# Differences of Sound and Morphology in Skeletal Class III Patients

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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# ความแตกต่างของเสียงและลักษณะโครงสร้างใบหน้าในผู้ป่วยที่มีความผิดปกติของความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3

น.ส.ณัฐาภรณ์ ประวิตรางกูร

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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| Thesis Advisor | Assistant Professor PINTUON CHANTARAWARATIT, D.D.S., M.Sc., Ph.D. |

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ณัฐาภรณ์ ประวิตรางกูร : ความแตกต่างของเสียงและลักษณะโครงสร้างใบหน้าในผู้ป่วยที่มีความผิดปกติของความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3. ( Differences of Sound and Morphology in Skeletal Class III Patients) อ.ที่ปรึกษาหลัก : ผศ. ทพญ.ดร.พินทุอร จันทรวราทิตย์

[ความเป็นมา] การศึกษานี้มีวัตถุประสงค์เพื่อประเมินความแตกต่างในการผลิตเสียงสระระหว่างกลุ่มที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3 และประเภทที่1 ในคนญี่ปุ่น และเพื่อหาความสัมพันธ์ระหว่างเสียงสระกับลักษณะทางเซฟาโลเมตริกในผู้ที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3

[วัสดุและวิธีการ] ชายญี่ปุ่นที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3 (ANB<0°) และประเภทที่ 1 (0.62°<ANB<5.94°) กลุ่มละ18 คน มาทำการวิเคราะห์ทางอะคูสติกจากเสียงสระญี่ปุ่น (/a/, /i/, /u/, /e/, /o/) และการวิเคราะห์ทางเซฟาโลเมทริกจากภาพถ่ายรังสีเซฟาโลแกรมด้านข้าง โดยใช้โปรแกรม Praat หาความถี่พื้นฐาน (F0), ฟอร์แมนท์ 4 ตัวแรก (F1, F2, F3 และ F4), พื้นที่กราฟฟอร์แมนท์ และใช้โปรแกรม ImageJ วิเคราะห์เซฟาโลเมทริก จากนั้นหาความสัมพันธ์ระหว่างตัวแปรอะคูสติกและลักษณะทางเซฟาโลเมทริกในผู้ที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3

[ผลลัพธ์] ผู้ที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3 มีค่า /o/F2 สูงกว่าและค่า /o/F4 ต่ำกว่าอย่างมีนัยสำคัญ ความยาวของขากรรไกรล่าง, SNB และoverjet ของผู้ที่มีความสัมพันธ์ของกระดูกขากรรไกรประเภทที่ 3 นั้น มีความสัมพันธ์เชิงลบในระดับปานกลางกับตัวแปรอะคูสติก

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KEYWORD: speech, Skeletal Class III malocclusion, Acoustic analysis, vowel sounds

Natthaporn Pravitharangul : Differences of Sound and Morphology in Skeletal Class III Patients. Advisor: Asst. Prof. PINTUON CHANTARAWARATIT, D.D.S., M.Sc., Ph.D.

[Background] This study aimed to explore differences in vowel production using acoustic analysis in skeletal Class III and Class I Japanese participants, and to investigate the correlation between vowel sounds and cephalometric variables in skeletal Class III subjects.

[Materials and Methods] Japanese males with skeletal Class III (ANB<0°) and Class I skeletal relationships (0.62°<ANB<5.94°) were recruited (n=18/group). Acoustic analysis of vowel sounds and cephalometric analysis of lateral cephalograms were performed. For sound analysis, an isolated Japanese vowel (/a/, /i/, /u/, /e/, /o/) pattern was recorded. Praat software was used to extract acoustic parameters such as fundamental frequency (F0) and the first four formants (F1, F2, F3, and F4). The formant graph area was calculated. For cephalometric analysis, cephalometric values were obtained by ImageJ. Correlations between acoustic and cephalometric variables in skeletal Class III subjects were then investigated.

[Results] Skeletal Class III subjects showed significantly higher /o/F2 and lower /o/F4 values. Mandibular length, SNB, and overjet of Class III subjects were moderately negatively correlated with acoustic variables.

Field of Study: Orthodontics Student's Signature ...............................

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Natthaporn Pravitharangul

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# 1. Background and Rationale

Morphological disparities in the maxillofacial region through malocclusion causes physiological dysfunctions (1), although morphology and function may compensate for each other to some extent (2). Physiological dysfunction includes speech distortion, which results in reporting reduced quality of life in many individuals with malocclusion (3). Children with speech impairment posed a higher risk of social, emotional, and/or academic difficulties than their peers (4), and this was associated with limitations in life activities across the life span (5). According to this, speech is considered an essential parameter when evaluating patients with craniofacial deformities, including cleft lip/palate and other conditions requiring orthognathic surgery (6). Speech production is a complex process that involves the hard and soft tissues of various structures, which ranges from vocal fold structures to the lips. Speech production reflects facial geometry and upper airway morphology. Any deviations in facial morphology interfering with the normal, dynamic sound production process may result in speech sound distortion.

Skeletal Class III relationships are characterized by a marked discrepancy in the position and relationship between the maxilla and mandible, resulting in a forward mandibular position and larger mandibular size. Individuals with skeletal Class III malocclusion consistently demonstrate sound distortions (7-9), also, greater mean articulation errors than those with Class II malocclusions (10). Thus, awareness of the potential effects of skeletal Class III malocclusion on speech is required to provide effective treatment planning and a referral to a speech pathologist.

Acoustic analysis is widely used in the detection and evaluation of speech-language disorders (11). Acoustic analysis evaluates the physical properties of sound using acoustic parameters, which are continuous variables. In contrast, the classic perceptual assessments are categorical (yes/no), and so severity cannot be defined or minor deviations might not be detected. Therefore, acoustic parameters are more objective and quantifiable measurements if speech-language disorders need to be assessed.

Common acoustic parameters include fundamental frequency (F0) and formants. Mean F0 is a well-known cue for speech intelligibility (12), and the F0 of each vowel corresponds to the extent of jaw opening (13). Vowel formant frequencies are useful in describing vowels, as the first two formants can distinguish between vowels in most languages (14). Moreover, a relationship between formants and articulatory pattern has been established (15). The frequency of the first formant (F1) is related to vertical tongue movements and jaw opening, and the frequency of the second formant (F2) is correlated with forward and backward movements of the tongue and lip rounding during speech production (15). The third (F3) and fourth formants (F4) enhance the naturalness of vowels and are typically included in the vowels of synthetic speech (14).

Although previous researches of individuals with skeletal Class III have focused on consonants (7, 8), vowels have a greater impact on speech intelligibility. By replacing either vowels or consonants with noise, intelligibility was 2:1 for vowel-only (consonants replaced by noise) to consonant-only (vowels replaced by noise) sentences (16). Thus, vowels are essential for speech communication and are the focus of the present study.

Previous studies of vowel sound differences in individuals with skeletal Class III malocclusions have focused mainly on changes in speech sounds between pre- and post-orthognathic surgery (17-19). However, orthodontic appliances can affect sound production (20). Thus, subjects undergoing orthodontic treatment in the presurgical stage might not accurately reflect the sound production of individuals with skeletal Class III malocclusion. Although speech adaptation has been shown in subjects with labial fixed appliances placed after a month (20), clearly focused investigations of vowel sound in skeletal Class III subjects prior to orthodontic treatment are scarce (9, 21). One study found no acoustic difference between Chinese children with Class III and Class I skeletal relationships (21), while another reported that /u/ was different between two groups of young Chinese males (9). These results may differ when other languages are considered. A further limitation of these studies of Chinese vowels is that the sample sizes were relatively small (8–12 participants per group).

The lack of literature and study design limitations has resulted in inconclusive findings about vowel sound differences in skeletal Class III individuals. The effect of morphological differences on these individuals' sound production, as well as the importance of vowels in speech intelligibility, prompted our investigation of vowel differences in skeletal Class III malocclusion in Japanese subjects. Therefore, the aim of this study was to compare vowel sound production differences in skeletal Class I and Class III Japanese individuals using acoustic analysis, and to determine the correlation between vowel sound production and cephalometric variables in Class III subjects. This study will add to our understanding of how jaw disharmonies contribute to speech distortion, emphasizing the clinicians to raise awareness about the importance of carefully evaluating speech and referring appropriately for speech evaluation in skeletal Class III patients.

### 1.1 Research Questions and Hypotheses

1) Are there any differences of sound production between normal and skeletal Class III patients?

$H_0$: there is no difference of sound production between normal and skeletal Class III patients.

$H_A$: there is at least one difference of sound production between normal and skeletal Class III patients.

2) Are there any correlations between sound production and cephalometric variables in skeletal Class III patients?

$H_0$: there is no correlation between sound production and cephalometric variables in skeletal Class III patients.

$H_A$: there is a correlation between sound production and cephalometric variables in skeletal Class III patients.

<u>Factor that will be examined are as follows</u>:

- Sound parameters:

1. Fundamental frequency (F0)

2. Formants: The first formant (F1), The second formant (F2), The third formant (F3), The fourth formant (F4)
3. Formants graph

- Cephalometric parameters:

1. Skeletal measurement: SNA, SNB, ANB, MPA, Facial height, Maxillary length, Ramus, Mandibular body length, Total mandibular length
2. Dental measurement: overjet (OJ), overbite (OB)
3. Hyoid bone measurement: HS, HC3, HMP, HGp, HMe
4. Airway measurement: palatal pharyngeal space (PPS), superior posterior pharyngeal space (SPPS), middle pharyngeal space (MPS), gonial pharyngeal space (GoP), inferior pharyngeal space (IPS), epiglottic pharyngeal space (EPS)

## 1.2 Research Objective

1.2.1 To compare the differences of sound production between normal and skeletal Class III patients.

1.2.2 To investigate the correlation of sound production and cephalometric variables in skeletal Class III patients.

## 1.3 Benefits of This Study

1.3.1 To be aware of any potential effects of skeletal malocclusion on speech.

1.3.2 To provide enhanced treatment planning and appropriate referrals to speech pathologists in skeletal malocclusion patients impacting speech sound production.

