FIXED-JAW EFFECTS ON TONGUE KINEMATICS & VOWEL ACOUSTICS IN AMYOTROPHIC LATERAL SCLEROSIS

A Thesis by

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Bachelor of Arts, Wichita State University, 2007

Submitted to the Department of Communication Sciences and Disorders
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Arts

May 2013

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The following faculty members have examined the final copy of this thesis for form and content, and have recommended that it be accepted in partial fulfillment of the requirement for the degree of Master of Arts with a major in Communication Sciences and Disorders.

Antje Mefferd, Committee Chair

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ACKNOWLEDGMENTS

I would like to thank, first and foremost, my professor and committee chair, Dr. Antje Mefferd, for sharing her love of research with me and providing me with a safe environment to learn. She continually challenged me to think outside of the box, for which I am grateful. Without her patient guidance and support, this thesis would not have been possible. I would also like to thank my committee members, Dr. Douglas Parham and Dr. Randolph Ellsworth, who volunteered their time to assist me in the completion of this paper. I truly appreciate the advice they offered me throughout this learning process.

In addition, I would like to thank Drew Callow for encouraging me to follow my dreams and for keeping me harmonious throughout this process. Lastly, I would like to thank my parents and my sister. They constantly supported me and provided me with reassurance when I needed it most. I will be forever grateful for your love.

ABSTRACT

This research examined tongue movements during speech in individuals with Amyotrophic Lateral Sclerosis (ALS) and controls under two speech conditions: (1) typical (jaw-free) and (2) bite block (jaw-fixed). The rationale of this study was based on previous reports that the tongue is differentially more affected than the jaw or lips by neuromuscular deterioration due to ALS; however, its impairment may be masked by compensatory jaw movements implemented to maintain speech function.

To determine bite block effects on speech movements, the time to reach the maximum tongue position during the production of /i/ was measures. Further, the maximum tongue positions during the production of /i/ and the speech acoustic measures (F1/F2) of the vowel /i/ were measured.

The time to the target position increased from the jaw-free to the jaw-fixed condition in all speakers with ALS. In contrast, two of three controls took less time to reach the target during the jaw-fixed than the jaw-free condition. Speakers with ALS tended to undershoot the target position to a greater extent than controls. However, relative change in vowel acoustics was greater for healthy controls than speakers with ALS. Differences in tongue performance between jaw-free and jaw-fixed conditions suggest that the tongue should be assessed in isolation of the jaw to better understand the impact of the disease on tongue speech performance. Further, little acoustic differences between experimental conditions suggest that acoustic measures are not sensitive to reflect underlying articulatory performance differences between healthy and impaired speakers with ALS.

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INTRODUCTION

1.1 Overview of ALS

Amyotrophic lateral sclerosis (ALS), otherwise known as Lou Gehrig's disease, is a progressive neuromuscular disease that affects the upper motorneurons in the cortex and the lower motorneurons in the brainstem and spinal cord. The term "amyotrophic" refers to the muscle atrophy, weakness, and fasciculation that take place in the lower motor neurons, whereas "lateral sclerosis" describes the hardness to palpation of the lateral columns of the spinal cord (Rowland & Shneider, 2001). The degeneration of the upper and lower motor neurons in individuals with ALS leads to spasticity, impaired reflexes, muscle fatigue, muscle weakness, and eventually muscular atrophy (Duffy, 2005).

According to the National Institute of Neurological Disorders and Stroke (2012), there are currently an estimated 20,000 to 30,000 people with ALS living in the United States and the incidence of ALS is approximately 1.89 per 100,000/year resulting in an estimated 5,000 people diagnosed each year. The mean age of onset for ALS is about 60 years and there is a slight male prevalence (Wijesekera & Leigh, 2009). ALS can be sporadic or familial. In sporadic ALS, the underlying reasons for the disease are currently unknown. In familiar ALS, a gene defect has been identified (Siddique & Ajroud-Driss, 2011). Only about 10% of cases have a family history of ALS (Siddique & Ajroud-Driss, 2011).

1.2 Classification of ALS

Based on its initial manifestation, ALS can be categorized in two forms: spinal and bulbar. A majority of individuals diagnosed with ALS have a spinal form of the disease and go on to develop bulbar symptoms. ALS is termed *spinal* if the initial symptoms are confined to the limbs (Caroscio, Mulvihill, Sterling, & Abrams, 1987). The symptoms of spinal ALS may start asymmetrically, but become symmetrical later. Individuals with spinal ALS often present with symptoms related to focal muscle weakness, which start distally or proximally in the upper limbs and lower limbs. Initially, there is generally no evidence of dysarthria or dysphagia in this form of ALS. However, at some point of disease progression, *bulbar* involvement usually occurs.

While the first signs and symptoms of ALS often occur in the limbs, 25% of patients identify their initial symptoms as being in the bulbar muscles (Duffy, 2005). Dysarthria and dysphagia are often the first representations of bulbar ALS. Within a couple of years, patients with bulbar onset will develop limb weakness. Due to dysphagia and respiratory deficiencies, individuals with bulbar deficits tend to have a more rapid course of the disease (Duffy, 2005). While cognitive deficits do not become the primary health concern in individuals with ALS, they tend to be more evident in individuals with bulbar onset (Abrahams et al., 1997). Because there is currently no cure for ALS, respiratory failure and other pulmonary complications due to weakened respiratory muscles are most often the cause of death.

1.3 Diagnosing ALS

A definitive test for diagnosing ALS does not exist despite numerous advances in medicine. Therefore, ALS is diagnosed based on the presence of characteristic clinical findings in conjunction with investigations to exclude other health conditions that may mimic ALS (Kinsley & Siddique, 2012). These syndromes include, but are not limited to, cervical spondylotic myelopathy, brainstem lesions, and inclusion body myositis (IBM). A diagnostic error in 5% to 10% of cases occurs as a result of "ALS-mimic" syndromes (Wijesekera & Leigh, 2009). As a result, electrophysiological, imaging, cerebrospinal fluid (CSF) or serological studies are often conducted as a means to distinguish signs of upper motor neuron (UMN) and lower motor neuron (LMN) deterioration that cannot be attributed to any other disease process. This, combined with progression compatible with a neurodegenerative disorder, is suggestive of ALS (Wijesekera & Leigh, 2009).

1.4 Clinical Features and Speech Characteristics of ALS

Prior to the onset of muscle weakness, patients may have noticed involuntary muscle twitching (fasciculations) or cramps. However, these are rarely the presenting symptoms of ALS (Wijesekera & Leigh, 2009). As the disease progresses, spasticity may develop and affect manual dexterity and gait. Early focal muscle atrophy commonly affects the muscles of the hands, forearms or shoulders, and proximal thigh or distal foot muscles (Wijesekera & Leigh, 2009).

