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MATHEMATICAL MODEL OF THE VOCAL DYNAMICS APPLIED TO THE ANALYSIS OF THE SWALLOWING BEHAVIOR

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ABSTRACT
The occurrence of dysphagia during swallowing, that is, difficult in the passage of the food bolus may originate from several organs related to swallowing. From the recognition of patterns for this movement and capture of signals under the responsible movement, it is possible to perform a mathematical study in order to evaluate the wear and decrease of the physiological ability of the muscles responsible for swallowing. From a low-cost system, based in the capture of audio and artificial neural networks, we propose a mathematical modeling to aid the diagnosis involving dysphagia in swallowing.

INTRODUCTION
Swallowing may be defined as a complex process that involves structures such as the oral cavity, larynx, pharynx and esophagus, with the objective of transporting food from the oral cavity to the stomach [1]. This process occurs in four stages: preparatory stage, oral stage, pharyngeal or pharyngo-laryngeal stage and esophageal stage, being responsible for the passage of the food bolus from the esophagus to the stomach [2]. The difficulty in transporting the food bolus to the stomach is called dysphagia. Dysphagia is usually associated to other disorders such as dyspnea, odynophagia, dysphonia, tracheobronchial aspiration, chest pain and others [3].

The main factors that cause dysphagia are related to swallowing disorders. These disorders are classified by the origin of symptoms, such as: neoplastic, obstructive lesions, metabolic disorders and neurological diseases. Regarding neurological dysphagia, the focus of this study is the degenerative disease called Amyotrophic Lateral Sclerosis (ALS). The obtaining of the dysphagia diagnosis may be performed through some tests, such as: i) timed water swallowing test; ii) fluoroscopy; iii) esophagogram contrasted with barium. These are established procedures; however, it is impossible to identify the dysfunction of the upper motor neuron that creates changes in the biological signals of the larynx region in the swallowing process [3-6].

A process used frequently in the literature for characterizing biological signals are intelligent systems. The study by Amitava et al. (2001) presents automated systems, developed with hybrid fuzzy logic and Neural Networks (NNs), in which the system recognizes the acceleration signals in the swallowing of food. In this study, the authors used two fuzzy logic sets and fuzzy causal network (FCN) type neural networks to recognized if there is dysphagia in food swallowing. The tests with swallowing with dysphagia (FCN-I) and with normal swallowing (FCN-II) using hybrid FCNs generated the results: a) FCN-I recognized the different signal for dysphagia acceleration, in the moment of ingesting each food; from the 33 signals analyzed, 94% presented dysphagia in swallowing for 100% of foods; b) on the other hand, with the use of the FCN-II group, a compound was applied in seven neural networks, and there was a recognition that 100% of signals were normal when swallowing 96% of foods. These results show the establishing of a feasible diagnosis tool.

From the clinical point of view, identifying and classifying patients with dysphagia with aspiration hazard is a diagnosis of major importance. According to Suryanarayanan et al. (1995), several techniques were developed to quantify several biomechanical parameters that characterize patients with dysphagia. An expert system was developed to classify patients with these techniques. For the diagnosis, the use of fuzzy logic is again reported in the classification of patients with pharyngeal dysphagia into four aspiration hazard categories. The following measurements were performed: non-invasive acceleration and pressure in swallowing, and, from these data collected, some parameters were obtained (displacement, speed, and others). Twenty-two patients were evaluated, eighteen of which were identified with some degree of dysphagia through biomechanic measurements with fuzzy

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classifier. When validating the system, the video fluorography method was used, confirming the diagnosis of the intelligent system.

