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Non-Invasive Exploration of Pharyngo-Laryngeal Functions for a Comprehensive Assessment of Swallowing: A Sensor Selection Procedure from scoping review

Report of the work package Hardware & Software Conception and development for the project “Non Invasive Device assessing Pharyngo-Laryngeal Effectiveness”

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Table des matières

Abstract.....	2
1. Introduction	3
2. Methods.....	3
3. Results.....	4
3.1 Method for Detecting the Efficiency of Oral and Pharyngeal Swallowing Phases.....	6
3.2 Method for Detecting Cough Activity	7
3.3 Method for Detecting Phonation Anomalies Related to OD	8
3.4 Method for Detecting Pulmonary Ventilation.....	8
3.4.1 Respiratory Cycle Detection	8
3.4.2 Detection of Pulmonary Ventilation Efficiency.....	10
4. Discussion	10
5. Conclusion.....	11
6. Funding	11
7. Bibliography	12

Abstract

Introduction: Oropharyngeal dysphagia is exclusively assessed through the ability to transport food from the mouth to the oesophagus (swallowing efficacy) and to perform this transport without aspiration into the lower airways (swallowing safety). However, these indicators do not consider the complexity of the pharyngo-larynx. Interactions between swallowing and other pharyngo-laryngeal functions (coughing, phonation, and respiration) are often neglected in swallowing analysis. To assess these inter-function interactions, it is necessary to observe and measure all these pharyngo-laryngeal functions. Our objective is to present a scoping review of non-invasive detection technologies for oral and pharyngeal swallowing phases, cough, voice, and pulmonary ventilation.

Methods: This scoping review follows the PRISMA guidelines. The identification of references was carried out in the PubMed database (articles in English and French) on the last ten years. Selected references would respect following eligibility criteria: describe at least one instrumental device capable of detecting physiological signals related to specific parameters at least one of the pharyngo-laryngeal functions of interest. Articles focusing solely on the human embryo and/or foetus, on instrumental device that is invasive, immovable, requiring active patient participation and/or hinders swallowing (e.g., mouth obstruction) are excluded. Article eligibility was assessed after reading the full articles and evaluating their relevance regarding pharyngo-laryngeal functions detection modalities.

Results: 116 collected articles highlight the diversity of non-invasive technologies which can be used to detect physiological signals related to the main pharyngo-laryngeal functions. A wide variety of objective data can be collected concerning swallowing, phonation, cough, and respiration.

Discussion and conclusion: A non-invasive instrumental examination of swallowing through the concept of pharyngo-laryngeal efficiency is technically feasible. However, no combination covering all the pharyngo-laryngeal functions of interest has been found in our review. For clinical use, the choice of sensor combination among those listed in our review depend on the quality of its input data but also on its design and ergonomics to ensure the interoperability between each sensor.

1. Introduction

Oropharyngeal dysphagia (OD) is a major public health issue. This swallowing disorder affects 50% of the elderly population and 80% of patients with neurological disorders and head and neck cancers. The main complications include respiratory infections and malnutrition, leading to extended periods of hospitalisation, antibiotic use, modified industrial foods and increased mortality rates [1]. Early detection of OD is crucial to control these complications and reduce their consequences. However, the standard methods (videofluoroscopy (VFS) and fiberoptic endoscopic evaluation of swallowing (FEES)) are considered invasive and not easily accessible [2], making diagnosis and monitoring challenging feat for most of the population.

In addition to these medical and technical limitations, there is a conceptual obstacle related to OD evaluation. OD is exclusively assessed through two efficiency indicators: "swallowing efficiency" and "swallowing safety." These refer respectively to the ability to transport food from the mouth to the oesophagus and to perform this transport without aspiration into the lower airways [3]. However, these indicators do not consider the complexity of the pharyngo-larynx. While coughing to clear aspirations is clearly identified as fundamental for swallowing, there are no indicators evaluating airway protection mechanisms at the pharyngo-laryngeal level. Airway protection is indirectly estimated by measuring the cough reflex triggering threshold [4] and its peak expiratory flow rate [5]. This does not allow the detection of simple throat clearing (between cough and speech) or non-sonorous expiratory reflexes, which are part of pulmonary defence mechanisms. Other pharyngo-laryngeal functions (PLF) – phonation and ventilation – are also neglected in swallowing analysis. However, interactions between phonation and swallowing exist, especially through voice modifications (wet voice) as a sign of silent aspiration in the absence of cough [6] or the prevalence of speech and swallowing disorders in neurodegenerative diseases [7]. Interactions with ventilation are ubiquitous and contribute to the physiopathology of swallowing disorders [8].