Patients with bulbar involvement usually develop mixed spastic-flaccid dysarthria because both the UMNs and LMNs are affected (Darley, Aronson, & Brown, 1969). Dysarthria is common in ALS due to a decline in motor control necessary to articulate speech sounds precisely. Speaking rate declines with disease progression and typically predates the decline of speech intelligibility (Ball, Beukelman, & Pattee, 2002). As dysarthria becomes more severe, intelligibility decreases leading to an impaired ability to communicate first in adverse speaking situations, such as in a noisy room, and eventually in all situations (Beukelman, Fager, & Nordness, 2011).

Perceptual-rating tasks have been conducted in the past with the intent of identifying speech characteristics in individuals with ALS (Darley, Aronson, & Brown, 1969). It has been shown that speakers with ALS have a high incidence of imprecise consonants, which are defined as being void of sharpness and precision. Furthermore, speakers often present with slow and hypernasal speech. The decrease in articulatory and speaking rates is often attributed to increased pause time and increased durations of sound production (Yunusova et al., 2010).

As ALS progresses, facial weakness affects the lower half of the face, which results in difficulty with lip seal and blowing cheeks (Wijesekera & Leigh, 2009). Fasciculations and muscle atrophy of the tongue develop as the disease progresses, and tongue movements are slowed due to disease progression. Motor denervation of bulbar musculature results in deterioration and eventual loss of the ability to swallow which leads to an increased risk of aspiration, malnutrition, weight loss, and dehydration.

While there is emerging literature on the effect that ALS has on the speech mechanism as a whole, little is known about the consequences of disease progression on individual articulators. In order to fully understand the disease progression of ALS, articulators should be assessed on an individual basis. In doing so, clinicians will have a better understanding of how to assess speakers with ALS in order to gain the most accurate information.

CHAPTER 2

MOTIVATION OF STUDY

2.1 Compensatory Speech Strategies

When discussing the speech of individuals with ALS, it has often been suggested that speakers with ALS use compensatory strategies to maintain intelligibility during the early stages of the disease. The compensatory strategies may mask the effect of ALS on speech. Typically, movements of the tongue and lips produce speech, whereas the jaw operates as a gross-adjuster of the oral opening during speech movements. Due to its role, the jaw often has been considered a stabilizer supporting tongue and lips during speech rather than an active articulator (Green, Moore, & Reilly, 2002). However, because the tongue deteriorates at a much faster rate than the jaw in ALS (DePaul et al., 1988; Langmore & Lehman, 1994), one longstanding hypothesis has been that the jaw may become more active during speech to compensate for the relatively weaker tongue. Indeed, kinematic studies have shown larger jaw movements in speakers with ALS than in healthy speakers during fast diadochokinetic syllable repetitions (Hirose, Kiritani, & Sawashima, 1982; Mefferd, Green, & Pattee, 2012) and word production (Yunusova, Weismer, Westbury & Lindstrom, 2008). Tongue motor performance independent of the jaw, however, has rarely been studied in ALS. Such information is important to determine if the large jaw movements are indeed promoting speech production or if larger than typical jaw movements are a symptom of deteriorating jaw motor control.

In healthy speakers, bite blocks have been used in the past to assess tongue performance in isolation of the jaw (Gay, Lindblom, & Lubker, 1981). Bite blocks are created by clenching a piece of dental putty between the molars. A catalyst is added to the dental putty to harden the material after an impression has been made. When the bite block is in the mouth, a 10mm gap is created between the front teeth. In 1979, Lindblom, Lubker and Gay reported almost perfect articulatory compensation for isolated vowels in the presence of a very large bite-block (25 mm), even at the first glottal impulse. This means that the articulatory adjustment to a very large bite-block was completed before the speakers could use auditory feedback and adjust tongue movement accordingly. Researchers concluded that the brain is able to adjust motor commands to specific conditions (such as a large bite block) during the planning stage before auditory feedback is available. Specifically, due to an abnormal configuration of the jaw's position during speech, speakers would adjust to the bite block by increasing their tongue movements. Further, in healthy speakers, movement durations did not change in response to the bite block (Solomon & Munson, 2004) and speakers achieved full acoustic compensation (Kelso & Tuller, 1983; Sussman, Fruchter & Cable, 1995). However, this understanding about a fixed-jaw effect on articulatory movements was based solely on acoustic measurements. It has not been studied directly by investigating the tongue movements.

It has long been suggested to use bite blocks in the evaluation of speakers with speech motor impairments to better understand the effect of the disease on each articulator (Netsell, 1985). However, to date the effects of bite blocks on speech production in speakers with dysarthria have rarely been studied. Particularly in ALS, where it is well-known that the disease does not affect all articulators equally, the use of a bite block may provide valuable insights to delineate in the effects of the disease on each articulator during speech production. Comparing the speaker's performance during bite block speech (jaw-fixed) and typical speech (jaw-free) may give insights as to how the disease affects articulatory movements (jaw-fixed condition) and how the speaker with ALS compensates for this articulatory decline (jaw-free condition).

To address this knowledge gap in the literature, the present study sought to determine if the effects of a fixed jaw (i.e., holding a bite block between the molars) on tongue movements and speech acoustics differed between speakers with ALS and healthy controls. Table 1 summarizes our hypotheses. Based on previous studies, we expected that healthy speakers would successfully compensate for the fixed jaw by increasing their tongue movements and reaching the same vocal tract configuration despite the unnatural position of the jaw. Further, the acoustic signal of the vowel production would remain unchanged between the jaw-fixed and jaw-free conditions. Finally, movement durations between the jaw-fixed and the jaw-free condition would not differ.

In persons with ALS, however, we expected that the ability to compensate for a fixed jaw would be diminished due to the disease-related decline in tongue range of motion. That is, speakers with ALS would show differences in their vocal tract configuration and the tongue would not reach the same position during the jaw-fixed condition when compared to the jaw-free condition. Consequently, the acoustic signal of a vowel production (i.e., /i/) would differ between the two experimental conditions as a result of differing tongue positions. Finally, movement durations of the tongue would be longer during the jaw-fixed position relative to the jaw-free condition because the bite block would create a gap between the front teeth, requiring speakers to increase their tongue movements in the inferior-superior dimension.

TABLE 1

STUDY HYPOTHESES

Variable	**Healthy Speakers**	**Speakers with ALS**
Tongue Position	Minimal change in tongue position between conditions	Large change in tongue position between conditions
Movement Duration	Similar durations between conditions	Longer durations between conditions
Acoustic Signal	Minimal change in vowel acoustics between conditions	Large change in vowel acoustics between conditions

CHAPTER 3

METHODS

3.1 Participants

Three participants with ALS and three age-and-sex-matched healthy controls were included in this study. All participants passed a hearing screening at 0.5, 1, 2, and 4 kHz at 30dB to assure adequate hearing. Participants were only included in this study if they were free of any neurological diseases other than ALS. To determine the severity of their speech impairment, all participants completed the Sentence Intelligibility Test (SIT; Beukelman, Yorkston, Hakel, & Dorsey, 2007). One listener transcribed ten recorded sentences that varied in length and complexity using the SIT software program. Based on these sentences, articulatory rates (AR) of all speakers were also calculated by recording the number of words spoken per minute. A combination of the sentence intelligibility scores and articulatory rates was used to group speakers into different speech severities. The results of the SIT scores and articulation rates classified two of the participants with ALS as having a mildly impaired speech function whereas one participant with ALS was severely impaired in their speech function.