1.3.3 To provide baseline data of skeletal profile effect on sound production as a fundamental information for further research in patients with facial deformity.

## 1.4 Conceptual Framework

(Figure 1)

## 2. Review Literatures

1. Speech production theory
2. Factors affecting acoustical properties of sound
3. Speech and morphology
4. Speech and malocclusion
5. Vocal tract configurations and its structure in skeletal Class III malocclusion patients
6. Vowels
7. Analyzing method

### 2.1 Speech production theory

Regarding vowel sound, a widely accepted acoustical theory describing speech production is the source-filter theory. This theory describes speech as a combination of two-step process, the laryngeal source and the vocal tract filter. As air from lungs expels through vocal fold, laryngeal source generates sound by vocal fold vibration. This is controlled by shape of vocal fold, determining fundamental frequency (F0). The generated sound signal in this stage is in form of complex periodic wave as illustrated by figure 2, containing energy at the fundamental frequency of vocal fold vibration and at multiples of the fundamental frequency called harmonics. Then, the sound signal passes through the vocal tract that act as a filter, it is intensified or damped in some frequencies, corresponding to resonance frequencies of the vocal tracts. This process is controlled by shape of the vocal tract, determining formant. In short, sound signal is produced by vocal fold vibration and then modified by the resonant properties of vocal tract. (22)

#### 2.1.1 Acoustic parameters

##### *2.1.1.1 Fundamental frequency (F0)*

When vocal fold vibrates in periodic manner, it produces complex periodic wave. The lowest frequency in periodic manner is called fundamental frequency (Fig.3). In other words, it is the frequency of vocal fold vibration, and perceived as a pitch. F0 correlates with changes in vocal fold tension and subglottal air pressure, and varied by other factors such as intonation, speaker emotion. In general, fundamental frequency is varied within a range of frequencies, this is heard as the intonation pattern or melody of natural speech. A bass voice has a lower fundamental frequency than a soprano voice. Males have lower F0 than females, and adults have lower F0 than children. Regardless of those factors, the general pattern of fundamental frequency variation is due to vowel height, to illustrate, higher fundamental frequency in high vowels and lower fundamental frequency in low vowels, corresponding to amount of jaw opening. This is to say, different vowels show different in F0, which is known as intrinsic F0. Thus, a person has a range of fundamental frequencies, rather than one specific fundamental frequency (22).

Clinical implication of F0 was demonstrated in previous studies. Presented voice pitch acoustically, normal listeners can lipread a speaker at up to two and a half times the rate possible on the basis of lipreading alone (23). Also, fundamental frequency enhances speech perception in noisy background in cochlear implant user (24).

#### *2.1.1.2 Formant*

Formant frequency (22) (Fig.4) is a resonance frequency of vocal tract, which is extended from larynx to tip of the mouth. The lowest formant frequency is known as the first formant (F1), and the second lowest formant frequency is known as the second formant (F2). Although the higher formants are not required in phonetic recognition, they enhance the naturalness of vowel and typically included in the vowels of synthetic speech (22).

Vowel formant frequencies are one of the most frequently reported acoustic measurement of speech. It is useful in describing vowels in most languages, and considered as an economic description, because only the first two formants are enough in differentiating between vowels. Moreover, it has been used in various applications such as study of speech in different speaker’s population, automatic speech recognition, and clinical assessment in aspect of speech, voice, and language disorder (25).

The relationship between formants and articulatory pattern are demonstrated (15). The frequency of the first formant (F1) is related to tongue height and jaw opening, and the frequency of the second formant (F2) is correlated with forward and backward movements of the tongue and lip rounding during speech production(15). Accordingly, the formant graph (plotted by formants) and vowel chart (plotted by point of articulation) are resembled.

*2.1.1.3 Formant graph*

It is an acoustic measure of vowel F1-F2 plot showing in polygon (25) (Fig.5), reflecting the articulatory pattern of vowel production, and it has also been called vowel space area. It is correlated to the intelligibility of speech, as larger spaces ensure a high degree of acoustic contrastivity indicating higher level of speech intelligibility. Assumingly, reduced vowel space reflects a constricted articulatory movement, in other words, it is a reduced range of tongue, jaw, and/or lip movement. Moreover, this graph has been used to evaluate speech disorder and effect of treatment on voice and speech production.

## 2.2 Factors affecting acoustical properties of sound (26)

2.2.1 Speaker related factor

Regarding anatomical and physiological aspect, gender, age, race, weight, health, and physiological condition play a role in acoustical properties of sound (26). According to Titze's study (27), adult males vocal fold is approximately 60% bigger than in females, rendering slower vibration. Thus, F0 in males is lower than females. Moreover, the adult male vocal tract is about 15% longer than female's, showing lower formant frequencies in men (28). Therefore, women's voices have higher F0 and higher formant frequencies than men's (29). Following general body growth pattern, laryngeal growth is also affected by hormonal change (30). This causes changes in the mass and length of vocal folds, leading to deepening of voice. Voice breaking in boys usually occurs as a distinct event during late puberty, due to the increased length of the vocal cords (31). Enlargement of vocal fold at puberty is also found by 63% in males, and by 34% in females(32). Correspondingly, it was found that fundamental frequency in females and males are lower than children (33).

Cultural, social and psychological factors also influence on acoustic characteristics. To illustrate, speaker language, dialect, intonation, and emotional state were founded to be a cause of acoustic variation. Even though same vowel is analyzed, variation in formant frequencies between language is evidenced. (26)

### 2.2.2 Speech material related factors

There are many speech samples used in acoustic analysis, such as isolated vowels, words, and connected speech using sentences, reading passages, or conversation. Isolated vowels have no influence of phonetic context and speaking rate, whereas words and connected speech are complicated by these effects. Also, reliability of measurement of formant frequencies in sustained vowel is higher than in connected speech. Vowel occurring in connected speech are perhaps more interesting in speech communication studies, however it is affected by coarticulation, speaking rate, and stress pattern. Furthermore, it can be difficult to identify target sound, especially in highly unintelligible cases (25).

Therefore, careful control and consideration of these factors, including the instruction to the speaker (e.g. speaking rate, vocal effort), are required to ensure that reliable results can be obtained.

### 2.2.3 Methodological factor

Differences in recording method and analysis equipment and techniques might affect the result of acoustic analysis (25). In Praat software, there are two methods used for obtaining formant value, which are direct measurement and Linear Predictive Coding (LPC). Direct measurement is performed by placing a cursor on vowel part that is selected, then the formant value is obtained and can be read directly from spectrogram. This method provides values quickly and easily; however, it is not accurate due to point selection, which is difficult to define the best time point representing formants. LPC analysis is a more common method extracting formants, and it can be used to measure in two ways. The first one is to read off the values of the peak selected by hand, which is presented in graphs constructed by LPC analysis. Contrast to the second method, known as formant tracking or automatic formant measuring, the chosen peaks are determined by algorithm of program. To minimize error caused by judgement of researcher, automatic tracking is used in this study.

## 2.3 Speech and morphology

Speech production is a complex process involving many parts of body, starting from vocal fold to the tip of the mouth, this is somewhat highlighting facial morphology, an integral part of the upper airway geometry.

Not only the vocal fold itself that is important in phonation, but also movement of larynx. Laryngeal movement in vertical direction cause changes in the angle between cartilages and the tension in vocal fold, thus effecting vocal fold vibration. With laryngeal elevation, the vocal tract is shortened, and the vocal fold is stiffened. These lead to change in the vibration pattern and increase the fundamental frequency. On the contrary to laryngeal lowering, vocal tract elongation and tissue relaxation are followed, affecting on vocal resonance and formant frequencies (34).

The hyoid bone is a horseshoe-shaped solitary bone, located in the midline of the neck, at the level of the base of mandible and the third cervical vertebra (35). This bone connects to larynx, pharynx, and tongue by muscles and ligaments; thus, it involves in speaking, breathing, and swallowing. During function, those muscles attaching between these structures contribute hyoid positional change, rendering effects on vocal tract configuration and vocal fold vibration, then results in sound change according to the source-filter theory. Therefore, hyoid bone position is of great clinical interest.

According to parallel growth of larynx and facial bone structure during puberty, some studies have hypothetical speculation that facial bone morphology would correlate to acoustic parameters. Recent studies reported correlation between sound and morphology. A lateral cephalometric study of 45 healthy subjects with age range from 9.3 to 36 years, Macari (36) found a significant negative association between the formant frequencies and the length of the mandible (Co-Gn) and maxilla (ANS-PNS) for vowels /a/, /i/, /o/, and /u/. Considering hyoid bone position (37), there was a moderate negative correlation between the high formants and the vertical position of hyoid bone in relation to the base of skull (SH) and the third cervical vertebra (C3H). Given that the length of the vocal tract is indicated by the position of the hyoid bone in relation to the cranial base and cervical vertebra, the result was aligned with previous reports indicating correlation between vocal tract length and the position of formant frequencies, especially with higher formants. As for F0 (38, 39), moderate negative correlations were shown between F0 and the length of the upper and lower jaw, facial length and facial width, whereas, the remaining facial sagittal projection parameters were not correlated. Also, there was a statistically significant moderate correlation between the average fundamental frequency for the vowel /ɑ/ and all vertical hyoid position (SH, C3H, H-PNS) except for the position of the hyoid bone in relation to the mandibular plane (MPH), while the correlation between F0 of other vowels and hyoid bone position was not mentioned in this literature (37). Even though correlation between sound and morphology was demonstrated, these studies were provided in wide range of sample age, ranging from children to adults, and lack of addressing in specific malocclusion type.

