3 Forward-Backward Probabilities

This paragraph recalls the definitions of Forward-Backward probabilities, which play a crucial role both in parameter estimation and in the actual restoration described in the following sections.

To estimate X 's hidden achievements from the observed achievement Y , knowledge of the value of X a posteriori is essential. This law a posteriori $p(x_{i+1}|x_i, y)$ contains any information on X contained in the observations Y . This a posteriori probability can be calculated from the Forward probabilities $\alpha_t(x_i) = p(y_0, \dots, y_i, x_i)$ and the Backward probability $\beta_i(x_i) = p(y_{i+1}, \dots, y_n, x_i)$. The following recursivities are used to calculate the Forward and Backward probabilities at each moment of the Markov model.

- **Forward probability:** $\alpha_t(i)$ refers to the following probability:

$$\alpha_t(i) = p(X_t = x_i, Y_1 = y_1, \dots, Y_t = y_t) \quad (\text{B.44})$$

This expression can be calculated in a recursive way:

- **Initialisation:** $\pi_i f_i(y_1) \forall 1 \leq i \leq k$ where $\pi_i = p(X_0 = x_i)$ and f_i is the law of Y conditionally to X

– **Induction:** $\alpha_{i+1}(x_j) = [\sum_{i=1}^k \alpha_t(x_i) a_{x_i x_j}] f_{x_j}(y_{i+1}) \forall 1 \leq j \leq k$ and $1 \leq t \leq n - 1$ where a_{ij} is the transition probability from state x_i to state x_j .

• **Backward probability:** The calculation is similar to the previous approach. The Backward probability is defined by:

$$\beta_i(x_i) = p(Y_{t+1} = y_{t+1}, \dots, Y_n = y_n | X_t = x_i) \quad (\text{B.45})$$

referring to the joint probability of the partial sequence of the observation from instant $t + 1$ to the final time n . β_t is obtained from β_{t+1} by a regressive recurrence:

– **Initialisation:** $\beta_n(i) = 1 \forall 1 \leq i \leq k$

– **Induction:** $\beta_i(x_i) = \sum_{j=1}^k a_{x_i x_j} f_{x_j}(y_{i+1}) \beta_{i+1}(x_j) \forall 1 \leq i \leq k$ and $1 \leq t \leq n - 1$

B.5.4 Recognition method

To restore the hidden realisation, Bayesian methods are used. The Bayesian estimation derives its name from the intensive use of Bayes law, which allows from the two distributions $P(X)$ and $P(Y|X)$ to go back to the joint distribution $P(X,Y)$ given by:

$$P(X, Y) = P(Y|X)P(X) \quad (\text{B.46})$$

The a Posteriori Marginal Method (PMM)

This algorithm consists in maximising for each state the subsequent marginal state $P(X_t = x_t | Y = y)$ expressed as a function of the probabilities Forward and Backward.

$$\zeta_t(i) = P(X_t = x_i | Y = y) = \frac{\alpha_t(i) \cdot \beta_t(i)}{\sum_{1 \leq l \leq k} \alpha_t(l) \beta_t(l)} \quad (\text{B.47})$$

Thus, the solution is calculated directly, without iterative procedures based only on $\alpha_t(i)$ and $\beta_t(i)$ and so the marginal posterior probabilities $\zeta_t(i)$. Thereafter, the classification is established by choosing the maximising class maximising $\zeta_t(i)$.

$$x_t = \arg \max_{x_i} P(X_t = x_i | Y = y) \quad (\text{B.48})$$

Viterbi algorithm

The Viterbi algorithm (VA) is a recursive algorithm of estimating the state sequence of a discrete time finite-state Markov process. The Viterbi algorithm is used for finding the most likely sequence of hidden states called the Viterbi path that results in a sequence of observed events. It is based on the calculation of probabilities

$$\delta_t(i) = \max_{x_1, x_2, \dots, x_{t-1}} P(X_1 = x_1, X_2 = x_2, \dots, X_{t-1} = x_{t-1}, X_t = \omega_i, Y_1, Y_2, \dots, Y_{t-1}) \quad (\text{B.49})$$

corresponding to the optimal path, each one ranging from x_1 to x_i visited at instant t .

