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Vowel-Specific Articulatory Kinematic Patterns in Individuals with Dysarthria Secondary to Amyotrophic Lateral Sclerosis

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ABSTRACT

Based on previous acoustic studies, people with dysarthria secondary to amyotrophic lateral sclerosis (PALS) experience different degrees of difficulty in producing vowels; therefore, some vowels may be harder to produce than others. The current study aims to identify as to why there are vowel-specific production difficulties by looking at the articulatory underpinnings of both the tongue and jaw. The participants included twenty-two PALS and twenty-two sex- and age-matched controls. The target stimuli were nine monophthongs in American English that were placed in a /h/-vowel-/d/ context in a carrier phrase. To record the tongue and jaw movements of each participant, an electromagnetic articulography was used. The results of the current study showed that there are three characteristics of vowels that show clear kinematic differences between PALS and typically aging individuals, such as 1. Being a high or mid-high vowel, 2. Requiring the greatest amount of tongue movement as seen in typically aging individuals, and 3. Requiring the least amount of movement as seen in typically aging individuals. This vowel-specific pattern was observed in tongue kinematic variables but was not seen in jaw kinematic variables.

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Introduction

Amyotrophic Lateral Sclerosis (ALS)

Amyotrophic lateral sclerosis (ALS) is a degenerative and progressive disease affecting an individual's motor neurons (Rowland & Schneider, 2001). In the United States, ALS affects roughly 31,000 individuals with an addition of 5,000 new diagnoses every year. The disease affects individuals between the ages of 55 and 75. Once symptoms develop, an individual's life expectancy shortens to two to five years (Centers for Disease Control and Prevention, 2022). The symptoms of ALS include weakness, cramping, and spasms of the muscles (Zarei et al., 2015). Genetics is the one known cause of ALS, but only accounts for between five to ten percent of ALS patients. The cause of ALS in the remaining ninety to ninety-five percent of patients is unknown. Patients who developed ALS due to genetic reasons have familial ALS. In familial ALS, about twenty percent of cases are due to superoxide dismutase 1 (SOD1) that experiences mutations in gene encoding. In the other eighty percent of familial ALS patients, it is other genes that experience mutations that result in ALS (Rowland & Schneider, 2001).

The two main onset types of ALS are spinal and bulbar. Spinal onset of ALS consists of motor neuron implication in the cervical, lumbosacral, or thoracic part of the spinal cord. Bulbar onset of ALS shows motor neuron implication in the brainstem, more specifically to the cranial motor neurons. Bulbar onset also more often displays onset of dysphagia and/ or dysarthria (Binazzi et al., 2009).

People with Dysarthria Secondary to ALS (PALS)

Out of all the ALS patients in the United States, 80% of them develop dysarthria, which further impairs their speech production. In dysarthria, the muscles involved in speech production lose their ability to function. The symptoms of dysarthria do not always present themselves immediately in people with dysarthria secondary to ALS (PALS), as some symptoms do not occur up until the loss of eighty percent of motor neurons in the individual's body. These symptoms may not prevail until up to sixty months after an ALS diagnosis (Tomik & Guiloff, 2010).

The type of dysarthria PALS may develop could include upper motor neuron (UMN) or spastic, lower motor neuron (LMN) or flaccid, mixed UMN and LMN, extrapyramidal (hypokinetic, hyperkinetic), or cerebellar (ataxic) (Tomik & Guiloff, 2010). The common symptoms found in individuals with dysarthria include slurred speech, breathy voice quality, and fatigue (Sterling, et al., 2009). Tomik and Guiloff (2010) also found that the speech of individuals with dysarthria included poor articulation, incorrect productions of consonants, hypernasality, and harshness quality.

All of these characteristics of dysarthria reduce speech intelligibility in PALS. Among many physical functions they lose during the progression of the disease, the impairment and loss of verbal communication was found to be the major factor impacting their quality of life negatively (Felgoise et al., 2016). Felgoise et al. (2016) ran a study in which the ability to communicate verbally (i.e., Speaking) is directly linked to the quality of life in PALS. They found that an initial impairment to individuals' ability to communicate verbally resulted in a poorer quality of life. They also found this in individuals with no ability to speak at all (Felgoise et al., 2016).

Articulatory Subsystem Involvement: Articulator-Specific Dysfunction

In PALS, all speech subsystems are involved: respiratory, laryngeal, velopharyngeal, and articulatory subsystems. Researchers investigated to identify the subsystem that is the major contributor to reduce speech intelligibility in PALS. Among the multiple speech subsystems, the articulatory subsystem contributes the most to speech intelligibility, as it resulted in a 57.7% decline in intelligibility (Rong, 2019). Rong (2019) reported that a coexistence of a slowed jaw and lip movement with less distinctiveness between consonants and vowels further decreased speech intelligibility. In many previous studies, the tongue and jaw, critical parts of articulatory subsystem, were investigated and the results consistently indicated atypical tongue and jaw movement in PALS (Lee et al., 2020; Shellikeri, et al.2016; Yunusova et al., 2008).

The tongue is a key articulator that plays a significant role in shaping the vocal tract when producing speech. The tongue is anatomically and functional coupled with the jaw (Rong, 2019). In other words, the tongue is connected to the jaw by tissue connections of the skin, muscles, and connective tissue; therefore, the two articulators do tend to function together and support each other. One of unique characteristics of PALS is that they lose control of their tongue first, and later they lose control of their jaw. (Carpenter et al., 1978; Lawyer & Netsky, 1953). This is referred to differential involvement of articulators (Lee & Bell, 2018). The characteristics of each articulator are described in the section below.

Tongue

The loss of tongue function occurs first in PALS. Lee and Bell (2018) discussed the idea of the differential involvement of articulators in terms of the articulator most severely impacted due to ALS. They concluded that the tongue received the most involvement due to ALS (Lee & Bell, 2018). Lee et al. (2020) further examined the tongue’s loss of function and explained the confinement of the tongue in terms of the restriction to height range in the oral cavity. This limited height range for the tongue affects how PALS produce speech, since their tongue cannot physically move to reach the necessary heights to produce certain sounds (Lee et al., 2020). Lee and Bell (2018) also concluded that in PALS, the overall area that the tongue can move around in (working space) reduces. They further found that the range of movement of the tongue in both the anterior-posterior (front-back) dimension and superior-inferior (higher-lower) dimension reduces. They finalized that the tongue movement reduction in the anterior-posterior dimension it is more significant (Lee & Bell, 2018). Yunusova et al. (2008) suggested that the differential impairment between articulators highlighted that the tongue movements diverge more than typically aging speakers. On the other hand, the jaw does not experience dysfunction as early on as the tongue and presents dysfunction much differently in its movement patterns (Yunusova et al., 2008).

Jaw

Research established that the jaw does not experience dysfunction until later in the progression of ALS (Yunusova et al., 2008). Lee and Bell (2018) found that the range of movement of the jaw in individuals with severe dysarthria increased, as the tongue range of movement decreased. They suggested this further supported the differential involvement of articulators, as the movement of the jaw in the anterior-posterior (front-back) dimension was significant (Lee & Bell, 2018). Yunusova et al. (2008) noted the exaggerated jaw movements when individuals produced high vowels. They also discussed the differential impairment between articulators and suggested that the movement of the jaw is not as different from typically aging speakers in comparison to the tongue movement (Yunusova et al., 2008).

Compensation

Mefferd and Dietrich (2020) found that the jaw movements in PALS appeared more exaggerated as their tongue movement reduced. This shows how the jaw exaggerates its movements to compensate for the loss of tongue function. The jaw makes up for the loss of tongue function, since the jaw does not undergo impairment until further on when ALS progresses into its latest stages (Mefferd & Dietrich, 2020). Lee and Bell (2018) also found that the working space of the jaw displays more exaggerated in individuals with severe dysarthria in the anterior-posterior (front-back) dimension. They suggested that this is due to the jaw compensating for the tongue since its function stays relatively preserved (Lee & Bell, 2018).

Effects of ALS: Speech Sound-Specific Dysfunction

In addition to articulator-specific dysfunction addressed above, speech sound-specific dysfunction has been observed in PALS as seen by Yunusova et al. (2008). Their study showed that depending on the target vowels and consonants next to it, there is a varying degree of difference between the control speakers and PALS when they examined the tongue and jaw movement. In PALS, the characteristics of the vowels they produce will impact how their articulators move (Yunusova et al., 2008). To further investigate this, Lee et al. 2019 examined vowel-specific impairment with controlled context in the population based on acoustic observation. They found a difference between PALS and typically aging speakers in terms of vowel-specific intelligibility. They hypothesized that each of the vowels possess their own unique traits that affect PALS at different levels based on their severity (Lee et al., 2019).

Each of the American English (AE) monophthongs (vowels) has their own unique features that affect the level of complexity it takes to produce them and how that affects the speech intelligibility (Lee et al., 2019). When PALS produce vowels, their productions of specific vowels are more challenging than others (Lee et al., 2019). Yunusova et al. (2008) concluded that the movements of the jaw in PALS were characterized by vowels. They found that the jaw distance and speed in PALS remained similar to typically aging speakers, but their productions had a longer duration (Yunusova et al., 2008).

A previous study showed how the dysfunction of the jaw impacts errors in vowel productions, particularly for the high vowels (Lee et al., 2020). They found that the jaw exaggerates during opening movements, but it does not perform this same level of exaggeration for closing movements. This results in lower placement of the tongue, thus, causing an undershoot when producing high vowels (Lee et al., 2020).

