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DEPARTMENT OF COMMUNICATION SCIENCES AND DISORDERS

TONGUE AND JAW MOVEMENTS IN “IOWA” BETWEEN SPEAKERS WITH AND WITHOUT DYSARTHRIA SECONDARY TO ALS

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ABSTRACT

Purpose: Dysarthria is a type of motor speech disorder secondary to various neurological conditions including amyotrophic lateral sclerosis (ALS). The purpose of the current study is to identify 1) articulatory kinematic correlates of severity of dysarthria measured by speech intelligibility and speaking rate and 2) articulatory kinematic characteristics of the tongue and jaw in individuals with ALS. *Methodology:* Temporal and spatial articulatory kinematic data were collected using electromagnetic articulography from 21 individuals with dysarthria secondary to ALS and 20 healthy-aging individuals. The speech intelligibility data included the results of 139 listeners. Selected kinematic variables were examined in two ways: first, the correlation between the kinematic variables and speech intelligibility/speaking rate and second, the comparison of articulatory kinematic variables across groups (speakers with severe dysarthria secondary to ALS, speakers with mild dysarthria secondary to ALS, and healthy-aging speakers). *Results:* Temporal measures for tongue body and jaw such as duration and speed were significantly correlated with speech intelligibility and speaking rate. Speakers with higher intelligibility and faster speaking rate had greater tongue movements in the inferior-superior dimension. Across groups, speakers with severe dysarthria secondary to ALS had smaller convex hull areas, which represents articulatory working space, than speakers with mild dysarthria secondary to ALS. *Discussion:* During target word production, in addition to temporal measures, tongue body movement in the inferior-superior dimension and convex hull area may be valuable indicators of disease progression in ALS.

Key words: dysarthria, amyotrophic lateral sclerosis (ALS), tongue, jaw, kinematics

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It is also necessary for me to thank my family and friends for supporting me throughout my fours at Penn State. I would not be where I am today if it were not for them.

Introduction

Dysarthria is a type of motor speech disorder that causes difficulties in articulatory muscle control. It is secondary to conditions involving damage to the central and/or peripheral nervous system, such as Parkinson's disease (PD), stroke, traumatic brain injury, and amyotrophic lateral sclerosis (ALS). The current study focused on speakers with dysarthria secondary to ALS.

Dysarthria affects the components of communication, including phonation, respiration, resonation, prosody, and articulation, due to irregularities in the speed, strength, tone, range, and accuracy of movements within the speech articulators (Duffy, 2005). According to Duffy (2005), abnormalities in speech production reflect a variety of ways it is challenging for people with dysarthria to maintain muscular control, such as incoordination, paralysis, spasticity, flaccidity, and excessive or reduced articulatory movement.

Index of Severity of Dysarthria in ALS

In individuals with ALS, severity of dysarthria has often been measured by speech intelligibility and speaking rate. Speech intelligibility is the degree to which one can be understood when speaking. Decreased speech intelligibility is one of the main characteristics of dysarthria and it is an area that has been examined in many studies (Kim, Hasegawa-Johnson, & Perlman, 2011; Higgins & Hodge, 2002; Liu, Tsao, & Kuhl, 2005; Turner, Tjaden & Weismer, 1995). Increasing speech intelligibility is the ultimate goal when treating patients with dysarthria because one's ability to speak and be understood influences how well one functions in his or her every day life. Speech intelligibility is significantly influenced by articulatory function (Lee, Hustad, & Weismer, 2014; Rong et al., 2016). In other words, it can be challenging to understand what speakers with dysarthria are saying since dysarthria can cause a loss of muscle control in the articulators, such as the tongue (Kuruvilla, Green, Yunusova, & Hanford, 2012).

Speaking rate is typically measured by the number of words per minute (wpm) in connected speech production. Speakers with slower speaking rate present more severe dysarthria in ALS. Since both speech intelligibility and speaking rate are associated with severity of dysarthria, the two measures are highly correlated. Speakers with slower speaking rate exhibit lower speech intelligibility. Speaking rate decline, however, occurs earlier than speech intelligibility in individuals with ALS (Ball, Willis, Beukelman, & Pattee, 2001; Ball, Beukelman, & Pattee, 2002; Yorkston, Strand, Miller, Hillel, & Smith, 1993). In addition, the speaking rate decline pattern has shown a linear relationship with speech function decline in individuals with ALS (Yorkston et al., 1993). Therefore, speaking rate has been used as a valuable measure when examining changes in speech during disease progression in ALS.

Influence of Severity on Speech Production Measures

As mentioned above, dysarthria is a type of motor speech disorder. Much effort has been made to understand speech production-based variables that influence the severity of dysarthria. Previous research has shown that motor control in the articulatory domain contributes to speech intelligibility in a substantial way (Lee et al., 2014; Rong, Yunusova, Wang, & Green, 2015). Articulatory motor control has been studied with acoustic and articulatory kinematic approaches. In acoustic studies, longer segmental duration, reduced vowel working space, and shallower formant slope were identified as key speech acoustic characteristics in individuals with dysarthria (Lansford and Liss, 2014; Mulligan, Carpenter, Riddel, & Delaney, 1994; Turner et al., 1995; Weismer, Laures, Jeng, Kent & Kent, 2000; Weismer, Jeng, Laures, Kent, & Kent, 2001). In articulatory kinematic studies, depending on the primary etiology, the findings have been varied (e.g., Parkinson's Disease vs. ALS). In ALS, longer segment duration, slower articulatory movement speed, reduced coordination among articulators, and reduced movement extent have been noted (Green et al., 2013; Kent & Netshell, 1978; Shellikeri et al., 2016; Weismer et al., 2000; Weismer, Yunusova, & Westbury, 2003).

Influence of the Target Word on Articulatory Kinematic Findings

In articulatory kinematic studies, the reduced movement extent of the articulators was influenced by the target word (Yunusova, Weismer, Westbury, & Lindstrom, 2008). The selection of a target word is crucial because each target word's spatial articulatory kinematic characteristics are different. More importantly, spatial articulatory kinematic differences in individuals with dysarthria could be detected in certain words, however, not in all words. Yunusova and her colleagues (2008) suggested that words that require greater articulatory movement would be more sensitive to speech impairment in dysarthria.