By recurrence:

$$\delta_{t+1}(j) = \max_{x_1, x_2, \dots, x_t} P(X_1 = x_1, X_2 = x_2, \dots, X_t = x_t, X_{t+1} = x_j, Y_1, Y_2, \dots, Y_t) \quad (\text{B.50})$$

Otherwise:

$$\delta_{t+1}(j) = \max_{x_t} [P(X_{t+1} = x_j | X_t = x_t) \max_{x_1, \dots, x_{t-1}} P(X_1 = x_1, X_2 = x_2, \dots, X_t = x_t, Y_1, Y_2, \dots, Y_t)] \quad (\text{B.51})$$

$$\delta_{t+1}(j) = \max_{x_i} [P(y_t | X_t = x_i) \cdot \max_{x_1, \dots, x_{t-1}} P(X_1 = x_1, X_2 = x_2, \dots, X_t = x_i, Y_1, Y_2, \dots, Y_{t-1})] \quad (\text{B.52})$$

The argument that achieves the maximum is given by:

$$\gamma_{t+1}(j) = \arg \max_{x_i} (a_{ij} \cdot f_i(y_t) \cdot \delta_t(i)) \quad (\text{B.53})$$

Algorithm

- **Initialisation:**

$$\delta_1(i) = P(X_1 = x_i) = \pi_i \quad \forall 1 \leq i \leq k \quad (\text{B.54})$$

- **Recurrence**, $\forall t = 2, 3, \dots, T$, $\delta_t(j)$ are kept for all j and the corresponding $\gamma_t(j)$ where $\delta_{t+1}(j) = \max_{x_i} (a_{ij} \cdot f_i(y_t) \cdot \delta_t(i))$ and $\gamma_{t+1}(j) = \arg \max_{x_i} (a_{ij} \cdot f_i(y_t) \cdot \delta_t(i))$.

- **End of the recurrence** The maximum a posteriori is given by: $\max_x P(X = x, Y = y) = \max_i \delta_T(i)$ and $\hat{x}_T = \arg \max_i \delta_T(i)$.
- Then, the optimal path is given by performing a downward reading of the stored values: $\hat{x}_t = \gamma_{t+1}(\hat{x}_{t+1}) \forall T - 1 \geq t \geq 1$

EM algorithm for parameter estimation

It consists in maximising the likelihood function of the observation $Y=y$ with respect to the model parameters. It is used to determine from an initial value θ^0 of the parameters, a sequence $(\theta^q)_{q \in \mathbb{N}}$ whose likelihood in $Y = y$ is an increasing function converging towards a local maximum.

In the following, the iterations of the EM-algorithm are briefly described in the case of the hidden Markov model.

Noting by $\psi_t(i, j)$ the joint probability of being at time t in class ω_i and at the next time in class ω_j knowing the sequence of observations:

$$\psi_t(i, j) = p(X_t = x_i, X_{t+1} = x_j | Y = y) = \frac{p(X_t = x_i, X_{t+1} = x_j, Y = y)}{p(Y = y)} \quad (\text{B.55})$$

This expression can be written according to Forward-Backward probabilities:

$$\psi_t(i, j) = \frac{\alpha_t(i) a_{ij} f_j(y_{t+1}) \beta_{t+1}(j)}{\sum_{l=1}^k f_l(y_{t+1}) \sum_{j=1}^k \alpha_t(j) a_{il}} \quad (\text{B.56})$$

A posteriori probability $P(X_t = x_i | Y = y)$ can also be written according to the $\psi_t(i, j)$:

$$P(X_t = x_i | Y = y) = \sum_{j=1}^k \psi_t(i, j) \quad (\text{B.57})$$

The formulas for re-estimating the parameters of the model at iteration $q+1$ are the following:

- Initial probabilities and transition matrix at iteration $q + 1$:

$$\pi_i^{(q+1)} = \frac{1}{n} \sum_{t=1}^n P^{(q)}(X_t = x_i | Y = y) \quad (\text{B.58})$$

and

$$a_{ij}^{(q+1)} = \frac{\sum_{t=1}^n \psi_t^{(q)}(i, j)}{\sum_{t=1}^n P^{(q)}(X_t = x_i | Y = y)} \quad (\text{B.59})$$