To assess these inter-function interactions, it is necessary to observe and measure all these PLF. However, recent literature reviews focusing on non-invasive swallowing evaluation tools (i.e., devices that do not penetrate the body and do not cause tissue damage) only mention technologies for objective assessment of food bolus transport from handling to swallowing [9], [10]. Non-invasive evaluation of all PLF represents a technical challenge, requiring multiple and complementary sensors. This study aims to present a scoping review of non-invasive detection technologies for oral and pharyngeal swallowing phases, cough, voice, and pulmonary ventilation, for clinical use at adult.

2. Methods

This scoping review follows the PRISMA (Preferred Reporting Item for Systematic Review and Meta-Analysis) guidelines.

The identification of references was carried out on 8th February 2022 in the PubMed database. This database has been selected because it includes citations and abstracts of articles from all types of biomedical research (review and clinical trial). Our search consisted of keywords covering: 1/the four PLF (swallowing, airway protection, phonation, and respiration), 2/the detection of PLF of interest, 3/the instrumentation for detection method and 4/the non-invasive nature of the method used. Reference identification was done using the combination of keywords "(swallowing OR respiration OR breathing OR coughing OR airway protection OR phonation OR voice) AND (assessment OR evaluation OR detection OR observation) AND (sensor OR instrument OR device) AND non-invasive". To narrow down our investigation, we applied the following two filters: I/article recency and given the rapid evolution of technologies, our search focused on the last ten years (any article published before 2012 was not included in this search); II/language of articles: the search was conducted in English and French (the language of the authors).

Note: The number of occurrences for voice was deemed unsatisfactory. Therefore, we subsequently extended the recency filter to the last twenty years concerning phonation function and conducted additional recordings with combination of keywords "(phonation OR voice) AND (assessment OR evaluation OR detection OR observation) AND (sensor OR instrument OR device) AND non-invasive".

The screening of references was made by one investigator based on reading the abstracts of the articles according to predetermined selection criteria. Inclusion criteria for articles: article describing at least one instrumental device capable of detecting physiological signals related to at least one of the PLF of interest (respiration, swallowing, airway protection and/or phonation); the physiological signals captured must be related to at least one of the following parameters: any parameter related to oral and/or pharyngeal swallowing phases, cough, voice, respiratory cycle and/or oxygen saturation (SpO₂). Exclusion criteria for articles: the research focuses solely on the human embryo and/or foetus; the instrumental device is invasive, immovable, requires active patient participation and/or hinders swallowing (e.g., mouth obstruction). The articles were retrieved and their eligibility was assessed according to their relevance regarding PLF detection modalities after reading the full articles.

For each article included, we extracted the relevant data according to pre-established forms tested by the team before their use. The categories of these forms are: 1/the technology(ies) cited, 2/the PLF(s) that each of the above-mentioned sensors can detect, and 3/the parameter(s) measured to objectify the PLF(s) concerned, and 4/the conditions under which the sensors are used, especially their positioning.

3. Results

The procedure of article selection is detailed in flow diagram in Figure 1. The results of the state-of-the-art non-invasive detection technologies for assessing PLF are summarised in Table 1.