Table 2 provides the demographics and speech characteristics of speakers with ALS. Articulatory rates (AR) were recorded in words per minute, whereas sentence intelligibility scores (SIT) were recorded as percentages. An average AR of healthy speakers is approximately 200 words per minute. Therefore, A1 and A2 were within the normal range for AR and their speech was fully intelligible. A7 was significantly slower than the other speakers with ALS and only half of his speech was intelligible due to hypernasality and imprecise articulation.

TABLE 2

ARTICULATORY RATE (AR) AND SENTENCE INTELLIGIBILITY (SIT) IN SPEAKERS WITH ALS

ID	Sex	Age	Severity	AR	SIT	Speech Characteristics
A1	M	67	Mild	170	98	Mild articulatory imprecisions
A2	M	59	Mild	211	99	Mild articulatory imprecisions
A7	M	53	Severe	96	55	Hypernasality, slow and imprecise articulation

3.2 Experimental Tasks

All participants were asked to complete five repetitions of the sentence “See a kite again” at a typical speaking rate under two conditions: (1) jaw-free and (2) jaw-fixed. The vowel /i/ in the word “see” was analyzed for the purpose of this study. This vowel was chosen because it requires the tongue to be very close to the palate. When the jaw is fixed at a larger jaw opening than during unconstrained speech (jaw-free), then the tongue has to move further to reach the same position during the vowel production. Tongue excursions have to become larger, but completed in the same timely fashion; therefore, movement speed of the tongue also has to be increased. Thus, successful compensation can be observed when the jaw is lowered and the tongue still reaches the same position relative to the jaw-free condition in the same amount of time.

3.3 Experimental Setup

Prior to data collection a custom bite block was created for each participant using dental putty (Henry Schein). The bite block was prepared based on the descriptions by Netsell (1985) with an inter-incisal distance of 10mm. This distance is most commonly used for bite block and has been suggested by Netsell (1985) as an ideal opening distance to assess tongue and lip movements independent of the jaw.

Movement data acquisition

Speech movements were tracked using the 3D Electromagnetic Articulograph (AG500, Medizintechnik Carstens, Bovenden, Germany). The participant is seated in a plexiglass cube with six electromagnets, which create an electromagnetic field inside of the plexiglass cube. When small sensor coils (2mm x 2 mm) are moved in this electromagnetic field, a low electrical current is induced. The electrical current varies in strength depending on the position of the sensor inside the cube and the proximity to the electromagnets. The electrical current is so low that it needs to be amplified before submitting its values to an algorithm, which calculates positional data in three dimensions of each sensor at a sampling rate of 200 Hz.

Figure 1 displays information about the sensor set-up and head-reference coordinate system. The vowel space was reoriented so it would be referenced to the shape of the mouth. As a result, the dimensions were flipped. To track speech movements, two sensors were attached to the sagittal midline of the tongue approximately 1.5cm and 4cm posterior to the tip of the tongue. Two additional sensors were placed on the lateral surface of the right and left lower canine teeth and another sensor was placed at the midline of the lower lip at the vermillion border. Further, three head reference sensors were placed on plastic goggles, which the participant wore during the data collection. Only the movements of the posterior tongue sensor were analyzed in this study. These reference sensors on the goggles, the jaw, and the lower lip were used to create a head-referenced coordinate system. The sensors on the goggles also were used to track head movements, which later were removed from the speech movements registered by the tongue sensors.

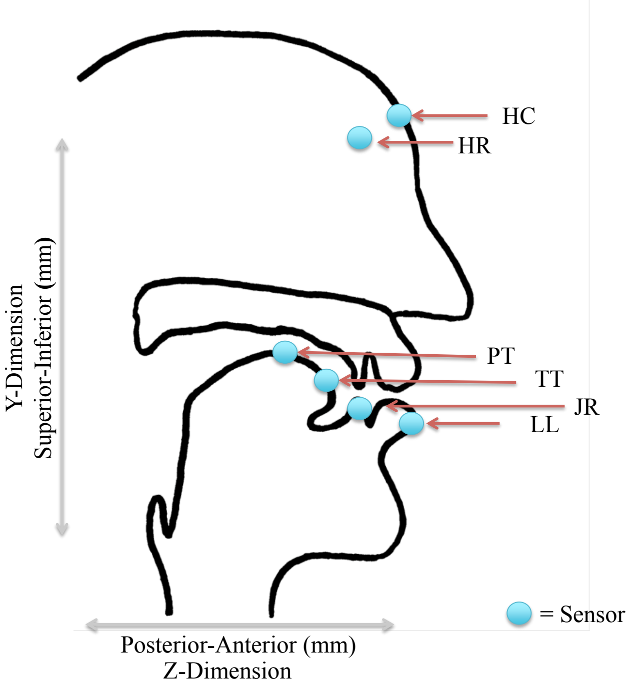

Figure 1. Electromagnetic sensor set-up. HC = Head center reference sensor, HR = Head right reference sensor, PT = posterior tongue sensor, TT = tip of tongue sensor, JR = jaw right sensor, LL = lower lip sensor.

Acoustic data

A small lavalier microphone was mounted to the outside of the plexiglass cube under which the participant was seated. This created a mouth-to-microphone distance of approximately 20cm. The microphone could not be placed closer to the mouth because it would have distorted the electromagnetic field inside of the cube. Acoustic data was synchronized in time with the kinematic data and was recorded with a sampling rate of 16 kHz and a quantization level of 16 bits.

3.4 Data Analysis

Kinematic data

Kinematic data was head-corrected using the NormPos software program (Medizintechnik Carstens, Bovenden, Germany). In addition, a local coordinate system was established with an origin defined at the center of the lower lip when lips are closed. In the case that the lower lip sensor contained tracking errors, the origin was established based on the center head sensor or the tip of the tongue sensor. Movement in the superior-inferior dimension was defined as the Y-dimension and movement in the anterior-posterior dimension was defined as the Z-dimension. Lateral tongue movement (X-dimension) was not analyzed in this study because speech movements predominantly occur in the anterior-posterior and superior-inferior dimensions.

Figure 2 displays waveform (top panel) and time histories of the posterior tongue sensor in the *y* and *z* dimensions during the production of the entire sentence “See a kite again.” In this study, the maximum vertical tongue position (*y*-dimension) and its corresponding position in the anterior-posterior plane (*z*-dimension) during the production of /i/ in “see” was of interest. As previously stated (See page 10), the vowel /i/ in “see” was chosen because it is a high vowel and it requires the tongue to be close to the palate. The vowel onset of /i/ in “see” was determined based on the acoustic waveform. To determine the *temporal adjustments* of the tongue in response to the fixed jaw, the relative time between vowel onset and the maximum vertical tongue position was measured, recorded, and compared between the jaw-free and jaw-fixed position (see Figure 2). The smaller the change in duration, the better the talker compensated for the fixed jaw. Relative times were also compared between participants with ALS and healthy controls for the jaw-free and jaw-fixed position to determine the effect of ALS on durational adjustments.

