ORTHOGNATHIC SPEECH PATHOLOGY:
UNDERSTANDING HOW CLASS III JAW DISHARMONIES INFLUENCE SPEECH
UTILIZING SPECTRAL MOMENT ANALYSIS

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ABSTRACT

(Under the direction of David Zajac)

Patients with severe jaw disproportions seek orthodontic care and orthognathic surgery to address issues with mastication, esthetics and speech; speech concerns surpass impaired chewing function as a motivator for surgery. Pathologic speech impedes communication, profoundly impacting quality of life. We hypothesized that deviations from normal central frequencies of consonant sounds correlate with severity of anterior-posterior and jaw disproportions. To test our hypothesis, we evaluated 31 patients with dentofacial deformity and 10 reference individuals for status of occlusal relationships and qualitative characteristics of speech patterns. Qualitative assessment was completed by a speech pathologist through direct evaluation. Audio recordings were collected on each subject and quantitatively analyzed to measure sound frequency distortions. Overall, these experiments revealed that 77% of Class III subjects produced abnormal dentalized sounds compared to 10% of controls and that a shift existed in the /t/ and /tʃ/ central tendency relative to controls. Trends correlating severity of Class III with articulation distortion were found with 3 tested phonemes: /k/, /s/ and /ʃ/. These findings provide critical insight into the complex interplay between craniofacial and vocal structures, and may elucidate how the treatment of dentofacial deformities may impact speech-sound disorders.
ACKNOWLEDGEMENTS

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ANB</td>
<td>A-point – Nasion – B-point</td>
</tr>
<tr>
<td>AOB</td>
<td>Anterior Open Bite</td>
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<tr>
<td>ASHA</td>
<td>American Speech-Language-Hearing Association</td>
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<tr>
<td>BBSO</td>
<td>Bilateral Sagittal Split Osteotomy</td>
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<tr>
<td>BSSRO</td>
<td>Bilateral Sagittal Split Ramus Osteotomy</td>
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<tr>
<td>DFD</td>
<td>Dentofacial Deformity</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>IQR</td>
<td>Interquartile Range</td>
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<tr>
<td>NHS</td>
<td>National Health Service</td>
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<tr>
<td>OB</td>
<td>Overbite</td>
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<tr>
<td>OJ</td>
<td>Overjet</td>
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<tr>
<td>QoL</td>
<td>Quality of Life</td>
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<tr>
<td>SLP</td>
<td>Speech Language Pathologist</td>
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<tr>
<td>SSD</td>
<td>Speech Sound Disorders</td>
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<tr>
<td>SMA</td>
<td>Spectral Moment Analysis</td>
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<tr>
<td>UNC SoD</td>
<td>University of North Carolina School of Dentistry</td>
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<tr>
<td>VOT</td>
<td>Voice Onset Time</td>
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LIST OF DEFINITIONS

ANB°: A cephalometric measurement for the angle formed when connecting A-point (the deepest concavity of the maxilla), to Nasion (the most anterior, superior point where the frontal and nasal bones meet), to B-point (the deepest concavity of the anterior aspect of the mandible).

Class I: Normal relationship of the jaws, with the maxilla (top jaw) slightly anterior to the mandible (lower jaw).

Class II: A relationship of the jaws in which the maxilla is more anteriorly positioned from the mandible than ideal. This can be due to excess growth of the maxilla (hyperplasia) or insufficient growth of the mandible (hypoplasia).

Class III: A relationship of the jaws in which the mandible is more anteriorly positioned from the maxilla than ideal. This can be due to insufficient growth of the maxilla (hypoplasia), or excess growth of the mandible (hyperplasia).

Dyslalia: A neuromuscular or structural defect of the speech organ which can include soft or hard tissue defects

Malocclusion: Positioning of the teeth or jaws that deviates from ideal occlusal relationship

Overbite: The amount of vertical overlap of the maxillary and mandibular teeth, especially referring to the anterior relationship. When the overbite value is negative, it is also called ‘open bite’

Open bite: When there is negative vertical overlap of the teeth, i.e., the teeth do not touch. Also referred to as ‘negative overbite.’

Overjet: The relationship of the maxillary and mandibular teeth in the sagittal plane of space (anteroposterior). A positive relationship indicates the maxillary teeth are more anterior than the mandibular teeth (ideal is 1-2mm). A negative relationship indicates the mandibular teeth are anterior to the maxillary teeth.

Phoneme: A perceptually distinct sound used in language. It is denoted with /_/ marking.

Spectral Moment Analysis: A method of simplifying and analyzing a sound waveform and using statistical descriptive measures.

Spectral Moment, First: Central Tendency of the energy burst of the sound wave. Also known as: the mean, or central frequency.

Spectral Moment, Second: Variance, or Standard Deviation
Spectral Moment, Third: Skew of the wave energy. A positive skew indicates lower frequencies, a negative skew leans toward higher frequencies.

Spectral Moment, Forth: Kurtosis, or a measure of the peakedness of the energy curve.

Under bite: a colloquial term used to describe negative overjet
CHAPTER I: BACKGROUND OF DYSLALIA

Introduction

The formation of speech requires complex neuromuscular control and coordination of respiration, phonation and articulation.\(^1\) Disordered speech can arise from any number of breakdowns along this pathway. Articulation problems as a group are referred to as speech sound disorders (SSD). Dyslalia indicates a neuromuscular or structural defect in the speech organs, “which can be caused by any malformation of deformity of the oral cavity, usually by Class I, Class II or Class III malocclusion is manifest in the lisping speech defect.”\(^2\) Dyslalia is an under-utilized term, not commonly used by speech pathologists. It is sometimes conflated with dysarthria, which describes motor speech disorders due to muscle weakness or dyscoordination. However, dysarthria leaves out the role of hard tissue structures such as the palate, alveolus and teeth. The lack of appropriate terminology is indicative of the gap of knowledge between speech pathology and malocclusions. But in this regard, orthodontists could be primary allies in the treatment of dyslalia as the treatment of malocclusions is their specialty.