## 2.4 Speech and malocclusion

Any deviations of facial morphology interfering with the normal dynamic process of sound production, possibly result in sound distortion. Concerning this issue, it has been addressed in facial deformity patients, not only in cleft patients, but also patients who required orthognathic surgery. The delayed language development, articulation disorders, resonance disorders, and voice disorders were reported in patients with cleft palate with or without cleft lip 16.33%, 88.56%, 43.26%, and 19.13%, respectively (40). Moreover, deleterious effects on sound production were observed in mandibular prognathism(41, 42) and mandibular retrognathism (42, 43) cases.

### 2.4.1 Speech in Skeletal Class III malocclusion

Regarding speech effect in skeletal Class III malocclusion, contradiction among studies was found. Past researches were mostly focused on changes of sound between before and after orthognathic surgery (8, 17, 19, 44), whereas, studies focusing before orthodontic treatment are very few (9, 21).

In orthognathic surgery case, Jorge (44) reported a significant increase of F0 at 3 months after mandibular setback surgery in one Class III patient, and returned to its presurgical value in 12 months after. Even though lower positioning of the hyoid bone was expected in this case due to mandibular setback procedure, the result showed upward position of hyoid bone, hypothesized that this was due to the predominant effect of mentoplasty. F0 change was in accordance with hyoid bone position in cephalometric radiograph as expected, higher F0 for laryngeal elevation at 3 months, and returned of F0 for returning to its presurgical position at 12 months. Mishima (19) found no significant change of F0 and formants at 6 months post-operation, except F2 for /i/ and /u/ in males. Also, voice characteristics of Class III group were observed in F0 in females, F1 and F2 for /a/ in males, F1 for /u/ and F2 for /i/ in females, which were higher in normal group. Ahn (17) showed that BSSRO in mandibular prognathism patients caused significant changes toward normal group, comparing at 6 weeks, 3 months, and 6 months post-surgery. Lee (8) stated that there were significant differences in /s/ sound between Class III patients before surgery and normal controls for spectral peak I and its bandwidth, and also, there are significant differences for spectral peak II and its bandwidth at 12 months after the osteotomy between Class III and control group.

Investigating in subjects prior to orthodontic treatment, only two literatures were found. Xue (21) reported that skeletal Class III malocclusion children (7-8 years), with both gender combined, tended to have higher Fl, F2, and F3 than normal group, but no significant in formants and F0 were found. In the same line of thought, another study of Xue (9), conducted in young male adults (16-25 years), also showed quite similar results that there was no significant difference in both F0 and formants of all 4 vowels in Chinese, except higher F1 of /u/ in the Class III malocclusion group than in the control group. The reduced vowel space for male patients with Class III malocclusion was found.

However, only small number of samples were investigated in majority of these studies. Moreover, with restricted number of available literatures and controversy of findings, apparently, there is no consensus in sound difference between skeletal Class III malocclusion and normal group.

## 2.5 Vocal tract configurations and its structure in skeletal Class III malocclusion patients

As mentioned, sound production is affected by vocal tract and vocal fold configuration, the difference in anatomical position of vocal tract and vocal fold may result in sound change. Pharyngeal airway dimensions are influenced not only by the growth of the maxilla and mandible, but also by the positions of the hyoid bone and tongue. There are several studies investigating structure positional difference between skeletal Class III and normal patients, however, controversy of finding was found.

### 2.5.1 Pharyngeal airway

According to lateral cephalogram evaluations, the antero-posterior dimension of the pharyngeal airway space (PAS) is affected not only by head position (45), but also size of bony surroundings of PAS (46, 47), and skeletal patterns of the mandible (48). Ten degrees change in cranio-cervical angulation leads to a change of about 4 mm in the PAS (45). Trenouth and Timms (47) observed a positive correlation between pharyngeal airway and mandibular length (Go-Me), and distance between the third cervical vertebra and hyoid bone (C3H), in 70 subjects between 10 and 13 years of age. Studied in 60 skeletal Class I adult patients, Muto found that the PAS significantly correlated with hyoid position (C3H), maxillary and mandibular size, SNA and SNB, and mandibular inclination (46). Another study investigated pharyngeal airway space at the level of the soft palate and base of the tongue in females with a normal mandible (n = 31), mandibular retrognathism (n = 30), and mandibular prognathism (n = 38), they found that pharyngeal airway diameter was largest in the group with mandibular prognathism, followed by the normal mandible and mandibular retrognathism groups (48).

With respect to ANB angles, oropharyngeal airway has no correlation with ANB angles (46, 47, 49), while some studies reported a negative correlation (50, 51). As shown by computed tomography studies, oropharyngeal airway volume in skeletal Class II is lower than skeletal Class III and Class I (50, 52), but there is no significant difference in oropharyngeal airway volume (lower than PNS area) between skeletal Class I and III in numerous of studies (49, 50, 52).

Regarding to mandibular position, oropharyngeal airway has a positive correlation with SNB angles (46, 50), in contrast to Hong's study which reported no correlation (49). Muto studied pharyngeal airway space in 3 groups of patients according to SNB angles, mandibular prognathism group showed the largest pharyngeal airway diameter, followed by the normal mandible and mandibular retrognathism groups (48). Also, the mean OP airway volume of subjects with retruded mandible was significantly smaller when compared with the subjects with higher SNB angles (50).

### 2.5.2 Hyoid bone position

Position of hyoid bone showed downward movement with increasing age (53, 54). Inferior positioning of hyoid bone in males was significantly more pronounced than females, whereas horizontal position was stable (54). Though, some studies showed no relation to age (55), indicating some heterogeneity in position. Its positional change is thought to be correlated to speech and deglutition, however, this could also be as a result of compensation of pharyngeal collapse, since the change continues after maturation of swallowing and speech (55).

Different in hyoid bone position between skeletal Class I and III were found. A lateral cephalometric study in 110 patients by Mortazavi (56) reported that vertical position measuring between palatal plane and hyoid bone in skeletal Class III showed more superior positioning than in skeletal Class I. While horizontal position between the third cervical vertebra and hyoid bone (C3H) showed no significant difference. Accordingly, Jose (57) also concluded that there was no statistical difference of hyoid bone position in antero-posterior dimensions between skeletal I, II, and III individuals. However, another study showed no difference of hyoid bone position in any parameters between skeletal Class I and Class III patients, except C3H distance (58).

In addition, some studies reported a positive correlation between pharyngeal airway space and the distance between the third cervical vertebra and hyoid bone (C3H) (46, 47). According to Jiang's study (51), there were significant correlations between multiple parameters describing airway dimensions and hyoid bone position, investigated in 254 normal Chinese adolescent by computed tomography. It was found that SNA, SNB, and ANB angles were positively correlated with hyoid bone position parameters. Also, oropharyngeal volume has a negative correlation with ANB angles, and a positive correlation with SNB angles, whereas there was no correlation between airway length and ANB and SNB angles.

### 2.5.3 Tongue

Skeletal pattern morphology affects the position and the movements of the tongue during function. In rest position, Class III subjects have significantly more inferiorly (59, 60) and anteriorly (60) tongue posture as compared to Class I subjects, and the difference is mainly presented in the posterior regions (59, 60). During deglutition, tongue movements in patients with skeletal Class III malocclusion are also different from those with skeletal Class I malocclusion (60), indicating adaptive change due to skeletal pattern. Also, the tongue volume was also larger in Class III group (61).

## 2.6 Vowels

Vowels are the sounds produced without any obstruction in the vocal tract, while consonants are sounds produced by temporary obstruction.

Previous studies showed that vowels have greater impacts than consonants on speech intelligibility. By replacing either vowels or consonants by noise, studies showed that intelligibility was 2:1 for vowel-only (consonants replaced by noise) to consonant-only (vowels replaced by noise) sentences (16) (62). This impact was also proved in both young normal-hearing and elderly hearing-impaired listeners (63).

### 2.6.1 Vowel classification

Regarding articulatory phonetics, vowels are classified according to the position of the tongue and lips.

“Front-back” and “high-low” vowels are classified by tongue position in horizontal and vertical dimensions, respectively.  A front vowel is pronounced with the highest point of the tongue is positioned forward in the mouth. A back vowel is pronounced with the highest point of the tongue is positioned backward in the mouth. On the other hand, a high vowel is pronounced with the highest point of the tongue is positioned near the roof in the mouth. A low vowel is pronounced with the highest point of the tongue is positioned far from the roof in the mouth. Vowel diagram or vowel chart are plotted according to tongue position.

“Rounded” and “unrounded” vowels are classified by the amount of rounding in the lips during the vowel articulation

2.6.2 Japanese vowels

There are five vowels in Japanese (/a/, /i/, /u/, /e/, /o/) (Figure 6). The 5-vowel system (as found in Japanese) is the most common vowel system in world’s languages (64).

To be phonetically accurate, the Japanese vowel /u/ should be symbolized as [ɯ], since it is produced with less lip rounding than typically associated with /u/ (65). Thus, the Japanese /u/ can be described as unrounded, while English /u/ is considered a rounded vowel. The only rounded vowel in Japanese is vowel /o/ (66, 67).

2.6.3 Differences between Japanese and English vowels

There are two major differences between Japanese and English vowels (68).

1) the number of vowels

There are more vowels present in English than in Japanese (Figure 6 and 7).

2) tense/lax distinctions.

In contrast to English vowels, there is no tense/lax distinction in Japanese.

Tense/ lax vowels are classified according to muscle tensions or movements during vowel production. A tense vowel is produced with extra muscle tension, and a lax vowel is produced without much tension. For example /i/ as in “live” (liv) is a lax vowel, and /i/ as in “leave” (li:v) is a tense vowel.