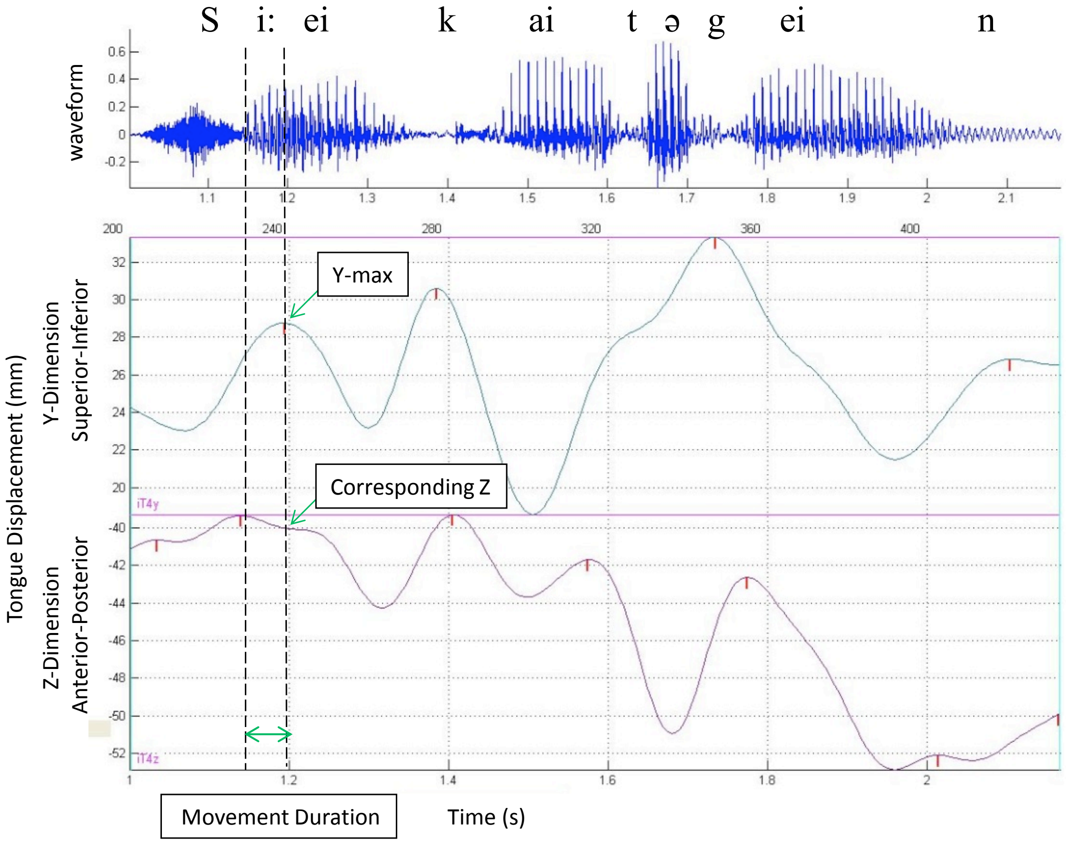

Figure 2. Tongue movements and the acoustic waveform of the target utterance.

To determine the *spatial adjustments* of the tongue in response to the fixed jaw, the maximum displacement of the tongue in the superior-inferior dimension (Y-max) and the corresponding position in the z-dimension (anterior-posterior movement) were extracted for each repetition of the word “see.” The relative change in tongue position (Y-max; Z) between jaw-free and jaw-fixed conditions was then calculated (see Figure 3). The smaller the relative change in the position, the better the talker compensated for the fixed jaw. Absolute values of the tongue position during each speech condition could not be compared between participants because positional data was dependent on the origin of the coordinate system, which differed among speakers. Deriving the relative change in tongue positions permitted comparisons between participants.

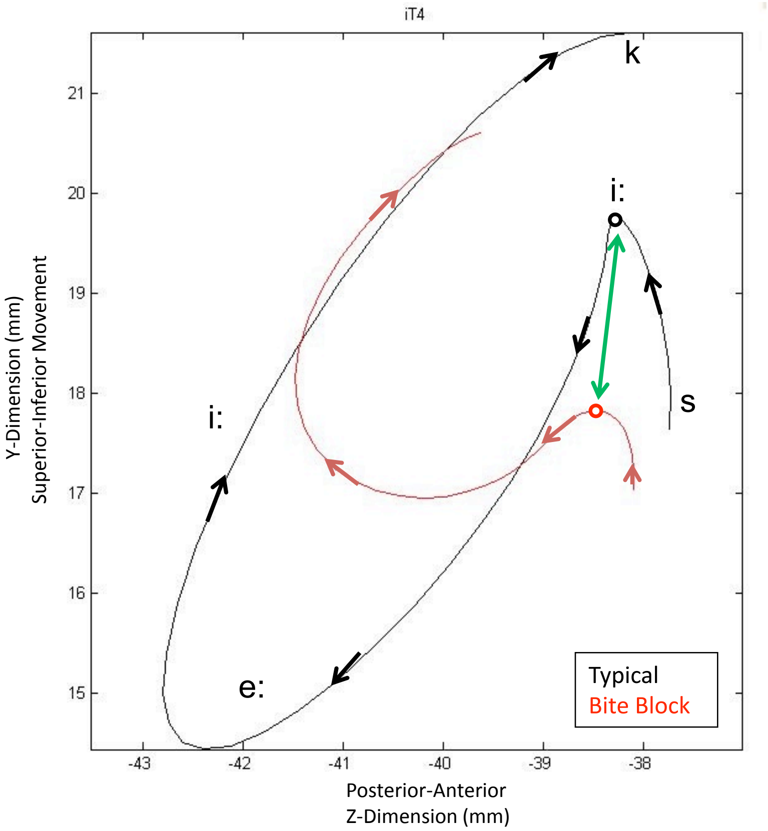

Figure 3. A healthy speaker's posterior tongue movement trajectory during the phrase "See a k" in the sagittal dimension. Black (darker) and red (lighter) arrows indicate movement direction. Green arrow indicates one of the dependent variables of the study - the relative positional change of the tongue during the production of /i/ in response to bite block.

Acoustic data

Acoustic data was analyzed using the linear predictive coding algorithm (LPC) with the default settings in TF32 (Milenkovic, 2005, University of Wisconsin). To determine the acoustic consequences of tongue adjustments in response to the bite block, the F1 and F2 values of the vowel /i/ in “see” were extracted at the point of the maximum vertical tongue position for each repetition in each condition (see Figure 4). F1 relates to tongue height and F2 relates to tongue movement in the anterior-posterior dimension.