Epidemiology of Speech-Sound Disorders

In research cited by the American Speech-Language-Hearing Association (ASHA), the incidence and prevalence of SSD in the United States is unknown due to inconsistencies in diagnostic procedures and reporting. A systematic review of the United Kingdom’s National Health Service (NHS) data, however, indicates anywhere between 2-25% of children aged 5-7 has a SSD\(^3\). However, because speech is learned throughout childhood, part of distinguishing normal from pathologic speech comes down to understanding the developmental milestones of
speech acquisition. For example, a 3-year-old who says ‘wabbit’ for ‘rabbit’ is viewed differently than an adult who struggles with the proper articulation of the /r/ sound. It is generally thought that language stabilizes around age 8. So, focusing in on this slightly older demographic: reporting National Health Interview Survey of 2012 indicates that 4.9% of adolescents aged 11-17 have a speech-language disorder and approximately 3.5% of adults have a SSD. However, compared to the general population, there is a much higher prevalence of disordered speech amongst of the subpopulation of adolescents and adults who have a skeletal discrepancy of the jaws: 77.8% of adolescents with an anterior open bite had some level of dyslalia, with distortion being the most common. Indicating a causal link between malpositioned jaws and SSD.

Quality of Life

Human speech distinguishes the intelligence of Homo sapiens from the rest of the animal kingdom. It is thought to have been intertwined in the evolution of our species as a means by which we disseminate knowledge – feeding into the development and advancement of tools. So, for those who suffer from a SSD, there is an implicit assumption on behalf of the observer that the speaker is of inferior intelligence – when this is seldom the case. In a survey by Bennett and Runyan, indicated that 66% of educators thought that communication disorders had an adverse effect on educational development regardless of the child’s intellectual aptitude.

Pathologic speech can significantly impede communication, which in turn profoundly impairs social interactions and quality of life (QoL). Interestingly though, when comparing the Dental Aesthetic Index correlation to QoL – the correlation was actually poor, indicating that what could be perceived as mild to moderate malocclusion may have a significant negative impact on an individual’s quality of life. Therefore, there is good reason to inquire with the
patient what is the impact of their malocclusion on daily life, because it may not map directly to the measured severity. In particular, 10-13 year old children with a SSD have reported lower self-perception.\textsuperscript{12} Hughes outlines ways in which children and adolescents with communication disorders are disproportionally affected by bullying from their peers. The ramifications of which might be self-isolation, refusal to participate in classroom discussion out of fear of ridicule, or occasionally reciprocal bullying.\textsuperscript{13}

**Speech Sound Disorders as they Relate to the Craniofacial Complex**

The orthodontic profession focuses on building healthy smiles that help our patients to feel more confident. In the general population, this is geared toward improving esthetics, but for 2.5% of the US population, the discrepancy of the teeth and jaws are handicapping\textsuperscript{14} resulting in difficulty with mastication, breathing and speech. When the teeth don’t fit together properly due to an underlying skeletal discrepancy, it will be referred to as a ‘skeletal malocclusion’ and is often considered a dentofacial deformity.

Dentofacial Deformity (DFD) is a term specifically used to describe severe cases on the spectrum of malocclusions, and includes conditions associated with aberrant jaw function and psychosocial concerns.\textsuperscript{15} Common DFD cases are those in which the patient has an ‘underbite’ where the lower jaw (mandible) is forward of the upper jaw (maxilla). In dentistry, this is considered a Class III skeletal relationship. Conversely, patients may have a maxilla that is too far forward of the mandible, and this is called a Class II skeletal relationship. (For the sake of comparison, a Class I relationship is when the maxilla is slightly in front of the mandible. This is the normal occlusion, or the ideal relationship.) The Class I, II and III relationships describe the horizontal position of the jaws. Orthodontists also evaluate the vertical position of the jaws, and ideally would like to see 1-2mm of overlap of the maxillary teeth over the mandibular teeth. This
is called the ‘overbite.’ When there is a lack of overlap, and instead there is open space, the patient is considered to have an ‘open bite.’ In such cases, it can be difficult to position the tongue against the articulating structures to create the correct sound.

**Diagnosis**

Wide variation exists in modalities used by Speech Language Pathologists (SLP) for the diagnosis of a SSD; but most often involve visual and auditory subjective assessment of sound. The basic work-up typically includes: a case history, formal articulation and phonological tests, stimulability evaluation, connected speech sample, a speech intelligibility measure, oral / facial examination and finally an auditory sensitivity assessment to help rule out potential hearing disturbances along the input pathway.⁴

To develop a general understanding of the patient’s speech concern, there are a multitude of formal articulatory and phonological testing systems. In such an assessment, the SLP directly observes the patient and listens for substitutions, omissions or distortions (visual or auditory) in consonant and vowel production. Some of the most common testing systems include:

- *Fisher-Logeman Test of Articulation Competence* in which the number of articulation errors are counted and the type of error is classified as a substitution, omission, or distortion error. Distortion errors are further categorized as visual, acoustic or combination of the two.

- *The Arizona Articulation Proficiency Scale* and the *Bzoch Error Pattern Diagnostic Articulation Test* goes one step further to grade each error in terms of severity.

- *Goldman-Fristoe Test for Articulation* is one of the most comprehensive assessments because it combines the evaluation of individual words, of phonemes spoken in the fluency of a sentence and stimulability of misarticulated phonemes.
The oral-motor examination is another important component of the exam, in order to evaluate for structural deviations (dyslalias) that may be the cause of the speech disorder. The SLP looks for intact hard and soft palate, the presence or absence of dentition (possibly leading to the use of a prosthesis) and the state of the occlusion. Motor function is assessed by evaluating non-speech oral movements (range of motion and control of tongue posture). To round out the exam, the SLP conducts a brief standardized auditory evaluation of pure tones and speech-sound discrimination.

While SLP are highly trained professionals to detect the nuances and disturbances of speech patterns, there is inherently a subjective element to the assessment described above. As such, some clinicians choose to use adjunctive measures to further describe the SSD by use of evaluating speech acoustics (i.e., the sound wave).

One such technique is to evaluate the component frequencies of a particular sound. The fundamental frequency (denoted “F0”) is the rate of vibration of the vocal folds in the larynx. The Formant Frequencies (“F1, F2, or F3”) are a measure of the resonances of the supralaryngeal cavities (i.e., pharynx, oral, nasal), much like the harmonics in a cord. This is a helpful tool for evaluating vowel phonemes.

Another method to evaluate the sound waves is to simplify the data using statistical principles. This allows for the visualization and analysis of the sound wave as a randomized distribution curve. The curve is then described by four features, or *moments*. The first moment (M1) is central tendency or frequency, it is the mean frequency of the sound energy. It roughly corresponds to pitch, so higher central tendencies will sound higher, and conversely lower central tendencies – will have a deeper quality to the pitch. The second moment (M2) is the variance (standard deviation) of spectral energy; it indicates the spread over which the sound
energy is distributed. The third moment (M3) is the skewness or tilt of the sound energy curve. Perhaps not intuitive on this statistical descriptor however: a positive M3 indicates a shift toward the lower frequencies, whereas a negative M3 is leaning toward the higher frequencies. The fourth moment (M4) is the kurtosis / peakedness that the sound energy curve takes. Collectively this method of evaluating sound waves is called a Spectral Moment Analysis (SMA) (Figure 1).

