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Vocal fold biomechanics: simulation and analysis of the neuroregulatory pattern

Biomecánica de las cuerdas vocales: simulación y análisis del patrón neuro regulador

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Abstract

The intrinsic muscles of the larynx are responsible for generating and coordinating the variety of movements that develop during the process of human voice production. Recent research indicates that these movements depend on a neuroregulatory pattern that coordinates the intrinsic muscles of the larynx according to the anatomical and functional characteristics underlying the vocal folds of everyone. Finding the parameters that model the neuroregulatory pattern is an open and ongoing field of research that has been little studied. The aim of this paper is to evaluate a new experimental methodology to model the neuroregulatory pattern that coordinates intrinsic muscle movements and to characterize it on a novelty curve using a set of biological parameters that are extracted from a small segment of the acoustic wave of the speech signal known as the prefonatory preamble.For this purpose, an acoustic wave bank of voice signals generated at the Luis Guillermo Ibarra Ibarra National Rehabilitation Institute, and endorsed by the NOM-012-SSA3-2012, is used. The results show a clear and objective mathematical differentiation of the neuroregulation patterns executed in the vocal cords of everyone, also differentiated by gender.

Vocal cords, Neuroregulatory pattern, Vocal cord biomechanics, Pattern modeling

Resumen

Los músculos intrínsecos de la laringe son responsables de generar y coordinar la variedad de movimientos que se desarrollan durante el proceso de producción de la voz humana. Recientes investigaciones refieren que dichos movimientos dependen de un patrón neuroregulador que coordina los músculos intrínsecos de la laringe de acuerdo con las características anatómicas y funcionales que subyacen en las cuerdas vocales de cada individuo. Hallar los parámetros que modelan el patrón neuroregulador, es un campo de investigación abierto y continuo que ha sido poco estudiado. El objetivo de este artículo es evaluar una metodología experimental para modelar el patrón neuroregulador y caracterizarlo en una curva de novedad utilizando un conjunto de parámetros biológicos que se extraen desde un segmento de la onda acústica de la señal de voz conocido como preámbulo prefonatorio. Para tal fin se utiliza un banco de ondas acústicas de señales de voz generado en el Instituto Nacional de Rehabilitación Luis Guillermo Ibarra Ibarra, y avalado por la NOM-012-SSA3-2012. Los resultados muestran una clara y objetiva diferenciación matemática de los patrones de neuroregulación que se ejecutan en las cuerdas vocales de cada individuo diferenciándose asimismo por su género.

Cuerdas vocales, Patrón neuroregulador, Biomecánica de las cuerdas vocales, Modelado de patrones

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1 Introduction

The intrinsic muscles of the larynx are responsible for generating and coordinating the variety of movements that take place during the production process of the human voice. They basically organize 3 actions: adjust the tension of the vocal cords, generate movements to unite the two vocal cords in the midline of the glottic canal and generate movements to move the vocal cords away from the glottic canal (Quatiery & Malyska, 2012).

Recent research by Nilbakth (Nibakth, A. Tafreshiha, & Zocolan, 2018) indicates that the subcortical system of the human central nervous system contains independent sensory circuits, whose mission is to integrate the proprioceptive information collected by the cells of the epithelial tissues that They coat the vocal cords to model a neuroregulatory pattern that adjusts the movements of the intrinsic muscles of the larynx according to the anatomical and functional characteristics that underlie the vocal cords of each individual. The parameters that shape the neuroregulatory pattern is an open and continuous field of research that has been little studied.

In this sense, Ramos Casados et al: (Ramos, 2014): and Quatiery et al: (Quatiery & Malyska, 2012) point out that, since there are physiological alterations that cause changes in the viscosity and elasticity of the vocal cords, the sensory information Proprioceptive is also modified, to which Malmgrem adds that (L. Malmgrem, 1992) the subcortical system introduces a disturbance that results in a deficit of mechanoreceptors that adjust the tension of the intrinsic muscles of the larynx according to anatomical conditions. and functional of each individual.