The five-vowel system of Japanese and lacking tense/lax distinction can lead us to the assumption that students of English may have difficulty producing English vowels that do not exist in their native language.

## 2.7. Analyzing method

2.7.1 Sound analysis

Speech analysis of most previous studies were relied on perceptual evaluation of researchers, and few trained professionals, which were prone to the effects of subjectivity. It was assessed as correct or incorrect, substitution, omission, or distortions (69). According to this, severity cannot be defined, also minor deviation might not be detected. In order to standardize and establish more objective analytical method, acoustic analysis has been performed (22). Acoustic analysis is a study of physical properties of sound, namely fundamental frequency (F0), and formants. Since it is presented in a numeric scale and associated with vocal tract articulation, acoustic measurement is widely used in sound study currently. Besides, clinical application of acoustic analysis is further used to detect and assess speech-language disorders in children and adults.

### 2.7.2 Software

There are many programs providing acoustic analysis. As it has been used in many studies, the Praat software is chosen. It is under constant development and regularly updated. Moreover, this software is compatible to many computer platforms, and provided for free via the Internet (www.praat.org). The version used in this study is 6.0.40.

### 2.7.3 Lateral cephalograms

Cephalometric measurements of the PAS in lateral cephalograms are reliable, although these are 2-dimensional analyses. Determining pharyngeal airway space between lateral cephalograms and 3-dimensional computed tomography scan is highly correlated, with considerably high accuracy in predictability (70). Moreover, measuring dimension and position of movable structures involving vocal tract, such as pharyngeal airway, and tongue, high reproducibility from lateral cephalometric radiographs was found in previous study (71). Recent study also showed a strong correlation between lingual volume measured using MRI and the radiographically determined area of the lingual shadow (72). Moreover, cephalometric measurement using lateral cephalogram is simple, less cost and relatively easy to compare with other methods.

# 3. Research Methodology

## 3.1 Participant recruitment

This cross-sectional study took place at the Orthodontic Department of Tokyo Medical and Dental University (TMDU) hospital from October 2018 to November 2021. Owing to the COVID-19 pandemic, the subject recruitment period was prolonged, and the subjects were chosen.

Subject inclusion and exclusion criterias are demonstrated in Table 1. 18 males for skeletal Class III group and 18 males for skeletal Class I group were recruited.

For the skeletal Class III group, participants were recruited before receiving an orthodontic treatment. They were all confirmed by board-certified orthodontists to need orthodontic treatment combined with orthognathic surgery.

For the skeletal Class I group (73), subjects with Class I jaw and dental relationships were enrolled in post-orthodontic treatment. They were recruited during their retention phase.

## 3.2 Ethical consideration

Approval was given by the Ethics Committee at TMDU (protocol number D2018-017, approved on 21/08/2018). Participants or their guardians was received an explanation regarding the study. They all gave informed written consent to participate prior to enrolment.

## 3.3 Sample size estimation

To perform a power analysis, G*Power version 3.1.9.6 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) was used. The required sample size was calculated using acoustic data from Xue’s study (9). The estimated sample size was 18 per group. Hence, a total of 36 participants was required for a power of 0.95, alpha of 0.05, and effect size of 1.2.

## 3.4 Data acquisition

### 3.4.1 Sound recordings

The recordings were taken in a quiet room with a digital recorder (Audio-Technica AT2020, Audio-Technica Corporation, Japan). Amplitude resolution of the digital audio recorder was set at 16 bits, and sampling frequency was 44.1 kHz. With a similar distance from the microphone, each participant was asked to pronounce five Japanese vowels; /a/, /i/, /u/, /e/, and /o/.

An isolated vowel pattern was used as a speech sample pattern. This pattern targeted at vowels, which is not influenced by phonetic context or speaking rate (74). To control any order effects, a vowel list in the form of a Latin-square matrix was used (75) (Figure 8). Each row began and ended with the same vowel, and each column included all five vowels. To reduce any errors when reading the matrix, participants read each matrix three times at a comfortable pitch and loudness. The matrices were displayed on a screen in PowerPoint. Therefore, each vowel was recorded six times per recording, yielding a total of 18 (6 times*3 recordings) sound samples per vowel were recorded for each speaker.

### 3.4.2 Lateral cephalograms

Lateral cephalograms oriented in the Frankfort horizontal plane were obtained using an Axiom Aristos VX digital X-ray system (Siemens, Asahi Medical Systems, Tokyo, Japan). For the skeletal Class III group, lateral cephalograms were taken for diagnosis on the patients' first visits to the hospital. For the skeletal Class I group, these were taken for evaluating treatment outcomes during their retention periods.

## 3.5 Analysis

### 3.5.1 Sound analysis

Praat software version 6.0.40 (Phonetic Sciences, University of Amsterdam, Netherlands) was utilized. Boundaries for each vowel were defined using the annotation function. Sounding parts were then re-examined by the same investigator and adjusted if needed. If sound from the environment was detected in sounding period, that data were discarded from the analysis. Window length analysis was 0.025 s, centred at the middle portion of each vowel (17). Average values for F0, F1, F2, F3, and F4 were extracted. Outliers were then checked by modified Z-score (76). After reviewing the data, 2,751 of 3,240 samples (84.91%) were included in this study.

To illustrate the articulatory movement area, the formant graph area was calculated using the shoelace algorithm. The formant graph is pentagon-shaped, representing each vowel in the F1–F2 plane. F1 was represented by the vertical axis (y-coordinate), and F2 was represented by the horizontal axis (x-coordinate). These coordinates were used in Excel software for calculating the formant graph area as follows:

$$\begin{aligned}\text{Area} &= 0.5 * |(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + \ldots + (x_{n-1}y_n - y_{n-1}x_n) + (x_ny_1 - y_nx_1)| \\ &= 0.5 * |(F2/a/F1/o/ - F1/a/F2/o/) + (F2/o/F1/u/ - F1/o/F2/u/) + \\ &\quad (F2/u/F1/i/ - F1/u/F2/i/) + (F2/i/F1/e/ - F1/i/F2/e/) + (F2/e/F1/a/ - F1/e/F2/a/)|\end{aligned}$$

3.5.2 Cephalometric analysis

Cephalometric landmarks used in this study are demonstrated in Figure 9. All measurements were evaluated using ImageJ software version 1.49 (National Institutes of Health, Bethesda, Maryland, USA), and are shown in Figures 10 and 11 and defined in Table 2. The airway width was measured in relation to the Frankfort horizontal plane. The cephalometric measurement method was modified from previous studies (37, 77, 78).

## 3.6 Statistical analysis

Descriptive statistical analysis was performed to compute the mean and standard deviation of age, body mass index (BMI), acoustic, and cephalometric parameters in both groups. The data distribution was investigated using the Shapiro–Wilk test. Mann–Whitney *U* and independent-sample t-tests were used to detect a difference in age, BMI, acoustic variables, and cephalometric parameters between the skeletal Class III and Class I groups in non-parametric and parametric tests, respectively. Pearson correlations were used to investigate correlations between acoustic and cephalometric variables in the skeletal Class III group. To confirm intrarater reliability, the intraclass correlation coefficient (ICC) of cephalometric measurement was calculated.

A *p*-value $<0.05$ was considered statistically significant. All analyses were performed using SPSS version 22.0 software (IBM Corp., Armonk, NY, USA).

# 4. Results

## 4.1 Subject characteristics

Table 3 demonstrates age, BMI, cephalometric values, and statistical calculations for each group. Excellent intrarater reliability (ICC > 0.95) was shown for all cephalometric measurements.

Age and BMI were abnormal distributed, and no differences in age and BMI were found between the two groups.

Regarding cephalometric characteristics, SNB, ANB, MPA, body mandibular length, total mandibular length, and facial height were significantly different between groups. Compared with the Class I group, the Class III group exhibited significantly smaller overjet (OJ), significantly greater HMe for hyoid bone position, and significantly greater middle, gonial, and inferior pharyngeal spaces (MPS, GoP, and IPS, respectively) for airway width.

## 4.2 Vowel sound analysis

The data distribution of all acoustic parameters was normal. There were no significant differences between the Class III and Class I groups for all vowels, except for /o/. The skeletal Class III group showed significantly higher frequency in F2/o/ and lower frequency in F4/o/ ($p < 0.05$) compared with the Class I group (Table 4). Formant graphs plotted by mean F1 and F2 values of each group are illustrated in Figure 12. Regarding formant graph area, there was no significant difference between the two groups.

## 4.3 Correlation between acoustic and cephalometric variables

In the skeletal Class III group, the data distribution of all acoustic and cephalometric parameters were normal, and significant correlations between these parameters are shown in Table 5. Scatter plots demonstrating correlations between acoustic parameters and significant differences in cephalometric characteristics of the skeletal Class III group regarding mandibular length, SNB, and OJ are shown in Figure 13. There was a significant negative correlation between overjet and F2/o/ ($r=-0.516$).

Significant negative correlations between body and total mandibular length and F4/o/ (*r*=−0.598, −0.589, respectively) were found. Also, significant negative correlations between SNB and F0/i/ (*r*=−0.474) and F4/e/ (*r*=−0.508) were noted, and a significant positive correlation between OJ and F1/a/ (*r*=0.617) was observed.

# 5. Discussion

This aim of this study was to compare sound production parameters between participants with skeletal Class III and Class I relationships, and to identify the correlation between sound production and cephalometric variables in the skeletal Class III group. Our findings show that individuals with skeletal Class III have different /o/ (back and rounded vowel) production compared with typical production, implying a different vowel articulation pattern due to anatomical differences. Vowel production in Class III subjects was negatively correlated with most mandibular characteristics, such as mandibular length and SNB, and OJ.