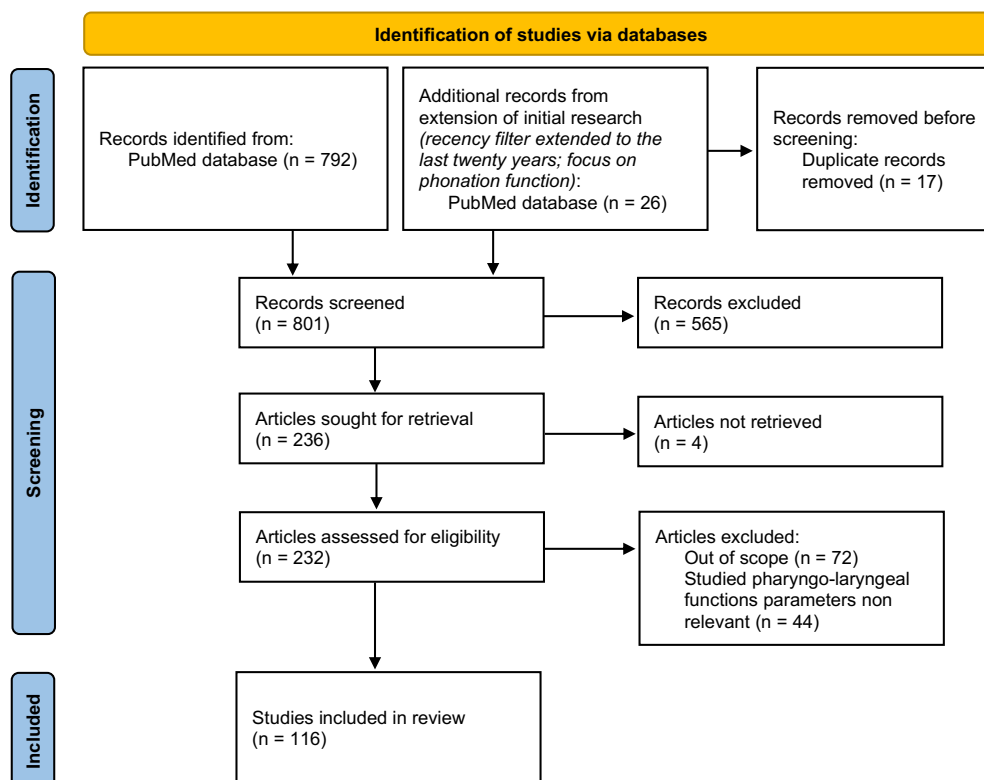


Figure 1: Flow diagram of scoping review

Table 1: Summary of technologies used for observation and measurement of PLF and the number of articles out of the 116 collected where these technologies are mentioned for each PLF.

Technological Domain	Mentioned sensors	Pharyngo-Laryngeal Functions				
		Swallowing	Cough	Phonation	Respiration	
					Respi. cycle	SpO ₂
Video analysis	Photometry with image processing, motion tracking	2	0	1	11	0
Electromyography	Surface EMG	7	0	0	6	0
Acoustic	Microphone, contact microphone, stethoscope, PVDF	12	4	9	7	0
Strain Sensors	Force sensor resistance, flex sensor, stretch sensor, inductance plethysmography, tensiometer, airflow sensor transducer	7	0	0	17	0
Inertial Sensors	Accelerometer, gyroscope	14	1	5	10	0
Electrical Impedance	EKG, electrical impedance tomography	2	0	3	14	0
Ultrasonic	Ultrasound machine	4	0	3	7	0
Electromagnetic Impedance	Radar, GEMS	0	1	2	16	0
Capnography	Capnograph	0	0	0	5	0
Thermal Sensors	Thermistor, infrared thermometer	0	0	0	6	0
Other Spectroscopic Instruments	fNIRS, Bragg grating fibre, PPG, oximeter, videocapillaroscopy	0	0	1	14	11

Note: The total citation number is higher than the number of collected articles since some technologies were combined in certain article works. EMG: Electromyography; MEMS: Micro-Electro-Mechanical Systems; PVDF: Polyvinylidene Fluoride Film; EKG: Electroglottography; ECG: Electrocardiogram; GEMS: Glottal Electromagnetic Micropower Sensor; fNIRS: Functional Near-Infrared Spectroscopy; PPG: Photoplethysmography.