Although it is true that the biomechanical deficit of the vocal cords is visible in the acoustic wave of the voice signals, as seen in Figure 1, Leuche & Alalli et al: (Sidtis, 2011) do not recommend further investigation of the changes in the acoustic properties reflected in the voice signal, and if they suggest delving into the analysis of the biological parameters that generate said disturbance, and in the study of these parameters, it is possible to find information that helps to find the neuroregulatory pattern that produces it.

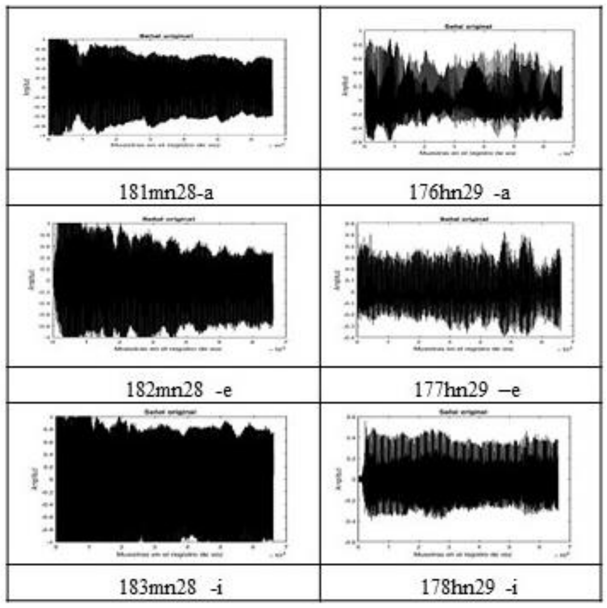

Figure 1 Sound waves of various voice signals from a woman (left) and a man (right)

The objective of this article is to evaluate a new experimental methodology to model the neuroregulatory pattern that coordinates the movements of the intrinsic muscles and characterize it in a novelty curve using a set of biological parameters that are extracted from a small segment of the acoustic wave of the voice signal known as prefonatory preamble.

For this purpose, a bank of acoustic waves of voice signals generated at the Luis Guillermo Ibarra Ibarra National Rehabilitation Institute is used, and endorsed by NOM-012-SSA3-2012. The results show a clear and objective mathematical differentiation of the neuroregulation patterns that are executed in the vocal cords of each individual, also differentiating themselves by gender.

In section 2 the foundation of the experimental methodology presented here is explained in detail, section 3 shows the results provided by the method and in section 4 the results and robustness of the method are analyzed to characterize a plurality of neuroregulatory patterns. that are specified based on the particularities and anatomical, physiological and morphological differences of the vocal cords of each person.

2 Materials and methods

For the experimental corpus a bank of voices was built (Siordia, Bank of voices of Mexican speakers, 2013) (Siordia, Rivera, J.Corona, V. Valadez, & X. Hernández, 2011).

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The acquisition of voice signals was carried out in the Phoniatrics department of the National Rehabilitation Institute of Mexico City (Siordia, Hernández, Jimenez, & Rivera, 2012) where 40 Mexican men and women participated, all from the Federal District, with ages between 28 and 45 years of age performing 5 phonatory tasks corresponding to the vowels a, e, i, o, u, under the scheme shown in Figure 2.

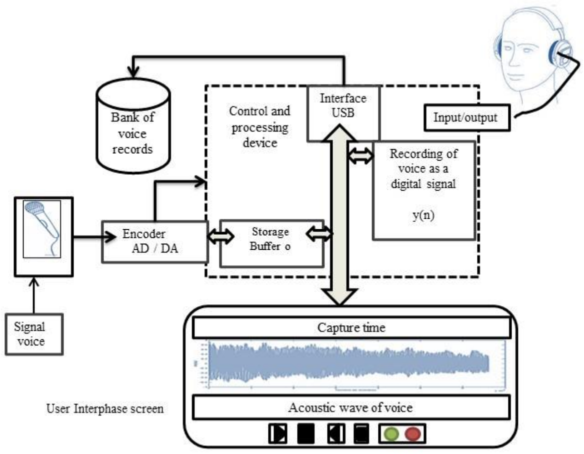

Figure 2 General scheme for the acquisition of the voice signal

For the acquisition of the signals, a professional microphone of the Shure brand model SM58 was used for voice, placed at a distance of 10 cm from the mouth of the speaker, and the records were stored in digital WAW format with a sampling frequency of Fs = 22050bits / sec, in monophonic channel at 16 bits resolution, for further processing and analysis.

