

F2 Slope and Closure Duration Measured Using an Oral Palatal Sensor for Determining Tongue Strength

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ABSTRACT: This study investigated the relationship between tongue strength and acoustic features using a custom-made oral palatal sensor. Participants were asked to pronounce nine monosyllabic words composed of different articulation positions (alveolar, alveolar-palatal, velar) and consonant strengths (plain, tense, aspirated). The F2 slope and closure duration were measured using speech recordings, while tongue pressure was evaluated using an Iowa Oral Performance Instrument (IOPI). Results showed that tense consonants, which require stronger tongue–palate contact, exhibited significantly steeper F2 slopes and shorter closure durations than plain and aspirated consonants. Additionally, tongue pressure and F2 slope were highest in consonants articulated with the tongue tip (alveolar position). These findings suggest that the F2 slope and closure duration can serve as non-invasive, acoustic markers for estimating tongue strength during speech production. This approach may aid in evaluating articulatory function and designing rehabilitative technologies for individuals with speech or neuromuscular disorders.

KEYWORDS: *Tongue strength, Articulation, Palatal sensor, Formants, Tongue pressure, Closure duration*

1. ABSTRACT

The tongue plays an important role in bodily functions such as speaking, breathing, and swallowing. It is characterized by finely coordinated voluntary and involuntary sensorimotor actions that are finely and intricately coordinated. These tongue movements have been used as indicators for the early detection of impairments such as speech disorders caused by pathological neurological damage, degenerative diseases, and aging. For example, stroke, Parkinson's disease, and Alzheimer's disease can cause problems in chewing and swallowing and may involve issues in coordinating the tongue and pharyngeal muscles during the involuntary stage [1,2]. In addition, these diseases are accompanied by abnormalities in the motor nerves, leading to language-related problems such

as dysarthria, which is the inability to properly control articulatory organs, and aphasia, which involves damage to the language center due to brain injury, resulting in difficulties in speaking, reading, and writing [2]. During pronunciation, the tongue regulates airflow and creates various sounds by contacting other parts inside the mouth. For this reason, the tongue must be sufficiently strong and its position must be precise to produce clear and accurate pronunciations. The tongue moves precisely during pronunciation, and its position defines its relationship with other parts of the mouth such as the molars, front teeth, and palate. For example, the pronunciation of consonants such as /k/, /tS/, and /t/ depend on the tongue's position and the area in contact with the mouth. The tongue comprises various muscles that allow its tip, middle, and root to move independently and produce various sounds and pronunciations. Ultimately, the degree of tongue tension caused by the muscles is an important indicator of accurate pronunciation and subtle differences between words. Therefore, devices for tongue movement assessment and rehabilitation have been continuously developed. These devices are commonly based on electropalatography (EPG). EPG can precisely record contact information between the tongue and palate over short time

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intervals of several tens of milliseconds, and it helps visualize articulatory patterns at the phoneme, word, and phrase levels [3-6]. Representative EPG devices include the Smart Palate System (Completespeech, USA) [7], LinguaGraph (Rose Medical Solutions Ltd., UK) [8], and WinEPG (Articulate Instruments Ltd., UK) [9]. In addition, research on intraoral interfaces designed to control various electronic devices through tongue movement is actively being conducted [10,11]. These devices are used as assistive technologies to help individuals with limited hand or arm movement control digital devices such as smartphones, tablets, and computers. Devices such as EPG and various intraoral interface tools commonly detect a user's tongue movements and are based on custom-made palate plates to fit the user's oral structure. The representation of the contact force during tongue movements remains a challenging issue. Some studies have attempted to distinguish the intensity of contact using electrical impedance analysis. However, it is difficult to achieve a high signal-to-noise ratio because of intraoral biological motion noise and individual differences in bioimpedance characteristics. In this study, the characteristics of the contact force of the tongue on a palatal sensor, such as an EPG-based sensor, were examined using acoustic analysis. Formant characteristics were observed using monosyllabic utterances containing selected consonants. Specifically, the slope of the second formant was analyzed to examine the contact force of the tongue. In addition, the validity of the proposed approach was examined by comparing it with data measured using a standard tongue pressure measurement device, the Iowa Oral Performance Instrument (IOPI; IOPI Medical, USA), which is commonly used to assess tongue strength.