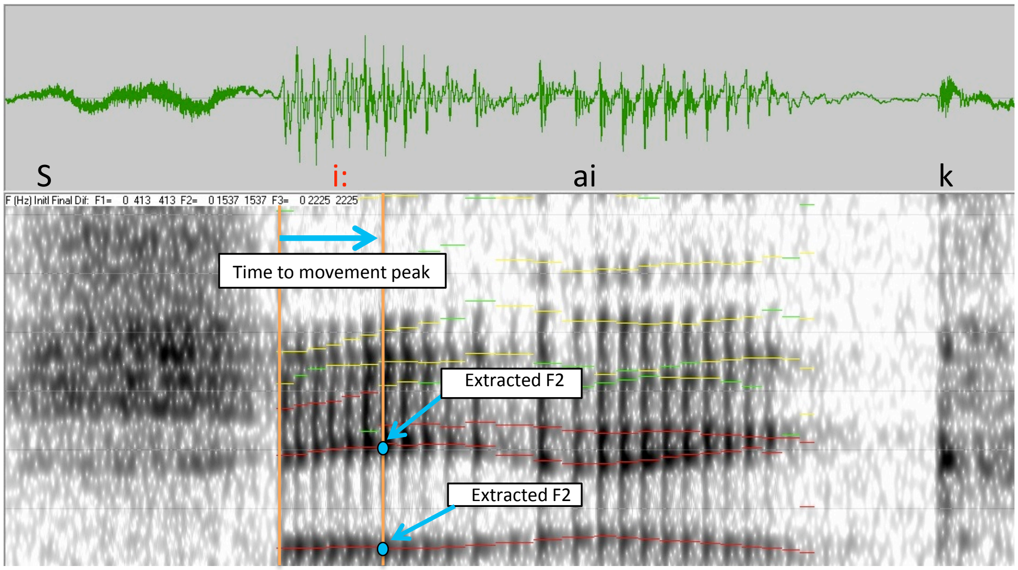

Figure 4. Spectrographic display and acoustic waveform of the phrase “See a k” used to determine F1 and F2 values of the vowel /i/.

This point was identified in the acoustic signal by setting one cursor to the onset of /i/ in “see,” which was defined in the waveform and in the spectrogram as the first glottal impulse in “see,” and then moving another cursor along the *x*-axis (time) until the duration was reached that was recorded during the kinematic analysis as the duration to the maximum vertical tongue position. The resulting F1 and F2 values during the time of the maximum vertical position were extracted. These F1 and F2 values were used to calculate a positional data point in the acoustic vowel space. The effect of the bite block was determined by calculating the relative change in the F1/F2 position for /i/ between the jaw-free and jaw-fixed position. The smaller the relative change, the better the talker compensated for the bite block. To determine the effects of ALS, the relative changes in F1/F2 position for /i/ were compared between the ALS group and the control group.

Statistical Analysis

The dependent variables were (1) movement durations to the target, (2) the relative change in tongue position, and (3) the relative change in F1/F2 vowel space. Independent variables were (1) the two groups of speakers (ALS, controls) and (2) the two speech conditions (jaw-free, jaw-fixed). Due to the small number of participants, data analysis was completed in a descriptive fashion.

CHAPTER 4

RESULTS

4.1 Durational Findings

Figure 4 showed movement durations to the maximum tongue position during the vowel /i/ for each participant for the jaw-free and jaw-fixed conditions. It can be noted in Figure 4 that in two of the control speakers, durations decreased from the jaw-free to the jaw-fixed condition. However, in one of the control speakers (C2), the opposite was true; durations were shorter in the jaw-free condition when compared to the jaw-fixed condition. When comparing the durations of the jaw-free and the jaw-fixed conditions in the ALS group, all speakers with ALS exhibited longer durations during the jaw-fixed condition than the jaw-free condition.

When comparing between groups within the jaw free condition, one speaker with mild ALS (A2) had similar durations as controls, whereas the other speakers with mild ALS (A1) demonstrated longer durations. In the jaw-fixed conditions, all three speakers with ALS had longer durations than two of the controls. Finally, the speaker with severe ALS (A7) presented with longer durations than the two participants with mild ALS in the jaw-free and jaw-fixed conditions.

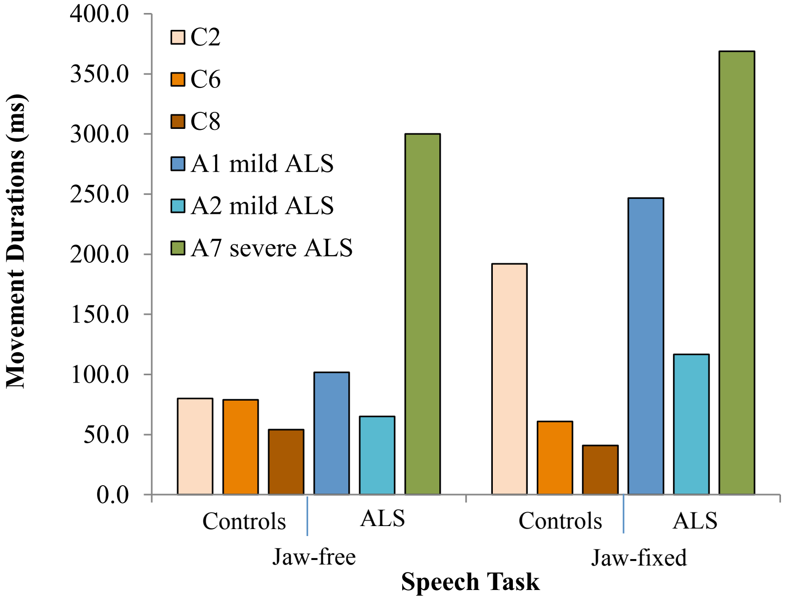

Figure 5. Movement durations across conditions.

4.2 Kinematic Findings

Tongue positions for healthy speakers and speakers with ALS are displayed in Figure 6 and Figure 7, respectively. For better illustration of the data, the tongue positions during the jaw-free condition were normalized across all participants and represented as only one data point. In general, talkers with ALS undershot their target position in the *y*-dimension (tongue height) to a greater extent than controls. Further, talkers with ALS overshot the target in the *z*-dimension (tongue advancement) to a greater extent than controls.

Analyzing the data within each group on an individual basis, findings show speaker-specific responses to the jaw-fixed condition. C2 slightly *under*shot the target position of the vowel /i/ in the *y*-dimension while C8 slightly *over*shot the target position in the *y*-dimension. C6 was relatively close to the target position in the *y*-dimension. However, the location of the tongue in the x-dimension was approximately 5 mm from the target and therefore much further advanced than in the other controls.