The skeletal Class III group exhibited distortion of the back and rounded vowel, which is the vowel /o/ in Japanese. This vowel production requires backward tongue articulation and lip rounding. Thus, restriction of tongue and lip movements in the skeletal Class III group may have distorted this vowel. As shown in previous studies, skeletal Class III subjects positioned their tongues more inferiorly and anteriorly than subjects with Class I malocclusion (60), and moved their lips differently during pronunciation (79). Our finding is consistent with a Chinese study (9), which showed the back and rounded vowel discrepancy in skeletal Class III individuals. Xue's study proposed that restriction of lip protrusion was a cause of Chinese /u/ discrepancy (9), another Chinese back and rounded vowel (65). However, Japanese /u/ is a central and unrounded vowel (66, 67), therefore, /u/ distortion was not found in our study. Moreover, /o/ was not included in Xue's investigation. As two main features classifying vowels are tongue position (front-back and high-low vowel) and lip rounding (rounded-unrounded vowel), these structures play important roles in formants (15). Considering that /o/ is the only back and rounded vowel in Japanese (65, 67), the effect of backward tongue movement restriction and difficulty in lip rounding in the skeletal Class III group may be most noticeable with this vowel. Thus, no significant differences in other vowels were observed, except for /o/.

Regarding the acoustic–articulation relationship, a higher frequency in F2/o/ and lower frequency in F4/o/ in the skeletal Class III group compared with the Class I group suggested a different pattern of vowel articulation because of anatomical deviation. As F2 frequency is correlated with forward and backward tongue position and lip rounding (15), higher F2/o/ in the Class III group indicates a more forward tongue position and/or less lip rounding than the Class I group during /o/ pronunciation. This is supported by previous studies (60, 79). As for F4, it enhances the naturalness of vowels (14) and is generated from the laryngeal cavity (80). Constriction of the laryngeal vestibule or expansion of the ventricle decreases F4 frequency (81). The difference in F4/o/ may indicate varying degrees of naturalness as well as a different pattern of laryngeal articulation during /o/ pronunciation. Therefore, our findings suggest that the skeletal Class III group produced /o/ with a more forward tongue position and/or less lip rounding than the Class I group. Moreover, patterns of laryngeal articulation corresponding to the naturalness of this vowel differed between these two groups.

In terms of speech intelligibility, there was no difference between the skeletal Class III and Class I groups. Acoustic parameters that related to speech intelligibility are formant graph area (25) and F0 (12), and our study found no difference between the groups for these parameters. Many studies (9, 19, 21) also showed no difference in F0. However, distortion of /o/ was detected, which a speech distortion could reduce quality of life in these individuals (5).

Thus, it is important to carefully evaluate back and rounded vowel production in skeletal Class III individuals. Due to their anatomical limitations, these individuals might need support and training to ensure more backward tongue movement or lip rounding when producing this vowel. Myofunctional training following orthognathic surgery may help patients adapt to their new oral environment following the sudden change.

Acoustic parameters were mostly negatively correlated with mandibular characteristics in individuals with skeletal Class III malocclusion, particularly long and protruded mandible. In the Class III group, negative correlations were found between F2/o/ and OJ, and F4/o/ and mandibular length. F0/i/ and F4/e/ were negatively correlated with SNB, while F1/a/ was positively correlated with OJ.

Negative correlations between F2/o/ and F4/o/ and cephalometric characteristics of Class III subjects support findings of /o/ distortion in this study. Our results are also consistent with a previous study reporting a correlation between F4/o/ and mandibular length (36).

Negative correlations between SNB and F0/i/ and F4/e/ could be explained by the positive correlation between pharyngeal airway volume and SNB found in previous work (82). To illustrate, previous studies have observed a negative correlation between F0 and the volume of the pharyngeal airway space (83), and changes in F4 depend on F0 (83, 84). Thus, a relationship between F4 and SNB may be expected.

The positive correlation between F1/a/ and overjet in Class III subjects could be due to lower tongue position in the skeletal Class III group compared with Class I individuals. According to the formant graph (Figure 12), F1 is correlated with tongue height (15), and a certain degree of low tongue articulation relative to the oral cavity is required to produce /a/. However, lower tongue position in skeletal Class III subjects compared with Class I individuals has already provided greater tongue-to-palate distance (85). Therefore, these Class III individuals may require less mouth opening to produce this vowel.

This study used an objective method and a larger sample size to investigate vowel sound production, with no differences in age or BMI between the Class III and Class I groups. Hormonal change affects laryngeal growth (30). This causes changes in the mass and length of vocal folds, leading to deepening of voice. Hence, all recruited subjects were in their post growth spurt. Studies in obese individuals reported lower F0 (86), and also voice characteristics of discreetly hoarse, breathless, and unstable (87). Thus, the significant differences of acoustic parameter between group found in this study were not in account of age and BMI. Moreover, this research also included the high formants (F3, F4), which have been neglected in many studies.

Although cephalometric measurements in lateral cephalogram are 2-dimensional analyses, it is reliable and reproducible (71, 88). Moreover, without requiring an additional examination for cephalometric measurements, lateral cephalograms were readily available through routine orthodontic examination and were sufficient for our objectives.

The study results may be relevant to many languages because the 5-vowel system (as found in Japanese) is the most common vowel system in world's languages (64). To relate our findings to the English language, /o/ and /u/ are considered rounded and back English vowels (65, 67), and distortion of these English vowels may be observed in Class III individuals.

Limitations of this study were regardless of vertical skeletal pattern and tissue movement during sound production. Although skeletal open bites affect airway dimension (89), and open bites of 2 mm are associated with consonant sound production errors (90), it may not have much effect on vowel sound production (91). Cephalograms with the hyoid bone in rest position might not accurately reflect articulation position during vowel production. Real-time imaging, such as that obtained from ultrasound, magnetic resonance imaging movies, and motion capture systems, is required to provide information on soft and hard tissue articulations during vowel production. Further research is needed on skeletal discrepancies regarding other sagittal and vertical patterns and overbite, as well as on other languages.

The observation of vowel sound distortion in the skeletal Class III malocclusion group and its correlation with craniofacial structures emphasize the need to address this problem in patients with abnormal skeletal relationships. Further evaluation and consultation with a speech pathologist is therefore needed, providing a more appropriate and individualized multidisciplinary treatment plan towards the improvement of patient's speech production. Moreover, informing patients of the chance of changes in speech after orthognathic surgery is necessary.

# 6. Conclusion

Skeletal Class III Japanese subjects produced significantly distorted back and rounded vowel sound compared with individuals with skeletal Class I relationship. These findings suggest that different vowel articulation patterns arise because of anatomical position and adaptive changes in the Class III group. Speech distortion in patients with facial deformity and changes in speech after orthognathic surgery may be expected. Accordingly, myofunctional training in these patients might be suggested. Ongoing evaluation and consultation with a speech pathologist are needed to ensure an appropriate and individualized multidisciplinary treatment plan and positive speech production outcomes.

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*Table 1. The inclusion and exclusion criteria of this study*

| Criteria | Skeletal Class I group | Skeletal Class III group |
|---|---|---|
| Inclusion criteria | Native Japanese speakers | Native Japanese speakers |
| | $0.62° < ANB < 5.94°^{a}$ | $ANB < 0°$ |
| | Overjet > 0 mm | Overjet < 0 mm |
| | Post orthodontic treatment | Prior orthodontic treatment |
| | normal occlusion | planned for an orthognathic surgery |
| Exclusion criteria | Facial asymmetry (chin deviation more than 4 mm) | |
| | Congenital facial malformations | |
| | History of surgery at head and neck area | |
| | Recent history of respiratory tract infection | |
| | Presence of an intraoral orthodontic appliance | |

[a] mean ± SD of norms of Japanese males, according to Izuka and Ishikawa's study (73).

*Table 2. Definition of cephalometric measurements.*

| Cephalometric measurements | Definition |
|---|---|
| Skeletal measurement | |
| SNA (°) | Anteroposterior position of maxilla relative to cranial base |
| SNB (°) | Anteroposterior position of mandible relative to cranial base |
| ANB (°) | Anteroposterior relationship of maxilla and mandible relative to each other |
| MPA (°) | Vertical relationship of mandible relative to FH plane |
| Facial height (mm) | Distance between N and Me |
| Maxillary length (mm) | Distance between ANS and PNS |
| Ramus (mm) | Distance between Ar and Go |
| Mandibular body length (mm) | Distance between Go and Pog |
| Total mandibular length (mm) | Distance between Co and Gn |
| Dental measurement | |
| Overjet (OJ, mm) | Horizontal overlap between upper and lower incisors, on occlusal plane |
| Overbite (OB, mm) | Vertical overlap between upper and lower incisors, perpendicular to occlusal plane |
| Hyoid bone measurement | |
| HS (mm) | Distance between H and sella |
| HC3 (mm) | Distance between H and C3 |
| HMP (mm) | Perpendicular distance between H and mandibular plane |
| HGp (mm) | Distance between H and Gp |
| HMe (mm) | Distance between H and Me |
| Airway measurement | |
| PPS (palatal pharyngeal space, mm) | Pharyngeal space on the line passing PNS, parallel to FH plane |
| SPPS (superior posterior pharyngeal space, mm) | Pharyngeal space on the line passing midpoint of soft palate, parallel to FH plane |

| | |
|---|---|
| MPS (middle pharyngeal space, mm) | Pharyngeal space on the line passing U, parallel to FH plane |
| GoP (gonial pharyngeal space, mm) | Pharyngeal space on the line passing Go, parallel to FH plane |
| IPS (inferior pharyngeal space, mm) | Pharyngeal space on the line passing C2, parallel to FH plane |
| EPS (epiglottic pharyngeal space, mm) | Pharyngeal space on the line passing E, parallel to FH plane |