Vowel Articulatory Kinematics in Typical Individuals

Tongue and jaw movements in typical individuals were investigated by Noiray et al. (2008), in which they used x-ray microbeam (XRMB) and digital ultrasound imaging (HOCUS) to examine the differences between /i/ and /ɪ/. This study focused more on height and the differences in vowel contrast, in which they found that both the tongue and jaw do contribute to vowel contrast between the two vowels in typical individuals, but the tongue played more of a role than previous studies found (Noiray et al., 2008). Noiray et al. (2014) further studied these contrasts between different pairings of vowels in (h)-vowel-/d/ context: /i-ɪ/, /e-ɛ/, and /ɛ-æ/. They found that in typical speakers, their productions of front vowels yielded for more variability which was used to make noticeable differences in vowel categories (Noiray et al., 2014).

There is limited research done in terms of typical individuals and typically aging individuals that investigates articulatory kinematics for the investigation of typical tongue and jaw movement patterns in monophthongs, especially when placed in controlled consonant contexts. Most studies conducted have used a selected subset of vowels embedded in varying consonant contexts when the focus was to reveal articulatory kinematic differences in clinical populations such as ALS, Parkinson's Disease, and Cerebral Palsy (Yunusova et al., 2008). As a result, vowel-specific articulatory kinematic characteristics in typical individuals are not established. This limits the interpretation of the difference between the populations (e.g., ALS vs. Control).

The Current Study

The current study aimed to examine the tongue and jaw movements during vowel production in PALS and sex- and age-matched typically aging individuals. By looking at the typical patterns of movement of the tongue and jaw in typically aging individuals for specific vowels, it can help us understand which vowels may naturally require more movement from the tongue and jaw. Thus, the findings can help understand the tongue and jaw movements in PALS. In addition, the current study analyzes vowel-specific and severity group differences as well as the interaction between the two for both the tongue and jaw. In the current study, there are two research questions:

Research Question 1 (RQ1): What are the vowel-specific patterns of articulatory kinematics of the tongue and jaw in typically aging individuals? To determine vowel production in PALS, it is critical to understand the typical patterns of tongue and jaw movement while producing vowels. From there, it can be determined which vowels may naturally require a greater movement or less of a movement. This will help us to understand inherent vowel-specific articulatory kinematic characteristics and to give us a better understanding when we look at the population of PALS.

Research Question 2 (RQ2): Are these vowel-specific patterns similar or different in PALS than in typically aging individuals? To examine the articulatory kinematic differences in PALS, we examined the movement in X (Anterior-Posterior) and Y (inferior-superior) dimensions as well as the overall movement in the two dimensions. Also, speed and duration were examined.

Method

Participants

The current study involved twenty-two PALS (Males = 11; mean age = 63 yrs old; SD = 9 yrs) and twenty-two typically aging individuals (Males = 11; mean age = 63 yrs old; SD = 7.4 yrs). The PALS were recruited from the Penn State Hershey ALS Clinic and Research Center and the ALS Association greater Philadelphia chapter. For PALS, the inclusion criteria consisted of: (a) having both a diagnosis of ALS and dysarthria, (b) being a native AE speaker, and (c) having hearing within normal limit. All of these participants met the El Escorial criteria. This criterion stated that each of these participants had definite, probable, probable laboratory-supported, or possible ALS diagnosis (Brooks et al., 2000). The participants in the current study are from the same participant pool that was used in a previous study, Lee et al., 2019. However, one participant from the previous study (Lee et al., 2019; n = 23) is excluded in the current study due to sensor errors.

Table 1 shows the demographic information of the PALS. Table 1 includes each participants' age, sex, home state, onset type, time since onset of dysarthria (months), ALSFRS-R total score, ALSRS-R bulbar score, Sentence Intelligibility Test (SIT; %; Yorkston et al., 1996), speaking rate (words per minute), and severity. ALSRS-R stands for ALS Functional Rating Scale-Revised (Cederbaum et al., 1999). The ALSFR-R total score ranks 12 separate items from a score of 0 to 4, with 0 representing worst function to 4 representing normal function. This produces a total score that ranges from 0 to 48. The ALSFR-R bulbar score calculates a score based on the sum of three items that are related to bulbar function. These three items are speech, swallowing, and salivation. A score of 0 shows that the speaker is not able to speak, not able to swallow, and has copious sialorrhea. A score of 12 shows that the speaker has no clinical impairments in bulbar function.

Table 1

Demographic Information of Participants with ALS

ID	Age (Years)	Sex	Home State	Onset Type	Time since onset of dysarthria (Months)	ALSFRS-R total score	ALSFRS-R bulbar score	SIT (%)	Speaking Rate (wpm)	Severity
PALS1	60	M	PA	Bulbar	9	42	9	97.58	202	Mild
PALS2	76	F	PA	Bulbar	18	29	9	97.58	133	Mild
PALS3	80	M	PA	Bulbar	1	37	6	94.85	131	Mild
PALS4	61	F	PA	Mixed	5	29	9	94.55	131	Mild
PALS5	65	M	PA	Bulbar	12	45	9	90.00	126	Mild
PALS6	60	M	PA	Mixed	49	35	10	92.42	124	Mild
PALS7	64	F	PA	Bulbar	15	45	9	91.21	109	Mild
PALS8	64	M	PA	Bulbar	37	44	8	91.82	108	Mild
PALS9	67	M	PA	Mixed	201	23	6	93.64	102	Mild
PALS10	68	M	PA	Spinal	8	9	7	67.58	118	Severe
PALS11	50	M	PA	Bulbar	16	25	9	42.73	100	Severe
PALS12	71	F	WV	Bulbar	15	39	9	93.03	94	Severe
PALS13	69	F	PA	Bulbar	20	35	7	71.21	94	Severe
PALS14	48	M	PA	Spinal	10	34	9	70.30	88	Severe
PALS15	66	F	NY	Bulbar	33	37	5	94.24	83	Severe
PALS16	64	M	PA	Bulbar	51	40	6	79.55	80	Severe
PALS17	66	F	PA	Bulbar	5	32	6	11.52	77	Severe
PALS18	63	F	PA	Spinal	11	12	4	11.82	70	Severe
PALS19	47	M	PA	Mixed	36	24	3	10.00	70	Severe
PALS20	43	F	PA	Spinal	120	24	8	58.79	65	Severe
PALS21	64	F	PA	Bulbar	19	39	5	25.76	57	Severe
PALS22	66	F	PA	Bulbar	44	20	2	6.67	48	Severe

The group of PALS were further divided into two groups, mild and severe, based on the severity of dysarthria they had. Their sentence intelligibility score was found through a Sentence

Intelligibility Test (SIT; Yorkston et al., 1996). The threshold used as the cut-off for the group assignment was a 90% sentence intelligibility score and 100 words per minute (wpm) speaking rate (Ball et al., 2001; Lee & Bell, 2018). Ball et al. (2001) showed PALS experience an abrupt decline in intelligibility when their speaking rates are approximately 100 wpm on the SIT stimuli sets.

The group of twenty-two typically aging individuals served as the control group. The control group was sex- and age-matched (± 5 years) to the twenty-two PALS. They were recruited from State College area. The inclusion criteria for typically aging speakers included: (a) being a native AE speakers; (b) did not have a known speech, language, or neurological disorders; and (c) passed a hearing screening in at least one ear at 250, 500, 1000, 2000, and 4000 Hz at 30dB (Lee et al., 2019). Twenty-one typically aging speakers passed the hearing screening in their better eat at 30dB. One speaker (PALS 3) did not pass the hearing screening originally, but after that speaker performed the test again with hearing aids, that speaker passed.

Procedures

Stimuli for this study were nine AE monophthongs: /i, ɪ, ɛ, æ, u, ʊ, o, ʌ, ɑ/. The vowel /ɔ/ was not included in the current study due to the merging between /ɑ/ and /ɔ/ in the production of /h/-vowel-/d/ words. Each of the monophthongs were placed in /h/-vowel-/d/ context. Each stimulus was produced by the speakers in the carrier phrase “I say a ___ again” three times for each word in a randomized order.

In order to collect the articulatory movement data of the tongue and jaw, an electromagnetic articulography (Wave System, NDI) system was used. A six-degree-of-freedom reference sensor was attached to the forehead of the participant. The movement sensors were attached to lower lip, jaw, tongue tip and tongue body (25 mm from the tongue apex) in the midsagittal plane. The bite plane of each participant was collected for data translation and rotation. For the current study, the data from the tongue body and the jaw are analyzed. The tongue and jaw data were coupled in the current study (Lee et al., 2017).

Analyses

Waveform and wideband spectrogram displays in TF32 (Milenkovic, 2001) were used to establish the onsets and offsets of each of the vowels where both first and second formant frequencies (F1 and F2) are clearly identified. Later on, the vowel onset and offset time sampling points were then used to extract kinematic data from the same segment. The kinematic data were rotated and translated, making the origin, (0, 0, 0), the low boundary of the maxillary central incisors along the midsagittal plane. In addition, the bite plane of each participant became the X-axis of the coordinate system. The X-values reflect changes in advancement of both the tongue and jaw movements, thus, in the anterior-posterior (AP) dimension. When the target articulator moves forward in, the X-coordinate values increase. The Y-values reflect changes in the height of the tongue and jaw, thus, in the superior-inferior (SI) dimension. When the target articulator moves up, the Y-coordinate values increase. The coordinate values (X and Y) of the tongue and jaw movements were extracted for the target vowel onsets and offsets.