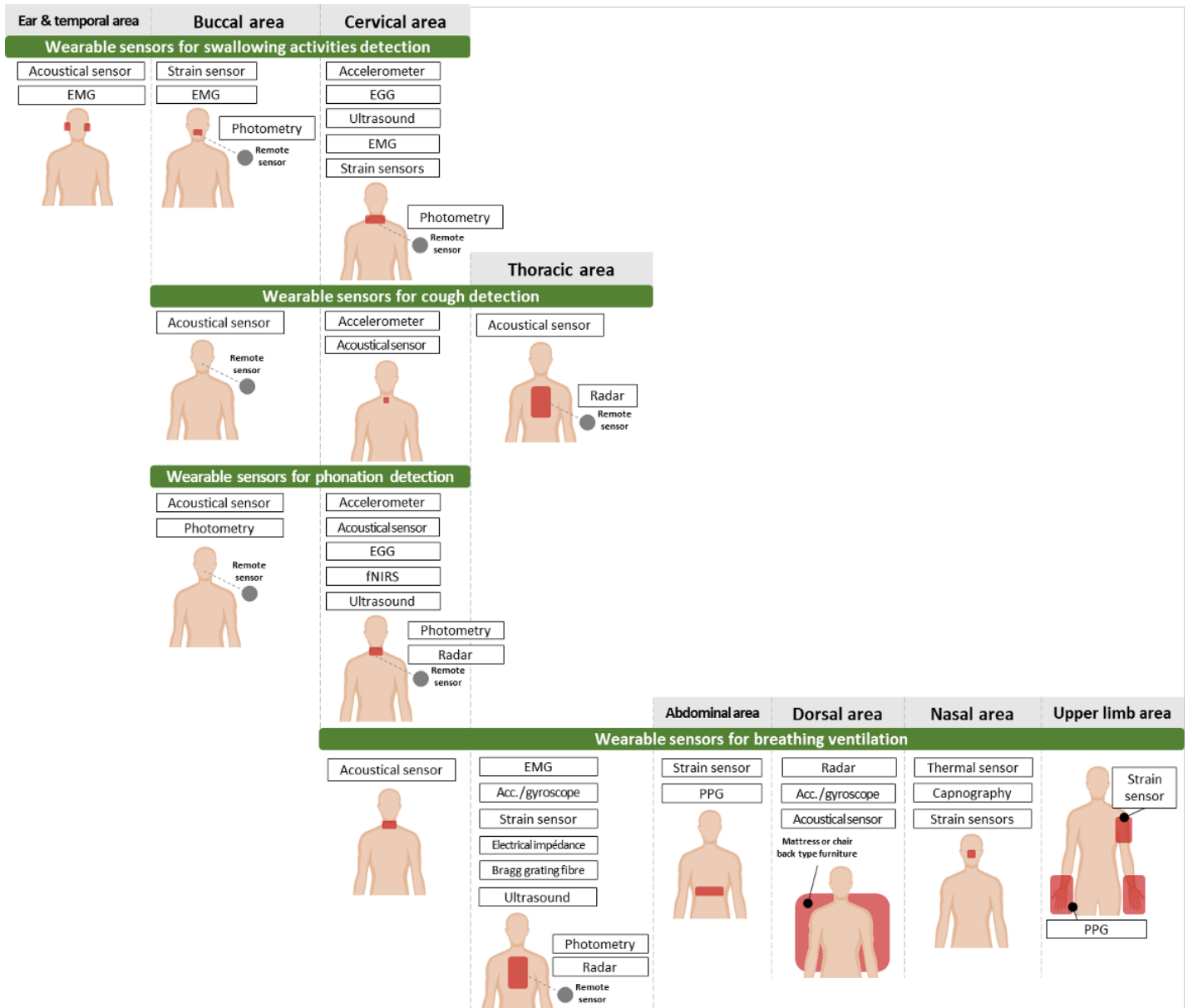


Figure 2: Sensors for detection of 4 pharyngo-laryngeal activities classified according to the area of the body on which the sensor must be positioned. EMG: Electromyography; EGG: Electroglottography; fNIRS: Functional Near-Infrared Spectroscopy; PPG: Photoplethysmography; Acc: Accelerometer.

3.1 Method for Detecting the Efficiency of Oral and Pharyngeal Swallowing Phases

Various capturing methods allow detection and monitoring of the activity and movements of anatomical structures involved in oral and pharyngeal swallowing phases.