It has been speculated that individuals with dysarthria have reduced articulatory working space according to previous acoustic studies particularly related to vowel working space (Turner et al., 1995; Weismer et al., 2000; Weismer et al., 2001). Therefore, by examining articulatory kinematics using a word that requires greater articulatory movement as well as covering substantial area of articulatory working space, the articulatory kinematic characteristics associated with severity of dysarthria can be further understood. For this study, the target word was “Iowa.” When a speaker is producing the word “Iowa,” vocal tract configuration covers more of its vowel working space (Story & Titze, 2002).

Tongue and Jaw

The tongue is a primary articulator that shapes the vocal tract for intelligible speech production. In individuals with ALS, previous studies have shown that the tongue is most significantly impaired in the earlier stages of the disease (Carpenter, McDonald, & Howard, 1978; DePaul, Abbs, Caligiuri, Gracco, & Brooks, 1988). Thus, in the current study, the tongue movement pattern was examined with various articulatory kinematic variables to understand its association with severity of dysarthria. The tongue is anatomically coupled with the jaw and it interacts with the jaw during speech production. Therefore, to understand tongue movement impairment in natural speaking conditions in individuals with dysarthria secondary to ALS, parallel examination of jaw movement is crucial. Previous studies have found that articulatory movement measures may be indicative of disease progression (Rong et al., 2015; Shellikeri et al., 2016). In addition, previous studies established smaller tongue body movements and larger jaw movements during speech production in individuals with dysarthria secondary to ALS (Hirose, Kiritani, & Sawashima, 1982; Shellikeri, Yunusova, Thomas, Green, & Zinman, 2013; Yunusova et al., 2008). Yunusova et al. (2008) proposed that this opposing relationship between the tongue and jaw movements might be an example of a compensatory behavior. The current study focused on the movement of the tongue and jaw to understand its contribution to the severity of dysarthria in individuals with ALS.

Objective

The purpose of the current study is to identify tongue and jaw articulatory kinematic characteristics in individuals with ALS. The target word, “Iowa,” was carefully chosen to represent articulatory impairment in ALS. There is a gap in our knowledge on what specific tongue and jaw movements are impacting severity of dysarthria when measured by speech intelligibility and speaking rate. To further our understanding and eventually establish an effective intervention, it is important to understand the relationship between articulatory kinematics and speech intelligibility as well as between articulatory kinematics and speaking rate. The following research questions were pursued:

1. What is the tongue and jaw kinematic correlates of speech intelligibility and speaking rate in individuals with dysarthria secondary to ALS?
2. What is the difference in tongue and jaw movement for “Iowa” production between individuals with and without dysarthria?

Methodology

Speakers

Twenty-one speakers with dysarthria secondary to ALS participated in the current study. The speakers with dysarthria secondary to ALS were between the ages of 43 to 80 (mean = 63, SD = 9). Table 1 presents characteristics of each participant with dysarthria secondary to ALS. All twenty-one speakers were from the Mid-Atlantic region in the United States. There were 10 male and 11 female speakers. Nineteen speakers used speech as their main means of communication and the remaining two speakers used both speech and augmentative and alternative communication (AAC). The 21 speakers with dysarthria secondary to ALS were assigned to two severity groups: Severe and Mild. The cutoff for the severity group assignment was 110 words per minute (wpm) speaking rate (Ball et al. 2001; Ball et al. 2002). When determining severity of the disorder, 14 were classified as having severe dysarthria and 7 were classified as having mild dysarthria. All speakers with dysarthria secondary to ALS had to meet the criteria in order to participate in the study. The criteria are that they had to be a native speaker of American English and they had to pass a hearing screening at 250, 500, 1000, and 2000 Hz at 40 dB in at least one ear. One speaker (PALS9) had a hearing loss and he passed the hearing screening at 250, 500, 1000, and 2000 Hz at 65 dB in his better ear.

In addition to these 21 speakers with dysarthria secondary to ALS, 20 healthy-aging male and female speakers also participated in the study. There were 8 male and 12 female speakers between the ages of 47 to 80 (mean = 63, SD = 8) and they were all from the Mid-Atlantic region in the United States. These 20 participants acted as the age-matched control group. All healthy-aging speakers were required to meet the criteria in order to participate in the study. The criteria are that they had to be a native speaker of American English and they could not have any known speech, language, or cognitive disorders. In addition, all healthy-aging speakers passed a hearing screening at 250, 500, 1000, and 2000 Hz at 35 dB in at least one ear. All participants signed a consent form and the Institutional Review Board (IRB) at the Pennsylvania State University granted approval for this study.

Listeners

For speech intelligibility, 139 listeners participated in the current study. Speech intelligibility scores were collected for both speakers with dysarthria secondary to ALS and healthy-aging speakers. Three listeners were assigned to each speaker. When there was more than a 10% difference between the three listeners' speech intelligibility scores, the deviated score was identified and a new listener was recruited for that speaker. To meet this requirement, 16 listeners' scores needed to be replaced with new listeners' scores. There were 100 female and 39 male listeners between the ages of 18 to 36 (mean=22, SD=4). All listeners: 1) were native speakers of American English; 2) had no known speech, language, or neurological disorders; and 3) did not have extensive experience communicating with people with motor speech disorders. All speakers passed a bilateral hearing screening at 25 dB HL for the frequencies of 500, 1000, 2000 and 4000 Hz.

Procedures

The target word, "Iowa," was embedded in the following phrase: "I say a _______ again" and each speaker produced three repetitions of the phrase. Speech samples were collected using 3-dimensional electromagnetic articulography: WAVE system (Northern Digital Inc.). Acoustic and kinematic information was collected using the WAVE system. Before attaching the movement sensors to the speakers' articulators, the bite plane of each speaker was obtained. To obtain the bite plane of a speaker, a reference sensor was attached to the speaker's forehead and three movement sensors were attached to a bite plate. Two movement sensors were attached on the sagittal plane on the bite plate and the remaining movement sensor was attached on the coronal plane. The bite plane data were utilized to rotate and translate kinematic data using a tailored R code (R Core Team, 2014). After rotation and translation, the origin (0, 0, 0) was located in front of the maxillary central incisors along the midsagittal plane. After obtaining the bite plane, the first two movement sensors were attached to the tongue. One sensor was attached approximately 10mm from the tongue apex (tongue tip) and the second sensor was placed approximately 15mm from the tongue tip sensor (tongue body). The remaining two movement sensors were placed on the lower lip and jaw on the midsagittal plane. X-coordinate values increase with target articulator advancement toward the front of the speaker's mouth, y-coordinate values increase with target articulator upward movement toward the top of the speaker's mouth, and z-coordinate values increase with the target articulator's lateral movement to the right side of the speaker's mouth. The sampling rate of the kinematic data was 100Hz and a low pass filter at 10Hz was used. In this study, the kinematic data from the tongue body and jaw sensors were analyzed. Before beginning the speech tasks, all participants were given two minutes to familiarize themselves with the sensors.