- Parameters characterising Gaussians:

$$\mu_i^{(q+1)} = \frac{\sum_{t=1}^n y_t \cdot P^{(q)}(X_t = x_i | Y = y)}{\sum_{t=1}^n P^{(q)}(X_t = x_i | Y = y)} \quad (\text{B.60})$$

and

$$(\sigma_i^2)^{(q+1)} = \frac{\sum_{t=1}^n (y_t - \mu_i^{(q+1)})^2 \cdot P^{(q)}(X_t = x_i | Y = y)}{\sum_{t=1}^n P^{(q)}(X_t = x_i | Y = y)} \quad (\text{B.61})$$

Appendix C

Identification grid for swallowing disorders and associated factors

Trouble recherché	Oui	Non
Toux		
après la déglutition de salive		
après la déglutition de liquides		
après la déglutition de solides		
- si aux solides, préciser la texture :		
Modification de la voix		
Type de modification (modification du timbre ou de l'intensité, voix voilée ou voix mouillée après la déglutition)		
- constante		
- après la déglutition de salive		
- après la déglutition de liquides		
- après la déglutition de solides		
Autres troubles		
Déglutition lente / difficile		
Blocages intermittents de la déglutition		
Localisation du blocage		
Difficultés de mastication		
Bavage (trop de salive ou fuite labiale de salive)		
Présence de fuites alimentaires labiales		
Reflux alimentaires par le nez		
Présence d'une salive anormalement épaisse		
Présence d'une xérostomie (bouche sèche)		
Existence de problèmes infectieux pulmonaires récurrents		
Temps de repas augmentés		
- durée du petit déjeuner (minutes)		
- durée du repas de midi (minutes)		
- durée du repas du soir (minutes)		
Positions de la tête et du cou dangereuses		
- lesquelles ?		
Positions de la tête et du cou favorables		
- lesquelles ?		
Utilisation de matériels spécifiques pour les repas		
- lesquels ?		
Nécessité d'une aide pour l'alimentation		
Existence de problèmes dentaires		
- lesquels ?		
Existence de difficultés sociales liées à un trouble de déglutition		
- lesquelles ?		
Relevé des médicaments utilisés		

Figure C.1: Identification grid for swallowing disorders and associated factors (Desport et al., 2011)

Appendix D

Information note-Consent

NOTE D'INFORMATION

Titre du projet : « ESwallHome ».

Institution : UTC.

Responsable scientifique : Dr. Jacques Demongeot

Madame, Monsieur,

Nous vous proposons de participer à une recherche intitulée « Suivi de la déglutition à domicile ». Il est important de lire attentivement cette note d'information avant de prendre votre décision. N'hésitez pas à demander des explications et poser librement toutes vos questions.

Si vous décidez de participer à cette recherche, un consentement écrit vous sera demandé.

I. OBJECTIFS DU PROJET

Le principal objectif de ce projet est de créer un outil non-invasif d'analyse en temps réel de l'activité de déglutition permettant d'aider le médecin dans le diagnostic précoce et le suivi thérapeutique des troubles de déglutition.

Votre participation est totalement volontaire et ne sera pas rétribuée. Vous pouvez décider d'arrêter votre participation à tout moment sans subir aucun préjudice ni conséquence.

II. PROCEDURE

Les sessions d'enregistrements se dérouleront au cours de votre présence au sein de l'Université de Technologie de Compiègne, au centre d'Innovation, dans la salle 02-28 ou bien dans les locaux de l'hôpital pendant une journée où vous aurez rendez-vous avec votre médecin.

Durant chaque rencontre, quelques différents exercices vous seront proposés afin de relever des échantillons de votre activité de déglutition et de votre voix. Chaque rencontre durera à peu près une demi-heure.