The signals originating from the cervical region have neuromotor information that may aid in capturing data that characterize a disease; however, the method of collection and the region have influence in the acquisition of these characterizing elements — such as range, frequency and periodicity, according to Torisu et al. (2014), who used the capture of electromyography of the muscles, in the dorsal region of the neck, obtained by electrical intra-oral stimulation. In these records before and after the application of local anesthetic, in a group of 17 volunteers, the results showed a dorsal constriction of the neck in the electromyography activity. The perceived intensity of the electrical stimuli as scored in a visual analogue scale (VAS) was 61 mm ± 4 before the anesthetic and 15 mm ± 2 after the anesthetic. With the use of the intraoral electrical stimulus, it was possible to verify the constriction of muscular activity. This is due to the nociceptive afferent nerves and non-nociceptive fibers. With this, they conclude that there is a correlation between the neural region and the cervical region, raising the possibility of electromyography, mechanic and acoustic captures.

Regarding the development of mathematical models that correlate the larynx region and swallowing, a study performed by Trabelsi et al. (2011) shows a model obtained by the technique of finite elements of a human trachea, used to analyze the behavior of this system during swallowing. In this model, a simulation is made of the behavior of the swallowing movement in patients before and after the implantation of the Dumona prosthesis. The use of the prosthesis, in the correlation with the proposal of this article, is to simulate and verify the effect of the response of the organ to wear and the decrease of the physiological swallowing ability. In this regard, the loss occurred around 26.4% in one patient and 18.9% in the second case, where an increase in mechanical pressure was also observed.

Therefore, the mathematical modeling as a decodifier of the workings of biological systems and its essential aspects with the objective of understanding its workings as a function of some variables and conditions is corroborated with the process of production and normatization of technologies applied to these real systems. Supported by this perspective, modeling a physiological system has as a principle to reproduce its action and, thus, to be able to evaluate the parameters with which we may interfere or which we may vary.

However, due to the natural aspects of the human body in which many complex interactions are composed, mathematically modeling physiological systems allows for the development of a diagnosis proposal that may be more effective as a result of the technique applied, thus generating more safe results [11]. Hence, the utility arising from mathematical models in this context is to provide a description of the behavior of the system through mathematical expressions that may be examined and analyzed. Thus, not knowing the pathology of dysphagia or underestimating the facts that lead to it may lead to clinical damage — such as dehydration, malnutrition, pneumonia, and others.

In this context, the proposal of this article, for the digesting process, in the pharynx — swallowing stage, is to present the results of the: i) mapping of the swallowing malfunction (dysphagia); ii) proposing a diagnosis tool for the disorder in the larynx mechanism; iii) acquisition of a mathematical model by computer identification.

MATERIALS AND METHODS

This experiment has the approval of the Research Ethics Committee from the State University of Rio Grande do Norte, Brazil under the following report number: 761.227.

The data was captured from experiments performed with two subjects, one male and one female with an average age of 23 years. The test was divided into two stages, each one with fifteen samples. The first stage was ingesting 180 ml of water, and the second stage was ingesting two units of water biscuit crackers. During the ingestion of foods, the individuals remained seated, facing the computer, with the microphone on the neck. No time limit was stipulated for the ingestion of any of the substances ingested; it was left for the participant to decide so that the swallowing occurred the most natural way possible.

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Acquisition System

During the preprocessing stage, we used a stereo throat microphone with 16 bits resolution and 48 kHz sampling frequency attached to a data acquisition system through the high definition audio controller plate (model Realtek 8086-9C20), both connected to a portable computer (notebook). The file was saved in the default format of Windows Operating System and was later converted to WAV format. This conversion is necessary for compatibility with MatLab®. The audio file was converted into a matrix that contains the information of the two audio channels, and then we performed the simple average of these two channels, creating a new vector. Finally, we performed the simple average of the vector, obtaining a single value entry into an Artificial Neural Network (ANN). In the processing step, a vector of 30 dimension containing all samples acquired was used for the training, validation and test of ANN. After the processing step, the output of the ANN is a vector indicating the classification of THE food swallowed as solid or liquid.