**Figure 1: Spectral Moment Analysis**

**Skeletal Correction of Severe Malocclusion**

Recently, there has been success in treating Anterior Open Bite patients non-surgically with use of intrusion appliances such as the Fisher, Erverdi or Invisalign. The premise being that by intruding the posterior teeth, you can reduce the occlusal interference and allow the mandible to auto-rotate into a more anterior-superior position and thereby close the anterior open bite. This method can work for patients with a Class II skeletal discrepancy in which the more anterior positioning of the mandible is favorable. However, in our Class III patient population where the
mandible is already displaced anteriorly, this treatment approach does not work. Therefore, we resort to surgical interventions.

Traditionally, treatment of DFD largely distills down to one of three surgical options: 1. Movement of the maxilla (LeFort) typically in the anterior direction (advancement), 2. Movement of the Mandible (Bilateral Sagittal Split Osteotomy ‘BSSO’, or sometimes called a Bilateral Sagittal Split Ramus Osteotomy ‘BSSRO’) or 3. a combination of the two. Determination of which surgery to undertake is made at the discretion of the orthodontist and oral surgeon, often with some influence from insurance companies. Surgery is not rendered for speech concerns alone in non-cleft patients; numerous factors such as esthetics, mastication and airway are all taken into account when designing the appropriate surgical intervention.
CHAPTER II: SUMMARY OF THE LITERATURE

Observational Assessment

Leavy et al. collected an observational sample of 115 patients with occlusal variation: Class I (n=60), Class II (n=47), Class III (n=8) from the Montifore Department of Orthodontics. 32% of the patients spoke primarily Spanish at home. As a result, the study focused on voiceless consonants that had linguistic overlap between English and Spanish (the target sounds examined were /m/, /p/, /t/, /f/, /s/, /sh/, /ch/, /th/, and /l/). Audio and video were recorded of each subject, and distinctive feature analysis was used to evaluate the presence and type of distortion. This evaluation found that 62% of subjects had some sound production error, with /s/ and /t/ being the most common. Of those patients with a sound production error, 79% had a visual distortion of the tongue or lip posture during the sound formation. 16

In evaluating a subset of the population with Anterior Open Bite (AOB), Ocampo-Parra et al. conducted a thorough examination of consonant sounds in 132 Columbian adolescents. Their observational study found that 77.8% had some level of dyslalasias, with the most common error being distortion. 7 Interestingly, however, the authors note that there is not a correlation between the severity of the AOB and the severity of the dyslalasias. That being said, the authors did not define the thresholds for mild, moderate or severe AOB cases, so it is not clear how correlation was assessed.

Vallino’s study of patients with skeletal malocclusions found patients with higher rates of articulation errors than are seen in the general population. Twenty-nine of the thirty-three subjects evaluated with the Fisher-Logeman Test of Articulation Competence had articulation
distortions, with the most common being /s/ and /z/. The rates of error were the highest amongst the Class III cases: 10 Class III cases, 9 of which had articulation errors. Conversely, the Class II subjects were better able to compensate for their malocclusions.\textsuperscript{17}

Nájera et al. in their 2016 observational study of 40 Spanish-speaking patients evaluated the relationship between occlusion and phonology using prosthodontic principles. The rationale of this study was to investigate the mechanism of how vertical skeletal discrepancies correlate to the phoneme formation via the relationship of external soft tissues (ie, the lips). They compared the rates of phoneme pronunciation errors as they related to variation in the vermillion border-incisal edge. They also compared phoneme errors to severity of crowding. They reported “no relationship was found between a faulty pronunciation of the phonemes and a decreased or increased vermilion border.” This indicates that lip posture is not the way by which sound errors are produced in those patients with AOB.\textsuperscript{18}

Laine’s 1992 study of Finnish-speaking undergraduate students is perhaps one of the most comprehensive studies to be done: This study evaluated 451 individuals; 20\% had no occlusal anomalies and the remainder had at least one occlusal anomaly in any dimension. In the sagittal dimension: distal molar occlusion (DMO ~ Class II), mesial molar occlusion (MMO ~ Class III), excess overjet, negative overjet where all recorded. In the vertical dimension, subjects were recorded as having incisal open bite (ie, AOB) or incisal deep bite. Lateral open bites were also noted in 8 patients. In the transverse dimension: crossbite and scissor bites were recorded. Articulatory speech disorders were evaluated by two speech pathologists as the subjects read a passage from a Finnish text. The speech pathologists evaluated acoustically for a speech-sound distortion and noted visually whether the distortion was due to placement too far anteriorly, posteriorly or laterally. The sounds found to be distorted were medioalveolar consonant
distortions of /s/, /r/, /l/, /n/ and /d/. Anterior variants were more common (28%) followed by posterior variants (5%) and lateral variants (2%). This study found higher risk-ratios for patients with vertical (AOB, risk ratio = 3.4) and transverse (lateral crossbites, risk ratio = 1.7) discrepancies. In the anteroposterior plane: MMO and the rate of articulatory distortion ranged from 3.7 times increased risk (for negative overjet) to 4.5 (for Class III molar relationship). However, despite the overall large sample size and the inclusion of a range and overlap of different occlusal features, this study only included 29 subjects with Class III skeletal characteristics (MMO +/- negative OJ). Moreover, deviation from normal occlusion is not noted and the assessment is qualitative, and as a result, it is difficult for such a study to draw conclusions about how the severity of the malocclusion correlates to the degree of speech-sound distortion. Nevertheless, this study demonstrates that no single occlusal trait can be made responsible for a SSD (and indeed, there are those with normal occlusion who also have speech distortions), but the use of risk ratios helps to prioritize those features with the greatest impact.

**Surgical Outcomes**

One way to gain insight into the effect of DFD on sound production is to see how the interventional therapy resolves the pathology. With regard to those with skeletal malocclusions, this amounts to surgical correction of the orthognathic discrepancy.