Acoustic Analyses

TF32 (Milenkovic, 2002) was used to define the temporal boundaries of this study's target word, "Iowa." The wideband spectrographic display was used to identify the onset of the word starting point (/aɪ/) and the offset of the word ending point (/ə/). After defining the temporal boundaries, kinematic data (x-axis and y-axis) were obtained for the tongue body and jaw. Figure 1 demonstrates an example of the temporal boundaries of the target word with its synchronized kinematic data.

Kinematic Analyses

Tongue kinematic data remained coupled with jaw kinematic data in the current study. Therefore, the tongue kinematic data represent the movement of the tongue and jaw. Comparison to jaw kinematic data provides information on whether the tongue kinematic variable findings are statistically significant solely due to the movements of the tongue body. Listed and defined below are the multiple kinematic measurements analyzed in this study.

Duration. The duration (word starting point to word ending point) was measured in seconds (s) and used to calculate the speed of the tongue body and jaw movements.

Speed. When producing the target word, the speed of the two articulators (tongue body and jaw) was calculated by dividing the overall three-dimensional (3D) distance (mm) by the duration (s).

Distance for x- and y-axes and overall 3D distance of tongue body and jaw. This measurement shows how much the articulators moved on each dimension (x-axis: anterior-posterior; y-axis: inferior-superior) as well as the combination of the three dimensions.

Displacement for x- and y-axes and overall 3D displacement of tongue body and jaw. This measurement shows the distance between the word starting and ending points during the target word production on each dimension (x-axis: anterior-posterior; y-axis: inferior-superior) as well as the combination of the three dimensions.

Range for x- and y-axes of tongue body and jaw. This measurement is the difference between the maximum and minimum movement points along the x- and y-axes.

Convex hull. To represent the range of motion in multiple dimensions, two-dimensional convex hull area was calculated for tongue body and jaw. In this measure, movement data of x-axis (anterior-posterior plane) and y-axis (inferior-superior plane) were used. The convex hull area represents the working space, overall range of motion, of each articulator during target word production.

Figures 2, 3, and 4 illustrate the differences between spatial kinematic variables (distance vs displacement, range of movement, and convex hull, respectively) examined in the current study.

Experimental Design and Statistical Analyses

Pearson correlation coefficients were used to test the relationship between kinematic variables and speech intelligibility as well as between kinematic variables and speaking rate. One-way analysis of variance (ANOVA) with Tukey post-hoc test was used to investigate how kinematic variables are different by severity and presence of ALS (Severe, Mild, and Control groups).

Results

Tongue and Jaw Kinematic Correlates of Speech Intelligibility

In the current study, there were two spatial and two temporal tongue kinematic correlates of speech intelligibility. The two spatial tongue body kinematic measurements that were significantly correlated with speech intelligibility were distance ($r = .443$, $p = .044$) and range ($r = .672$, $p = .001$) on the y-axis. Speakers with lower intelligibility had a shorter spatial distance and range along the y-axis. Figure 5 shows the scatterplot of speech intelligibility and tongue body range in the inferior-superior dimension.

One of the temporal measures, duration, was found to be significantly correlated with speech intelligibility ($r = -.454$, $p = .039$). In addition, tongue body movement speed was significantly correlated with speech intelligibility ($r = .465$, $p = .034$). Speakers who had lower speech intelligibility had a longer duration and slower speed.

There were multiple spatial jaw kinematic correlates of speech intelligibility; 3-dimensional Euclidian distance, x-axis distance, y-axis distance, displacement, x-axis range and convex hull area. The 3D Euclidian distance ($r = -.570$, $p = .007$) of the target word was significantly correlated with speech intelligibility. Speakers with lower speech intelligibility had greater jaw movement distance. Both the distances of the jaw on the x- ($r = -.514$, $p = .017$) and y-axes ($r = -.521$, $p = .016$) were significantly correlated with speech intelligibility. Speakers with lower intelligibility had longer jaw distances on the x- and y-axes. Another spatial kinematic correlate of speech intelligibility was jaw displacement ($r = -.491$, $p = .024$). Speakers with higher speech intelligibility had a shorter jaw displacement. The range ($r = -.462$, $p = .035$) along the x-axis was significantly correlated with speech intelligibility. If a speaker had higher intelligibility, the range of jaw movement along the x-axis was shorter. Jaw convex hull area (r =

-.615, p = .003) was negatively significantly correlated. Speakers with lower speech intelligibility had a greater jaw convex hull size.

Unlike the tongue body movement speed, jaw speed (r = -.356, p = .113) was not significantly correlated with speech intelligibility, suggesting that the tongue body's motion caused the significance for speed. Table 2 shows the tongue and jaw kinematic correlates of speech intelligibility.

Tongue and Jaw Kinematic Correlates of Speaking Rate

In the current study, there were three spatial and two temporal tongue kinematic correlates of speaking rate. The three spatial tongue body kinematic measurements that were significantly correlated with speaking rate included distance (r = .456, p = .038) and range (r = .693, p = .000) on the y-axis as well as convex hull area (r = .682, p = .001). Speakers with lower intelligibility had a shorter spatial distance and range along the y-axis as well as a smaller convex hull area. Figure 6 shows the scatterplot of speaking rate and tongue body range in the inferior-superior dimension.

The two temporal tongue body kinematic measurements that were significantly correlated with speaking rate included duration (r = -.491, p = .024) and speed (r = .704, p = .000). Speakers who had lower speaking rate had a longer duration and slower speed.

None of the jaw kinematic variables were significantly correlated with speaking rate. The significant variables of speaking rate for tongue body (distance and range on the y-axis, convex hull area, and speed) were not significant for jaw. These findings suggest that the tongue body's motion caused the significance across these variables. Table 2 also shows the tongue and jaw kinematic correlates of speaking rate.