The horizontal line in Figure 7 represents the tongue position of the healthy control speaker who undershot the target in the vertical dimension the most. The two speakers with ALS were still below the position of the control speaker who undershot the most. Surprisingly, the speaker with severe ALS (A7) undershot the target in a comparable extent to one of the speakers with mild ALS (A2). The severe speaker with ALS, however, displayed further advancements of the tongue during the jaw-fixed position than both speakers with mild ALS or any of the control speakers. It is also noteworthy that one of the speakers with mild ALS (A1) displayed the closest tongue position relative to the jaw-free position of all participants in the study.

Table 3 summarizes the relative change in tongue position from the jaw-free to the jaw-fixed position for each participant in each movement dimension and as a 2D Euclidean distance measure. The tongue height change, A-P tongue change, and 2D position change are recorded in millimeters.

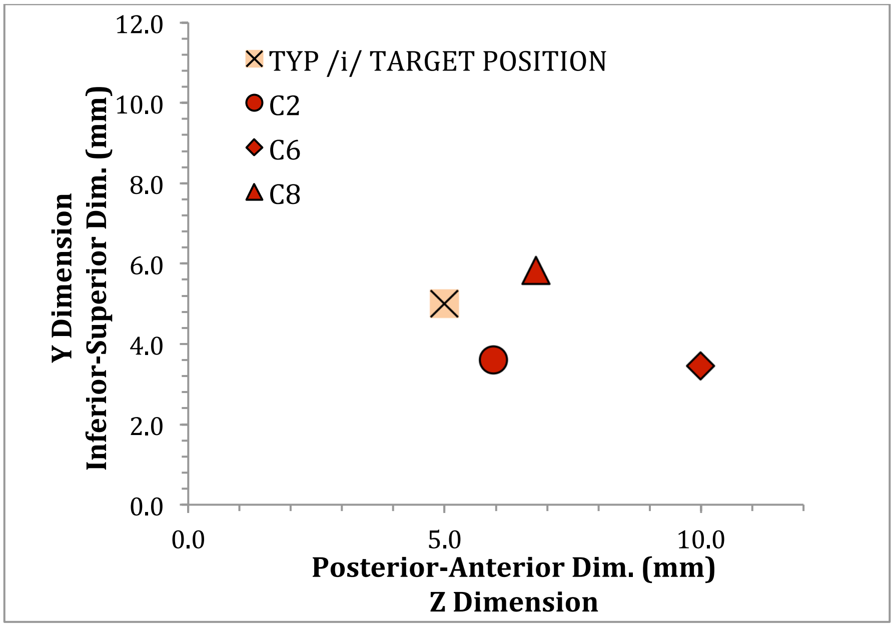

Figure 6. Tongue positions of the controls.

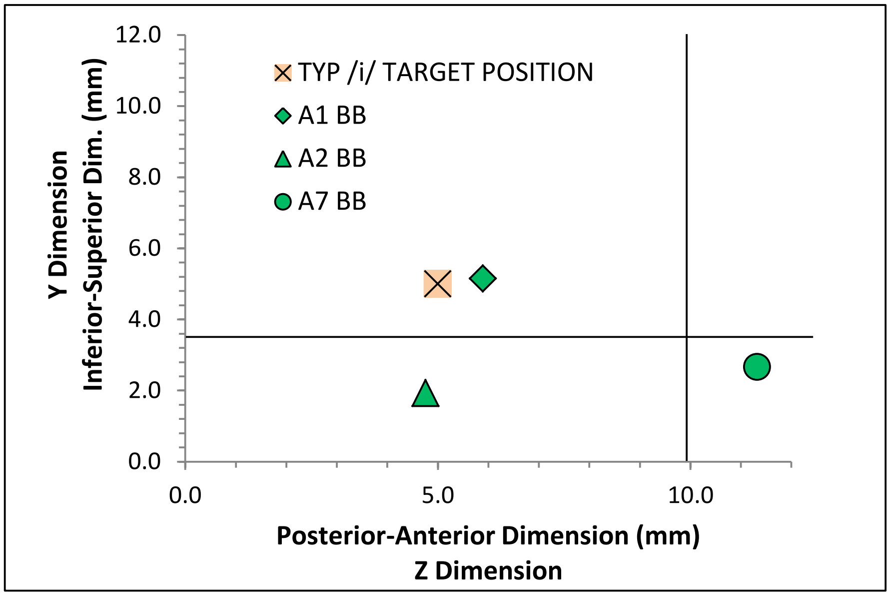

Figure 7. Tongue positions of the speakers with ALS.

TABLE 3

RELATIVE CHANGES IN TONGUE POSITION BETWEEN THE JAW-FREE AND JAW-FIXED CONDITIONS

Code	Tongue height change	A-P tongue change	2D position change
A1	0.2	0.9	0.9
A2	-3.1	-0.2	3.1
A7	-2.3	6.3	6.7
C2	-1.4	0.95	1.7
C6	-1.5	5.0	5.2
C8	0.8	1.8	2.0

4.3 Acoustic Data

This study examined vowel acoustics to determine whether or not the effect of the bite block could be detected in the acoustic domain. Change in F1 is associated with change in tongue height (superior-inferior dimension), whereas change in F2 is associated with change in tongue advancement (posterior-anterior dimension). To illustrate the change from the jaw-free to the jaw-fixed condition, all data of the jaw-free condition was normalized and represented as one data point. The relative change in F1/F2 vowel space was then plotted for each participant. Figures 8 and 9 show the acoustic results of the controls and persons with ALS, respectively. Further, Table 4 shows the relative change from the jaw-free to the jaw-fixed condition for each formant (F1, F2) and the 2D Euclidean distance in F1/F2 acoustic vowel space from the jaw-free to the jaw-fixed condition change. Data are represented in Hz.

In general, controls showed differences between the jaw-free and the jaw-fixed conditions in both the F1 and F2, as well as the 2D Euclidean distance in F1/F2 vowel space. One should note, however, that for formant acoustic measures, relative changes in F1 and F2 from one condition to another of approximately 50Hz are still within a natural variability change (Peterson & Barney, 1952) and should not be interpreted as a condition effect (see F1 values of all control speakers in Table 4), whereas changes above 50 Hz are more likely elicited by the speech condition (see F2 values of C2 and C6 in Table 4). In contrast to healthy speakers, the speakers with ALS showed similar F1 and F2 values of the vowel /i/ during the jaw-fixed condition as in the jaw-free condition.