One of the first studies to compare the effect of surgical correction of the malocclusion on SSD was conducted by Turvey et al. on a sample of nine patients with AOB. In this study, patients were evaluated by a speech pathologist for articulatory disturbances of the /s/ and /z/ both acoustically and visually. These sounds were chosen since interdental lisping of the /s/ and /z/ was felt to be a quintessential characteristic of patients with AOB. Interdental lisp was evaluated on a four-point scale from 0 (no problem) to 3 (severe). Similarly, tongue thrust was
evaluated on a four-point scale, with the 3 (severe) indicating an interdental rest posture of the tongue and protrusion of the tongue during swallow. Patients were evaluated following corrective surgery at three-month intervals for one year. Eight of the nine patients demonstrated improvement of the lisping behavior; of these, three had complete self-correction and five had progressive improvement. The ninth patient demonstrated initial improvement, but at the 12-month evaluation, there was a relapse toward pathologic tongue function.

In a prospective evaluation of 40 female surgical patients, Dalston and Vig collected audio recordings before and either 6 or 12 months after surgery. Recordings consisted of words and sentences taken from the Iowa Pressure Articulation Test and Fisher-Logemann Test for Articulation Competence. Patients also read the Rainbow Passage. Three speech pathologists each evaluated all speech samples for hyponasality, hypernasality and articulation impairment. Each parameter was evaluated on a 6-point scale, with 1 indicating normal nasal resonance /articulation, and 6 denoting severe distortion. Pre-operative findings had an overall low-rate of errors: with average scores across these parameters judged to be 1.0-1.1/6 on the scale of severity. Misarticulations were perceived in only 1% of consonants. Of these, 70% of the errors were distortions, primarily with the /s/ and /z/. Subjects were re-analyzed 6-12 months after surgery and intra-subject statistical calculations were performed. Study findings indicated seven of forty patients had perceived change in nasal resonance, but the change was not considered clinically significant. “Thus, despite the fact that these patients experienced significant morphologic alterations to their vocal tracts, their speech remained perceptually unaltered.” Three subjects did experience changes in articulation; one patient’s articulation improved and for two patients, articulation became impaired. The case that improved was treated with a mandibular setback surgery (presumably a Class III patient), while those whose speech
deteriorated were treated with Maxillary impaction and mandibular advancement (presumably Class II with vertical excess). The authors conclude that there was sufficient adaptation of the speech organ that any changes were not perceptible to trained judges. This could be due to auditory-feedback mechanism, which allowed normal-speaking individuals to return to baseline, and dissuades the notion that surgery can have a corrective effect.

Conversely, Vallino’s group (in addition to the observational study described above) evaluated 34 surgical cases with a combination of skeletal malocclusions: Class II malocclusions (n=11), Class II malocclusions with AOB (n=12), Class III malocclusions (n=6) and Class III malocclusions with AOB (n=5). Surgical procedures varied and were dependent on the case-type in order to restore the patient to appropriate OJ and OB. The subjects were evaluated pre-operatively and at a number of time-points during the healing and adaptive post-operative phase of treatment. The assessment consisted of the Fisher-Logemann Test for Articulation. Hoarseness, pitch and resonance were also recorded. Other anatomical evaluations were also conducted including a pressure-flow technique to estimate the velopharyngeal port area, and hearing tests to assess middle ear function. In her thorough study of cases with severe skeletal malocclusion, Vallino found the following changes: 1) an 88.2% reduction in number of articulation errors, 2) stable or improved nasal resonance in all examined subjects 3) adequate velopharyngeal port areas before and after surgery in all speech tasks and 4) normal thresholds for pure-tone hearing sensitivity before and after surgery. 21

The studies by Dalston and Vig, and Vallino used very similar methodologies with regard to a heterogeneous patient population, surgical intervention and analysis tools (Fisher-Logemann Test for Articulation), but reached different conclusions on the corrective impact of orthognathic surgery on SSD. This could be due to the nature of the presenting malocclusion.
The Dalston and Vig paper does not delineate the types of pre-operative malocclusions, only that a variety of surgical procedures were used. One might be able to infer that a mandibular setback was used in the Class III population whereas the mandibular advancement was used in the Class II population, but was the ‘superior repositioning of the maxilla’ done in conjunction with an advancement for Class III, or done with a rotation to close an AOB? Without this baseline information, it is difficult to comment on associations between the skeletal and speech patterns. Additionally, this study may not be generalizable to patients with a speech-sound concern since the cohort in this study had an overall low rate of misarticulations and hypo/hypernasality, which also begs the question of how the outcomes were being measured between the two studies. Dalston and Vig calculated the total number of errors across the groups, whereas Vallino based the statistics on the number of subjects with articulation errors. It could be argued that the rounding effect that happens as a result of the Vallino approach inflates the perception of articulation errors. However, the low ratio of 1% of articulation errors in the Dalston and Vig paper might be impacted by evaluation of phonemes that are unlikely to be impacted by alveolar or dental articulation structures (such as the /m/, or /b/) which would skew the denominator and thereby dilute the impact. It is interesting to note though, that the number of articulation errors actually increased post-surgery in Dalston and Vig’s study, whereas Vallino found a continued decrease. This could be due to type of initial malocclusion and the surgical correction, since more errors seemed to be associated with superior repositioning of the maxilla.

Focusing on the Class III population, both Mishima et al. and Ahn et al. evaluated changes in vowel sounds before and after mandibular setback surgery (Bilateral Sagittal Split Ramus Osteotomy, BSSRO). Mishima evaluated 16 Class III (8 male; 8 female) cases in a Japanese population. Fundamental (F0) and formant frequencies (F1, F2) were used to evaluate
the voice characteristics of the subjects before and after mandibular setback surgery.

Recordings of the subjects making the Japanese vowel sounds: /a/, /i/, /u/, /e/ and /o/ were captured before and 6-months post-surgery. The results were also compared to a group of 50 reference subjects (25 male; 25 female) to evaluate how the surgery patients might have ‘normalized.’ The authors found significant differences between the Class III population and the reference population across four of the five vowel sounds in the female subjects and for certain formant frequencies specific to the males and females. However, no significant change in the F0 before or after surgery, and only slight changes in the formant frequencies (F2) in males.22

The lack of detectible changes in these vowel frequencies could be that Mishima’s group missed a critical window of normalization before reverting back to their pre-surgical levels.

In Ahn’s study of eight Korean Class III male subjects, attempt was made to take a closer look at the adaptation that takes place in the months following surgery. The authors used similar quantitative measures for evaluation of speech changes before and after surgery by measuring the Formant Frequencies F1 and F2 of eight vowel sounds: /a/, /e/, /i/, /o/, /u/, /\/, /æ/, and /u:/ as configured with the consonant /d/ to yield: /da/, /de/, /di/, /do/, /du/, /d\/, /dæ/, and /du:/.