The kinematic measures in this study were split up into two groups, temporal measures and spatial measures. Temporal measures consisted of movement duration (seconds) and movement speed in millimeters per second (mm/s) of both the tongue and jaw. Spatial measures consisted of overall movement distance, movement distance and range of motion in the X dimension and in the Y dimension for the tongue and jaw.

For the temporal measures, movement duration was measured based on the vowel onsets and offsets measured as described above. To calculate the movement speed for the tongue and jaw, the three-dimensional (3D) distance was divided by the duration of the target vowel segment (Lee et al., 2017).

For the spatial measures, the overall movement distance was calculated as a cumulative movement distance of 3D sensor coordinate values throughout the target vowel segment timeseries. The movement distance in the AP dimension was measured using the cumulative X-coordinate value changes, to represent the changes in advancement of the articulators during the target vowel production. The movement distance in the SI dimension was measured using the cumulative Y-coordinate value changes, to represent the changes in height of the articulators during the target vowel production.

A total of 2376 (44 speakers x 9 vowels x 3 repetitions x two articulators) were analyzed and among these, 35 tokens showed sensor errors, thus 2341 data points were included in the current study.

Statistical Design and Analysis

Split-plot analysis of variance was conducted to test vowel-specific difference, severity group difference, and the interaction between the two (Vowels x Severity groups) using Statistical Package for the Social Sciences (SPSS; IBM SPSS v27). A Bonferroni post-hoc test was used when statistical significance was detected with 0.05 of the alpha level.

Results

Research Question 1 (RS1): What are the vowel-specific patterns of articulatory kinematics of the tongue and jaw in typically aging individuals?

Tongue

All the tongue temporal and spatial variables showed significant differences across the vowels, which is shown in Table 2. Figure 1, on the far-right panels, displays the vowel-specific movement distance for the control group. The top panel shows the tongue movement and the bottom panel shows the jaw movement extent. Figures 2 and 3, on the far-right panels, show vowel-specific tongue and jaw movement distance and range of motion in each dimension for each vowel in the control group. As seen in Figures 2 and 3, even though vowel-specific tongue movement differences are observed in both X and Y dimensions, a greater systematic difference was observed in the tongue Y dimension distance and range of motion compared to in the X dimension.

Table 2

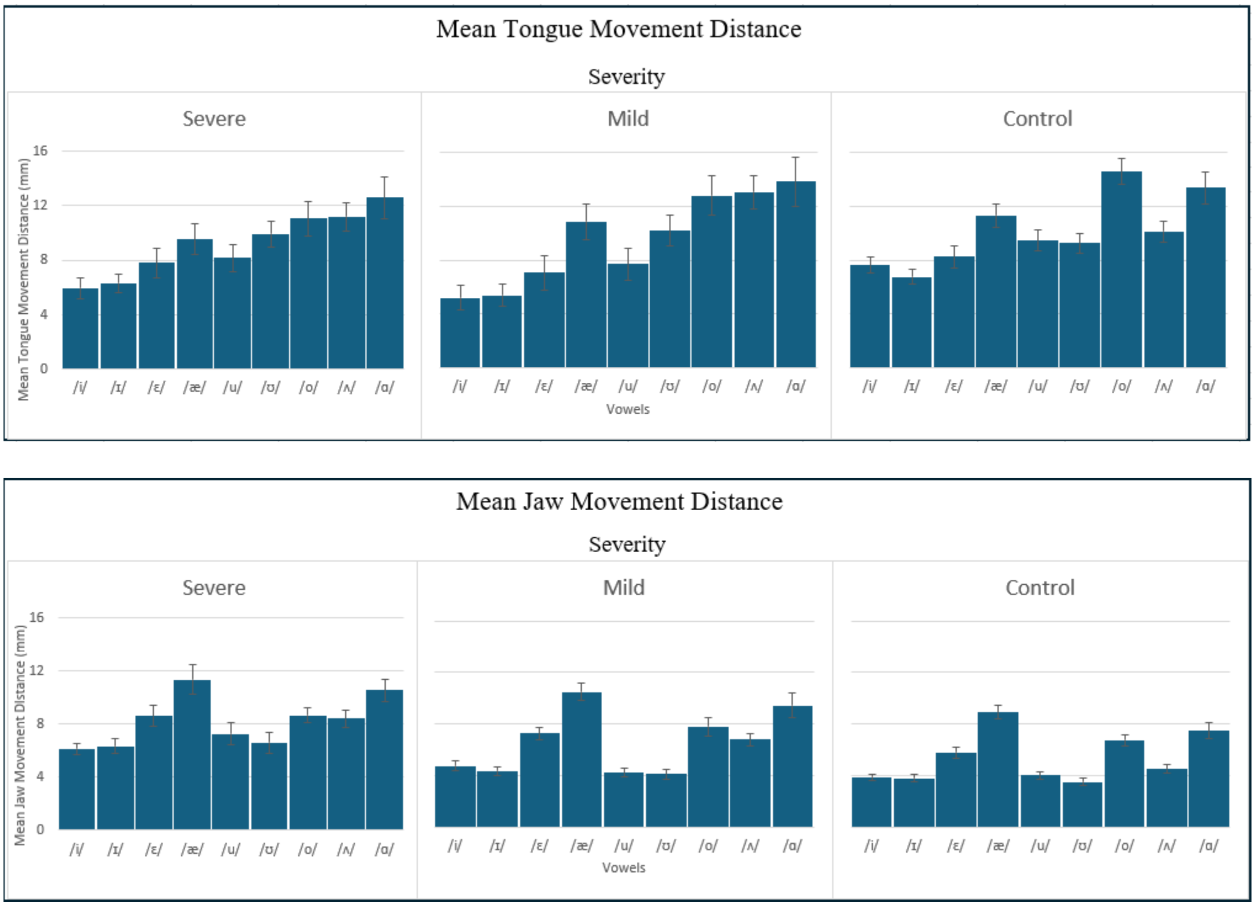
Summary of Statistical Test Results Examining Tongue and Jaw Movement Differences across Vowels in Typically Aging Individuals

Articulator	Variables	Numerator df	Denominator df	F	Sig.
Tongue	Movement Distance	8	558.697	62.485	<0.001
	X Distance	8	576.584	5.671	<0.001
	Y Distance	8	557.951	88.235	<0.001
	X Range	8	576.665	3.337	0.001
	Y Range	8	557.566	89.120	<0.001
	Speed	8	576.264	36.569	<0.001
Jaw	Movement Distance	8	161.348	19.28	<0.001
	X Distance	8	163.296	13.689	<0.001
	Y Distance	8	160.363	22.935	<0.001
	X Range	8	161.823	13.254	<0.001
	Y Range	8	159.064	22.606	<0.001
	Speed	8	165.002	12.875	<0.001
Tongue and Jaw	Vowel Duration	8	558.805	128.834	<0.001

Tongue Movement Distance. As shown in Figure 1, the control group did show a difference between back vowels and front vowels. Movement distance in back vowels tend to be greater than front vowels, with the exception of front vowel /æ/ in "Had" (11.33mm). Within the same front-back dimension, high vowels showed less movement than low vowels. The overall range of difference across vowels in movement distance values was 7.83mm. The vowel that showed the greatest movement distance was /o/ in “Hoed” (14.59mm). The vowel that showed the shortest movement distance was /ɪ/ in “Hid” (6.76mm).

Figure 1

Descriptive Data of Tongue and Jaw Movement Distance across Severe, Mild and Control Groups

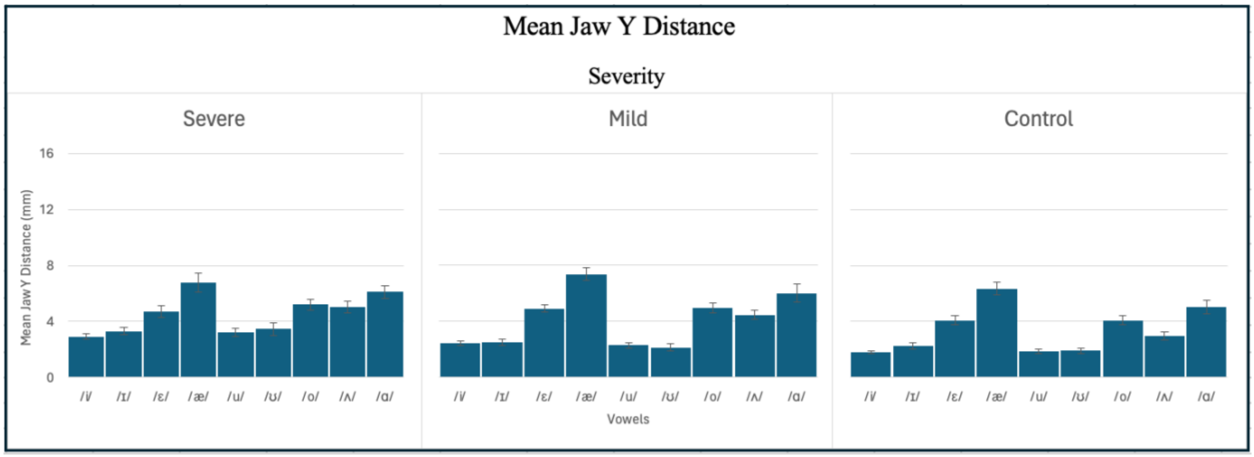


Note. The error bars represent one standard error.