For the recording to happen, it was necessary that the individual hit the microphone button to release the channel, and then the person responsible for the tests activated the command to make the software start receiving the information captured by the microphone. This sequence is necessary to reduce the noise produced during the pressing of the button on the microphone. The delay from the activation of the button was removed in step iii.
In short, the signal processing was carried out in four steps: (i) acquisition of data: obtaining the audio from the microphone during the recording the sound produced by the swallowing; (ii) pre-processing of data: vectoring audio acquired; iii) extraction of characteristics: extraction of the two channels of audio and application of simple average and (iv) analysis and classification of the signal: sending data to the neural network for training, validation and testing.

Classification tool

ANNs are considered tools of great potential for use in biomedical engineering and have been used to classify and recognize different patterns, such as, for example, biomedical signals, audio, image, among others.
In this study, the ANN was used with the goal of classifying the types of foods ingested into liquid or solid. The type of ANN used was a multilayer perceptron due to the complexity of the problem to be solved. The proposed architecture has an entry neuron that is responsible for receiving the swallowing data acquired during the acquisition process; two internal layers responsible for the processing of data, where the first layer has 40 neurons and the second layer has 80 neurons; and finally, an output neuron that returns the data processed by the network, as shown in Figure 1.

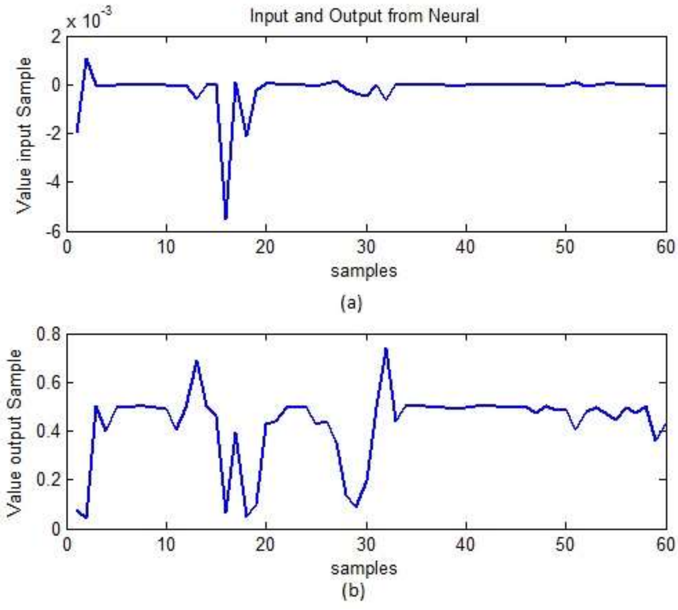

Figure 1. Input signal (a) and output signal (b) of the ANN — to be used as signal estimation.

The activation function used was the sigmoid and the algorithm used for the training of the ANN was the Gradient Descending Backpropagation. This algorithm establishes random synaptic weights and, in accordance with the inputs of the network, it calculates a result and compares it to the expected value. The error is calculated and propagated in the opposite direction to the network so that the weights (W) and biases (b) are adjusted. The weights are always changed in the opposite direction of the direction of the largest square error. This type of algorithm is the most commonly used in multiple layer networks. The number of times prescribed was 2,000, the goal, minimum value of performance, was defined as 0.00001. The data set used was defined as 70% for training, 15% for validation and 15% for testing.

In addition to the samples vector used for the training of the ANN, we used a vector containing the information of the expected output. This vector helps during the learning of the network by informing what type of food is at the entry. The representation used was of binary values, where 0 represents the liquid and 1 represents the solid.

As output, a vector with actual values was generated. The ANN produces values that are close to the desired values. For example, for this proposal of identifying the type of food, the closer to zero, this means that the network has identified that entry as a liquid, and the closer to the value one, the entry was identified as a solid. The test bench composed is illustrated in Figure 2 and the method of data acquisition is illustrated in Figure 3.

Figure 2. Image of the devices used in the experiment: in A, the laptop is used for the storage and processing of the signal; the element B is the throat microphone used for the acquisition of the audio produced during the swallowing of food; the element C is the microphone button that allows the release of the channel, allowing the recording to be made.