Recordings were made after orthodontic decompensation but before surgery, then again at 6-weeks, 3-months and 6-months postoperatively. Intra-subject analysis was performed, as well as comparison to a group of 8 subjects with normal occlusion. Results indicated changes in F1 and F2 frequencies across all 8 vowel sounds in the 6-week and 3-months post-surgery. At the 6-month postoperative evaluation, F1 and F2 for the /a/, /e/ and /æ/ normalized, /o/ shifted toward the normal, and the remaining vowel sounds (/i/, /u/, /u:/, /\/) resumed near their pre-operative values.23 This study is valuable in its effort to put quantitative metrics to phoneme changes
before and after surgery. This also provides helpful insight into the adaptation that takes place in
the post-surgical recovery.

In summary, there is evidence indicating higher rates of SSD amongst patients with
AOB and Class III DFDs with the most common error being the /s/. There is mixed evidence
about the improvement of SSD after surgery when evaluating for rates of articulation production
errors.
CHAPTER III: CURRENT INVESTIGATION

Introduction

Speech formation requires complex coordination of air-flow against articulating structures including the tongue, cheeks, teeth and alveolus. So, it follows that pathologic speech can occur when the oral cavity is deformed.\textsuperscript{24} There can be numerous causes of jaw deformities, here called dentofacial deformities (DFD), including clefting of the palate, hypoplasia/hyperplasia of the maxilla or mandible either bilaterally or unilaterally. Such deformities present as severe Class II, Class III, Anterior Open Bite (AOB) or lateral open bite.

In the US, 2.5% of people have a DFD and an estimated 4.9% of adolescents have a speech or language disorder.\textsuperscript{5} However, Speech Sound Disorders (SSD) are closer to 80% amongst patients with negative overjet or AOB.\textsuperscript{7} This discrepancy of SSD amongst DFD patients and the general population may be indicative of a causal link. A qualitative, observational study found patients with open bites as small as \textasciitilde 2\,mm demonstrate sound production errors.\textsuperscript{16} Another observational study found that the highest rates of articulation errors were in the Class III population (90\% of Class III patients).\textsuperscript{17}

However, published data are primarily qualitative and based on speech pathologists’ subjective assessment on the presence or absence of articulation error. As such, there has not been a quantitative assessment to evaluate how the severity of occlusal and skeletal features correlates with SSD.

One method by which clinician scientists can attain quantitative metrics on sound production is via Spectral Moment Analysis (SMA). SMA is an under-utilized tool that uses
statistical descriptors to define unique characteristics of a sound wave.\textsuperscript{25,26} The first spectral moment is the mean or central tendency of the energy distribution (M1, measured in kHz). The second moment describes the variance or standard deviation of the sound energies from the central frequency (M2, measured in kHz). The third spectral moment is the tilt, or skewness of the energy distribution (M3, unitless value). It can lean positive, which un-intuitively indicates lower frequencies, or negative, which reflects higher frequencies. And the fourth spectral moment is the kurtosis, or peakedness, of the energy concentration (M4, unitless value).

**Purpose of this study**

The purpose of this study is to expand on the current body of literature and conduct a more focused assessment of the Class III subpopulation of those with DFD in order to better understand the correlation between occlusal discrepancies (caused by underlying skeletal disharmonies of the jaws) and aberrant speech.

**Hypothesis**

We hypothesize that when compared to reference subjects with ideal jaw proportions, patients with underbite or open bite have a difference in central frequencies (kHz) from stop (/t/ or /k/), fricative (/s/ or /ʃ/) and affricate (/tʃ/) sounds, and that increasing severity of jaw deformity would be correlated with increasing severity of speech abnormality (using a type I error level of 0.05).

**Aims of the study**

Aim 1: To qualify the prevalence of auditory and visual speech distortions in the skeletal Class III population as compared to the control population using qualitative assessment.

Aim 2: To compare the first spectral moment (kHz) of five articulating sounds (/t/, /k/, /s/, /ʃ/, /tʃ/) between the Class III subjects and a reference population.
Aim 3: To evaluate linear correlations for an association between the severity of malocclusion (via overjet, overbite and ANB angle) and shifts in central tendency (M1) of five phonemes.

Study Design

The study design is an observational cohort study (IRB approval 18-1406) to compare a reference population with sound and occlusal data collected from the UNC SoD DFD Clinic (described below).

Subjects

UNC SoD Department of Orthodontics DFD Clinic evaluated cases from across the region for surgical work-up. Residents collected orthodontic and surgical records including occlusal measurements, photos, panorex and cephalogram radiographs and dental models. Occlusal measurements consisted of: measurements in three planes of space: vertical (overbite), anterioiopteral (overjet, discrepancy of dental relationships as measured at the molars, premolars and canines), and transversely (presence of absence of crossbite). Beginning in May 2018, a brief speech assessment was incorporated into the standard of care and collected for all patients who are native English-speakers. Thirty-one Class III cases were analyzed (described later). A reference population (n=10) was recruited as a convenience sample from orthodontic residents, dental students and dental staff (Table 1).

Methods

Methodology for this study was adapted from Zajac et al. 2012. Subjects were qualitatively evaluated for auditory and visual distortions of the /ta/, /la/ and /sa/ sounds by a speech language pathologist (SLP) to assess if the sound was normal, interdental, dentalized, backed or lateralized.
Subjects were then directed into a sound-attenuated booth (Eckoustic Noise Control Products: Eckel Industries of Canada Limited) and fitted with a head-mounted microphone input into the Kay Pentax Computerized Speech Laboratory system (CSL Model 4500). Patients were directed to read a series of 60 phrases comprising of 20-English words (Table 2) and nested within a carrier phrase (“say ____ again”) to help simulate spontaneous speech.

The 20 words (Table 1) focus on five consonant sounds that target three specific types of production: stop sounds (/t/ and /k/), fricatives (/s/, /ʃ/ pronounced “sh”), and affricate sound (/tʃ/ pronounced “ch”).