Photometry with image processing and motion tracking enables tracking the movements of prominent anatomical structures related to swallowing from video sequences: at the buccal level (e.g., mouth widening and opening, lip protrusion) and cervical level (thyroid cartilage movement). It is possible to quantify the subject's swallowing process, filmed from the oral phase to the pharyngeal phase, in the form of a plot or 3D animation [11], [12].

Oral and pharyngeal phases can also be detected by recording the electrical activity of the muscles involved in swallowing using electromyography (EMG). EMG can measure the activity of five different muscle groups mobilised during swallowing efforts: temporal, mandibular, orbicular, submental and infrahyoid [13], [14]. Its use provides access to the intensity of muscle activity and the timing of muscle group contractions relative to each other, from oral intake to swallowing.

Swallowing acoustics also provides rich information about oral and pharyngeal phases. Depending on the chosen sound origin, technology, size and signal processing, the technology is modified. A miniaturised microphone inserted into the external auditory canal captures chewing sounds [15]. Placed below the mandibular margin or opposite the laryngeal structures, the microphone records pharyngo-laryngeal swallowing sounds which can then be analysed to identify bolus transit in the hypopharynx or laryngeal and pharyngeal movements and their dysfunctions [16]–[19]. These pharyngo-laryngeal sounds can be captured by a stethoscope, MEMS (Micro-Electro-Mechanical Systems) microphones [20], throat microphones [18] or similar devices [16].

At the cervical level, larynx elevation and anteriorisation during swallowing can be recorded by strain-sensitive sensors. These sensors convert received constraints into electrical energy. These constraints can be pressure [21] or flexion induced by larynx movements [22] or neck stretching during swallowing [23]. These constraints are captured by a force sensor resistance, a flexion sensor on the anterior neck and a stretch sensor around the neck respectively. In the mouth, force sensor resistors attached with adhesive on the hard palate allow detection and quantification of tongue contraction during bolus retro-propulsion due to the pressure exerted by the tongue against the hard palate for support [24].

The initiation of swallowing can also be identified by linear accelerations of hyolaryngeal structures resulting from it, captured by an accelerometer [25]. It should be positioned on the laryngeal cartilages, especially on the anterior surface of the laryngeal prominence [26]. It would then be possible to extrapolate from this type of signal the measurement of hyolaryngeal structure displacement during swallowing [18]. The accelerometer would also be sensitive to vibrations inherent in bolus transit from which it might be possible to determine abnormalities such as material passage into the airways [2].

Measuring electrical impedance by electroglottography (EGG) at the cervical level is used to locate swallowing by detecting glottic plane closure during the pharyngeal phase. During swallowing, the EGG signal is in the form of a wave characterised by slow modulation (low frequency) which reflects the slow movements of the larynx [27]. Some authors of our review use this device as reference tool for this movement detection [11]. The impedance principle similar to EGG technology can also be used through the pharynx to assess pharyngeal peristalsis during bolus transit [28].

Finally, other types of movements can also be recorded to study swallowing using ultrasound. We found two uses for ultrasound in swallowing movement analysis. The first focuses on observing and measuring the opening of the upper oesophageal sphincter during bolus transit [29]. The second concentrates on contractions of pharyngeal structures during bolus transit, whose velocity can be analysed using the Doppler mode [30]. Another intended use of ultrasound is to measure tongue muscle mass, a potentially predictive element of OD for certain pathologies [31].

3.2 Method for Detecting Cough Activity

Methods identifying airway protection mechanism activity are mainly based on cough detection to expel foreign bodies. A microphone, positioned in the examination room [32], [33] or placed on the trachea or chest [34], captures explosive sounds generated by coughs whose sound patterns are identifiable through spectral and amplitude analysis of the signal [34]. These acoustic characteristics are also used to classify coughs based on the presence of pneumonia [33] or the risk of aspiration [32].

Accelerometers in supra-sternal position can also specifically detect coughs. During coughing, speech becomes unintelligible, and interferences related to swallowing and daily activities are limited [35]. Typical chest movements during coughing can be recorded by radar which uses electromagnetic waves to establish the position and speed of objects (in this instance, the chest). Coughs are characterised by peaks of reflected wave intensity [36].