Tongue Distance on X dimension (Front-back). As shown in Figure 2, the control group did not show substantial difference between front and back vowels. The overall difference range across vowels in X distance values was 1.95 mm. The vowel that showed the greatest X distance was /o/ in “Hoed” (5.74 mm). The vowel that showed the shortest X distance was /ʌ/ in “Hud” (3.79 mm). The post-hoc test revealed that tongue X distance is greater for /o/ than for /ʌ/.

Figure 2

Descriptive Data of Tongue and Jaw Movement Distance in X and Y Dimensions across Severity Groups



Note. The error bars represent one standard error.

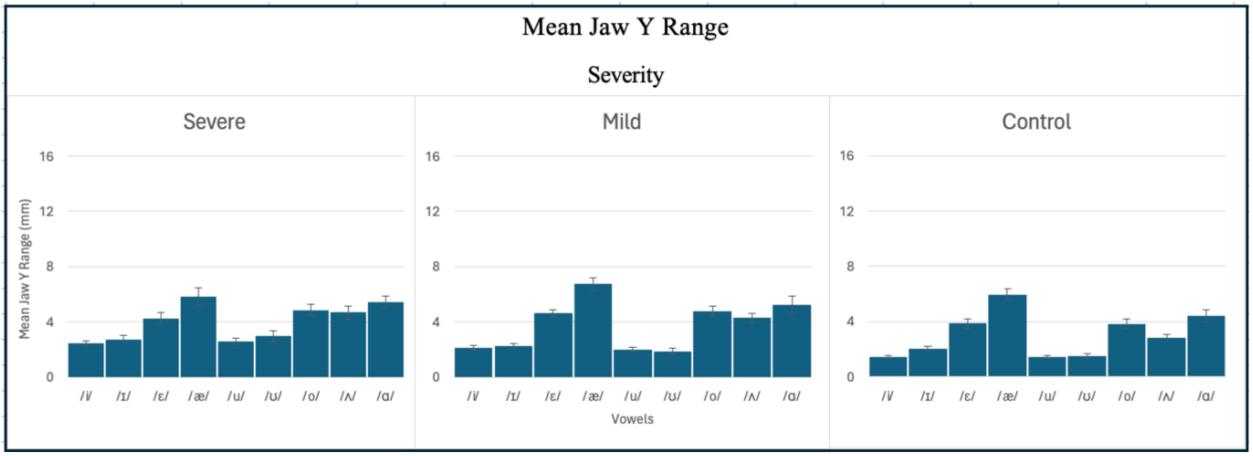
Tongue Distance on Y Dimension (Height). As shown in Figure 2, the control group did show a greater difference between the vowels in the Y dimension than in the X dimension. The overall difference range across vowels in Y distance values was 8.48 mm, which is much greater than the one observed in X distance.

Movement distance in the Y dimension in back vowels tends to be greater than in the front vowels. Within the same front-back dimension, high vowels showed less tongue movement in the Y dimension than in the low vowels. This is the same pattern observed in overall tongue movement distance. Thus, the vowel-specific tongue movement distance is largely driven by vowel-specific tongue movement distance in the Y dimension. The vowel that showed the greatest Y distance was /o/ in “Hoed” (11.78mm). The vowel that showed the shortest Y distance was /ɪ/ in “Hid” (3.30mm).

Tongue Range of Motion on X Dimension (Front-back). As shown in Figure 3, the control group did not show much difference between front and back vowels. The overall difference across vowels in X range values was 1.46 mm. The vowel that showed the greatest X range was /i/ in “Heed” (4.72mm). The vowel that showed the shortest X range was /ʌ/ in “Hud” (3.26mm).

Figure 3

Descriptive Data of Tongue and Jaw Range of Motion in X and Y Dimensions across Severity Groups



Note. The error bars represent one standard error.

Even though the main effect results showed a significant tongue X movement across vowels, the Bonferroni post-hoc tests did not show any significant vowel-specific differences.

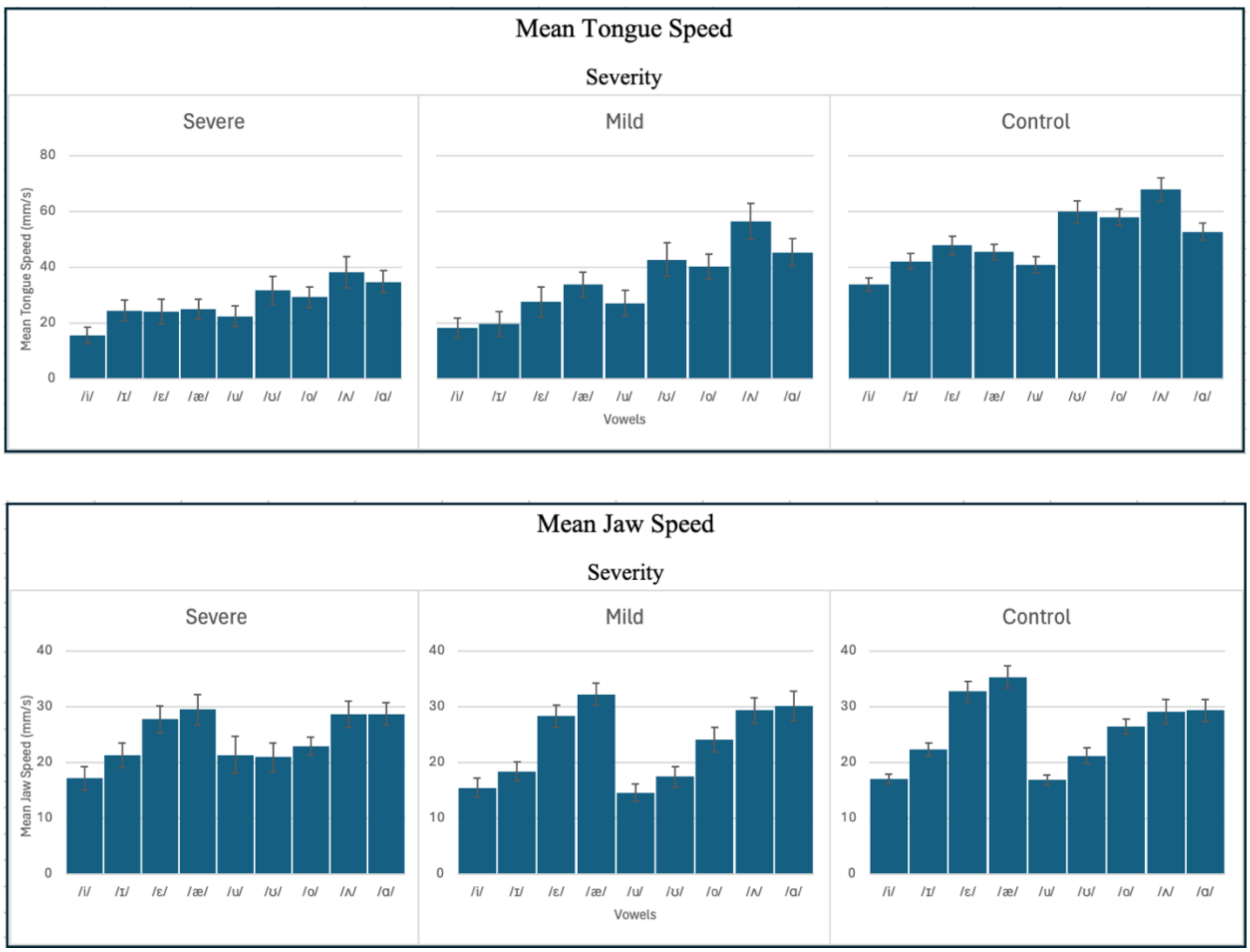
Tongue Range of Motion on Y Dimension (Height). As shown in Figure 3, the control group did show a difference between front and back vowels. Within the same front-back dimension, high vowels showed less tongue range of motion in the Y dimension than low vowels. The pattern observed is similar to the ones in overall movement and tongue movement in the Y dimension. The overall difference range across vowels in the Y range values was 8.84 mm, which is much greater than the one observed in X range. The vowel that showed the greatest Y range was /o/ in "Hoed" (11.66mm). The vowel that showed the shortest Y range was /ɪ/ in "Hid" (2.83mm).

The tongue results from typically aging individuals show that in the X dimension there is limited difference between vowels, but in the Y dimension there is a substantial difference between vowels. Greater movement and range of motion were observed in back vowels than in front vowels, and in low vowels than in high vowels.

Tongue Speed. As shown in Figure 4, the control group did show a difference between front and back vowels. The overall difference across vowels in speed (mm/s) was 34.09mm/s. The vowel that showed the greatest speed was /ʌ/ in “Hud” (67.90mm/s). The vowel that showed the slowest speed was /i/ in “Heed” (33.81mm/s). This shows how, for the control group, back vowels are faster to produce than front vowels. The one exception is vowel /u/ in “Who’d”, which takes a bit longer to produce since it is a tense vowel (40.91mm/s).

Figure 4

Descriptive Data of Tongue and Jaw Movement Speed across Severity Groups



Note. The error bars represent one standard error.