<table>
<thead>
<tr>
<th>Consonant Phoneme</th>
<th>Vowel Phoneme</th>
<th>Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>/k/</td>
<td>/æ/</td>
<td>Cap</td>
</tr>
<tr>
<td>/k/</td>
<td>/a/</td>
<td>Cop</td>
</tr>
<tr>
<td>/k/</td>
<td>/i/</td>
<td>Key</td>
</tr>
<tr>
<td>/k/</td>
<td>/u:/</td>
<td>Coo</td>
</tr>
<tr>
<td>/t/</td>
<td>/æ/</td>
<td>Tap</td>
</tr>
<tr>
<td>/t/</td>
<td>/a/</td>
<td>Top</td>
</tr>
<tr>
<td>/t/</td>
<td>/i/</td>
<td>Tea</td>
</tr>
<tr>
<td>/t/</td>
<td>/u:/</td>
<td>Too</td>
</tr>
<tr>
<td>/tʃ/</td>
<td>/æ/</td>
<td>Chap</td>
</tr>
<tr>
<td>/tʃ/</td>
<td>/a/</td>
<td>Chop</td>
</tr>
<tr>
<td>/tʃ/</td>
<td>/i/</td>
<td>Cheap</td>
</tr>
<tr>
<td>/tʃ/</td>
<td>/u:/</td>
<td>Chew</td>
</tr>
<tr>
<td>/s/</td>
<td>/æ/</td>
<td>Sack</td>
</tr>
<tr>
<td>/s/</td>
<td>/a/</td>
<td>Sock</td>
</tr>
<tr>
<td>/s/</td>
<td>/i/</td>
<td>See</td>
</tr>
<tr>
<td>/s/</td>
<td>/u:/</td>
<td>Sue</td>
</tr>
<tr>
<td>/ʃ/</td>
<td>/æ/</td>
<td>Shack</td>
</tr>
<tr>
<td>/ʃ/</td>
<td>/a/</td>
<td>Shock</td>
</tr>
<tr>
<td>/ʃ/</td>
<td>/i/</td>
<td>She</td>
</tr>
<tr>
<td>/ʃ/</td>
<td>/u:/</td>
<td>Shoe</td>
</tr>
</tbody>
</table>

Table 1 Word list of 20 sample words. Designed to focus on consonant phonemes that articulate against the dentition or alveolus (specifically /t/, (/tʃ/, /s/) with contrasting consonants (/k/ and /ʃ/). The consonants are paired with 4 vowel sounds that reflect sound production in four corners of the oral cavity.
Each phoneme was chosen for its articulation of the tongue to either the palate, alveolus or in the case of /k/ - to the velum. In this way, the selected phonemes were contrasts to one another. For example, the /t/ has a more anterior placement (the alveolus) whereas the /k/ has a posterior placement (the velum). Similarly, the /s/ also has an alveolar articulation, but the /ʃ/ articulates more palatally. Finally, the affricate /tʃ/ behaves somewhere in-between a fricative and a stop in its articulation against the palate.

Using CSL-TF32 software, sound waves were analyzed via the Fast Fourier Transform (FFT) algorithm using a linear frequency scale, simplifying the wave to resemble a statistical distribution curve within a static window of the spectra. It is then possible to describe this energy distribution curve by the four spectral moments of SMA.

In the analysis of speech waveforms for stop (/k/, /t/) and affricate (/tʃ/) sounds, the cursor was placed at the onset of the word to capture the burst of the sound energy, which is hypothesized to be the distinctive feature of the articulation. Conversely, sound energy is parabolic for the fricative (/s/ and /ʃ/) phonemes, and so the spectral moments were taken from a sample from the midpoint of the spectrogram, where the sound energy is estimated to be the highest.

The four spectral moments were transferred from the software readout and stored in a Microsoft Excel file. For each word, the mean for each spectral moment was calculated from the three repetitions of the word. The data set was then simplified to focus on the consonant phoneme (/k/, /t/, /tʃ/, /s/, /ʃ/) by taking the means of each spectral moments (M1, M2, M3, M4) from all four words within the phoneme category resulting in a mean value taken from twelve utterances (Figure 2).
Using SAS software version 9.4 (SAS Institute, Inc., Cary, NC), groups were compared and evaluated for associations across multiple parameters: 1) A comparison of prevalence of speech distortions between DFD patients and reference subjects (Aim 1). 2) A comparison of four spectral moments across the five phonemes between DFD patients and reference subjects (Aim 2). 3) An evaluation for trend in the central frequency (M1) associated with severity of DFD overjet, overbite and ANB angle (Aim 3).

Statistics

Generalized linear models were used to compare the differences between the DFD subjects and the reference population. Linear regression models were used to evaluate the variation of all four spectral moments across differences in overjet, overbite and ANB angle.
CHAPTER IV: RESULTS

Evaluation of demographic distribution revealed the median age and interquartile range (IQR) of the reference group was older than the DFD group: 30 years (IQR: 29-32.75) versus 19 (IQR: 16.5-22), respectively. There were more females than males in the DFD group (female n = 17; male n = 14) and equal distribution of males and females in the reference group (female n = 5; male n = 5) (Table 2). When later controlling for gender differences between the two groups, the association trends were no longer statistically significant based on a type I error level of 0.05. This is likely due to insufficient power to evaluate the genders separately. Forrest et al found that the spectral moment trends were 90% accurate between genders, for this reason, the data sets were not stratified on gender.

<table>
<thead>
<tr>
<th>Groups</th>
<th>n=</th>
<th>Male</th>
<th>Female</th>
<th>Median age (IQR) yrs</th>
<th>OJ Range (mm)</th>
<th>OB Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>41</td>
<td>19</td>
<td>22</td>
<td>20 (17 – 29)</td>
<td>-17 - +5</td>
<td>-7 - +5</td>
</tr>
<tr>
<td>DFD Patients</td>
<td>31</td>
<td>14</td>
<td>17</td>
<td>19 (16.5-22)</td>
<td>-17 - +1</td>
<td>-7 - +5</td>
</tr>
<tr>
<td>Reference Subjects</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>30 (29 – 32.75)</td>
<td>+1 - 5</td>
<td>+1 - 4</td>
</tr>
<tr>
<td>OJ ≤ 0</td>
<td>25</td>
<td>14</td>
<td>11</td>
<td>19 (17-22)</td>
<td>-17 - 0</td>
<td>-3 - +5</td>
</tr>
<tr>
<td>OJ &gt; 0</td>
<td>16</td>
<td>5</td>
<td>11</td>
<td>29 (22.75 – 32.25)</td>
<td>+1 - 5</td>
<td>-7 - 4</td>
</tr>
</tbody>
</table>

Table 2: Demographics between two groups

Table 2 Demographic break-down of gender, age and occlusal features across the groups and subgroups

Twenty-four of thirty-one Class III DFD patients had an auditory distortion (77%), as compared to only 1 subject in the reference group. Twenty-eight of thirty-one Class III DFD patients had visual distortion of either the /la/ /ta/ or /sa/ (90%); with the /sa/ being the most
common distortion (n=24). This is consistent with the alternate hypothesis that there was a higher prevalence of auditory and visual speech distortions in the Class III population.