2.1 Experimental model to extract biometric parameters

The human voice production process is the result of the combined action of a glottal source and the vocal tract filter. It is known that natural speech involves two kinds of interaction. One is termed biomechanical interaction - glottal flow acts as an active factor in determining the vibrating pattern of the vocal folds, the other acoustic interaction - glottal flow is not independent of the finite vocal tract acoustic load. (Childers & Lee, 1991). In this document we only consider the act of the biomechanical interaction of glottal flow as an active and adaptive factor to determine the parameters that model the neuroregulatory pattern of biomechanical actions that coordinates the abduction and adduction movements of the vocal cords of men and women with age and gender independence.

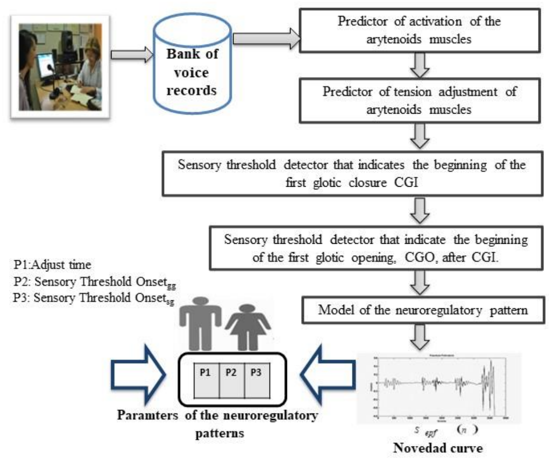

Figure 3 Experimental model to obtain biometric data from the voice signal

Figure 3 shows the experimental methodology to extract the biological parameters that model the neuroregulatory pattern. (Siordia, Bank of voices of Mexican speakers, 2013), (Siordia, Hernández, Jimenez, & Rivera, 2012). The numerical analysis of this procedure was carried out in Audition, v3.0, Origin v.8.5, and a set of mathematical algorithms were implemented in the MATLAB V19.0 software.

2.2 Predictor of periodicity of the air flow wave present under the trachea

In the biomechanical function performed by the intrinsic muscles of the larynx, they depend on a mechanoreceptor biomechanism illustrated in Figure 4 that coordinates the movements of the vocal cords -abduction and adduction- to synchronize them with the air pressure flow pulses that the lungs send. through the trachea (Ruffiner, 2009).

These air pressure flow pulses carry a periodicity that conditions the subcortical system to calculate the instant of time in which synchrony must be established, this phenomenon is important since it is directly related to the calculation of the tension to which they must be adjusted. the thyroarytenoid muscles before starting the voice signal production process, at the level of the larynx and without interference from the pharynx and the vocal tract.

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The first step consists of estimating the duration of the fundamental period T_0, by passing the acoustic wave of the voice signal y (n) through a predictor that uses a difference function of average magnitude AMDF (1), proposed by Ross in 1974 et al: and improved by Zeng in the year 2033 et al: ().

$$T_0 = AMDF(n) = \frac{1}{N}\sum_{j=m}^{m+N-1}|s(j) - s(j+n)| \quad (1)$$

Physiologically it represents the period of time that it would take for the mechanoreceptor biomechanism to complete the adduction movement that leads to the union of the vocal cords in the midline of the glottic canal, in this context the fundamental period is defined:

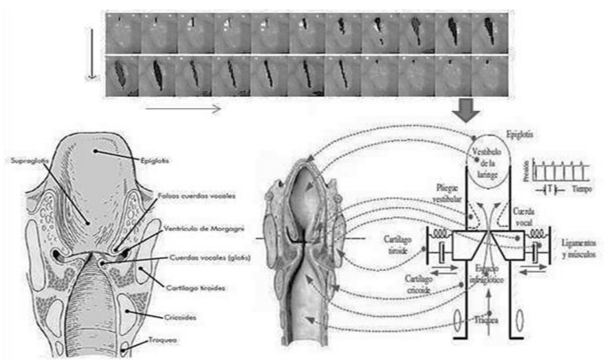

Figure 4 Biomechanism of the human larynx that regulates the movements of the thyroarytenoid muscles
Source: Adapted from (Ruffiner, 2009)

The larynx requires two consecutive glottic closures to complete the C_F (2) phonation cycle necessary to produce the voice signal.

$$C_F = 2\mathrm{To} \quad (2)$$

2.3 Predictor of tension adjustment of the thyroarytenoid muscles

Once the duration of the C_F (2) phonation cycle has been estimated, the subcortical system evaluates the characteristics of the elastic properties of the epithelial tissues and determines the time they require to synchronize the abduction and adduction movements with the passage of the column of air pressure flow that the lung presents under the trachea.

To find this sensory information, the mechanoreceptor biomechanism executes an addiction movement, which is called first contact (85), the occurrence of this physiological phenomenon is useful to estimate the tension-elongation adjustment that the thyroarytenoid muscles must establish according to the characteristics of elasticity and viscosity that underlie the vocal cords, since the correct synchronization of the abduction-adduction movements that give way to the air pressure flow pulses that are present under the trachea depends on this adjustment.

Physiologically, this first contact is established at the first global maximum observed in the acoustic wave of the voice signal, y (n) and to calculate it a predictor is used that adapts to the Percent of Max technique, which Vos and Rasch released in 1986 (86).

The prediction algorithm searches in y (n) for the first transient, U_min (3) that manages to reach a proposed dynamic threshold at 95% of the maximum amplitude value and, after that, it searches for the first transient that manages to overcome it, U_max (4), to ensure the prediction of this event.

$$u\min = \arg[\min(y(n) \le umbral * \min(y(n)))] \quad (3)$$

$$u\max = \arg[(\min(y(n) \ge umbral * \max(y)))] \quad (4)$$

With the data obtained with (3) and (4) a vector called change (4) is formed to delimit the segment within the signal and (n) where said phenomenon occurs.

$$cambio = (u\max, u\min) \quad (5)$$

$$ajuste = arg(min(cambio)) \quad (6)$$

Once the segment of the signal y (n) has been delimited, the predictor must look for the first transient where a sudden and abrupt change in the amplitude of the signal y (n) is established, this phenomenon is predicted by the adjustment function (6).

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With this information, the predictor calculates the instant of time, (7), that the subcortical system establishes so that the mechanoreceptor biomechanism adjusts the tension of the thyroarytenoid muscles to synchronize their addiction and abduction movements to give way to the periodicity of the air flows. that the effector system presents under the trachea.

$$t_{ajuste} = \left(\frac{ajuste}{F_s}\right) * 1000 \quad (7)$$

This biomechanical phenomenon that takes place at the level of the larynx produces pressure at a point of total occlusion and the rapid release of this pressure depends on the timing with which the receptor mechanical biomechanism must execute the rhythm of the opening and closing movements of the vocal cords, producing an intrinsically transitory, plosive-type excitation (Ruffiner, 2009).

2.4 Neuroregulatory pattern modeling

The neuroregulatory pattern is represented as a novelty curve, S_adjustment (n) (9), delimited by the adjustment function (6) where the subcortical system indicates to the mechanoreceptor biomechanism that it is ready to initiate, synchronize and automate the sequence of movements that will be implemented during the voice signal production process, (Pedro, 2019). To characterize this novelty curve, a predictive algorithm is used that is designed with a dynamic and adaptive function that models the amplitude envelope S_epf (n) (9) of said segment.