Tongue and Jaw Kinematic Differences across Groups

When comparing the tongue and jaw kinematic variables among healthy-aging speakers, speakers with mild dysarthria, and speakers with severe dysarthria, the current study found three general findings. Across all three pair contrasts (healthy-severe, healthy-mild, severe-mild), there was a significant difference in target word duration [$F(2, 32) = 25.887$, $p = .000$]. Speakers with severe dysarthria had the longest duration, speakers with mild dysarthria had the second longest duration, and healthy-aging speakers had the shortest duration.

The second finding established that there was a significant effect between speakers with severe dysarthria and speakers with mild dysarthria as well as between speakers with severe dysarthria and healthy-aging speakers for tongue body speed [$F(2, 32) = 20.163$, $p = .000$]. There was no significant difference between healthy-aging speakers and speakers with mild dysarthria for tongue body speed. However, this was not the case for jaw speed [$F(2, 32) = 0.935$, $p = 0.403$], suggesting that the tongue body's motion caused the significance for this variable. Speakers with severe dysarthria had slower tongue body speed than speakers with mild dysarthria and healthy-aging speakers.

The third finding established that speakers with severe dysarthria had significantly smaller tongue body convex hull areas [$F(2, 32) = 3.340$, $p = .048$] than speakers with mild dysarthria. There was no significant difference in tongue body convex hull area between speakers with mild dysarthria and healthy-aging speakers as well as between speakers with severe dysarthria and healthy-aging speakers. Figure 7 shows the tongue movements in "Iowa" across the three groups (speakers with severe dysarthria, speakers with mild dysarthria, and healthy-aging speakers) and their respective convex hull areas. Table 3 presents the descriptive information (spatial and temporal kinematic variables) across the three groups.

Discussion

There is a gap in our knowledge on what specific tongue and jaw movements are impacting speech intelligibility and speaking rate, which are the index of severity of dysarthria. To further our understanding and eventually establish an effective intervention, it is important to understand the relationship between kinematics and speech intelligibility as well as the relationship between kinematics and speaking rate. The current study questioned the tongue and jaw kinematic correlates of speech intelligibility and speaking rate in individuals with dysarthria secondary to ALS. It also examined the differences in tongue and jaw movement for "Iowa" production between individuals with and without dysarthria secondary to ALS.

Correlates of Speech Intelligibility and Speaking Rate

Among individuals with ALS, multiple variables of the tongue body and jaw were found to be significantly correlated with speech intelligibility and/or speaking rate. Two variables that were consistent with previous findings are that speakers with lower speech intelligibility and slower speaking rate had a longer duration and slower tongue body speed (Kuruvilla et al., 2012; Weismer et al., 2000; Weismer et al., 2001; Weismer et al., 2003; Yunusova et al., 2012). Another trend that supported previous findings is less tongue body movements and more exaggerated jaw movements during speech production in speakers with lower speech intelligibility (Hirose et al., 1982; Shellikeri et al., 2013; Yunusova et al., 2008).

When examining the relationships between the articulators (tongue body and jaw) and speech intelligibility, there were more jaw movement variables that were significantly correlated with speech intelligibility than tongue movement variables. However, the significant correlates of speaking rate were only tongue body variables. Speakers with higher speaking rate had greater tongue body movements. For example, speech intelligibility was significantly correlated with jaw convex hull size and not tongue convex hull, which represents overall working space of the articulator. On the other hand, speaking rate was significantly correlated with tongue convex hull size and not jaw convex hull.

The findings in the current study are consistent with previous studies as well as adding new knowledge to the articulatory kinematics of individuals with dysarthria secondary to ALS. The tongue data used in the current study are the result of tongue and jaw movement as the tongue data were not decoupled from the jaw data. One of the new findings was speakers with higher speech intelligibility and faster speaking rate presented greater tongue movement in the inferior-superior dimension. However, the jaw movement in the same dimension was not significantly correlated to speaking rate and speech intelligibility. In fact, the coefficient values (r-values) of the jaw movement in the same dimension indicated an inverse relationship with speech intelligibility and speaking rate. This inverse relationship was not statistically significant, but it is worth noting that the direction of the relationship was opposite of the one observed in tongue movement range (tongue + jaw).

Speakers with lower speech intelligibility showed smaller tongue body movement and greater jaw movement in the inferior-superior dimension. For the production of “Iowa,” the current study suggests two possible explanations. First, the inverted direction of the relationship of the tongue and jaw with speech intelligibility may be due to the incoordination of the articulators while producing the target word. Second, the difference in relationship direction may also be due to the jaw’s compensatory behavior in individuals with severe dysarthria secondary to ALS in order to preserve speech intelligibility. Since jaw function is relatively more preserved than tongue function in individuals with ALS, more severe speakers may have attempted to overcome the limited tongue movement by exaggerated motion of the jaw.

Group Comparison

A group comparison across Severe, Mild and Control groups showed three main findings. Two of which agreed with previous research: duration and tongue body speed (Green et al., 2013; Hirose et al., 1982; Kuruvilla et al., 2012; Murdoch & Goozée, 2003; Weismer et al., 2000; Weismer et al., 2001; Weismer et al., 2003). Speakers with severe dysarthria had a longer duration and slower tongue body speed than speakers with mild dysarthria and healthy-aging speakers. The new finding of the group comparisons was tongue convex hull area. Speakers with severe dysarthria had significantly smaller convex hull areas when producing the word "Iowa" than speakers with mild dysarthria.

Weismer and his colleagues (2012) suggested that the articulatory working space measurement can be “a good index of the motor integrity of the speech mechanism.” The articulatory working space is the area covered by articulatory gestures during speech production. The current study confirms this speculation based upon the large amount of articulatory working space covered during target word production in speakers with mild dysarthria. The finding suggests that decreasing articulatory working space is an indication of severity progression in speakers with dysarthria secondary to ALS.

Clinical Implications and Future Direction

The clinical implications of this study include the use of both spatial and temporal characteristics of tongue body and jaw in determining the severity of the disorder. As the intelligibility and speaking rate decreased, tongue body/jaw duration increased and tongue body speed decreased. In addition to this, speakers with lower speech intelligibility had greater jaw movements, yet smaller tongue body movements along the inferior-superior dimension. Speakers with a higher speaking rate had greater tongue body movements. In order to determine disease progression (severity progression), there is value in tracking the changes of tongue body and jaw spatial and temporal movements in speakers with dysarthria.