3.3 Method for Detecting Phonation Anomalies Related to OD

The sensors detecting phonation included in this review are sensitive to acoustic vibrations and/or movements of the vocal cords (VC). Their detection paves the way for analysing voice quality and glottic plane movements. This data forms a basis for objectifying modifications and specificities in voice tone indicative of swallowing alteration or silent aspiration in the absence of coughing [6], [7].

Acoustic vibrations from phonation activity can be recorded by a microphone. Microphony and various acoustic signal analysis methods remain the most accessible tools to overcome the subjectivity of the human ear [37], [38]. For vocal emission analysis, a wide range of acoustic microphones and technologies such as microphony [39] can be used, whether in contact with the neck or placed near the patient depending on the desired analysis quality. The accelerometer is also sensitive to these vibrations and some authors attribute it with the same qualities of acoustic analysis as the microphone [40], [41]. Placed at the laryngeal level, it allows a finer analysis of glottic vibrations at its different levels, especially for sub-glottic resonance [42] as well as the calculation of the number of vibrational cycles completed and the distance covered by the vocal cords [43].

VC closure is detectable by EGG during phonation while radar can identify their movements [44]. Electromagnetic sensors exploiting the functioning principle of a radar and whose signal would be fundamentally like that observed by EGG (called glottal electromagnetic micropower sensor (GEMS) and described as less cumbersome by its authors) would measure tissue movements of the vocal tract during speech [45]. Ultrasound performed at the neck level also allows observation of vocal tract motion including the movement of VC tissues [46]. Positioned under the chin, the ultrasound probe provides real-time access to speech and articulation effectors such as the tongue [47]. Movements of other speech effectors such as the lips and jaw can be quantified using motion tracking [48].

This review also found the use of functional near-infrared spectroscopic imaging (fNIRS) for monitoring phonation function. This technique allows continuous recording of local modifications in tissue oxygenation and perfusion using an optode positioned at the anterior face of the larynx. A decrease in laryngeal oxygenation level during speech is associated with vocal fatigue [49].

3.4 Method for Detecting Pulmonary Ventilation

The interactions between swallowing and ventilation are ubiquitous and contribute to the pathophysiology of swallowing disorders [12]. For breathing, two variables are distinguished. Firstly, identifying the different respiratory phases coordinated with swallowing: inspiration, apnoea, and expiration. The number of respiratory cycles per minute defines the respiratory rate which is a fundamental respiratory indicator [50]. Secondly, detecting SpO₂ provides information on the subject's respiratory state and potentially the presence of aspiration [51].

3.4.1 Respiratory Cycle Detection

EMG and accelerometers, positioned at the chest level, would allow the study of ventilatory function if interference induced by heart rate and other body movements is filtered out [52]. EMG would provide necessary information on inspiratory muscle activity from which respiratory cycles and respiratory frequency can be described [53]. Electrodes are placed on the diaphragm and/or intercostal muscles [54]. Accelerometers can be placed at the same locations as EMG [55]. Since their sensing mode is not solely sensitive to muscular activity, they can also be positioned on a bony surface of the chest such as

the sternum [56]. However, for a more detailed investigation of respiratory events [57], authors have combined a gyroscope with an accelerometer to combine linear acceleration and velocity measured by the accelerometer and displacement and angular velocity by a gyroscope. Another author also mentions the possibility of integrating an accelerometer into furniture in contact with the patient's chest (e.g., in a chair's backrest) rather than the patient to obtain information on the subject's breathing [58].

The respiratory cycle can also be detected from the stretching of the thoracic wall induced by respiratory movements. Inductance plethysmography can capture these movements using sensors integrated into stretch bands or clothing surrounding the chest and abdomen: the resistance of these sensors varies depending on the expansion of the thoracic cage and diaphragm [59]–[61].

Electrical impedance tomography is employed to estimate respiratory rate and apnoea episodes through changes in electrical conductance in the chest. This is achieved through electrical impedance tomography [62], [63] using a set of electrodes placed on the chest and derivatively from the electrocardiogram at the sternal notch, on the xiphoid and in the right mid-axillary line [64], [65].