$$S_{ajsute}(n) = \sum_{m=1}^{ajuste} y(n) \quad (8)$$

$$S_{epf}(n) = \sum_{i=1}^{ajuste} \sum_{m_1}^{w_1+m_1} \delta_{ajuste}(n) \quad (9)$$

where:

$$\delta_{ajuste}(n) = mediana\left(\left|\max\left(w_1(m_1)\right)\right|, \left|\min\left(w_1(m_1)\right)\right|\right) \quad (10)$$

In function $\delta_{ajuste}(n)$, (10), represents a dynamic threshold that estimates the median of the peaks and valleys existing in each window w_1 of size $m_1 = 2$ samples, defined in this way in order to accurately capture the amplitude value of the transients that occur in the segment delimited by $S_{ajsute}(n)$ (8).

3 Results

To validate the results of the proposed methodology, the acoustic waves of 9 voice signals were used, 4 correspond to the female gender and 4 to the male gender, this selection was thus determined to evaluate the response of the model to the variability of physiological conditions existing between both. genders. Likewise, voice signals corresponding to various phonatory tasks from the 5 vowels, / a /, / e /, / i /, / o /, / u / were selected, since their execution demands greater biomechanical activity of the strings. vowels for being voiced vowels.

Figure 5 shows the ability of the adaptation of the FDMA algorithm to solve the prediction of the periodicity of the airflow wave in female and male larynxes as shown in Figure 6.

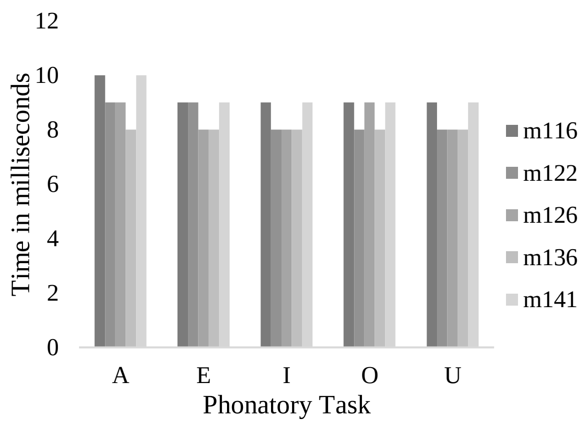

Figure 5. Estimated time of the periodicity of the airflow wave to which the female vocal cords should be synchronized.

This parameter responds to very particular conditions of anatomy, age, gender and elasticity and viscosity properties of the vocal cords that are difficult to model.

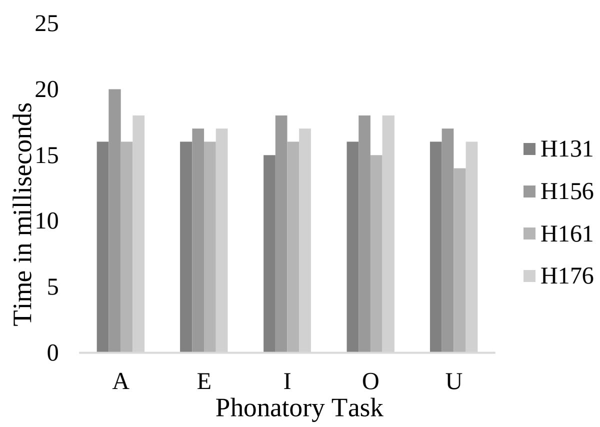

Figure 6 Estimated time of the periodicity of the airflow wave to which the male vocal cords should be synchronized

In Figure 7, the response of the model is observed when predicting that the period that the subcortical system has calculated for the mechanoreceptor biomechanism to establish the tension adjustment of the vocal cords of the female gender, is between 100 and 900 milliseconds.