Figure 3. Image of the subject who drank 180 ml of water and pressed the release button of the microphone channel while recording the audio.

Through the use of the methodology described in the introduction of this Article, and considering restrictions as a specific focus of analysis — which are range, pressure and speed, it can be stated that the methodology for the development of a mathematical model that represents the operation of liquid and swallowing with dysphagia is very complex, which is typical of physiological systems. The applicable model for analyses during the passage of the liquid food bolus, in this system, aims at a non-parametric way of analyzing the dynamics of this bioinspired system and correlating it with presentations of dysphagia with a neurological origin. The phenomenon of the model that enables the presentation of the dynamics of the system, in terms of the variables captured, is the pressure in the larynx converted to acoustic data that represents respectively: i) force transmitted to the food bolus of walls in the horizontal direction of the larynx for liquid food, water and to solid foods, water biscuit cracker.

Simplifying Assumptions

a) The wall of the larynx is assumed even along the length.
b) The bolus is a concentrated parameter;
c) The mechanical elements inherent in this system have negligible numbers in relation to the food ingested;
d) The movement analyzed is translational in x — without deflection, vibrations, and disturbances;
e) The influence of surrounding organs is ignored;
f) The value of the current output depends not only on the current inputs, but also on its past values. There is causality of the system, which implies that the transfer functions identified will be biproper or strictly proper.

In this work, the identification of a system can be understood as the process by which the dynamic model is determined from the analysis of experimental data. It also consists in the establishment of the experience of identification, the determination of an appropriate formulation of a model coupled with its parameters, and in a final procedure for validation of the model. The method of identification used in this article deals with the problem of constructing a dynamic model of some system to be studied from the observation of its input and output data. The four main steps of the methodology used, which will lead from the observed data to the model identified the swallowing by means of acoustic analysis are: i) practical aspects; ii) input and output data; iii) family of structure models and iv) validation procedures.

Practical aspects

In order to get some insight on the types of structures that will be proposed, we will do the following: a) through observation of the data, estimate the order of the system and the structure model; b) simulate this model with the input and compare the output simulated with the measured output on all the data record; c) check if there are more signs that significantly affect the output. It is then necessary to seek in the physical system what these signs may indicate to check whether they can be measured and thus included among the entries. Otherwise, the sources that cannot be followed or measured must be indicated, and they will be called “disturbances”; (d) examine whether some important nonlinearities were neglected. Then we must use the physics of the system to find out whether some of the signals measured are subject to non-linear transformations.

Input and Output Data

The obtaining of input data was performed with the intake of regular sips of water — for liquid food, and the process of chewing and swallowing of the water biscuit cracker. Thus, we considered a signal relating to the liquid as a noiseless square wave, and relating to solid food as a square wave with noise. The set of input signals chosen was applied and the output signals were recorded. The goal of this experiment is obtaining input and output data with a quantity of information empirically determined, appropriate in the presence of unknown disturbances.

The signals and input-output relationships will be previewed by graphs that show their amplitude variations in the time domain. However, extrapolations from the spectral analysis of signals, i.e., of its treatment in the frequency domain, such as: energy spectral density; energy and power signals will also be presented.

We determined the rate at which the signals were sampled. The input and output information was put on the same graph to analyze the fact that the presence or not of a DC level, and estimating an approximate time for the response to start — thus identifying a possible component of the response due to a previous entry, such as saliva, or some initial condition, such as motion events of the tongue and teeth.

Structure Models

In the process, a large quantity of model structures was tested and the identification process became a process of evaluation and choice between the resulting models. Our structure is of black box type, and we chose parameterization in terms of a parameter vector so that the family of candidate models generated the model of interest. The physical model of the system is not known (black box modeling).