2. FORMANT ANALYSIS AND THE SLOPE OF THE SECOND FORMANT

A formant is the resonant frequency of the vocal tract and plays a key role in determining speech characteristics. Generally, the first (F1), second (F2), and third formants (F3) vary depending on the place of articulation. They are related to tongue height, front-back position, lip shape, and certain nasal utterances [12]. F1 is closely related to tongue height; the lower the tongue position (as in /a/), the higher the F1 frequency, and the higher the tongue position (as in /i/), the lower the F1 frequency. F2 reflects the front-back position of the tongue; the more fronted the tongue position (as in /i/), the higher the F2 frequency, and the more retracted it is (as in /u/), the lower the F2 frequency. F3 is partially involved in the articulation of nasalized sounds. In particular, the F2 slope has drawn attention as an indicator of decreased tongue movement speed and reduced variation (slope reduction) in speakers with

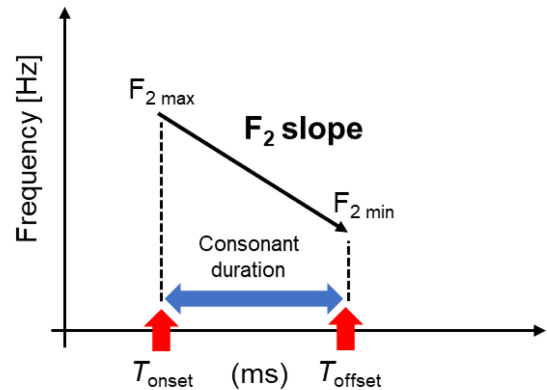


Fig. 1. Calculation of the F2 slope during a consonant.

articulation disorders [13]. This suggests that the time taken for the tongue to come into contact with and then detach from the palate is related to tongue strength and mobility. In other words, the weaker the tongue contact force, the more gradual the F2 variation and the longer the duration. Therefore, in this study, F1–F3 were analyzed while the speaker wore the palatal sensor, focusing on changes in the F2 slope. According to previous studies, in pronunciations that require a strong tongue force, the F2 slope increases, and the time taken for the tongue to detach from the palate after contact is shorter. Therefore, this study aimed to quantitatively analyze the relationship between tongue strength and articulatory characteristics. Fig. 1 illustrates the calculation of the F2 slope, which is expressed by Eq. (1). In this equation, $F_{2\min}$ and $F_{2\max}$ represent the minimum and maximum F2 frequencies within the consonant segment, respectively, and t_{onset} and t_{offset} indicate the time points at which the tongue starts and ends contact with the palate, respectively.

$$F2 \text{ Slope}[\text{Hz}/\text{ms}] = \frac{\Delta F2}{\Delta t} = \frac{F_{2\max} - F_{2\min}}{t_{\text{offset}} - t_{\text{onset}}} \quad (1)$$

3. IMPLEMENTATION OF THE PALATAL SENSOR

To analyze the F2 slope according to the pronunciation after wearing the palatal sensor, the sensor was fabricated using Invisalign, which is commonly used in dentistry for orthodontic purposes, and a flexible printed circuit board containing gold electrodes. The fabricated palatal sensor and a photo of the intraoral sensor being worn are shown in Fig. 2. As shown in Fig. 2(a), to fit the participants' hard palates, an impression of the maxilla was taken using dental impression material, and a mold was made by pouring plaster into the impression. Next, the hardened plaster model of the teeth was removed, and a biocompatible material sheet was thermally

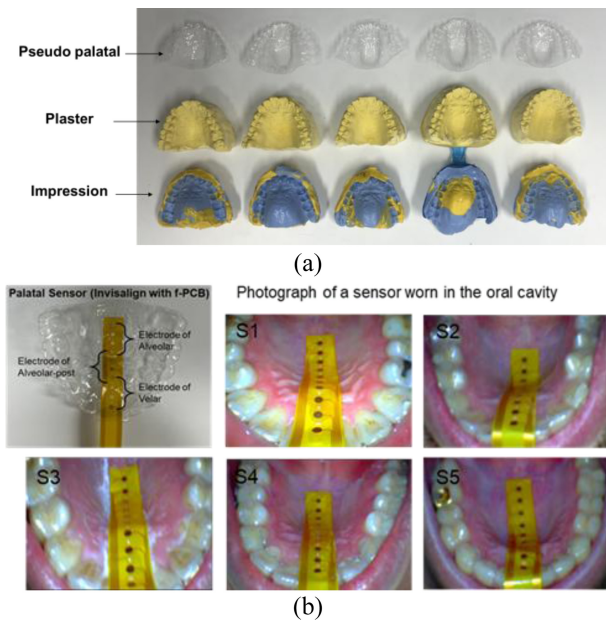


Fig. 2. Manufactured palatal sensor (a) Detail components for manufacturing sensors and (b) photograph when the sensor was worn by the participants.