Jaw

The jaw movement data in the control group are presented in Figures 1-4, on the far-right panels. The main effect statistical findings across vowels are presented in Table 2. Statistical analysis for jaw data of the control group suggests that there are vowel-specific differences (p-values below 0.05) in all kinematic variables: movement distance, X distance, Y distance, X range, Y range, and speed. This data is represented in Table 2.

As shown in the Figures, the vowel-specific jaw movement differences are driven by greater jaw movement in lower vowels than in higher vowels. Unlike the tongue data results, there is no notable difference between front and back vowels. The jaw movement difference is largely driven by vowel height dimension. In addition, there was no clear jaw movement difference in the Y dimension vs. X dimension unlike the tongue data results.

Jaw Movement Distance. As shown in Figure 1, the control group did show a difference between low/mid vowels and high vowels. The overall difference range across vowels in movement distance values was 5.43mm. The vowel that showed the greatest movement distance was /æ/ in “Had” (8.92mm). The vowel that showed the shortest movement distance was /ʊ/ in “Hood” (3.49mm). Low/ mid vowels tend to have a greater jaw movement distance than high vowels. There was no difference between front and back vowels.

Jaw Distance on X Dimension (Front-back). As shown in Figure 2, the control group did not show much difference between low/ mid vowels and high vowels. The overall difference range across vowels in X distance values was 2.75 mm. The vowel that showed the greatest X distance was /æ/ in “Had” (4.47mm). The vowel that showed the shortest X distance was /ɪ/ in “Hid” (1.72mm).

Jaw Distance on Y Dimension (Height). As shown in Figure 2, the control group did show a difference between low/ mid vowels and high vowels. The overall difference range across vowels in Y distance values was 4.57 mm. The vowel that showed the greatest Y distance was /æ/ in “Had” (6.35mm). The vowel that showed the shortest Y distance was /i/ in “Heed” (1.79mm).

Jaw Range of Motion on X Dimension (Front-back). As shown in Figure 3, the control group did not show much difference low/ mid vowels and high vowels. The overall difference across vowels in X range values was 2.76 mm. The vowel that showed the greatest X range was /æ/ in “Had” (4.16mm). The vowel that showed the shortest X range was /ʊ/ in “Hood” (1.40mm).

Jaw Range of Motion on Y Dimension (Height). As shown in Figure 3, the control group did show a difference between low/ mid vowels and high vowels. The overall difference range across in Y range values was 4.50 mm. The vowel that showed the greatest Y range was /æ/ in “Had” (5.94mm). The vowel that showed the shortest Y range was /i/ in “Heed” (1.43mm).

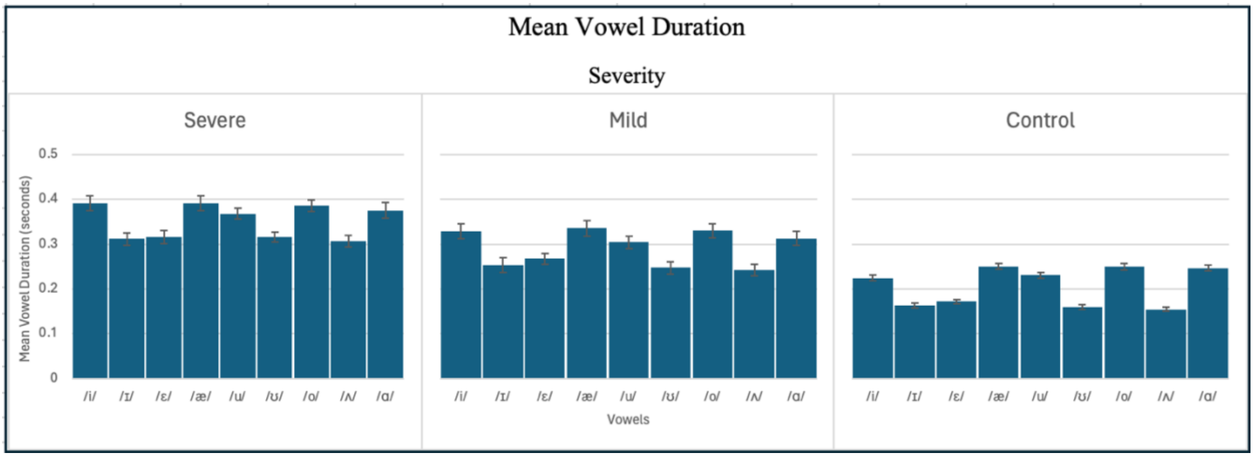
Jaw Speed. As shown in Figure 4, the control group did show a difference between low/ mid vowels and high vowels. The overall difference across vowels in speed (mm/s) was 18.52mm/s. The vowel that showed the greatest speed was /æ/ in “Had” (35.37mm/s). The vowel that showed the slowest speed was /u/ in “Who’d” (16.85mm/s). This shows how for the control group, high vowels are slower to produce than low/ mid vowels.

Vowel Duration

As shown in Figure 5, the control group showed statistically significant difference between vowels in terms of vowel duration. This is largely driven by tense-lax feature of the vowels. Other than that, unlike the kinematic variables discussed above, no systematic pattern was observed. The overall difference across vowels in duration was 0.10 seconds. The vowel that showed the greatest duration was /æ/ in "Had" (0.25s). The vowel that showed the shortest duration was /ʌ/ in "Hud" (0.15s).

Figure 5

Descriptive Data of Vowel Duration across Severity Groups



Note. The error bars represent one standard error.

Research Question 2 (RQ2): Are these vowel-specific patterns similar or different in PALS than in typically aging individuals?

Tongue

Table 3 shows statistical results of the main effects and interaction (Severity, Vowels, Vowels x Severity). Significant interaction was observed in all spatial tongue variables. Figures 1-4 show descriptive data of the tongue and jaw movement across the groups. On the far-left panel, data from Severe group of PALS are presented and on the middle panel, data from Mild group of PALS are presented.

Table 3

Summary of Statistical Test Results Examining Tongue and Jaw Movement Differences across Vowels and Severity Groups

Articulator	Variable	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Tongue	Movement Distance	Vowels	2169.890	8	271.236	37.746	<0.001
		Vowels x Severity	232.984	16	14.561	2.026	0.011
		Severity	63.685	2	31.842	0.425	0.657
	X Distance	Vowels	435.861	8	54.483	13.274	<0.001
		Vowels x Severity	306.654	16	19.166	4.670	<0.001
		Severity	38.467	2	14.234	0.447	0.643
	Y Distance	Vowels	1763.876	8	220.484	43.089	<0.001
		Vowels x Severity	187.484	16	11.718	2.290	0.003
		Severity	223.191	2	111.596	2.022	0.145
	X Range	Vowels	456.732	8	57.091	13.509	<0.001
		Vowels x Severity	389.369	16	24.336	5.758	<0.001
		Severity	28.642	2	14.321	0.528	0.594
	Y Range	Vowels	1869.856	8	233.732	45.511	<0.001
		Vowels x Severity	208.239	16	13.015	2.534	0.001
		Severity	294.83	2	147.415	2.606	0.086
	Speed	Vowels	30279.891	8	3784.986	30.031	<0.001
		Vowels x Severity	3058.711	16	191.169	1.517	0.092
		Severity	40554.908	2	20277.454	20.206	<0.001
Jaw	Movement Distance	Vowels	1250.283	8	156.285	24.904	<0.001
		Vowels x Severity	44.471	16	2.779	0.443	0.970
		Severity	563.434	2	281.717	5.715	0.006
	X Distance	Vowels	441.907	8	55.238	23.324	<0.001
		Vowels x Severity	39.190	16	2.449	1.034	0.420

		Severity	213.759	2	106.879	5.253	0.009
	Y Distance	Vowels	797.587	8	99.698	34.269	<0.001
		Vowels x Severity	26.297	16	1.644	0.565	0.909
		Severity	100.268	2	50.134	2.743	0.076
	X Range	Vowels	353.810	8	44.226	20.544	<0.001
		Vowels x Severity	40.473	16	2.530	1.175	0.286
		Severity	130.812	2	65.406	4.106	0.024
	Y Range	Vowels	727.411	8	90.926	32.877	<0.001
		Vowels x Severity	31.549	16	1.972	0.713	0.781
		Severity	71.776	2	35.888	2.135	0.131
	Speed	Vowels	10592.270	8	1324.033	16.773	<0.001
		Vowels x Severity	908.766	8	56.798	0.72	0.774
		Severity	394.993	2	197.496	0.313	0.733
Tongue and Jaw	Vowel Duration	Vowels	0.450	8	0.056	30.005	<0.001
		Vowels x Severity	0.055	16	0.003	1.817	0.028
		Severity	1.560	2	0.780	38.261	<0.001

Tongue Movement Distance. The overall difference range across vowels in movement distance values was 6.62 mm in the severe group of PALS and 8.66 mm in the mild group of PALS. The vowel that showed the greatest movement distance was /ɑ/ in "Hod" (Severe PALS: 12.59mm; Mild PALS 13.83mm). The vowel that showed the shortest movement distance was /i/ in "Heed" (Severe PALS: 5.97mm; Mild PALS: 5.17mm).

Even though main effect results showed significant interaction between vowels and severity in tongue movement distance, the Bonferroni post-hoc tests did not show significant vowel-specific severity group differences. Vowel-specific main effect was the same as what was observed in the control group. Greater tongue movement is observed in back vowels in comparison to front vowels; and in low vowels in comparison to high vowels. In addition, there was no significant severity difference.