Pendant les exercices de déglutition, il vous serait demandé de faire déglutir plusieurs textures d'aliments. Au cours de la déglutition, votre voix sera enregistrée à l'aide de deux microphones ; un mis au niveau du cou et l'autre sera mis sur la table pour accueillir le son environnemental. De plus, il vous sera demandé de porter un gilet qui permet d'acquérir le signal de la respiration pendant la prise alimentaire. Les informations seront recueillies de façon confidentielle et utilisées exclusivement dans le cadre de la recherche scientifique.

III. RISQUES ET INCONVENIENTS

Il n'existe pas de risque prévisible ou attendu dans cette recherche. Elle nécessite simplement d'être disponible pendant trente minutes à chacune des sessions pour y participer.

IV. AVANTAGES ET PROGRES ESCOMPTES

En participant au projet de recherche « ESwallHome », vous contribuez de façon importante à la recherche sur le développement de moyens technologique numériques au service de la médecine. Les données collectées durant cette étude permettront de mieux connaître les influences de certaines maladies sur des opérations



quotidiennes. Leur exploitation permettrait de faciliter le diagnostic et le suivi thérapeutique de ces maladies, y compris de façon précoce. Ceci présenterait un progrès et une aide certaine pour les médecins.

V. CONFIDENTIALITE

Les données sont recueillies de façon non identifiante et confidentielle. Les informations traitées lors de l'analyse apparaîtront dans les rapports mais de telle façon qu'aucune identification des personnes, source des informations, ne soit possible.

Les résultats de cette recherche pourront être publiés dans des revues scientifiques, présentés dans des réunions d'information clinique, toujours dans le respect de la confidentialité. Votre accord pour l'utilisation de ces informations est valable jusqu'au terme du projet, sauf si vous y mettez fin avant.

Dans le cas où vous décideriez votre retrait du projet de recherche, vos données ne seraient plus traitées, mais il ne serait pas possible de modifier les documents existants déjà publiés ou les rapports terminés.

Conformément à la loi « Informatique et libertés » du 6 janvier 1978, vous bénéficiez d'un droit d'accès et de rectification aux informations qui vous concernent. Si vous souhaitez exercer ce droit et obtenir la communication des informations vous concernant, veuillez-vous adresser à Dan Istrate, professeur à l'UTC au sein du laboratoire BMBI.

VI. PERSONNES CONTACTS

Pour plus d'informations sur cette étude, vos droits en tant que participant, si vous n'étiez pas satisfait ou si vous aviez des questions concernant cette recherche, merci de bien vouloir contacter les investigateurs :

Dan Istrate
UTC – Laboratoire BMBI
mircea-dan.istrate@utc.fr

VII. CONFIRMATION

Si vous acceptez de participer à la recherche après avoir lu cette note d'information, merci de signer et dater le formulaire de consentement éclairé ci-après (2 exemplaires).



FORMULAIRE DE CONSENTEMENT

Je soussigné(e), Madame, Mademoiselle, Monsieur

(nom, prénom).....

accepte librement de participer à la recherche intitulée :

« Suivi de la déglutition à domicile »

organisée par e-SwallHome, sous la responsabilité scientifique du Dr. Jacques Demongeot.

- J'ai pris connaissance de la note d'information m'expliquant l'objectif de cette recherche, la façon dont elle va être réalisée et ce que ma participation va impliquer,
- Je conserverai un exemplaire de la note d'information et du consentement,
- J'ai reçu des réponses adaptées à toutes mes questions,
- Mon consentement ne décharge en rien le médecin responsable de la recherche ni l'hôpital de leurs responsabilités et je conserve tous mes droits garantis par la loi.

Signature de la personne participant à la recherche

Signature de l'investigateur

NOM Prénom :

NOM Prénom :

Date :

Date :

Signature :

(faire précéder de la mention « Lu et approuvé »)

Signature :

(faire précéder de la mention « Lu et approuvé »)

Pour toute question relative à la recherche, ou pour vous retirer de la recherche, vous pouvez communiquer avec :

Monsieur Dan ISTRATE, enseignant-chercheur, au numéro de téléphone : 03 44 23 45 06 ou à l'adresse de courriel suivante : mircea-dan.istrate@utc.fr

Exemplaire pour le participant.