bonded to the plaster to fabricate an experimental Invisalign with a thickness of approximately 110 μm . A flexible printed circuit board containing gold electrodes was used to fabricate the sensor. Gold electrodes were used to measure the contact position and time at which the subject touched them with the tongue, and they were connected to a measurement device (Imp SFB7, ImpediMed, USA) through lead wires in the lip area. Fig. 2(b) shows the fabricated sensor inserted into the oral cavities of the subjects so that the tongue contact information could be measured and compared with the F2 slope.

4. EXPERIMENT

4.1 Measurement of the Formants

The formant components and F2 slopes were analyzed using Praat (ver. 6.3.09, Boersma & Weenink, 2023), software widely used in linguistics and phonetics. Praat can perform the analysis, synthesis, and manipulation of speech. It provides functions for identifying and quantitatively analyzing formants, which are the resonant frequencies of speech. This study set the analysis criteria to approximately 5000 Hz for males and 5500 Hz for females, reflecting sex differences in vocal tract size and oral structure [14]. The participants wore palatal sensors while pronouncing the target monosyllabic words, and tongue contact information and speech signals were simultaneously measured to analyze the formant components.



Fig. 3. IOPI device used to measure tongue pressure

4.2 Measurement of Tongue Pressure

In this study, tongue pressure for the same tongue strength was measured using an IOPI device for comparison with the F2 slope. IOPI devices are widely used to measure tongue strength, tongue endurance, and lip strength [15]. It is an effective tool for quantitatively evaluating muscles related to intraoral articulatory function [16,17]. An IOPI device consists of a disposable balloon-type probe and a pressure measurement module. The probe tube inserted into the oral cavity is 10.0 mm in length, 0.5 mm in thickness, and 5.5 mm in diameter. The participants pronounced the selected monosyllabic sound three times. The first two instances were practice sessions and the third was measured after a 5-minute rest. Fig. 3 shows the environment for the experiments based on the IOPI device.

4.3 Healthy Control Group

The non-clinical group that participated in the experiment consisted of young adults with no language-related disorders or neurological or psychiatric diseases who had normal vision, hearing, and cognitive function as assessed by the Korean version of the Mini-Mental State Examination (K-MMSE). The experiments were conducted with the approval of the Daegu University Institutional Review Board (IRB No. 1040621-201907-HR-061-02). The group consisted of five healthy participants (four males and one female) with an average age of 33.2 years (range: 25–40 years).

4.4 Selection of the Pronunciation Stimuli

The participants wore a palatal sensor for F2 slope evaluation based on tongue strength and pronounced the selected target monosyllables. The monosyllabic words used in the experiment and their evaluation methods are listed in Table 1.

The selected monosyllabic words were composed of

Table 1. Speech materials used in the experiments

Sound/Articulation position	Target syllable	Observation
Plain/Alveolar (PA)	/ta/	
Tense/Alveolar (TA)	/t-a/	
Aspirated/Alveolar (AA)	/tHa/	Formants
Plain/Alveolar palatal (PAp)	/tSa/	[Hz], F2 slope
Tense/Alveolar palatal (TAp)	/t-Sa/	[Hz/ms],
Aspirated/Alveolar palatal (AAp)	/tSHa/	Pressure
Plain/Velar (PV)	/ka/	[kPa]
Tense/Velar (TV)	/k-a/	
Aspirated/Velar (AV)	/kHa/	

different tongue strengths at the same place of articulation and different places of articulation with varying tongue strengths. These were combined with the representative vowel /a/. The target consonants for each place of articulation were the alveolar consonant /t/, the postalveolar affricate /tʃ/, and the velar consonant /k/. In addition, the tongue strength was categorized into three types: lenis (alveolar), tense, and aspirated. In total, nine types of monosyllabic words were used in the experiment.