Tongue Distance on X Dimension (Front-back). As shown in Figure 2, the mild and severe groups of PALS did show a tongue X distance difference between front and back vowels and between high and low vowels unlike the control group. The overall difference range across vowels in X distance values was 4.18 mm in the severe group of PALS and 5.45 mm in the mild group of PALS. The vowel that showed the greatest X distance in the severe group of PALS was /ɑ/ in “Hod” (7.33mm). The vowel that showed the greatest X distance in the mild group of PALS was /ʌ/ in “Hud” (8.09mm). The vowel that showed the shortest X distance was /i/ in “Heed” (Severe PALS: 3.16mm; Mild PALS: 2.64mm).

A significant interaction between vowels and severity groups was observed. The Bonferroni post-hoc tests showed that in vowel /i/, both the severe and mild group of PALS showed a reduced tongue X distance in comparison to the control group. Interestingly, in vowel /ʌ/, both the severe and mild group showed a greater tongue X movement than the control group.

Tongue Distance on Y Dimension (Height). As shown in Figure 2, the mild and severe groups of PALS did show a difference between front and back vowels. The overall difference range across vowels in Y distance values was 4.50 mm in the severe group of PALS and 6.96 mm in the mild group of PALS. The vowel that showed the greatest Y distance was /ɑ/ in “Hod” (Severe PALS: 7.71mm; Mild PALS: 9.94mm). The vowel that showed the shortest Y distance in the severe group of PALS was /i/ in “Heed” (3.22mm). The vowel that showed the shortest Y distance in the mild group was /ɪ/ in “Hid” (2.98mm).

A significant interaction between vowels and severity groups was observed. The Bonferroni post-hoc tests showed that in vowel /i/, both the severe and mild groups showed a reduced tongue Y distance in comparison to the control group.

Tongue Range of Motion on X Dimension (Front-back). As shown in Figure 3, the mild and severe groups of PALS did show a difference between front and back vowels; and between high and low vowels. The overall difference range across vowels in X range values was 4.32 mm in the severe group of PALS and 5.51 mm in the mild group of PALS. The vowel that showed the greatest X range was /ʌ/ in "Hud" (Severe PALS: 6.53mm; Mild PALS: 7.77mm). The vowel that showed the shortest X range /i/ in "Heed" (Severe PALS: 2.20mm; Mild PALS: 2.26mm).

A significant interaction between vowels and severity groups was observed. The Bonferroni post-hoc tests showed that in vowel /i/, both the severe and mild group showed a reduced tongue X range in comparison to the control group. In vowel /ɪ/, the mild group showed a reduced tongue X range in comparison to the control group. Interestingly, in /ʌ/, both the severe and mild groups showed a greater tongue X range in comparison to the control group.

Tongue Range of Motion on Y Dimension (Height). As shown in Figure 3, the mild and severe groups of PALS did show a difference between front and back vowels; and between high and low vowels. The overall difference range across vowels in Y range values was 4.51 mm in the severe group of PALS and 7.36 in the mild group of PALS. The vowel that showed the greatest Y range in the severe group of PALS was /ɑ/ in "Hod" (6.47mm). The vowel that showed the greatest Y range in the mild group of PALS was /o/ in "Hoed" (9.74mm). The vowel that showed the shortest Y range was /i/ in "Heed" (Severe PALS: 2.47mm; Mild PALS: 2.38mm).

A significant interaction between vowels and severity groups was observed. The Bonferroni post-hoc tests showed that in vowel /o/, the severe group showed a reduced tongue Y range in comparison to the control group. To produce back vowel /o/, it requires a greater tongue range in the superior-inferior dimension, since it is often more diphthongized. This vowel is displayed in Figure 6, in the bottom figure, as there is evidence of larger overall distance in the Y dimension in typically aging speakers, and it is reduced in this dimension in both groups of PALS. (Control: 11.78mm; Mild PALS: 9.83mm; Severe PALS: 6.98mm).

Figure 6

Tongue Movement Trajectories of Vowels that Showed Vowel-Specific Severity Differences

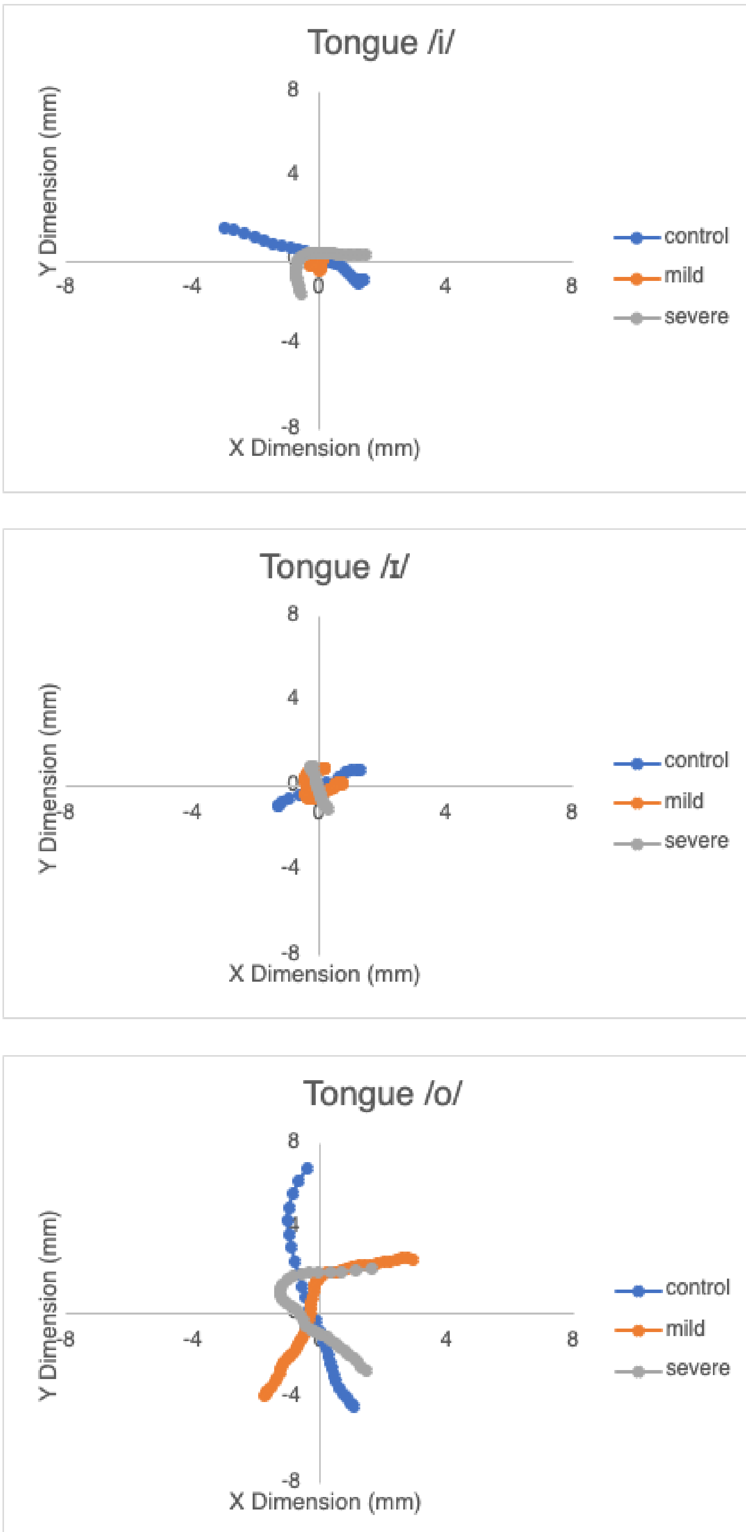
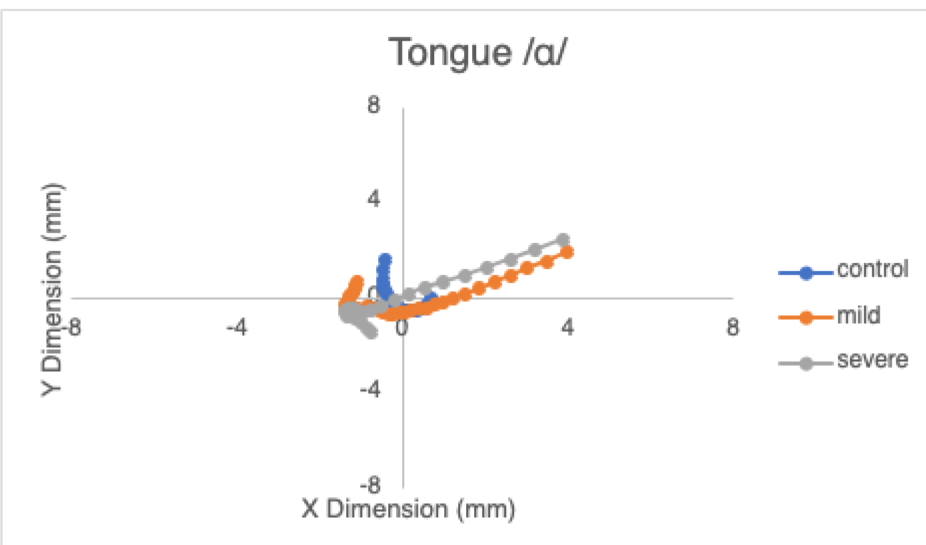


Figure 6 displays the three vowels that showed vowel-specific severity differences: /i/, /ɪ/, and /o/. These three vowels show a reduced tongue movement in PALS. In the figures displaying the two high front vowels, /i/ and /ɪ/, the tongue distance and overall movement trajectory for both severity groups of PALS are smaller than the control group which shows a greater movement distance. This shows how typically aging speakers use a larger tongue movement to produce these two high front vowels. This vowel-specific severity difference was also observed with back vowel /o/.