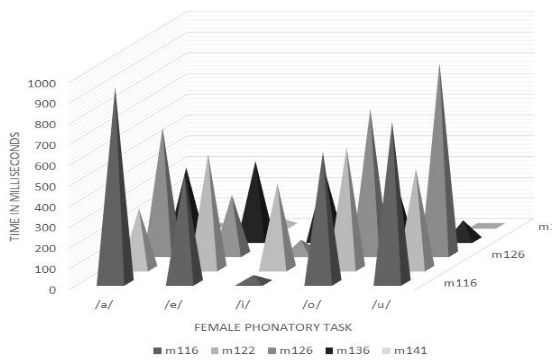

Figure 7 Adjustment time in voice signals of the female gender, when evaluating the five vowels (a, e, i, o, u)

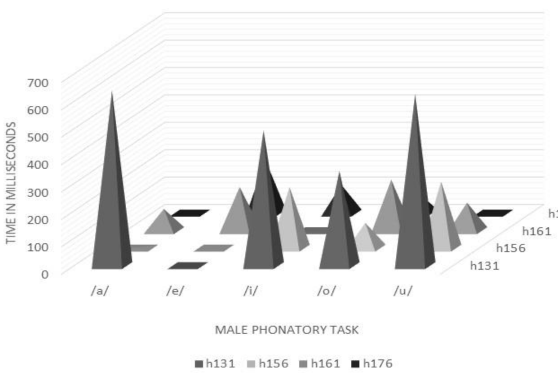

Figure 8 Adjustment times in voice signals of the male gender when evaluating the five vowels (a, e, i, o, u)

In the vocal cords of the male gender, the period estimated by the predictor is between 10 and 600 milliseconds, indicating clear differences between individuals, even when evaluating the response of the predictor under the same physiological conditions of each person, variability in times is demonstrated.

Adjustment

Figure 9 shows the novelty curves that are reconstructed from the predictor for a complete phonatory task, and the marking of the transient adjustment (6) establishes the prefonatory preamble that contains the neuroregulatory pattern.

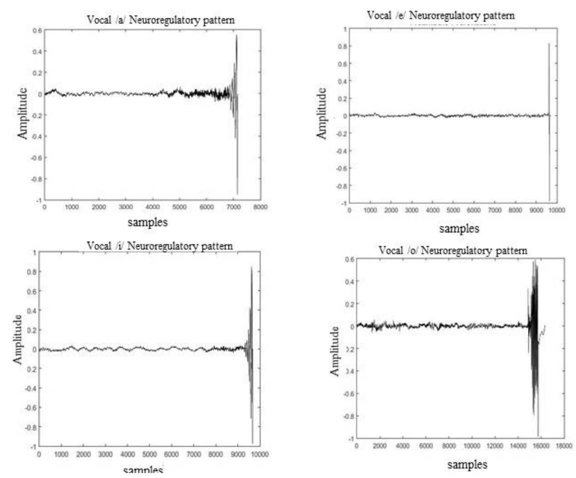

Figure 9 Novelty curves of the neuroregulatory pattern of vowels / a /, / e /, / i /, / o /, / u / in female vocal cords

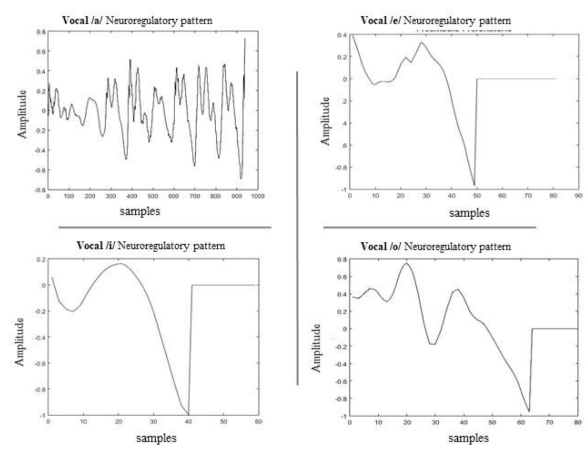

Figure 10

Conclusions

This methodology provides a robust and objective systematized tool to extract, from a voice signal, in real time, a set of biological parameters that characterize the neuroregulatory pattern that coordinates the movements of the intrinsic muscles of the larynx. The results obtained show a clear differentiation regardless of age and gender between individuals.

In general, all the algorithms that make up the model offer good performance; however, it is important to highlight the need to extend experimentation by gender to mathematically model the differences between the biological parameters that model the neuroregulatory patterns.

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