The selection of "Iowa" as the speech stimuli was found valuable by the number of significant correlates and group comparisons. The production of "Iowa" covers a substantial area of articulatory working space and it contains complexity in the tongue and jaw movements (circular trajectory involving a diphthong). These characteristics of the target word may have triggered the significance among the tongue body and jaw kinematic spatial and temporal measurements. Future studies should compare the complexity of speech stimuli when trying to determine which kinematic variables are indicative of disease progression.

Another clinical implication of the current study is the significance of working space area measured by convex hull as an indicator of disease progression. Speakers with severe dysarthria secondary to ALS had significantly smaller convex hull areas than speakers with mild dysarthria. Convex hull may be a valuable indicator in determining whether a speaker has progressed to the severe level of the disorder. Future studies should look further into the use of convex hull area as an indicator of disease progression by examining other complex speech stimuli. In addition, the paradoxical relationship observed in tongue and jaw coefficients warrants further research in the coordination of the two articulators as well as the potential compensatory behavior of the jaw.

Limitations

The following limitations need to be taken into consideration when interpreting and utilizing the data from the current study. The participants included 21 speakers with dysarthria and 20 speakers without dysarthria, which is a small sample size. The use of a small sample size can inhibit the use of generalizations across populations. Another limitation of the current study is the use of one speech stimuli. While the production of "Iowa" does involve complex articulatory movements, it would be valuable to study the tongue and jaw movements of other speech stimuli in order to expand the scope of the study's applicability and relevance. By examining other complex speech stimuli, additional findings may surface as well support those found in the current study.

Appendix A

Figures

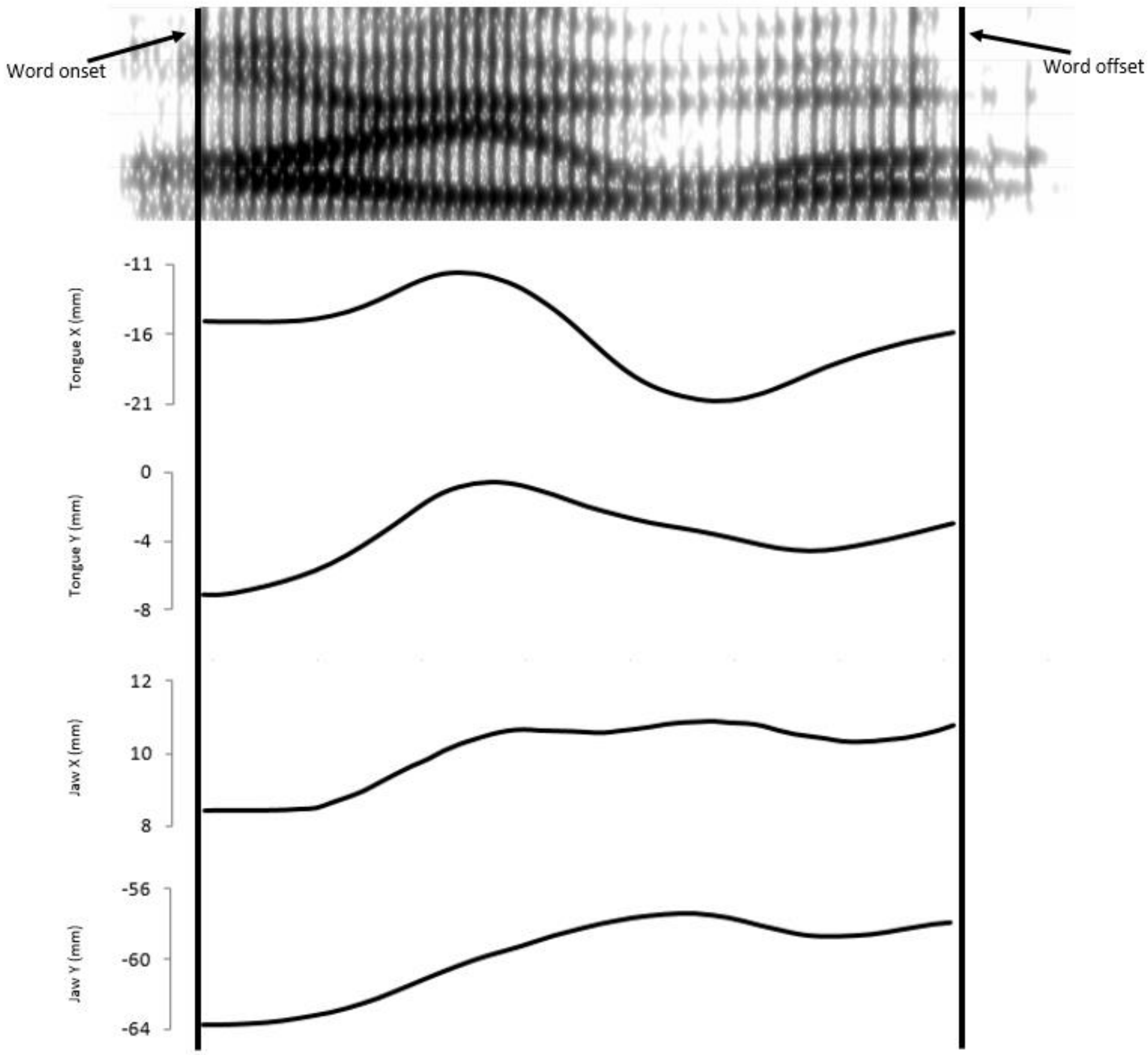

Figure 1. Movement time histories (x- and y- of tongue and jaw) over the duration of the target segment from which kinematic data were extracted. The word onset (/aɪ/) and word offset (/ə/) of "Iowa" are the target segment temporal boundaries.