FORMULAIRE DE CONSENTEMENT

Je soussigné(e), Madame, Mademoiselle, Monsieur

(nom, prénom).....

accepte librement de participer à la recherche intitulée :

« Suivi de la déglutition à domicile »

organisée par e-SwallHome, sous la responsabilité scientifique du Dr. Jacques Demongeot.

- J'ai pris connaissance de la note d'information m'expliquant l'objectif de cette recherche, la façon dont elle va être réalisée et ce que ma participation va impliquer,
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Signature de la personne participant à la recherche

Signature de l'investigateur

NOM Prénom :

NOM Prénom :

Date :

Date :

Signature :

(faire précéder de la mention « Lu et approuvé »)

Signature :

(faire précéder de la mention « Lu et approuvé »)

Pour toute question relative à la recherche, ou pour vous retirer de la recherche, vous pouvez communiquer avec :

Monsieur Dan ISTRATE, enseignant-chercheur, au numéro de téléphone : 03 44 23 45 06 ou à l'adresse de courriel suivante : mircea-dan.istrate@utc.fr

Exemplaire pour l'équipe de recherche.

Appendix E

Protocol

Protocole d'acquisition de données

Séquences d'enregistrement

1. Apnée (8 secondes) et Respiration spontanée (3 min)

Faire une apnée de 8 secondes suivi de 3 minutes de repos du sujet où les déglutitions spontanées pourront être annotées.

2. Déglutition

a. Salive (2-3 min)

Déglutitions provoquées de salive sur commande : 6 fois toutes les 30 secondes environ

b. Eau liquide

Déglutir deux verres d'eau à des proportions égales.

c. Compote

Prise d'une cuillère à café de compote (100 g),

3. Parole

Lire 3 phrases, répéter deux fois

Lire un enchaînement de phrase puis un extrait de texte

Consignes de lecture :

Mettre l'intonation en lien avec la ponctuation

Phrase 1 :

Le caractère de cette femme est moins calme.

Phrase 2 :

Vous poussez des cris de colère ?

Phrase 3 : Lentement, des canes se dirigent vers la mare.

Consignes de lecture :

Lire en continue en tenant compte de la ponctuation et donc de l'intonation

Paragraphe :

C'est en forgeant qu'on devient forgeron. Je voudrais des frites s'il vous plait. Quant à moi, je n'ai pas envie d'y aller. C'est une fille tout à fait à la page. Tu mets combien d'œufs pour préparer une quiche ? Marie-Hélène roule en moto tandis que Céline se déplace en métro. Voulez-vous lui passer le beurre ? Moi, ce que je veux, c'est la tranquillité pour chacun. Il s'occupe de ses oignons ! La perte de ma mère m'a jeté hors de mes gonds.

Consignes de lecture :

Lire en continue en tenant compte de la ponctuation et donc de l'intonation

« Personne ne me connaissait à Buckton. Clem avait choisi la ville à cause de cela ; et d'ailleurs, même si je m'étais dégonflé, il ne me restait pas assez d'essence pour continuer plus haut vers le Nord. A peine cinq litres. Avec mon dollar, la lettre de Clem, c'est tout ce que je possédais. Ma valise, n'en parlons pas. Pour ce qu'elle contenait. J'oublie : j'avais dans le coffre de la voiture le petit revolver du gosse, un malheureux 6,35 bon marché ; il était encore dans sa poche quand le shérif était venu nous dire d'emporter le corps chez nous pour le faire enterrer. »

Boris Vian, "j'irai cracher sur vos tombes"

4. Apnée-Sons (Toux, Bâillement)

Faire une apnée de 3 secondes, à répéter 3 fois

Faire une apnée de 8 secondes, à répéter 3 fois

Tousser, à répéter 3 fois

Bailler, à répéter 3 fois

Faire une apnée de 8 secondes.