4.5 Presentation of Stimulus Words and Experimental Environment

The presentation of word stimuli was implemented using the E-studio program by setting the exposure time and visual elements for each slide. The total time required to present each word was 5 s, and it consisted of fixation (500 ms), blank (250 ms), target syllable display (1 s), blank (250 ms), and pronunciation (3 s). The target monosyllables were presented randomly to prevent learning bias. Before the experiment, the participants were given a 5–10 minute rest and wore the palatal sensor to become familiar with pronunciation while wearing it. The experiment was conducted in a laboratory with a constant temperature of approximately 24 °C, air conditioning, and background noise levels of 25–30 dB SPL (sound pressure level). The overall experimental process, including word presentation and data acquisition, was conducted under the supervision of a trained speech/language pathologist.

5. RESULTS

5.1 F2 Slope According to Tongue Contact Force

Fig. 4 shows the frequency spectrograms of the speech data measured for each word stimulus, and the statistical relationships between the lenis, tense, and aspirated sounds. As shown in the graph at the top right of Fig. 4, the tongue contact

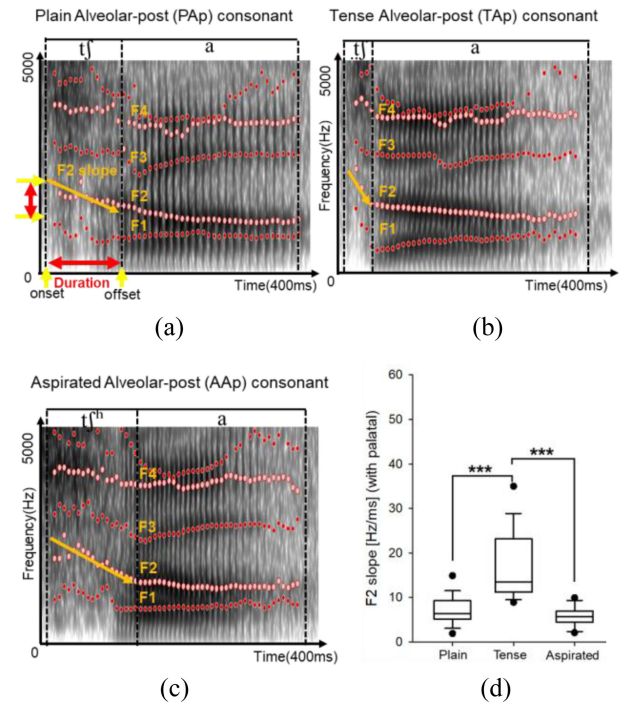


Fig. 4. Results of F2 slope and statistical analysis (a) Spectrogram showing a relatively flat F2 slope during the production of plain consonant, (b) tense consonant, (c) Aspirated consonant, and (d) Statistic results of F2 slope across plain, tense, and aspirated consonants (**p < 0.001).

time was measured to be the shortest, approximately 30–60 ms, for tense consonants, resulting in a steeper F2 slope.

To analyze the relationships among the F2 slopes of the lenis, tense, and aspirated sounds, a nonparametric statistical analysis was performed using R Studio (R Studio version 4.4.2). The statistical results in the lower right of Fig. 4 show the relationships among variables using the Friedman test with Bonferroni correction for post-hoc analysis. The statistical analysis revealed significant differences between the tense and lenis sounds and the tense and aspirated sounds, but there was no significant difference between the lenis and aspirated sounds.

5.2 Characteristics of Tongue Contact Force and Articulatory Position

Fig. 5 shows the characteristics of the F2 slope, tongue pressure, and contact duration measured for the selected word stimuli. Fig. 5(a) illustrates the relationship between the F2 slope and pressure, whereas Fig. 5(b) shows the relationship between the F2 slope and contact duration. In the areas of alveolar consonants (PA, TA, AA), postalveolar consonants (PAp, TAp, AAp), and velar consonants (PV, TV, AV), monosyllables containing tense consonants exhibited the