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Validation Procedures

For validation of the model, we applied test with validation data, data that were not used to estimate the model, in the simulation or prediction — to reproduce the output. Through the visual inspection of the results, we verified whether the adjustment was satisfactory. The validation was also made by submitting the identified system to the same set of inputs used in the identification process, and measuring the distance between the outputs.

RESULTS AND DISCUSSION

After the analysis of the data, the first conclusion was that, in the act of swallowing, where we was expected to obtain a square wave, we verified that the signal actually behaves in a triangular shape in two cases. In the case of the signal obtained for the swallowing of water, we can see clearly the frequency of the peristaltic wave; this can be stated because the liquid flows smoothly through the length of the esophagus, i.e., it does not inject noise into the system. In the case of the ingestion of the cracker, the signal may be compared with a modulation in amplitude where the frequency of breakage of food is the signal, and the frequency of the peristaltic wave is the carrier signal; when compared with the response of swallowing water, it further enhances this understanding.

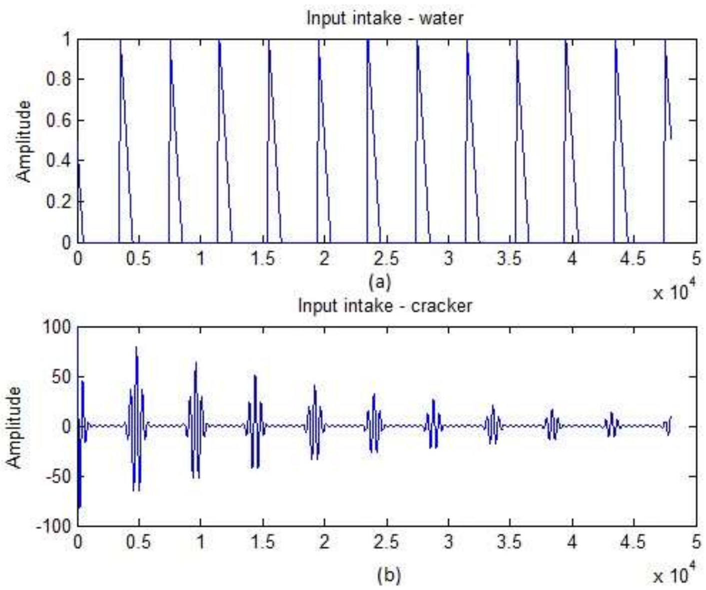

Figure 4. Graphs of swallowing water and cracker where: in a) we can notice a pattern of frequency approximately constant in the case of water; in b) we can notice the same repetition frequency pattern, but with a modulated signal related to the swallowing of the cracker.

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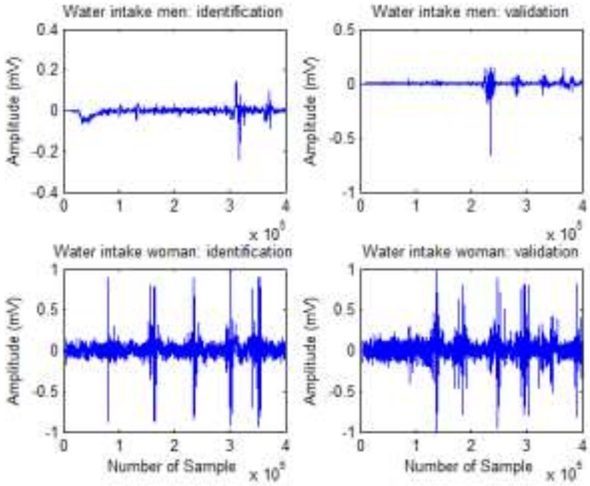

Figure 5. Data selected among fifteen samples of each subject to be used as identification data for the model and validation of the model in the ingestion of 150 ml of water.