Table 3. Descriptive values and statistical calculations for age, BMI, and cephalometric variables in males with skeletal Class I and Class III malocclusion [*p < 0.05, **p < 0.01 (independent-sample t-test, $^{b}$ Mann–Whitney U test)].

| | Group (n=18/group) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Skeletal Class I group | | | Skeletal Class III group | | | |
| parameters | Mean | SD | Range | Mean | SD | Range | *p*-value |
| Age (years) | 24.06 | 4.86 | 17.5-34 | 23.04 | 5.65 | 17.17-35.92 | .293$^{b}$ |
| BMI (kg/m$^{2}$) | 20.53 | 3.57 | 16.65-29.74 | 20.62 | 1.74 | 17.80-24.98 | .406$^{b}$ |
| Skeletal measurement | | | | | | | |
| SNA (°) | 80.72 | 4.45 | 72.99-88.47 | 80.70 | 4.66 | 73.28-90.19 | .992 |
| SNB (°) | 79.07 | 4.22 | 71.95-87.21 | 85.66 | 4.51 | 78.58-94.52 | .000** |
| ANB (°) | 1.65 | 1.19 | 0.69-4.98 | -4.96 | 2.76 | (-10.06) -(-0.5) | .000** |
| MPA (°)$^{c}$ | 21.69 | 4.96 | 13.03-31.40 | 29.57 | 5.09 | 22.08-39.68 | .000** |
| Facial height (mm) | 153.56 | 7.27 | 138.87-168.18 | 162.56 | 6.05 | 149.66-169.82 | .000** |
| Maxillary length (mm) | 64.83 | 2.80 | 59.26-71.79 | 62.69 | 4.79 | 53.56-72.68 | .111 |
| Ramus (mm) | 62.52 | 4.39 | 53.40-71.19 | 63.78 | 4.38 | 53.25-70.99 | .395 |
| Mandibular body length (mm) | 95.62 | 4.96 | 84.97-103.82 | 102.16 | 8.24 | 91.01-123.78 | .007** |
| Total mandibular length (mm) | 149.19 | 5.65 | 139.62-160.25 | 163.41 | 8.58 | 147.82-184.17 | .000** |
| Dental measurement | | | | | | | |
| OJ (mm) | 3.65 | .88 | 1.96-5.06 | -4.76 | 2.25 | (-10.81)-(-1.47) | .000** |
| OB (mm) | 2.64 | 1.69 | 0.84-6.82 | 1.74 | 3.52 | -4.44-7.91 | .628$^{b}$ |
| Hyoid bone measurement | | | | | | | |
| HS (mm) | 138.19 | 8.44 | 124.13-151.10 | 141.75 | 8.04 | 130.62-162.98 | .204 |
| HC3 (mm) | 48.03 | 6.06 | 39.47-59.22 | 50.25 | 4.73 | 42.06-58.12 | .230 |
| HMP (mm) | 13.57 | 4.87 | 4.30-22.24 | 13.43 | 7.80 | -2.28-30.16 | .948 |
| HGp (mm) | 43.06 | 7.47 | 31.82-57.39 | 47.17 | 8.37 | 31.75-61.05 | .129 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| HMe (mm) | 47.64 | 8.03 | 34.99-63.67 | 53.47 | 8.69 | 34.36-68.29 | .044* |
| Airway measurement | | | | | | | |
| PPS (mm) | 26.68 | 4.90 | 19.66-38.31 | 26.83 | 3.91 | 19.51-35.69 | .913[b] |
| SPPS (mm) | 13.59 | 3.84 | 7.05-22.12 | 16.44 | 5.03 | 7.11-23.45 | .064 |
| MPS (mm) | 18.98 | 5.53 | 11.48-28.00 | 24.24 | 7.44 | 9.98-42.02 | .022* |
| GoP (mm) | 14.48 | 5.14 | 8-27.89 | 19.77 | 7.14 | 8.35-35.45 | .020*, [b] |
| IPS (mm) | 14.91 | 5.45 | 7.17-28.65 | 19.08 | 6.72 | 9.17-33.27 | .049* |
| EPS (mm) | 15.17 | 5.32 | 7.07-28.94 | 18.67 | 5.67 | 9.14-27.56 | .065 |

SD, standard deviation; OJ, overjet; OB, overbite; PPS, palatal pharyngeal space; SPPS, superior posterior pharyngeal space; MPS, middle pharyngeal space; GoP, gonial pharyngeal space; IPS, inferior pharyngeal space; EPS, epiglottic pharyngeal space.

*$p$< .05, **$p$ < .01 (independent-sample t-test, [b] Mann-Whitney *U* test).

[c] Class III group: 5 subjects with hyperdivergent pattern and 13 subjects with normodivergent pattern. Class I group: 5 subjects with hypodivergent pattern and 13 subjects with normodivergent pattern.

*Table 4. Descriptive values and statistical calculations for acoustic parameters in males with skeletal Class I and Class III malocclusion. [*p < 0.05 (independent-sample t-test)].*

| | | Group (n=18/group) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Skeletal Class I group | | Skeletal Class III group | | | |
| Vowel | Acoustic parameter | Mean | SD | Mean | SD | t | *p*-value |
| /a/ | F0 (Hz) | 122.49 | 18.47 | 126.86 | 18.91 | -0.7 | .489 |
| | F1 (Hz) | 726.40 | 50.60 | 733.13 | 35.90 | -0.46 | .649 |
| | F2 (Hz) | 1201.85 | 77.97 | 1203.06 | 60.75 | -0.052 | .959 |
| | F3 (Hz) | 2699.30 | 157.57 | 2757.64 | 161.00 | -1.099 | .28 |
| | F4 (Hz) | 3502.30 | 224.79 | 3515.40 | 328.22 | -0.14 | .89 |
| /i/ | F0 (Hz) | 129.06 | 20.66 | 132.03 | 18.62 | -0.453 | .653 |
| | F1 (Hz) | 287.88 | 26.83 | 306.52 | 30.38 | -1.951 | .059 |
| | F2 (Hz) | 2226.89 | 127.17 | 2192.88 | 137.88 | 0.769 | .447 |
| | F3 (Hz) | 3104.89 | 191.14 | 2996.74 | 168.16 | 1.802 | .08 |
| | F4 (Hz) | 3666.30 | 232.96 | 3524.76 | 239.91 | 1.796 | .081 |
| /u/ | F0 (Hz) | 126.54 | 18.98 | 133.72 | 18.53 | -1.149 | .259 |
| | F1 (Hz) | 322.22 | 31.66 | 328.48 | 22.02 | -0.688 | .496 |
| | F2 (Hz) | 1430.42 | 188.18 | 1439.06 | 140.42 | -0.156 | .877 |
| | F3 (Hz) | 2312.23 | 101.37 | 2275.05 | 105.79 | 1.077 | .289 |
| | F4 (Hz) | 3368.09 | 155.77 | 3278.63 | 144.36 | 1.787 | .083 |
| /e/ | F0 (Hz) | 125.10 | 18.90 | 128.74 | 18.59 | -0.581 | .565 |
| | F1 (Hz) | 452.20 | 41.01 | 478.14 | 41.07 | -1.896 | .066 |
| | F2 (Hz) | 2004.80 | 112.07 | 1970.13 | 128.46 | 0.863 | .394 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | F3 (Hz) | 2669.98 | 117.62 | 2675.61 | 135.23 | -0.133 | .895 |
| | F4 (Hz) | 3496.21 | 240.91 | 3382.86 | 211.40 | 1.5 | .143 |
| /o/ | F0 (Hz) | 125.01 | 18.68 | 130.70 | 18.82 | -0.91 | .369 |
| | F1 (Hz) | 440.04 | 34.43 | 443.79 | 25.01 | -0.374 | .711 |
| | F2 (Hz) | 738.79 | 60.26 | 778.61 | 45.03 | -2.246 | .031* |
| | F3 (Hz) | 2699.77 | 147.36 | 2651.93 | 164.65 | 0.919 | .365 |
| | F4 (Hz) | 3296.67 | 106.86 | 3214.45 | 121.98 | 2.151 | .039* |
| Formant graph area ($Hz^2$) | | 320604.56 | 67262.95 | 308957.00 | 66803.75 | .521 | .606 |

SD, standard deviation; Hz, hertz.

**p* < .05 (independent-sample t-test)

*Table 5. Significant correlations between acoustic and cephalometric variables in the skeletal Class III group. [*p < 0.05, **p < 0.01 (Pearson correlation test)].*

| Acoustic variables | Cephalometric variables | *r* | *p*-value |
|---|---|---|---|
| F1/a/ | OJ | .617 | .006** |
| | PPS | -.549 | .018* |
| F4/a/ | EPS | .480 | .044* |
| F0/i/ | SNB | -.474 | .047* |
| F1/i/ | HMP | -.475 | .046* |
| F2/i/ | MPA | .486 | .041* |
| F3/u/ | ramus | -.603 | .008** |
| F4/u/ | ramus | -.548 | .019* |
| | HGp | -.541 | .020* |
| F1/e/ | HS | .472 | .048* |
| | HC3 | .496 | .036* |
| | PPS | -.530 | .024* |
| F3/e/ | Facial height | .479 | .044* |
| F4/e/ | SNA | -.470 | .049* |
| | SNB | -.508 | .031* |
| | Maxillary length | -.518 | .028* |
| | Ramus | -.531 | .023* |
| | SPPS | .514 | .029* |
| F1/o/ | PPS | -.518 | .028* |
| | SPPS | -.591 | .010** |
| | EPS | -.573 | .013* |

| | | | |
|---|---|---|---|
| F2/o/ | OJ | -.516 | .028* |
| F3/o/ | PPS | -.643 | .004** |
| F4/o/ | Mandibular body length | -.598 | .009** |
| | Total mandibular length | -.589 | .010* |

*r*, correlation coefficient; OJ, overjet; PPS, palatal pharyngeal space; SPPS, superior posterior pharyngeal space; EPS, epiglottic pharyngeal space.