Cahier d'observation (1/2)

Sujet

Code sujet	Date naissance	Poids (Kg)	Taille (cm)	Prise thé	Prise café
				Oui Non	Oui Non

Enregistrement

Heure début	Heure fin	Température (°C)

Déglutitions spontanées (3 min ventilation spontanée) :

Déglutitions volontaires de salive : toutes les 30 secondes

1 ^{ère} fois	2 ^{ième} fois	3 ^{ième} fois	4 ^{ième} fois	5 ^{ème} fois	6 ^{ème} fois	

Prise d'eau liquide

Volume	Support	1 ^{ère} fois		2 ^{ième} fois		3 ^{ième} fois	
		début	fin	début	fin	début	fin
5/10/15 ml	Verre/Paille						

Cahier d'observation (2/2)

Prise de compote de fruits

Quantité	1 ^{ère} fois		2 ^{ième} fois		3 ^{ième} fois	
	début	fin	début	fin	début	fin
1 cuillère café						

Parole : lecture de phrases phonétiquement équilibrées

Lecture	Ordre	1 ^{ère} fois		2 ^{ème} fois	
		début	fin	début	fin
Phrase 1					
Phrase 2					
Phrase 3					
Enchaînement de phrases					
Extrait de livre					

Apnée

Durée	Ordre	1 ^{ère} fois		2 ^{ème} fois		3 ^{ème} fois	
		début	fin	début	fin	début	fin
3 secondes							
8 secondes							