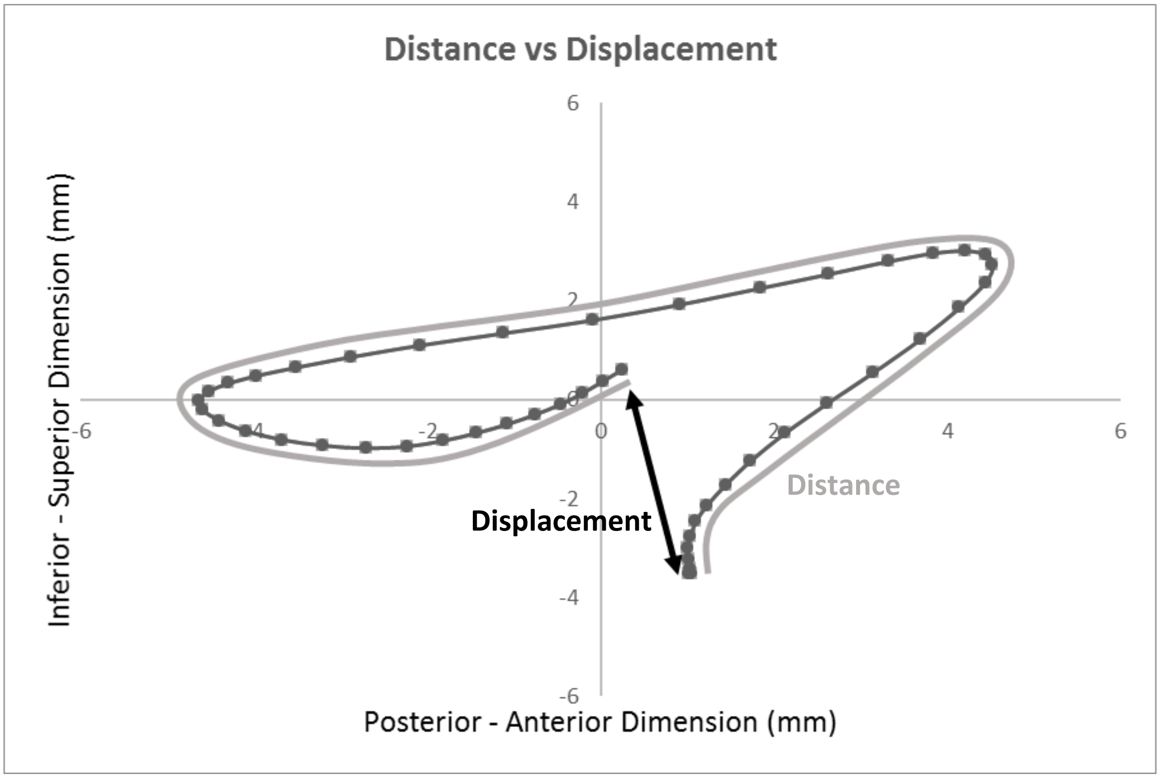

Figure 2. Spatial kinematic variable (distance vs displacement) of the target word, “Iowa,” examined in the current study.

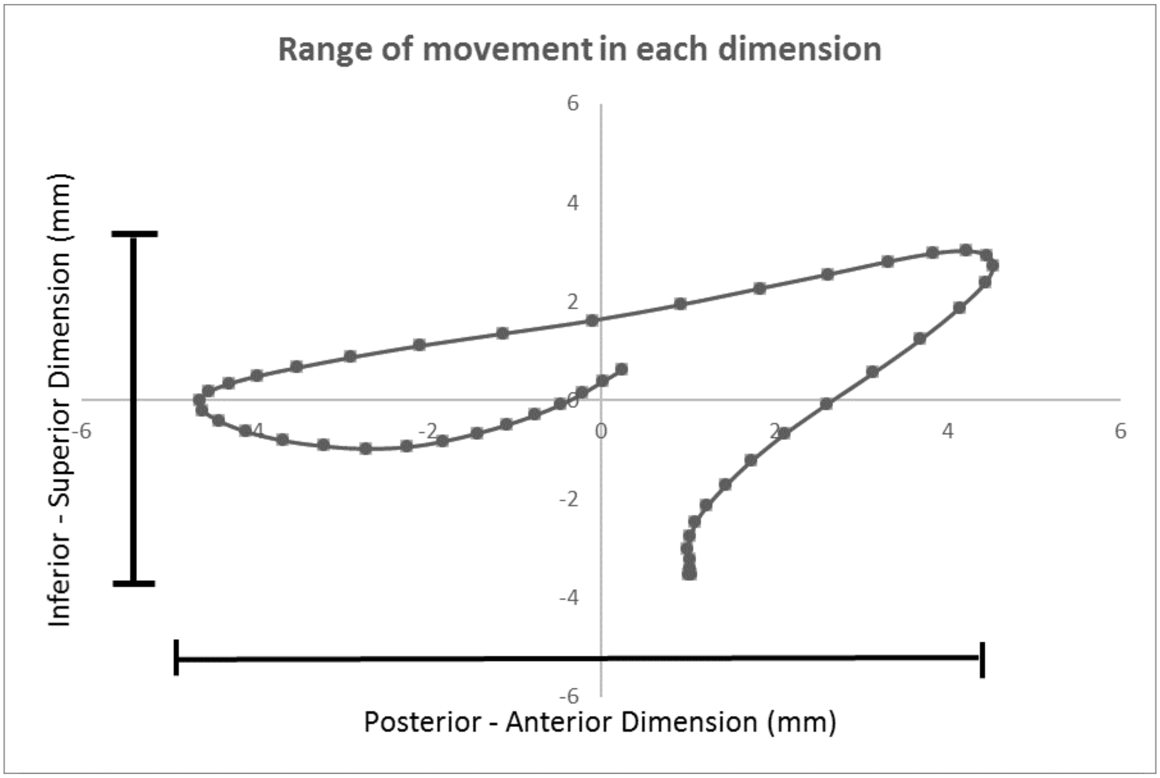

Figure 3. Spatial kinematic variable (range of movement) of the target word, “Iowa,” examined in the current study.