Radars can pinpoint respiratory phases in an aerial environment by detecting movements (position and speed) of the chest wall [36], [66], [67]. Experimental devices using the same technology, relocated from the patient's body, and integrated into furniture in contact with the subject (e.g., under the mattress) would yield similar results [68].

Diaphragm movements are accessible via ultrasounds used in sonography: these diaphragm movements and their travel time are evaluated, providing an estimate of respiratory cycles and their duration [69], [70].

The motion tracking technique infers respiratory cycles from the movement capture of photo-reflective markers placed at the chest level [71] or by exploiting the depth flow of the chest image [72].

Respiratory cycles can also be deduced from sounds generated during respiratory efforts. Tracheal and bronchial sounds captured by a microphone would include the three parts of the respiratory cycle (inspiration, apnoea, and expiration). In this context, the collected articles positioned their sensor at the sternocleidomastoid muscle [73], above the thyroid cartilage and below the jawline [74], at the tracheal level [75] or on the back surface below the lower tips of the shoulder blades [76].

Fibre optics is another technology capable of providing information about respiratory rate through light waves circulating in fibres (Bragg network) integrated into textiles [77] or in a medical device positioned on the body [78]. The quantities captured come from various sources: constraints from thoracic movements [79] and sounds (this sensor is as sensitive to voice as it is to cardio-respiratory sounds) [78]. It is a somewhat hybrid technology compared to those previously presented since it is sensitive to both constraints and vibrations.

The respiratory cycle can also be estimated through nasal airflow. Capnographs can detect the respiratory cycle from changes in carbon dioxide concentration measured during inhalation and exhalation [80]. The air flow sensor transducer and other similar technology (PVDF) deduces respiratory phases from pressures exerted on the sensor by airflow [81], [82]. Finally, thermistors can translate the convective heat contained in nasal breath into the respiratory cycle phase [83]. Some authors specify, however, that the use of an airflow sensor transducer associated with a thermistor would be more sensitive than the thermistor alone to detect characteristic breathing patterns [84]. Infrared light also describes airflow through thermography, thanks to temperature measurement using a non-contact oronasal infrared thermometer with or without motion tracking [85].

Other methods allow respiratory function monitoring without studying thoracic wall movements such as photoplethysmography (PPG) which measures oxygen level variations during breathing and deduces the respiratory rate [86]. Several studies have shown that positioning the device on the finger would be most appropriate for extracting the respiratory signal [69], [86] although other authors place the sensor on the wrist [87] or at the abdomen level [88]. However, this measurement remains dependent on the subject's resting position [86]. Other technologies (camera type) integrate infrared light to extract the respiratory rate by focusing on the dorsal veins of the hand [89].

A recent study also demonstrated that respiratory rate can be estimated using data obtained from a blood pressure monitor on the arm [90].

3.4.2 Detection of Pulmonary Ventilation Efficiency

Pulse oximetry is part of the sensor family which uses light to assess respiratory status. Its operating principle combines the PPG principle and that of absorption spectrophotometry. The goal is to deduce SpO₂ from blood haemoglobin and oxyhaemoglobin absorption rates of light. Through SpO₂, pulse oximetry provides information about the subject's respiratory state [91], [92]. It has been hypothesised that SpO₂ variations could be correlated with the presence of laryngeal aspirations. However, the scientific data available to us do not support the use of pulse oximetry for this purpose [51].

4. Discussion

This review highlights the diversity of non-invasive technologies which can be used to detect physiological signals related to the main PLF (see Table 1). A wide variety of objective data can be collected concerning these four PLF (swallowing, phonation, cough, and respiration). A non-invasive instrumental examination of swallowing through the concept of pharyngo-laryngeal efficiency is technically feasible.

Combining sensors is a necessary condition given the existing technologies available on the market. However, no combination covering all the PLF of interest has been found in our review. The only examples of combined analysis for multiple PLF related to the following pairs: swallowing/respiration [14], [21], [81], [93], [94] and cough/respiration [36]. Furthermore, based on our review and considering the main PLF to be detected, we observed that no sensor seemed capable of objectively assessing both the oral and pharyngeal phases of swallowing, airway protection efforts, phonation efficiency, subject respiratory cycles and SpO₂. Some sensors are so specific that they only allowed the detection of one indicator of interest. Only microphony and accelerometry covered all four PLF with a common limitation: they were unable to objectively evaluate SpO₂. The only sensor capable of objectively assessing both the oral and pharyngeal phases of swallowing was the microphone.