Figure 7 displays back vowel /ɑ/, which is just one of the remaining six vowels investigated that did not show vowel-specific severity differences. Unlike the figures for the three vowels that showed vowel-specific severity differences, this figure does not show a reduction in tongue movement. The control speaker showed the smallest movement in this figure in comparison to both groups of PALS who showed an increase in tongue movement.

Figure 7

Tongue Movement Trajectory of a Vowel that Showed No Vowel-Specific Severity Differences



Tongue Speed. As shown in Figure 4, the mild and severe groups of PALS did show a difference between front and back vowels. The overall difference across vowels in speed (mm/s) was 22.78 mm/s in the severe group of PALS and 38.29 mm/s in the mild group of PALS. The vowel that showed the greatest speed was /ʌ/ in “Hud” (Severe PALS: 38.27mm/s; Mild PALS: 56.48mm/s). The vowel that showed the shortest speed was /i/ in “Heed” (Severe PALS: 15.49mm/s; Mild PALS: 18.20mm/s). This shows how for both groups of PALS, back vowels are faster to produce than front vowels.

A significant main effect of vowels and severity was observed. There was no significant interaction observed. Significant vowel effect is the same as what was observed in the control group (RQ1). The Bonferroni post-hoc tests showed that tongue speed is slower in the severe and mild groups than in the control group.

Jaw

Statistical analysis was used to determine that there was a significant main effect of vowel observed in all the spatial jaw variables. There was no interaction observed between severity and vowel. A significant severity difference was observed in jaw movement distance, jaw X distance, jaw Y distance, and jaw X range.

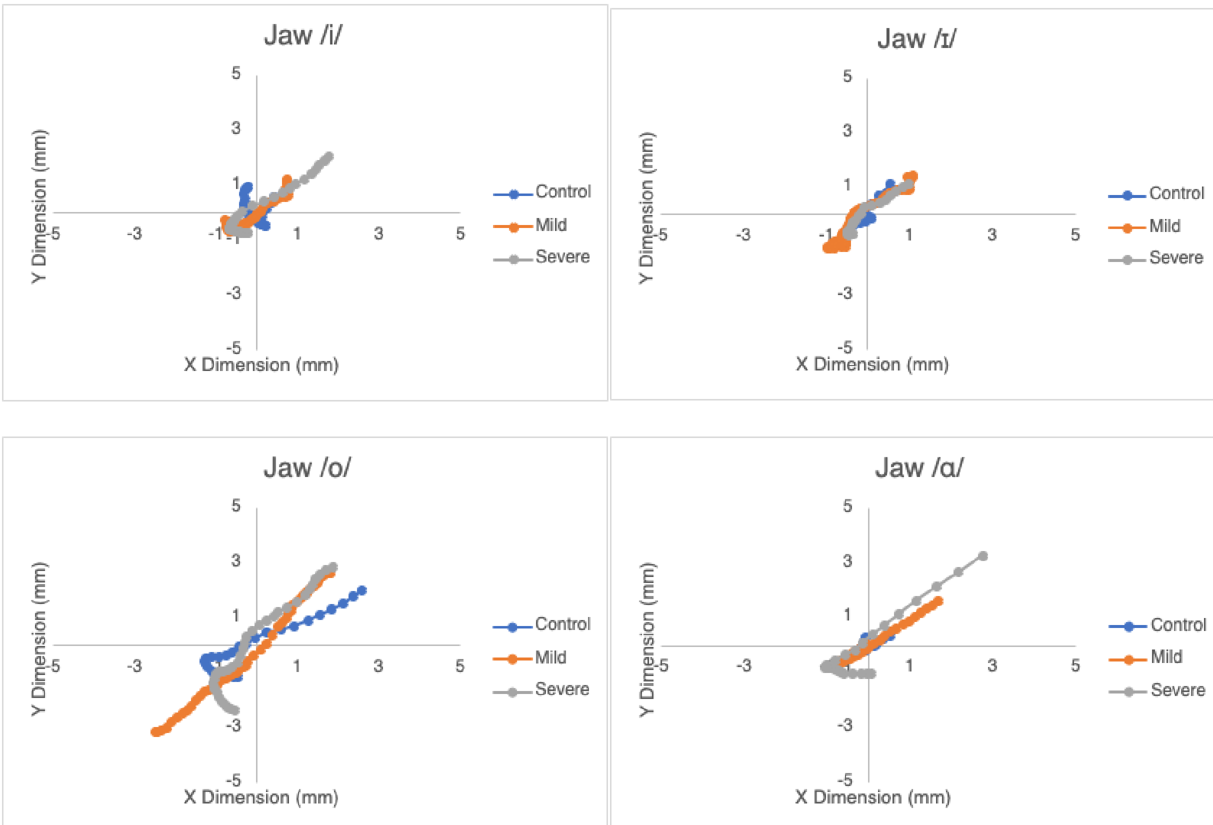
Jaw Movement Distance. As shown in Figure 1, on the left panel (Severe group of PALS) and on the middle panel (Mild group of PALS), in the bottom figure corresponds to jaw movement data. The mild and severe groups of PALS did show a difference between low, mid, and high vowels. The overall difference range across vowels in movement distance values was 5.19 mm in the severe group of PALS and 6.39 mm in the mild group of PALS. The vowel that showed the greatest movement distance was /æ/ in “Had” (Severe PALS: 11.35mm; Mild PALS: 10.48mm). The vowel that showed the shortest movement distance in the severe group of PALS was /i/ in “Heed” (6.16mm). The vowel that showed the shortest movement distance in the mild group of PALS was /ʊ/ in “Hood” (4.09mm).

A significant vowel difference and group difference was observed. The vowel pattern is the same as to what was observed in the control group. The severity difference is that the severe group of PALS showed a greater jaw movement in comparison to the control group. There was no significant interaction between vowels and severity groups.

Figure 8 displays the jaw movement trajectories of the same four vowels that were examined for tongue movement trajectories in Figures 6 and 7. In terms of significant main effect of vowel, the overall jaw movement for the two high front vowels, /i/ and /ɪ/, is smaller than the two back vowels, /o/ and /ɑ/. /o/ and /ɑ/ showed a much larger overall movement distance unlike the two high front vowels. In terms of severity, referring back to Figure 8, typically aging speakers displayed a smaller jaw movement during the production of the four vowels shown in comparison to the severe group of PALS. The severe group of PALS showed an exaggerated jaw movement.

Figure 8

Jaw Movement Trajectories that Showed More Exaggerated Movement in the Severe Group of PALS than in the Control Group



Jaw Distance on X Dimension (Front-back). As shown in Figure 2, the mild and severe groups of PALS did show a difference between low, mid, and high vowels. The overall difference range across vowels in X distance values was 3.16 mm in the severe group of PALS and 3.75mm in the mild group of PALS. The vowel that showed the greatest X distance in the severe group of PALS was /æ/ in “Had” (6.31mm). The vowel that showed the greatest X distance in the mild group of PALS was /ɑ/ in “Hod” (5.79mm). The vowel that showed the shortest X distance in the severe group of PALS was /ɪ/ in “Hid” (3.15mm). The vowel that showed the shortest X distance in the mild group of PALS was /u/ in “Who’d” (2.03mm).

A significant vowel difference and group difference was observed. The vowel pattern is the same as to what was observed in the control group. The severity difference is that the severe group of PALS showed a greater jaw X movement in comparison to the control group. There was no significant interaction between vowels and severity groups.

Jaw Distance on Y Dimension (Height). As shown in Figure 2, the mild and severe groups of PALS did show a difference between low, mid, and high vowels, which is consistent with the control group's vowel pattern. The overall difference range across vowels in Y distance values was 3.86 mm in the severe group of PALS and 5.23 mm in the mild group of PALS. The vowel that showed the greatest Y distance was /æ/ in "Had" (Severe PALS: 6.79mm; Mild PALS: 7.36mm). The vowel that showed the shortest Y distance in the severe group of PALS was /i/ in "Heed" (2.13mm). The vowel that showed the shortest Y distance in the mild group of PALS was /ʊ/ in "Hood" (2.23mm).

A significant vowel difference was observed. The vowel pattern is the same as to what was observed in the control group. There was no significant severity difference and no significant interaction between vowels and severity groups.

Jaw Range of Motion on X Dimension (Front-back). As shown in Figure 3, the mild and severe groups of PALS did show a difference between low, mid, and high vowels. The overall difference range across vowels in X range values was 2.96 mm in the severe group of PALS and 3.22 mm in the mild group of PALS. The vowel that showed the greatest X range in the severe group of PALS was /æ/ in "Had" (5.32mm). The vowel that showed the greatest X range in the mild group of PALS was /ɑ/ in "Hod" (4.73mm). The vowel that showed the shortest X range was /u/ in "Who'd" (Severe PALS: 2.36mm; Mild PALS: 1.51mm).

A significant vowel difference and group difference was observed. The vowel pattern is the same as to what was observed in the control group. The severity difference is that the severe group of PALS showed a greater jaw range of motion in the X dimension in comparison to the control group. There was no significant interaction between vowels and severity groups.