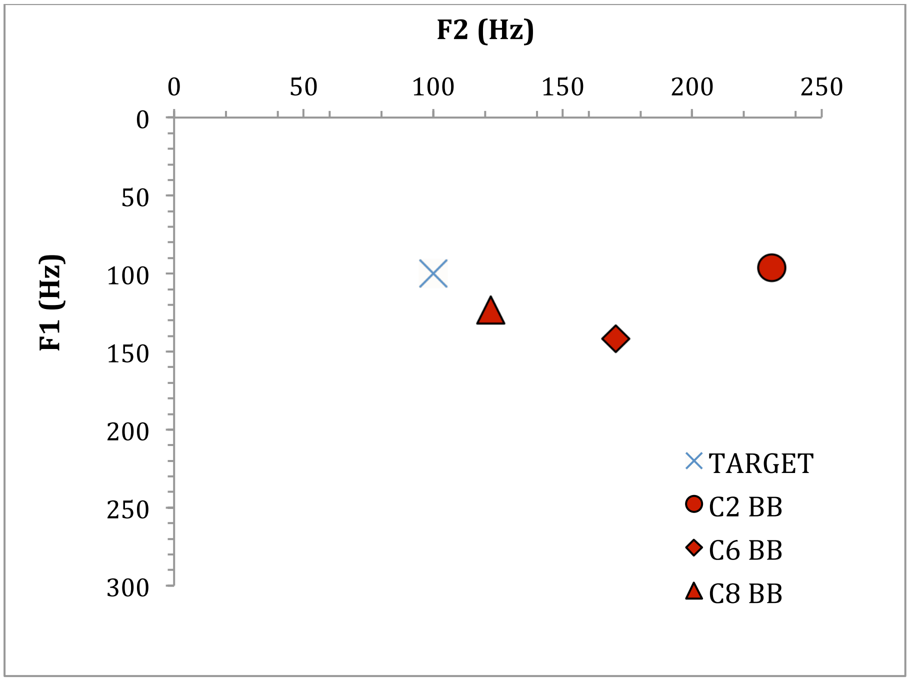

Figure 8. Vowel acoustics in controls.

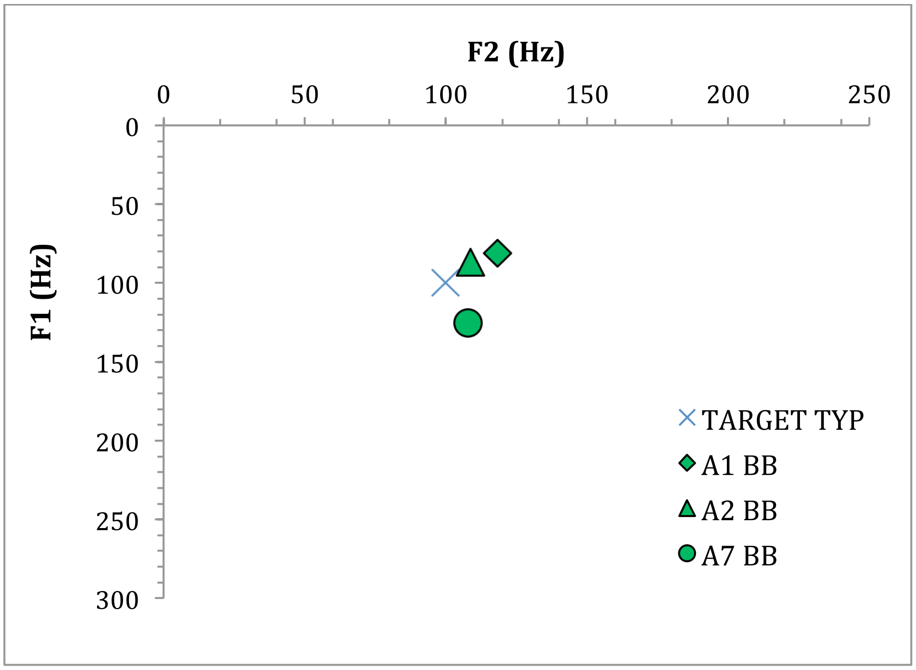

Figure 9. Vowel acoustics in speakers with ALS.

TABLE 4

CHANGES IN VOWEL ACOUSTICS

Code	Change in F1	Change in F2	F1/F2 distance change
A1	-18.7	18.3	26.2
A2	-13.3	8.7	15.9
A7	25.5	7.8	26.7
C2	-3.8	130.8	130.9
C6	41.6	70.6	81.9
C8	23.2	22.4	32.2

CHAPTER 5

DISCUSSION

The primary aim of this study was to research the effects of ALS on the articulators and to determine the extent to which jaw movements compensate for declining articulatory performance of the tongue in speakers with ALS. Tongue movements and vowel acoustics of speakers with mild and severe ALS were compared with those of healthy controls under two conditions: jaw-free and jaw-fixed. Bite blocks made out of dental putty were formed on an individual basis to fix the jaw. Based on previous acoustic studies, we expected healthy speakers to compensate for the fixed jaw (i.e., achieving the same tongue position during the production of the vowel /i/ in the same amount of time, achieving the same acoustic measures of the vowel /i/). Further, we expected speakers with ALS to be unable to fully compensate for the fixed jaw (i.e., not achieving the same tongue position during the production of the vowel /i/ and not achieving the same acoustic measures of the vowel /i/). Further, we expected that the time to the reach the maximum tongue excursion would be longer in the jaw-fixed condition for speakers with ALS due to increased distance and their potentially reduced speed capacity. These hypotheses for speakers with ALS were based on the literature reporting that ALS primarily affected the tongue in the head and neck (bulbar) system.

5.1 Durational Data

Limited research is available to compare our findings of durational changes in healthy speakers to previous studies. Only one study by Solomon and Munson (2004) is currently available, which reported on change in durations in response to a fixed jaw. In our study, durations to the movement peak slightly decreased from the jaw-free to the jaw-fixed position. This finding was rather unexpected because the tongue has to move a larger distance in the jaw-fixed condition to reach the same tongue height than in the jaw-free condition. An increase in tongue excursion may elicit an increase in tongue speed since movement excursion and movement speed are typically scaled (Ostry, Cooke, & Munhall, 1987). It is, therefore, possible that an increase in tongue speed may have shortened movement duration of the tongue in response to a fixed jaw. There was only one instance in which a control (C2) had much longer movement durations during the jaw fixed condition than the jaw free condition. Because this speaker also increased pause durations during the production of the target sentence in the jaw fixed condition, he may have slowed his speaking rate volitionally, perhaps to ensure speech precision.

In the ALS group, our findings proved to be consistent with our initial hypothesis. As expected based on previous research showing slower speaking rates in talkers with ALS than controls, tongue movement durations tended to be greater in speakers with ALS than controls in the jaw-free condition. Further, tongue durations increased in response to the fixed jaw condition in the ALS group. The individual with severe ALS displayed the longest durations during both conditions compared to those of controls and the participants with mild ALS. Although the data is very preliminary, it can be concluded that speakers with ALS may not be able to adjust their movement speeds to the fixed-jaw condition as well as healthy speakers, hence the longer durations. Articulatory speed constraints have been shown previously for lower lip and jaw movements in persons with ALS who had only mild speech impairments (Mefferd, Green, & Pattee, 2012). Prolonged movement durations during speech, reduced speed and excursions of the tongue have been also reported previously for speakers with ALS (Yunusova et al., 2012). Finally, the findings of this study suggest that as the severity of ALS increases, the time it takes the individuals to be able to reach the target tongue positions increases as well; perhaps because these speakers become more constrained in their ability to generate adequate speeds with disease progression.