Thus, the minimum combination of technologies would be microphony combined with a respiratory sensor such as a pulse oximeter. However, this combination requires multiple microphones to cover all the evaluated PLF: an aerial microphone for phonation, one in the ear canal to objectively assess masticatory effort, one at the neck level and one at the thoracic level to capture tracheal and bronchial sounds for swallowing, cough and respiratory flow. This would then bring the number of sensors to five for this combination. Simultaneously capturing PLF and all indicators of interest would require multiple sensors and thus imply a certain bulkiness. Therefore, for clinical use, the choice of sensor combination must meet a series of selection criteria defined according to the needs of the swallowing assessment. We will mention five (non-exhaustive list):

- The bulkiness of the sensors should not hinder the performance of the evaluated PLF.
- Interoperability between sensors must be verified. As a counterexample, the ultrasound used to investigate the oral cavity or the subject's neck requires the application of gel to the skin which can constrain the installation or functioning of other sensors on and around the ultrasound

capture area. However, adhesive ultrasound probes encapsulated in a gel-containing casing have recently been developed [69].

- Sensor synchronisation must be possible for simultaneous evaluation of each signal.
- Sensor portability should be favoured to perform an assessment in the most ecological examination conditions. As a counterexample, we have identified radar systems that require the installation of imposing and bulky equipment in the patient's environment [44]. However, this does not mean that all radars are cumbersome; this technology can be adapted, according to needs, into miniaturised transmitters and receivers that can be attached to the patient's clothing [36].
- In the perspective of developing a multi-sensor evaluation tool, the compatibility of selected sensors with reference examinations must be ensured. For example, this translates as compatibility in terms of ergonomics and artifact with the realisation of a VFS or a FEES, testing cough reflex sensitivity to citric acid or capsaicin associated with a spirometer to measure cough intensity.

The eligibility of a sensor is certainly strongly dependent on the quality of its input data but also on its design and ergonomics, which are, however, destined to evolve technically.

Ono et al. identified means of detecting food transport in 2010 [9]. Sensors were classified according to the three anatomical regions analysed: lip, tongue, and larynx. One type of sensor not mentioned in our literature review are sensors sensitive to pressure variations measuring lip occlusion force. The authors explained their choice to study lip strength by recalling that lip occlusion occurs in response to the swallowing reflex and the absence of lip closure leads to a lack of pressure in the oropharynx, hindering swallowing. In our review, lips are studied through video recording and motion tracking, which allows evaluation of mouth opening and lip protrusion but does not provide information on forces developed in this anatomical region. In any case, despite the potential interest of these lip pressure measurement sensors, they do not appear in our review since they contradict one of the exclusion criteria in our method. They hinder swallowing because the patient must exert pressure with their lips on a probe. Therefore, they cannot be used in real conditions during a meal.

Fontana et al. searched the literature in 2014 for sensors capable of objectively evaluating food intake by monitoring hand movements, chewing period and swallowing period [10]. The sensors revealed in this article were the accelerometer, microphone, EGG, and a magnetic impedance system. All these sensors have been found in our review, with a distinction concerning the magnetic impedance system: this technology has been used in the form of cervical sensors to monitor the movements of the thyroid cartilage during swallowing. This specific use corresponds to the eligibility criteria applied in our review. The reason this article did not come up in our review is because it was presented as an article dealing with food consumption detection, not swallowing detection.

5. Conclusion

This review allows the development of a multi-sensor tool capable of non-invasively exploring the pharynx-larynx in all its anatomo-functional complexity. The validation of such a medical device, using algorithms and artificial intelligence, would allow researchers to seek methods for automatically analysing sensor recordings to model pharyngo-laryngeal efficiency and swallowing disorders. This automation, combined with the non-invasive aspect, would allow the widespread use of this multi-sensor tool in populations at risk of dysphagia [95].

6. Funding

[...]

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