Jaw Range of Motion on Y Dimension (Height). As shown in Figure 3, the mild and severe groups of PALS did show a difference between low, mid, and high vowels. The overall difference range across vowels in Y range values was 3.39 mm in the severe group of PALS and 4.89 mm in the mild group of PALS. The vowel that showed the greatest Y range was /æ/ in "Had" (Severe PALS: 5.82mm; Mild PALS: 6.73mm). The vowel that showed the shortest Y range in the severe group of PALS was /i/ in "Heed" (2.43mm). The vowel that showed the shortest Y range in the mild group of PALS was /ʊ/ in "Hood" (1.84mm).

A significant vowel difference was observed. The vowel pattern is the same as to what was observed in the control group. There was no significant severity difference and no significant interaction between vowels and severity groups.

Jaw Speed. As shown in Figure 4, the mild and severe groups of PALS did show a difference between low, mid, and high vowels. The overall difference across vowels in speed (mm/s) was 12.33 mm/s in the severe group of PALS and 17.71 mm/s in the mild group of PALS. The vowel that showed the greatest speed was /æ/ in "Had" (Severe PALS: 29.50mm/s; Mild PALS: 32.29mm/s). The vowel that showed the shortest speed in the severe group of PALS was /i/ in "Heed" (17.17mm/s). The vowel that showed the shortest speed in the mild group of PALS was /u/ in "Who'd" (14.57mm/s). This shows how for both groups of PALS, low vowels are faster to produce than high vowels similar to the control group.

A significant vowel difference was observed, which is consistent with what was observed in the control group (RQ1). No significant interaction and no severity difference was observed.

Vowel Duration

As shown in Figure 5, a significant vowel duration difference was observed between control group and mild, and control and severe groups. PALS produced significantly longer vowel durations than the control group. The mild and severe groups of PALS did not show a difference between vowels in terms of duration.

Discussion

Research Question 1 (RS1): What are the vowel-specific patterns of articulatory kinematics of the tongue and jaw in typically aging individuals?

The current study is the first study to examine these vowel-specific kinematic characteristics in typically aging individuals. This study puts all AE monophthongs in the controlled consonant context of /h/-vowel-/d/ and uses an electromagnetic articulography system to measure the movement of both the tongue and jaw. Previous studies used different measures to track articulatory data, such as ultrasounds, and focused more on specific vowel contrasts, thus, a subset of vowels.

Previous studies in typical individuals showed that tongue height varies in the expected direction according to vowel height (Noiray et al., 2008, 2014) among front vowels, /i, ɪ, e, ɛ, æ/. In other words, tongue height varies following vowel height categories (high, mid, low vowels) mostly. Sometimes, the tongue height was flipped between /i/ and /ɪ/ but overall, the tongue height was consistent with vowel heigh categories (Noiray et al., 2008, 2014). In the current study, all AE vowels were examined in typically aging individuals. The findings indicated that typically aging individuals show much more tongue movement in the Y dimension than in the X dimension across vowels. Particularly, the extent of the tongue movement was much greater in the low vowels than the high vowels in the Y dimension. This pattern of more Y movement is displayed in the tongue kinematics and for both distance and range of motion.

It is essential to understand the vowel-specific and dimension-specific kinematic characteristics of typically aging individuals in order to identify speech difficulties and differences in PALS. If patterns are noticed in typically aging speakers, it is seen how these patterns change when an individual experiences ALS. The current data revealed a baseline of how the tongue and jaw typically move in the production of each vowel, and whether they require more distance moving in the X or Y dimension.

Research Question 2 (RQ2): Are these vowel-specific patterns similar or different in PALS than in typically aging individuals?

The patterns observed in PALS were different than the patterns observed in typically aging speakers. Certain vowels show clear kinematic differences between PALS and typically aging speakers but not others. The three characteristics of these vowels are 1. being a high or mid-high vowel (/i/, /ɪ/), 2. requiring the greatest amount of tongue movement as seen in typically aging individuals (/o/), and 3. requiring the least amount of movement as seen in typically aging individuals (/ʌ/).

The first characteristic is being a high or mid-high vowel, such as /i/ in the word "Heed" and /ɪ/ in the word "Hid". In PALS, they showed a reduced tongue movement for these two vowels in comparison to the control group. This reduction is more prevalent in the Y dimension. Referring to Figure 6, it shows how the tongue movement distance for these two vowels in the control group is larger than in both groups of PALS. Difficulties in high and mid-high vowel production were also observed in a previous study (Lee et al., 2020). They also found that the jaw was exaggerated in opening movements but not during closing movements in PALS, which resulted in reduced tongue raising movement in PALS. It is speculated that the reduced tongue raising motion in PALS impacted high/ mid-high vowels more than lower vowel production (Lee et al., 2020).

The second characteristic is requiring the greatest amount of tongue movement such as /o/ in the word “Hoed.” This vowel that requires the greatest amount of tongue movement revealed a reduced tongue movement in PALS compared to the control group. Referring to Figure 6, the control group showed a greater tongue distance in the Y dimension for the vowel /o/; however, in both the mild and severe group of PALS, they show a much smaller distance in the Y dimension. This is also highlighted in the mean tongue Y distance (Figure 2), as /o/ requires the greatest Y distance in typically aging individuals (11.78 mm). In the severe group of PALS, the mean tongue Y distance was 6.98 mm and in the mild group of PALS, it was 9.83 mm. Also, in the mean tongue Y range (Figure 3), /o/ requires the greatest Y distance in typically aging individuals (11.66 mm). In the severe group of PALS, the mean tongue Y range was 6.47 mm and in the mild group of PALS, it was 9.74 mm. Both of these variables in the Y dimension display this reduced tongue movement in PALS in comparison to typically aging speakers who produced /o/ with the greatest movements in the Y dimension.

This characteristic connects back to Lee and Bell (2018), as they found that limited height range in PALS affects their speech production, as their tongue is unable to reach greater distances in the Y dimension that may be needed to produce specific vowels. This is seen with the vowel /o/, as this vowel requires these greater tongue movements in the Y dimension. Typically aging individuals showed the greatest tongue Y distance and Y range for vowel /o/ in comparison to any other vowel for those variables, but it was not found to be have greatest movement in both groups of PALS.

Lastly, a vowel that requires the least amount of movement in typically aging individuals, such as /ʌ/ in the word “Hud” revealed a greater tongue movement in PALS. For example, in tongue X distance (Figure 2), to produce /ʌ/, typically aging individuals had a mean of 3.79 mm, which was the smallest X distance produced. In the severe group of PALS, the mean X distance was 6.86 mm, which was the second largest X distance. In the mild group of PALS, the mean X distance was 8.09 mm, which was the largest X distance. This same pattern was observed in tongue X range for the production of /ʌ/ (Control: 3.26 mm; Severe PALS: 6.53 mm; Mild PALS: 7.77 mm). Again here, typically aging individuals showed the smallest X range for /ʌ/, as both the severe and mild groups of PALS showed the greatest X range (Figure 3).

There are also “middle range vowels” that do not require the greatest or the least amount of tongue movement. PALS did not show significant movement difference while producing these vowels compared to typically aging individuals. For example, /ɛ/ in the word “Head” never had the greatest or least amount of tongue movement overall and in both X and Y dimensions or was the fastest or slowest in the control group. We also saw these same patterns of this vowel in the severe group of PALS and in the mild group of PALS, where it also never had the greatest or least amount of tongue movement and was never the fastest or slowest.

Lee and Bell (2018) discussed differential involvement of articulators, in terms of how the tongue and jaw experience differences in terms of their impairment. They explained how previous studies also found more severe impact on the tongue in comparison to the jaw (Lee & Bell, 2018). Shellikeri et al. (2016) conducted a study that investigated both longitudinally and cross-sectional data in PALS. They found that the reduced tongue movement and speed occurred at relatively early stages in ALS. Further on in the study, once the speaking rates of PALS started to decline, they found that at maximum speed, tongue movements reduced and jaw movements increased (Shellikeri, et al., 2016). Yunusova et al. (2008), also stated how the tongue and jaw show much different movement patterns. This was also seen in the findings of the current study, as the tongue and jaw movement patterns were different in PALS. There were evident patterns of reduced tongue movement in PALS for high and mid-high vowels (/i, ɪ/). There were also evident patterns of exaggerated jaw movements in PALS across all spatial variables. For example, referring to Figure 1, mean jaw movement distance in both the severe and mild group of PALS showed an increase in overall movement distance in comparison to the control group.

Limitations and Future Directions

One limitation of this study is the small number of participants investigated. Even though there were 22 PALS and 22 typically aging speakers, a future study with a greater sample size is needed to confirm the current findings. Another limitation is in terms of the heterogeneity of the current study. This study only investigated a small number of PALS which makes it difficult to apply these findings to a more diverse population. Lee et al. (2019) referred to ALS as a clinical symptom, as it affects every individual differently depending on the degree of involvement between UMN and LMN. Therefore, it is advised that the findings of this study be applied with caution, as every individual with ALS may experience varying symptoms.

The current findings indicate that, in PALS, tongue movement extent and range may vary with vowel categories and movement dimension. For example, descriptively, PALS showed greater tongue X range in back vowels in comparison to front vowels. This indicates dimension specific tongue movement characteristics in PALS and a future study needs to investigate the dimension specific characteristics further.

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