**p*< .05, ***p* < .01 (Pearson correlation test)

*Figure 1. Conceptual Framework*

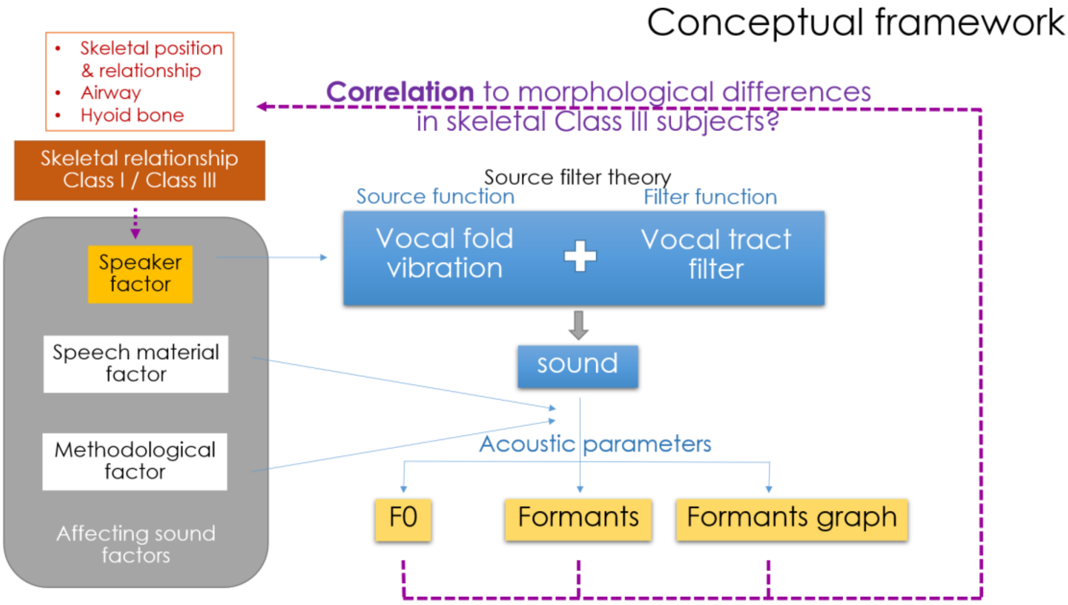


*Figure 2. Diagram describing source-filter theory.*

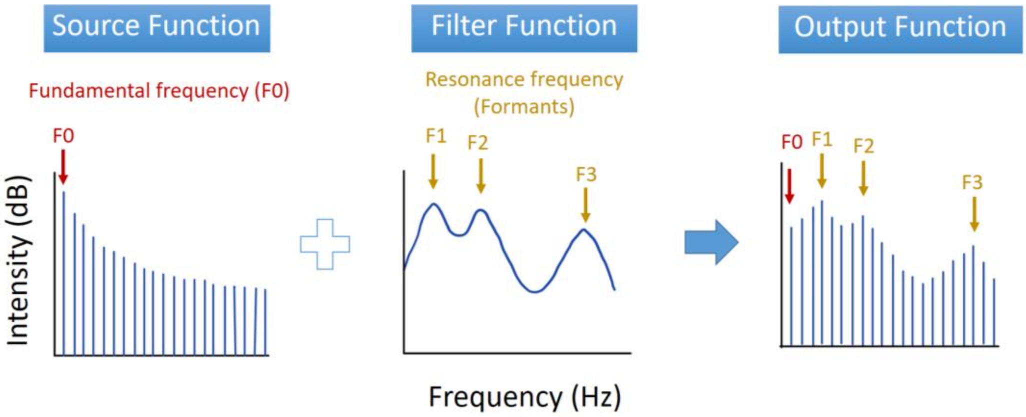


*Figure 3. Vocal fold vibration determines fundamental frequency.*

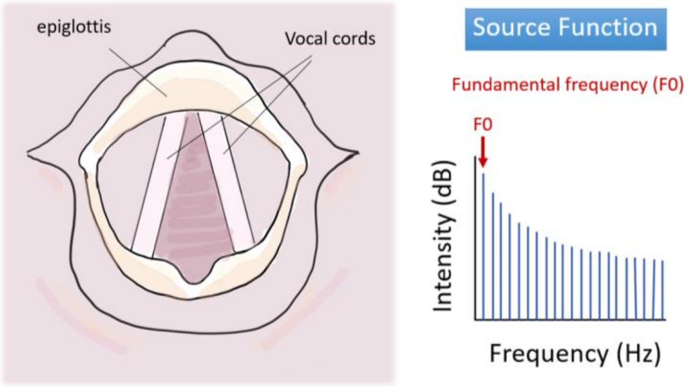


*Figure 4. Vocal tract starts from larynx to the tip of the mouth, determining formants.*

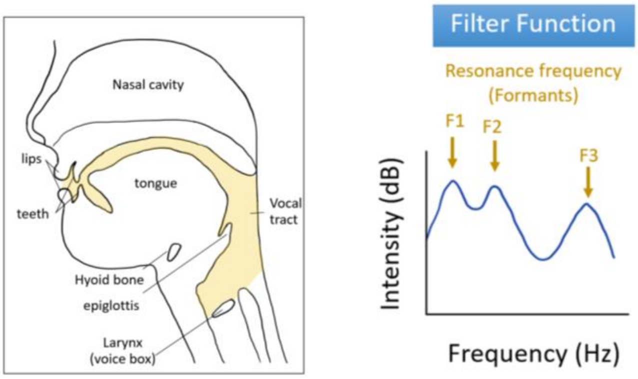


*Figure 5. An example of formant graph, taken from Ahn's study (17).*

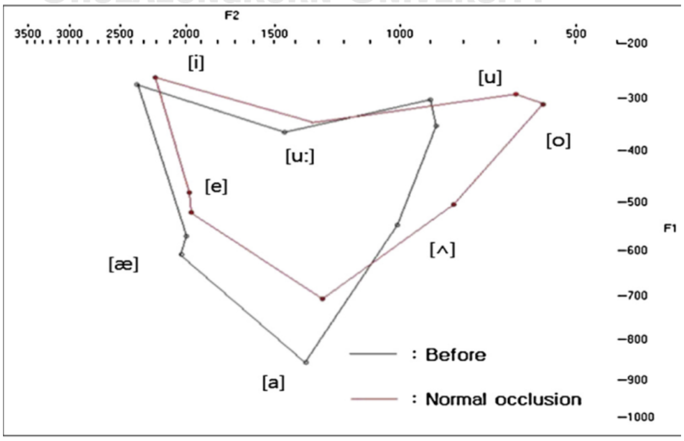


*Figure 6. Japanese vowels inventory, taken from Chung's study (65).*

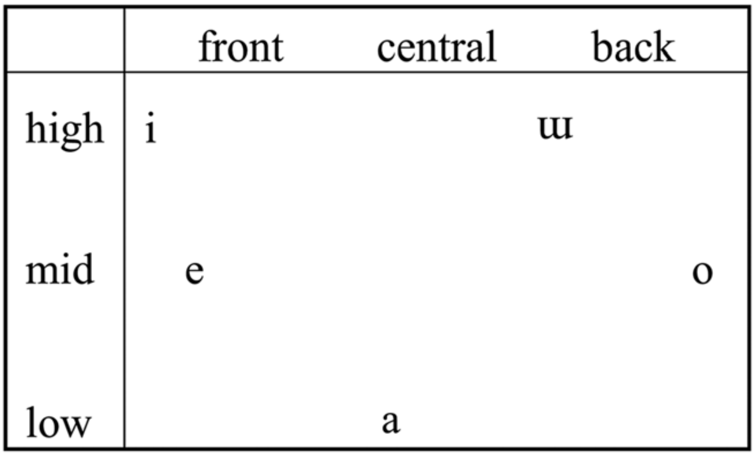


*Figure 7. English vowels inventory, taken from Chung's study (65).*

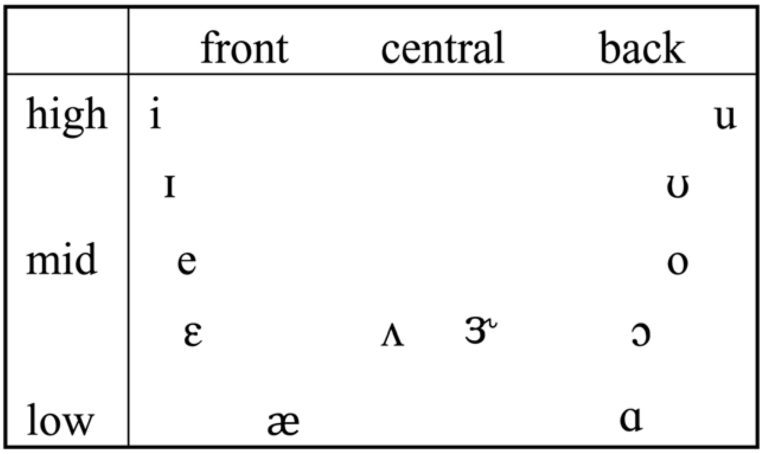


*Figure 8. A vowel list in a Latin-square matrix was used (75). The initial and last vowel was the same in each row, and all five vowels were presented in each column.*

| | | | | | |
|---|---|---|---|---|---|
| **/a/** | **/i/** | **/u/** | **/e/** | **/o/** | **/a/** |
| **/i/** | **/u/** | **/e/** | **/o/** | **/a/** | **/i/** |
| **/u/** | **/e/** | **/o/** | **/a/** | **/i/** | **/u/** |
| **/e/** | **/o/** | **/a/** | **/i/** | **/u/** | **/e/** |
| **/o/** | **/a/** | **/i/** | **/u/** | **/e/** | **/o/** |