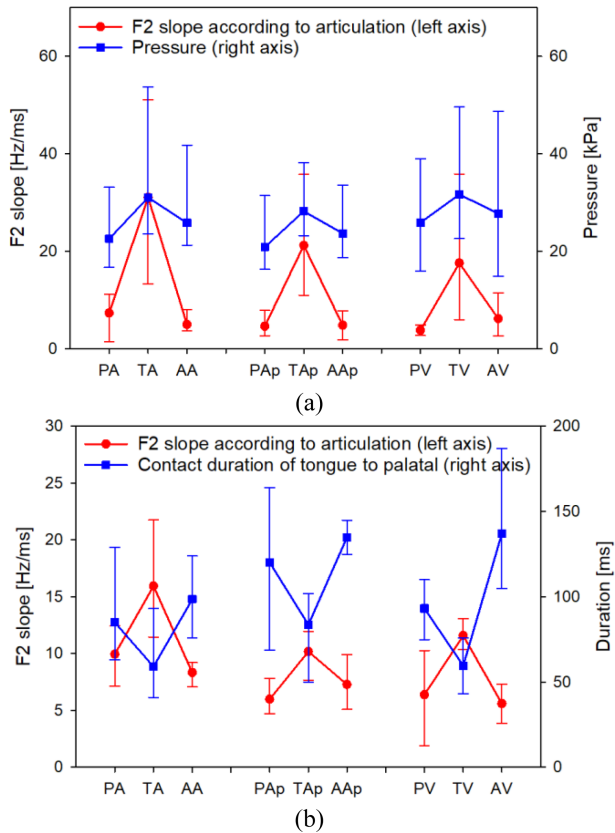


Fig. 5. F2 slope results according to pressure and duration at tongue contact condition (a) F2 slope (red line) and pressure (blue line) and (b) F2 slope (red line) and contact duration (blue line).

highest values in both F2 slope and tongue pressure. By contrast, it was not easy to distinguish between syllables containing lenis and aspirated consonants.

6. DISCUSSION

The experiment conducted in this study holds great significance as an experimental approach using different consonants at the same place of articulation as the stimulus for different articulatory positions to objectively analyze tongue contact force. The experimental results confirmed that the higher the tongue strength required for pronunciation, the greater the increase in the F2 slope and pressure data. Another notable feature is the tongue-position-related pattern. Fig. 5(b) shows that the F2 slope is higher and more concentrated when the tongue tip was located toward the front. This indicates that tongue strength is higher at the front of the mouth than at the back. Related studies have reported that consonants articulated at the alveolar area, such as /d/ and /t/, show greater strength and air pressure [18,19]. However, as shown in Figs. 5(a) and 5(b), the F2 slope shows a deviation of more than 6 dB across

repeated experimental measurements. This suggests that, although sufficient time was given for participants to become accustomed to pronunciation while wearing the palatal sensor, the range of tongue movement inside the oral cavity was restricted. Therefore, additional acoustic analyses, such as vowel space area, jitter, and shimmer, are required to examine the effects of wearing the oral plate sensor. Moreover, data from the five participants in this study cannot be generalized from a demographic perspective. In other words, the proposed study lacks the statistical power to perform intergroup variance analysis because of the small sample size of only five participants. Therefore, broader experiments will be required to enable statistical approaches and interpretations based on various age groups and participant conditions.

7. CONCLUSION

In this study, the F2 slope for tongue–palate contact was observed based on the formant and an analysis of tongue pressure. The experiment was conducted using lenis, tense, and aspirated consonants pronounced with different intensities at different articulatory positions to induce various levels of tongue muscle tension. This approach is meaningful in that it not only evaluates tongue contact force, but also analyzes the natural contact characteristics of the tongue by constructing actual speech sounds used in practice. The tense consonant data, in which the tongue made the strongest contact in all articulatory positions, showed the highest values, suggesting that the proposed F2 slope indicator can be applied to objectively evaluate tongue contact force. However, because the F2 slope deviation caused by wearing the oral plate sensor showed differences of more than 6 dB depending on the participant over repeated measurements, a method is required to reduce the variability of the results. In future research, experiments should be conducted to overcome these limitations by analyzing changes in the vowel space area and acoustic indicators due to sensor use. In addition, it will be necessary to embed a tongue contact force monitoring function using the F2 slope and implement it as a real-time measurement system.

CRedit Authorship Contribution Statement

Geunhyo Gu: Investigation, Methodology, Writing - original draft. **Jin Mo Lee:** Methodology, Writing - original draft. **Young Bin Park & Jung Jae Cho:** Methodology, **Hyeon-Min Shim:** Validation, Funding acquisition. **Seong Tak Woo:** Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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