When comparing the central tendency between the Class III subjects and the reference population, there overlap of either the point estimate or the 95% confidence interval for the /k/, /s/ and /ʃ/. Conversely, with the /t/ and /tʃ/, there was distinct separation of the two groups (p<0.001) (Table 3, Figure 3). These findings are consistent with the alternative hypothesis.

![Figure 3: A comparison the central tendency (M1) between the DFD patients and the reference subjects for each of the five phonemes.](image)

In evaluating the effect of OB, linear regression modeling showed a limited impact across the phonemes and spectral moments. The only effect on the first spectral moment was found with the /t/ phoneme when observed across the combined cohort of DFD patients and reference subjects (-0.1768 kHz/mm, p=0.02). The association of the third spectral moment with differences in OB was statistically significant in the DFD patient population based on a type I error level of 0.05 for the /s/ (-0.0633/mm, p=0.05). The third and fourth spectral moment of /tʃ/ were also statistically significant in the DFD patient group based on a type I error level of 0.05
(−0.1059/mm, \(p=0.004\) and −0.3633/mm, \(p=0.008\), respectively). (Note: skew and kurtosis, the third and fourth spectral moments respectively, are unitless variables.)

For those patients for whom we had cephalometric data on (primarily the DFD patients), the effect of the ANB angle on spectral moment data was evaluated with linear regression modeling. Across 20 parameters (5 phonemes each with 4 spectral moments), positive association was only found 1 parameter: the 1st spectral moment of /ʃ/ (0.0925 kHz/ANB°; CI: 0.008:0.1774, \(p=0.03\)).

Linear regression analysis was again used to investigate the influence of OJ on the central tendency (first spectral moment, M1). First, the trend was evaluated for the association of OJ to M1 across the combined sample of DFD patients and reference subjects for each phoneme. The /t/ and /tf/ phonemes showed statistically significant negative linear associations based on a type I error level of 0.05 (\(p=0.01\)) (Figures 6a, 7a). The /k/ and /s/ phonemes had positive linear associations, although these did not quite reach the a priori 0.05 level for statistical significance (\(p=0.09\) and 0.08, respectively). And, there was minimal evidence of departure from a horizontal linear trend for the /ʃ/ phoneme (\(p=0.5\)) (Figures 5a, 8a, 9a).

Theorizing that there may be a threshold effect for these general trend lines, parameter filters were applied to identify the potential threshold. Two sets of subgroups were identified and compared: 1) DFD patients vs. reference subjects, and 2) Subjects with OJ \(\leq 0\) vs. OJ >0.

For set 1) DFD vs. reference subjects: the DFD patient subgroup had a statistically significant positive correlation between OJ and M1 for three phonemes based on a type I error level of 0.05: /k/ (\(p=0.005\)), /s/ (\(p=0.004\)) and /ʃ/ (\(p=0.04\)) meaning that as OJ increased (became less negative), there was an increase in the central tendency frequency. This was also true of the
reference group for /k/ (p=0.01) and /s/ (p=0.04), but the correlation was not statistically significant for /ʃ/ (Figures 5b, 8b, 9b).

For set 2) comparing subjects with OJ ≤ 0 vs. OJ >0, the trends for association between negative OJ and M1 became stronger, while those with positive OJ became weaker across three phonemes: /k/ (p=0.002 for OJ ≤ 0, and p=0.1 for OJ>0), /s/ (p<0.001 for OJ ≤ 0, and p=0.09 for OJ>0) and /ʃ/ (p=0.02 for OJ ≤ 0, and p=0.8 for OJ>0). Correlation trends did not hold for the subgroups with the /t/ and /ʧ/ phonemes (Figures 5c-9c).

These findings are consistent with the alternative hypothesis that there are meaningful correlations between the central tendency (1st spectral moment) and the severity of the malocclusion as indicated by the amount of negative OJ (Aim 3).
CHAPTER V: DISCUSSION

Discussion of Results

Analysis of the qualitative and quantitative data is consistent with previously published literature indicating that there are higher rates of SSD in patients with malocclusions.\textsuperscript{16,17,24} However, this is the first study to utilize SMA as a quantitative tool in this patient population. The fact that the analysis was able to detect a shift in M1 of /t/ and /ʃ/ from the reference subjects to the DFD patients is indicative that this method is adequately sensitive to detect such changes. This is also the first study to evaluate the degree of sound production errors relative to the severity of the malocclusion.

Although there was only one phoneme (/t/) to show a correlation between variation in overbite and changes in M1, we believe this parameter is deserving of future study. It is likely the sample size is not yet large enough to draw conclusions upon since only nine patients had open bite (or, negative OB).

ANB as a parameter to indicate the degree of speech distortion turned out to be weak, since only the /ʃ/ showed any correlation with the severity of malocclusion. It is likely indicative of Type 1 error, which is set at 5%, such that one in 20 will indicate a positive association, even though such an association is due to chance alone.

In this study, OJ was the occlusal feature with the greatest impact on the first spectral moment; the influence of which appears to vary across phonemes. The influence of OJ on the /t/ and /ʃ/ phonemes appears to be binary as indicated by the point-estimate stratification between the DFD and reference group (Figure 3). When put into a linear regression model, the
correlation was only statistically significant when accounting for the trend over the entire data set, but did not hold when evaluating the trend within the DFD or negative OJ group independently. This suggests that the /t/ and /tf/ follow a threshold phenomenon. So the /t/ and /tf/ will have one frequency when the OJ is greater than zero, and a different frequency when the OJ is less than or equal to zero. On the other hand, with phonemes /k/, /s/, the strongest correlations were found when evaluating the negative OJ subgroup (OJ ≤ 0), supporting the hypothesis that the severity of SSD can map with the severity of malocclusion. A summary of the correlation trends can be seen in Figure 4.

![Figure 4: Point-estimates and 95% confidence intervals of the correlation trends to evaluate kHz change of the first spectral moment relative to changes in OJ. Based on the general sample (“Overall”) for each phoneme. Subsample comparisons of DFD vs. Reference population and OJ ≤ 0 vs. OJ >0 listed adjacently.](image-url)
Limitations

One of the unexpected limitations of this study was the reading ability of some DFD patients. We did not screen for reading acuity or reading/learning differences (such as dyslexia) prior to the speech assessment. For some patients there was frequent stumbling over the words. When a subject struggled with the word, he/she was coached on the correct pronunciation of the word, asked to repeat the entire phrase. It was noted that when a subject needed to repeat the phrase, it was done in a more cautious (rather than spontaneous) manner. It is unknown whether this may have an impact on the frequency output.