*Figure 9. Cephalometric landmarks and planes: A, subspinale; ANS, anterior nasal spine; Ar, articulare; B, supramentale; Co, condylion; C2, the most anterior-inferior point of the second cervical vertebra; C3, the most anterior-inferior point of the third cervical vertebra; Gn, gnathion; Go, gonion; Gp, the most posterior-inferior point on the mandibular symphysis; FH plane, Frankfort horizontal plane; H, hyoid bone, the most anterior-superior point of hyoid bone; Me, menton; Mand Plane, mandibular plane, tangent line of lower border of mandible; N, nasion; PNS, posterior nasal spine; Pog, pogonion; S, sella; U: tip of the uvula, the most posterior-inferior point of the uvula.*

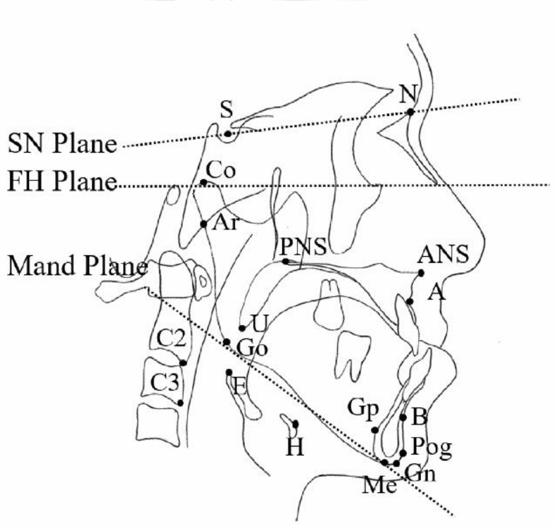


*Figure 10. Hyoid bone position measurements: (1) HS, (2) HC3, (3) HMP, (4) HGp, (5) HMe.*

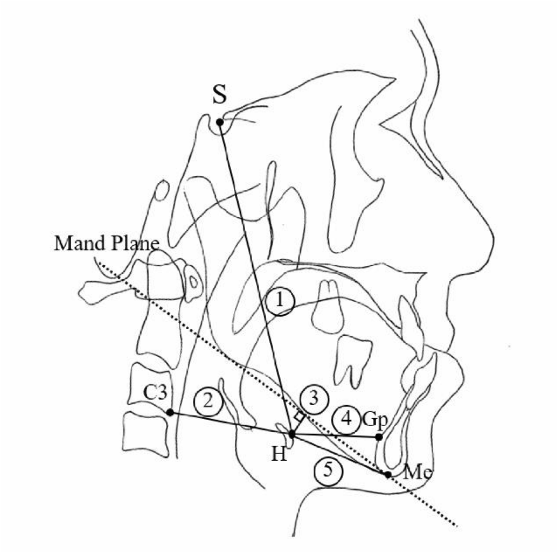


*Figure 11. Airway measurements: (1) PPS, palatal pharyngeal space; (2) SPPS, superior posterior pharyngeal space; (3) MPS, middle pharyngeal space; (4) GoP, gonial pharyngeal space; (5) IPS, inferior pharyngeal space; (6) EPS, epiglottic pharyngeal space.*

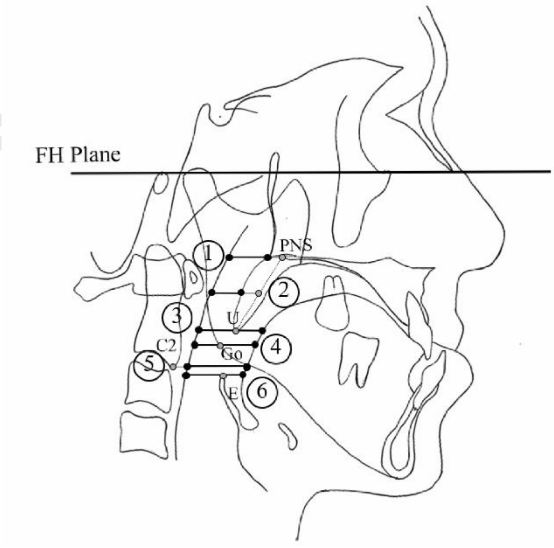


*Figure 12. Formant graphs of skeletal Class I (blue) and Class III malocclusion (orange) groups are shown, using the average of F1 and F2 values of each vowel.*

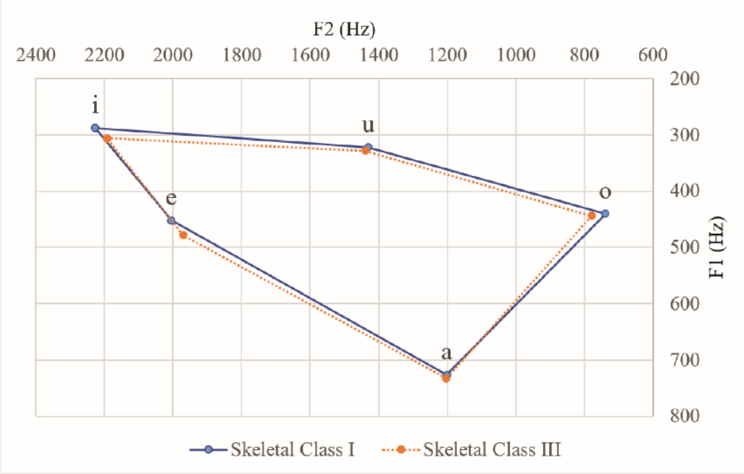
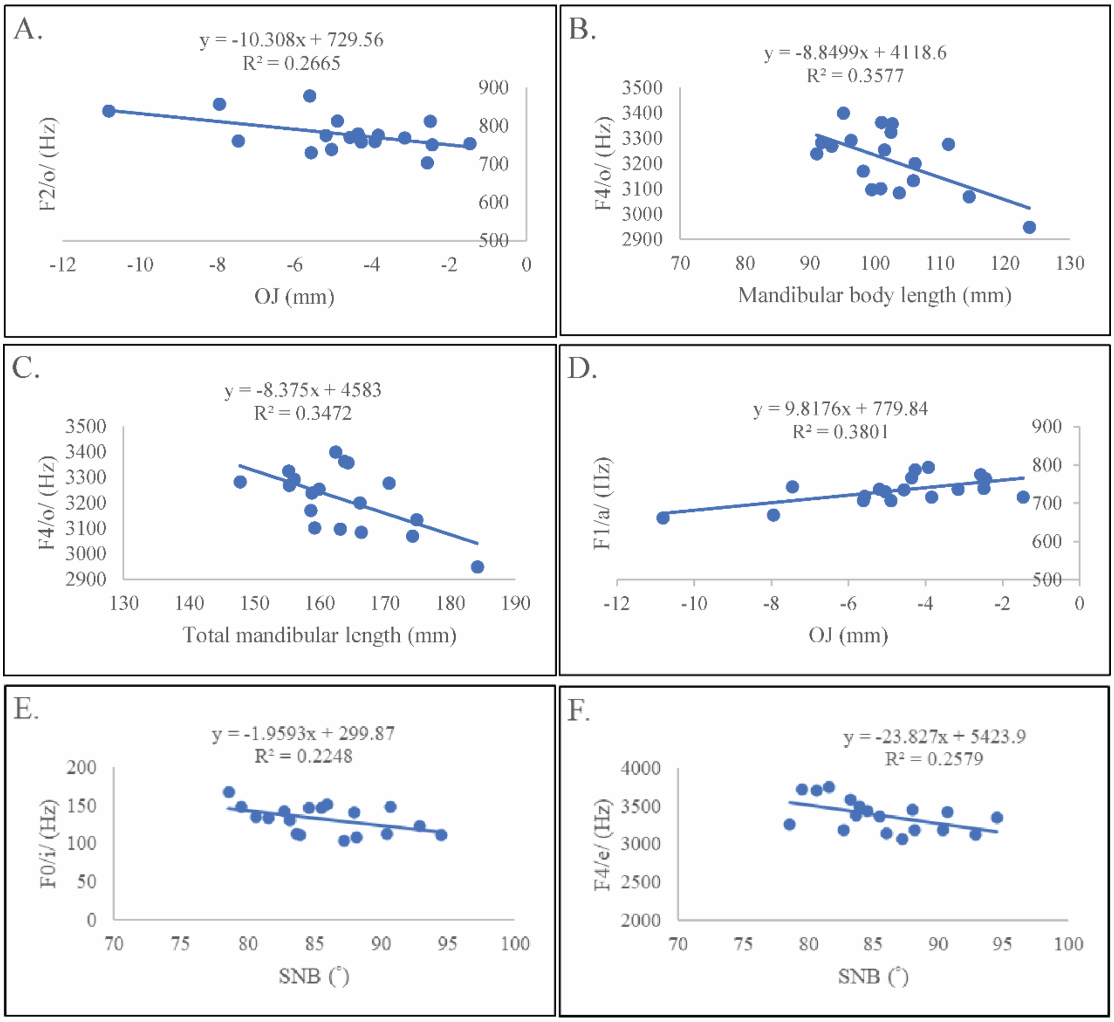


*Figure 13. Scatter plots showing correlations between acoustic parameters and significant cephalometric characteristics of the skeletal Class III group regarding mandibular length, SNB, and overjet (OJ); (A) F2/o/-OJ, (B) F4/o/-mandibular body length, (C) F4/o/-total mandibular length, (D) F1/a/-OJ, (E) F0/i/-SNB, (F) F4/e/-SNB.*



# VITA

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