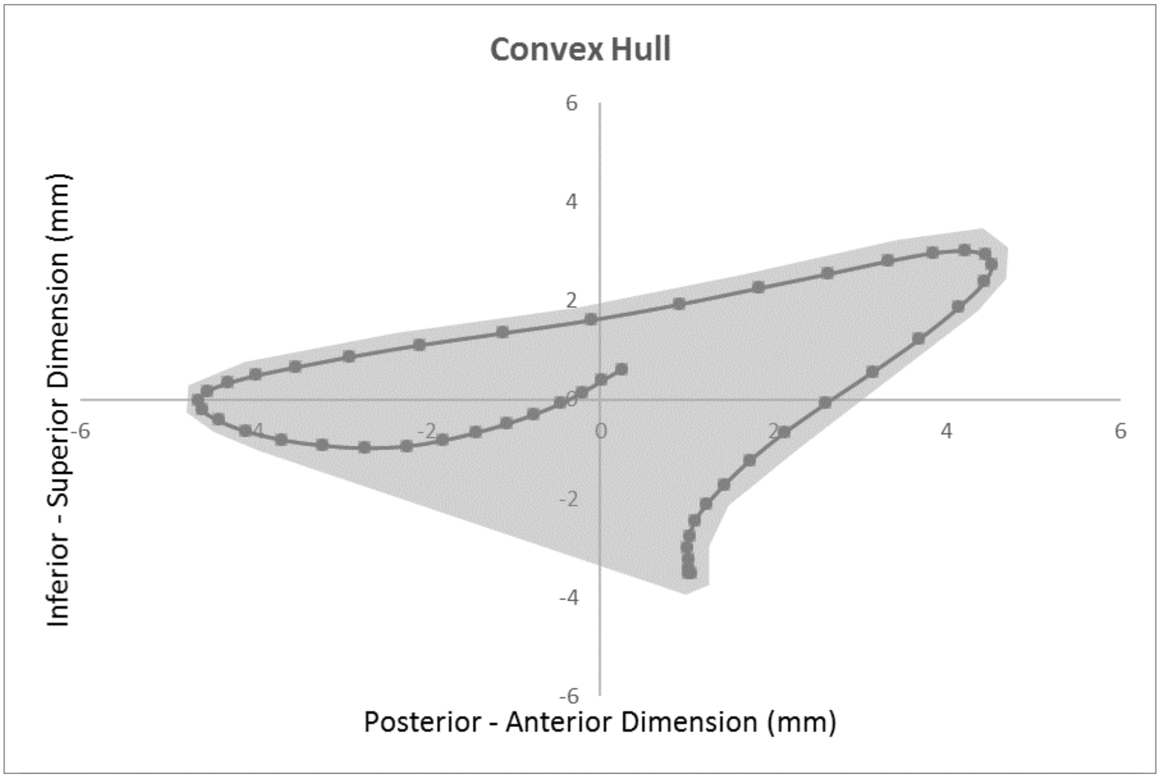

Figure 4. Spatial kinematic variable (convex hull) of the target word, “Iowa,” examined in the current study.

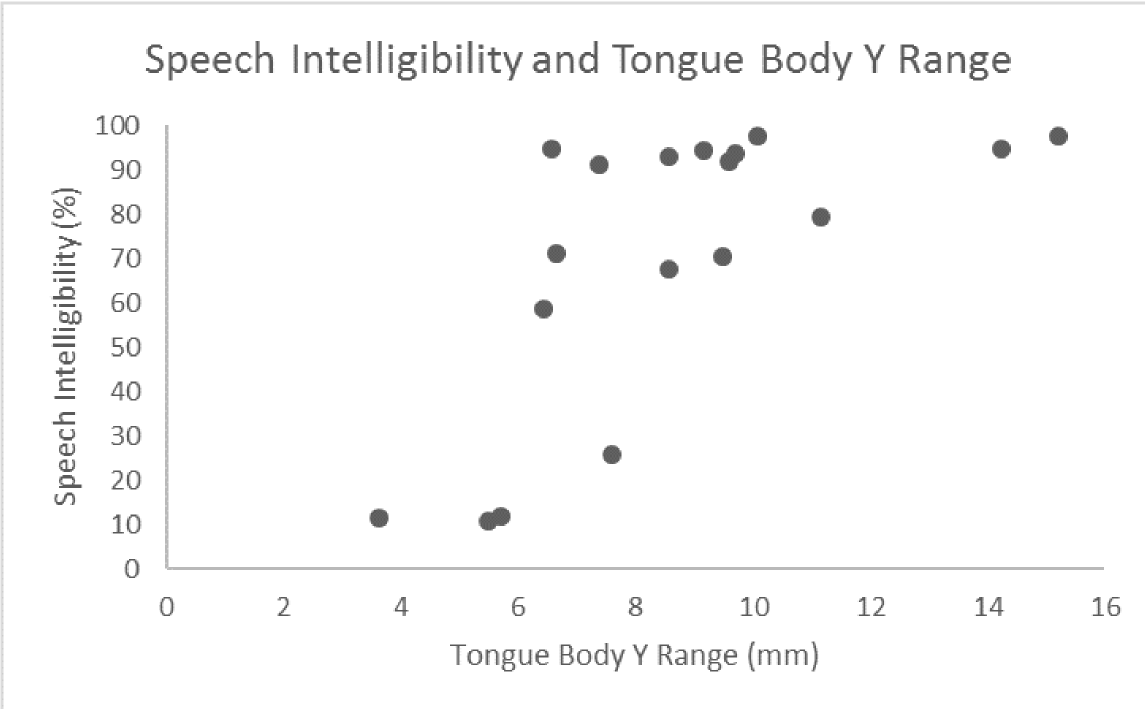

Figure 5. Scatterplot of speech intelligibility and tongue body Y range during target word production.