This study only evaluated those individuals who self-identified as having learned English as their native language. This is important, because some languages, such as Spanish, do not use certain phonemes (for example, the /ʃ/.) However, there may also be the influence of dialect differences, which were not screened for. It is understood that most dialect differences stem from variation in vowel sounds and therefore should not impact the production consonant phonemes evaluated in this study. Moving forward in future studies of this sample set that may involve the changes in vowel production before and after surgery (similar to Ahn’s and Mishima’s studies), it may be necessary to add the dialect parameter to the model.

Reference group was taken from a convenience sample of dental students, residents and staff. As a result, there is not one-for-one matching of gender and age, so the mean age of the reference group was older than the DFD patients. It may be prudent to recruit a younger cohort that is a better age match. A larger sample size will also be necessary to narrow the confidence intervals and draw more meaningful conclusions between groups.

Our analysis was conducted using a 20ms hamming window. Some data suggest that a 40ms interval may be more discriminate for such phonemes as /k/ vs. /t/. A subset comparative
evaluation of 20ms vs. 40ms from burst release to voice onset time (VOT) is planned to help refine the methodology prior to continuation of this study.

When simplifying the sound wave into a single statistical curve using the Fast Fourier Transform (FFT) algorithm, there are two scales that can be used: a linear frequency or the Bark transform analysis. The Bark frequency transform is a method of filtering the sigmoidal curve of a sound wave; modifying the scale from Hertz to Bark units. A Bark unit represents perceptually distinct frequencies, so for higher frequencies, this behaves much the same way a logarithmic scale would. In Forrest’s 1988 study, she found that the Bark transform analysis more accurately differentiated fricative sounds such as /s/ and /ʃ/, especially in the third spectral moment (M3). Conversely, in her Master’s thesis work, Hagle found that the linear analysis yielded more distinctive capacity for M3. The present study uses the linear frequency scales across all phonemes, but the use of Bark Transform Analysis may be worthy of greater consideration.

**Future Inquiry**

This study only looks at single consonants at the start of words, and does not evaluate ‘blends’ or how a consonant behaves in the middle of a word. Future study may involve the evaluation of vowel sounds and comparison of their interaction with consonants.

Further building out the database will allow for a deeper investigation of confounding variables. We also hope to be able to parse-out the influence of gender and ethnic background. Moreover, use multivariate regression analysis may allow for better distinction of the effect of overjet when controlling for overbite.

This study is a proof-of-concept pilot study. It is the first of its kind to use SMA in the evaluation of SSD in the Class III population. Based on these initial results which indicate
statistically significant difference between those with negative overjet in our DFD patient population and our reference subjects, it is warranted to carry this technique forward into a prospective study. Future study aims include a comparative evaluation using SMA of patients before and after orthognathic surgery to assess if the improvement of jaw and dental position has a corrective effect on SSD. This will be carried out with the secondary aim to monitor spectral moment changes over six and twelve-month follow-up to monitor the stability of the correction on the SSD.

Conclusions

1. There is a higher prevalence of auditory and speech distortions in Class III patients in the DFD population when compared to the reference population.

2. There are statistically significant differences of the first spectral moment between the Class III DFD population and the reference population.

3. OB and ANB angle had minimally significant impact on the central tendency variation.

4. The presence of negative OJ is the most statistically significant indicator for variation in the central tendency of the /k/, /s/ and /ʃ/ phonemes.
Table 3: Mean values of the First Four Spectral Moments for Five Phonemes between patients and reference group

<table>
<thead>
<tr>
<th>Phoneme</th>
<th>Central Tendency M1 (kHz)</th>
<th>Variance M2 (kHz)</th>
<th>Skew M3</th>
<th>Kurtosis M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>/k/ Reference</td>
<td>8.0219 (CI: 7.3843: 8.6595)</td>
<td>4.3912 (CI: 4.1749: 4.6074)</td>
<td>0.5261 (CI: 0.2579: 0.7943)</td>
<td>0.1992 (CI: -0.2624: 0.6608)</td>
</tr>
<tr>
<td>/k/ DFD</td>
<td>8.4308 (CI: 8.1063: 8.7552)</td>
<td>4.1056 (CI: 3.9342: 4.2769)</td>
<td>0.4543 (CI: 0.3679: 0.5406)</td>
<td>0.2533 (CI: 0.0173: 0.4893)</td>
</tr>
<tr>
<td>/t/ Reference</td>
<td>7.4467 (CI: 7.0133: 7.8802)</td>
<td>2.4092 (CI: 2.2541: 2.5643)</td>
<td>1.3484 (CI: 0.9991: 1.6977)</td>
<td>3.8386 (CI: 2.3008: 5.3764)</td>
</tr>
<tr>
<td>/t/ DFD</td>
<td>8.8230 (CI: 8.4102: 9.2358)</td>
<td>2.9855 (CI: 2.7404: 3.2306)</td>
<td>0.7514 (CI: 0.6419: 0.8609)</td>
<td>1.5677 (CI: 1.1099: 2.0254)</td>
</tr>
<tr>
<td>/s/ DFD</td>
<td>9.1949 (CI: 8.8274: 9.5624)</td>
<td>2.4907 (CI: 2.2897: 2.6916)</td>
<td>0.9941 (CI: 0.8307: 1.1575)</td>
<td>2.4651 (CI: 1.8864: 3.0438)</td>
</tr>
<tr>
<td>/∫/ Reference</td>
<td>5.2864 (CI: 4.9556: 5.6173)</td>
<td>2.5346 (CI: 2.3451: 2.7241)</td>
<td>1.6701 (CI: 1.4387: 1.9014)</td>
<td>4.4051 (CI: 3.0561: 5.7541)</td>
</tr>
<tr>
<td>/∫/ DFD</td>
<td>5.8745 (CI: 5.5369: 6.2121)</td>
<td>2.7261 (CI: 2.5752: 2.8770)</td>
<td>1.4293 (CI: 1.2626: 1.5960)</td>
<td>3.1370 (CI: 2.4172: 3.8568)</td>
</tr>
</tbody>
</table>

Table 3: Comparison of point-estimates and 95% Confidence Intervals for the first four spectral moments of five phonemes between the reference group and the DFD patients.
Figure 5: Analysis for the /k/ phoneme
Figure 6: Analysis for /t/ phoneme
Figure 7: Analysis for the /tʃ/ phoneme
Figure 8: Analysis for the /s/ phoneme
Figure 9: Analysis for the /ʃ/ phoneme
REFERENCES