5.2 Kinematic Data

The ability to reach the typical target position varied among healthy speakers and speakers with ALS. The mixed findings for healthy speakers were rather unexpected because previous research reported that healthy speakers can compensate for such constrained speech conditions (Gay et al., 1981). An interesting finding is that, in contrast to speakers with ALS, the deviations in tongue position among healthy speakers were more prominent along the palate than in the tongue height. Because critical features of the vowel /i/ are close constriction to the hard palate (high vowel) and tongue advancement (front vowel), it is possible that healthy speakers enhanced the tongue advancement in an attempt to compensate for insufficient tongue height. Alternatively, it is also possible that speakers have intrinsic knowledge about the articulatory-to-acoustic relations and non-linear “zones” within the mapping of articulation and acoustics. For example, it has been shown that incremental change in the location of tongue constriction along the palate may result in minimal acoustic change, whereas incremental change in the degree of tongue constriction at the same location of the palate may result in drastic acoustic change (Perkell et al., 2002; Stevens, 1989).

In the ALS group, two speakers undershot the target position in the vertical dimension, while one was very close to the typical target position. Although our observations are preliminary, these findings suggest that as ALS progresses, the ability to adjust to a fixed jaw becomes compromised. Our findings support the notion that individuals with ALS may increase their jaw movements during speech as a compensatory strategy to support relatively more affected tongue function.

5.3 Acoustic Data

Our findings showed acoustically incomplete compensation of the fixed jaw in healthy speakers. This finding is not in line with previous reports of full compensation (Gay et al., 1981; Lindblom et al., 1979; Lubker, 1979; Kelso & Tuller, 1983; Sussman, Fruchter & Cable, 1995). However, most of these studies reporting complete compensation did not complete statistical analyses on their results. Thus, differences between jaw free and jaw fixed conditions observed in these studies were interpreted as normal performance variability (McFarland & Baum, 1995). Later, publications appeared, which did report subtle changes in response to a fixed jaw. For example, McFarland and Baum reported small acoustic differences between jaw-free and jaw-fixed speech conditions; however, these were more dominant for consonant than vowel productions. Further, Jacks (2008) showed incomplete compensation of a fixed jaw for vowel productions even in healthy speakers. Our results are similar to the study by Jacks and also agree with our tongue movement findings; the overshoot in the posterior-anterior dimension (too much tongue advancement) in response to the fixed jaw corresponded to the observed shifts in the F2 (Figure 6).

While two of the three speakers with ALS undershot articulatory targets to a greater degree than controls, all speakers with ALS were closer to the target values for the vowel /i/ than healthy controls. These acoustic findings for speakers with ALS were rather surprising because they would not necessarily be predicted based on our observations of the tongue movement in these speakers, which suggested an inability to compensate for the bite block. Several explanations for the discrepancy between speech movement and speech acoustic findings are possible. For example, because we only analyzed one fleshpoint on the tongue, other parts of the tongue not observed in this study may have reached the target position during the production of the vowel /i/. Also, it is possible that speakers with ALS used other structures of the vowel tract to achieve the vowel /i/ acoustically (i.e., larynx height adjustment). Lastly, one has to keep in mind that speakers with speech impairments may have already distorted vowel productions during the jaw-free condition, which would move F1 and F2 measures outside of the range of healthy speakers. Even if speakers with ALS cannot reach their initial jaw-free position, a saturation effect in the acoustic domain may not reflect the difference between jaw-free and jaw-fixed position. When comparing absolute values of F1 and F2 during the jaw free condition between healthy speakers and speakers with ALS and found that values greatly deviated for the speaker with severe ALS (A7). We also performed an informal perceptual evaluation of the vowel /i/ of all speakers with ALS to test this hypothesis and concluded that this explanation may yield relevance for the severe speaker with ALS, who did have notable acoustic distortions during the jaw-free and jaw-fixed position. The two speakers with mild ALS, however, did not have perceivable vowel distortions in either speech condition. The discrepancy between their tongue movements and speech acoustic measures may rather be explained by one or both of the other explanations offered here.

5.4 Clinical Implications

Findings of this study suggest that differences in tongue height and tongue advancement between jaw-free and jaw-fixed conditions are not perceptually significant for speakers with ALS. As a result, listeners are unable to detect an acoustic difference between the conditions. Therefore, assessment of individual articulators with a bite block should be done when examining speech movements in order to reveal disease-related differences. In doing so, clinicians will be able to achieve a better understanding about the disease progression and the effect of the disease on articulatory performance. Additionally, durational measure could potentially be used to determine degree of speed constraint of the tongue and track disease progression.

5.5 Limitations and Future Directions

Conclusions of this study are preliminary due to the small sample size and a limited range of speech severity in participants with ALS. In order to draw more definitive conclusions about tongue movement performance in response to a fixed jaw, a similar study would have to be conducted using a larger sample size and speakers with a wider range of speech severity to detect differences between various levels of disease progression. Researchers should also evaluate the speech of speakers with ALS longitudinally in order to assess disease progression on individual articulators and determine potential compensatory strategies. Such insights may be useful for clinical work to help persons with ALS to maintain speech intelligibility for as long as possible.

Furthermore, future studies should include more than one fleshpoint to gain a better understanding about the changes of the overall tongue shape in response to a fixed jaw. Perhaps using magnetic resonance imaging (MRI) technology would successfully overcome this limitation; however, such data acquisition is more costly and bares new challenges, such as problems recording simultaneously high quality acoustic recordings within a noisy MRI scanner.

Another limitation was that only the relative change between jaw-free and jaw-fixed conditions could be compared in this study. Future studies should apply a standardized anatomically-based coordinate system with a unified origin (e.g., at the central lower incisors) to also compare the absolute performance between speakers in both groups in order to achieve a better understanding of how speech movements differ between subjects. Due to the instability of the articulograph (sensor tracking errors leading to missing data points), this methological approach was, unfortunately, not possible in our study.

5.6 Summary/Conclusion

This study was designed to investigate the effect of a fixed-jaw on tongue kinematics and vowel acoustics in speakers with ALS when compared to healthy controls. The results indicated durational changes in response to bite blocks in both groups. Yet, the direction of the durational changes varied. Tongue movement durations increased in response to a fixed-jaw in the group with ALS. In the group of healthy controls, a fixed-jaw had the opposite effect. Tongue movement durations mostly decreased.

Speech movements observed in this study suggest a disease-related inability to reach the same tongue height in the fixed-jaw condition when compared to the jaw-free condition. The findings of this study suggest that as the severity of ALS progresses, individuals are likely to increase their jaw movements in speech in order to compensate for a weakened tongue. Acoustically, the data suggest that reduced tongue height does not affect the acoustic signal of speakers with ALS. This finding was quite surprising because the kinematic data suggested an inability to compensate for the bite block.

The current findings support prior suggestions that speakers with ALS use compensatory strategies to maintain intelligibility during the early stages of the disease. In the future, preliminary findings of this study must be expanded to investigate more than one fleshpoint, follow speakers with ALS over a longer period of time, and include a larger sample size.

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