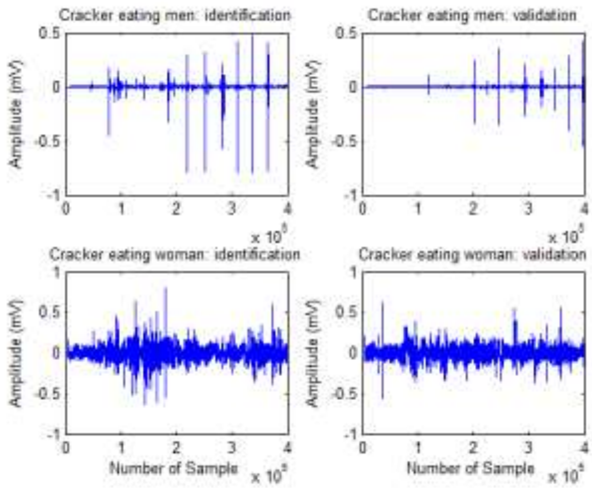

Figure 6. Data selected among fifteen samples of each subject to be used as identification data for the model and validation of the model in the ingestion of one cracker.

Physiological differences existing in the male and female human body can be noticed by observing Figure 5 and Figure 6. For the same muscle exercise performed, it is possible to notice a big discrepancy between the wave amplitudes.

CONCLUSION

From the method adopted for the capture of data, it is possible to characterize dysfunctions in the muscle tissue of the esophagus, using patterns of recognition by the ANN. The aid in the diagnosis of dysphagia in swallowing can be performed through this low-cost system, which can facilitate the access to this type of diagnosis in low-income communities; this test may be included in governmental public health systems, such as the Single Health System (SUS) from the Brazilian government.

By making the correct ANN training, it is possible to differentiate men and women and make the proper correction via software during data acquisition, as we have verified that the physiological differences may influence the accuracy of the results obtained.

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REFERENCES

1. Silva, L.M., 2006. Disfagia orofaríngea pós-acidente vascular encefálico no idoso. *Revista Brasileira de Geriatria Gerontologia*, *9*(2).
2. Clavé, P., Terré, R., Kraa, M., & Serra M., 2004. Approaching oropharyngeal dysphagia. *Revista Española de Enfermedades Digestivas*, *96*(2), 119-31.
3. Jotz, G.P., & Dornelles, S., 2012. Distúrbios da deglutição. *Revista Hospital Universitário Pedro Ernesto*, *11*(3), 70-76.
4. Dietrich-Neto, F., Callegaro, D., Tosta, E.D., Silva, H.C.A., Balallai, M.E.F., Lima, J.M.B. et al., 2000. Amyotrophic Lateral Sclerosis in Brazil: 1998 National Survey. *Arq Neuro-psiquiatr, 58,*607-615.
5. Majoor-Krakauer, D., Willems, P.J., & Hofman, A., 2003. Genetic epidemiology of amyotrophic lateral sclerosis. *Clin Genet.*, *63*(2):83-101.
6. Swash, M., & Schwartz, M.S., 1992. What do we really know about amyotrophic lateral sclerosis? *J Neurol Sci.*, (113), 4-16.
7. Amitava, D., Narender, P.R., Janardhan, N., 2001. Hybrid fuzzy logic committee neural networks for recognition of swallow acceleration signals. *Computer Methods and Programs in Biomedicine,* (64), 87-99.
8. Suryanarayanan, S., Reddy, N.P., & Canilang, E.P., 1995. A fuzzy logic diagnosis system for classification of pharyngeal dysphagia. *International Journal of Bio-Medical Computing,* (38), 207-215.
9. Torisu, T., Tanaka, M., Murata, H., Wang, K., Arendt-Nielsen, L., De Laat, A., & Svensson, P., 2014. Modulation of neck muscle activity induced by intra-oral stimulation in humans. *Clinical Neurophysiology*, (125), 1006-1011.
10. Trabelsi, O., Pérez del Palomar, A., Mena Tobar, A., López-Villalobos, J.L., Ginel, A., & Doblaré, M., 2011. FE simulation of human trachea swallowing movement before and after the implantation of an endoprothesis. *Applied Mathematical Modelling,* (35), 4902-4912.