Toux

1 ^{ère} fois		2 ^{ème} fois		3 ^{ème} fois	
début	fin	début	fin	début	fin

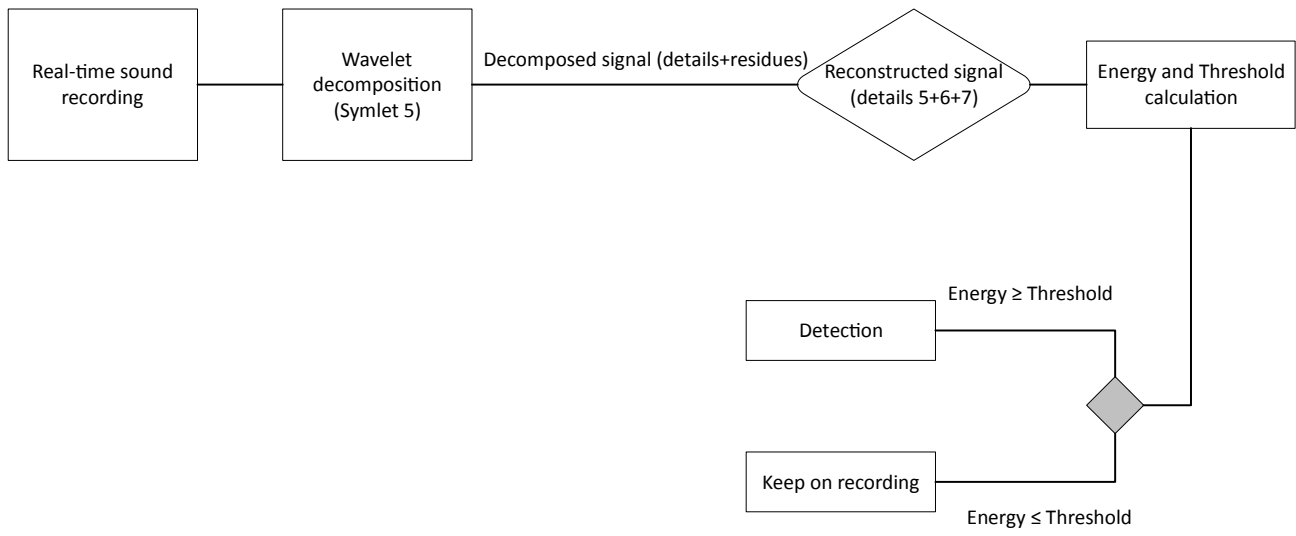
Bâillement

1 ^{ère} fois		2 ^{ème} fois		3 ^{ème} fois	
début	fin	début	fin	début	fin

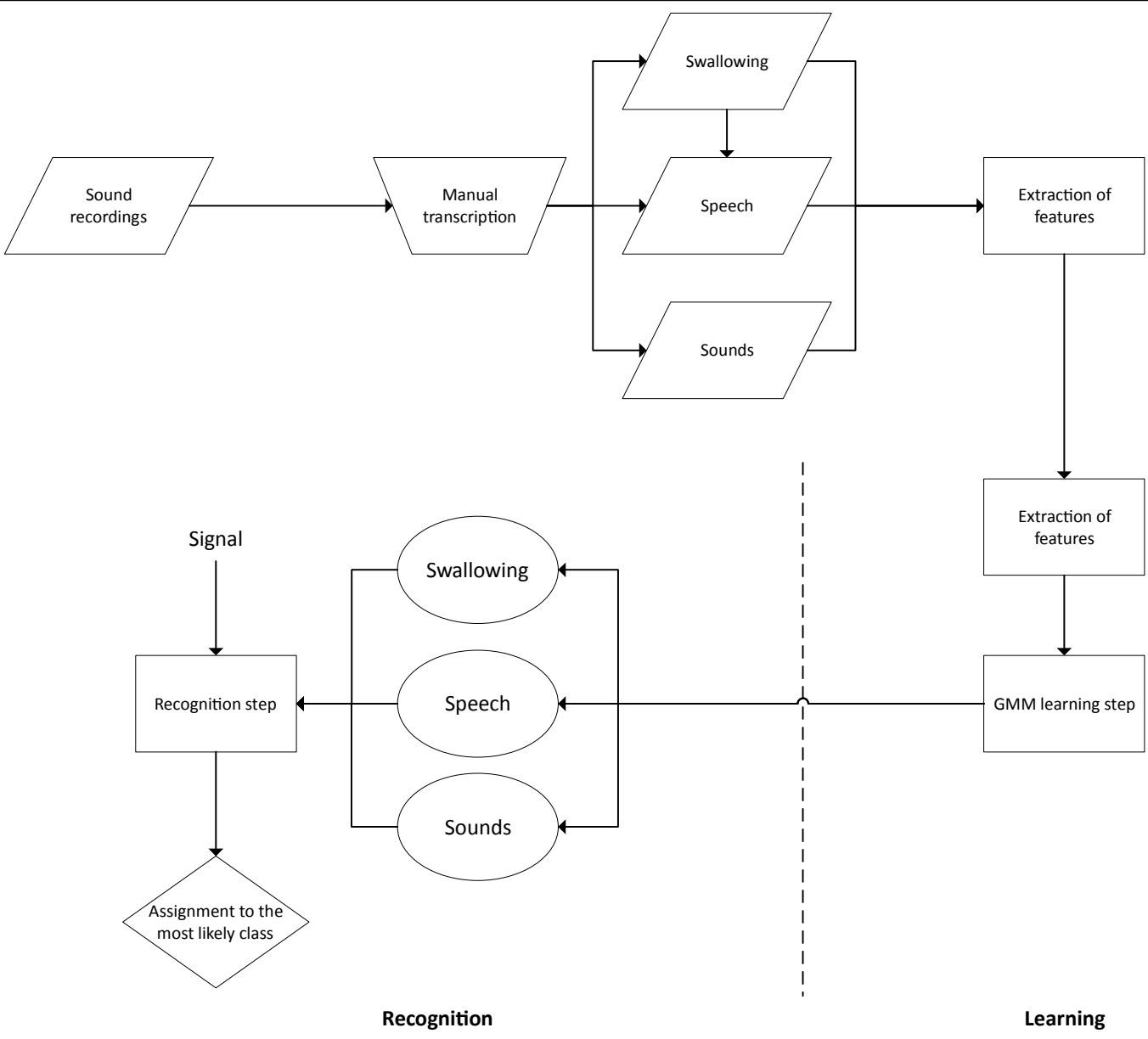
Commentaires

Appendix F

Programs-codes



Automatic Detection



Sound Classification

Table F.1: Automatic detection results

Number of references to be detected = 3501			
Events		References	
Number of Validated Events	67.55%	Number of Validated References	22.19%
Number of Partial Events	30.13%	Number of Partial references	63.95%
Number of False Alarms	24.92%	Number of Missed References	13.85%