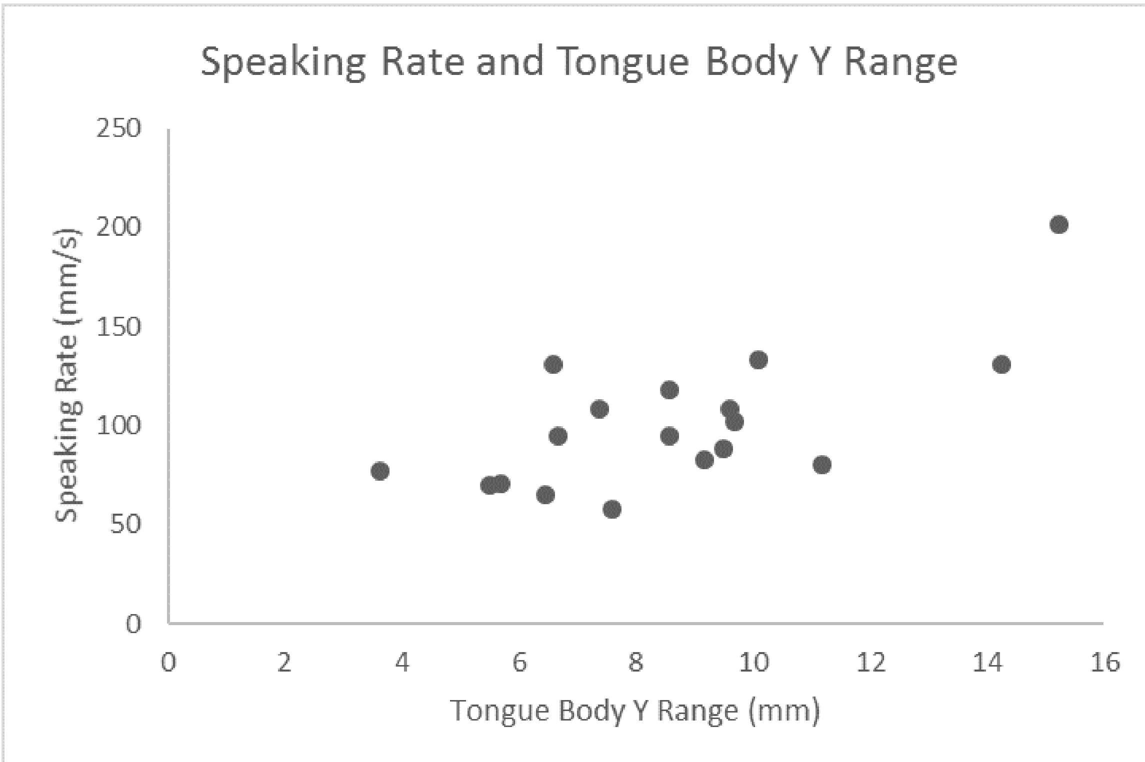

Figure 6. Scatterplot of speaking rate and tongue body Y range during target word production.

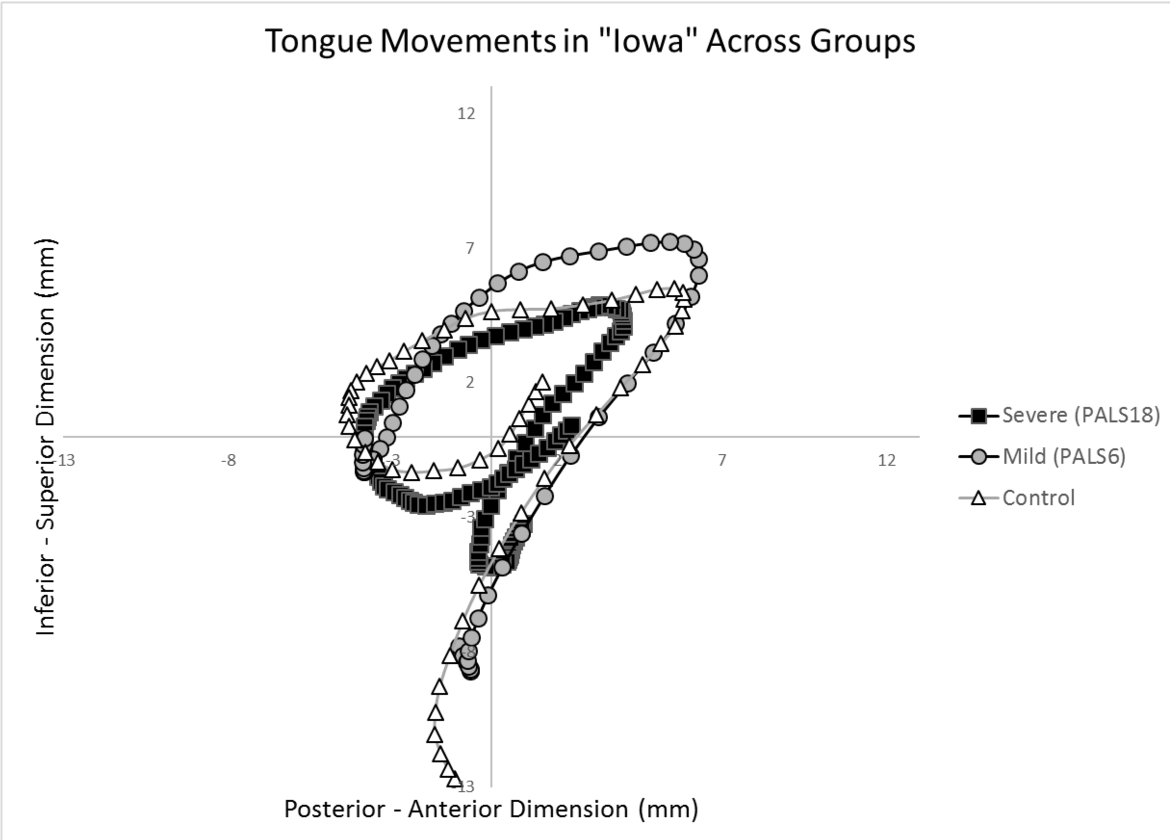

Figure 7. Tongue movement trajectories during target word production across groups. This figure exhibits the difference in convex hull areas: the speaker with severe dysarthria has the smallest convex hull area across the three groups.

Appendix B

Tables

Table 1. *Participant Information (Individuals with Dysarthria Secondary to ALS)*

Participant Code	Age	Gender	Time Since Onset of Dysarthria Symptoms (months)	Means of Communication	SIT Score (%)	ALSFRS-r Bulbar Subscore	Speaking Rate (wpm)
PALS1	47	Male	36	Speech	10.76	3	70.05
PALS2	65	Male	12	Speech	90.00	9	126.39
PALS3	60	Male	49	Speech	92.42	10	124.45
PALS5	50	Male	16	Speech	42.73	9	57.11
PALS6	60	Male	9	Speech	97.58	9	201.69
PALS7	43	Female	120	Speech	58.79	8	64.99
PALS8	64	Female	19	Speech	25.76	5	57.49
PALS9	80	Male	1	Speech	94.85	6	131.00
PALS10	66	Female	33	Speech	94.24	5	82.82
PALS11	63	Female	11	Speech/AAC	11.82	4	70.47
PALS12	66	Female	5	Speech/AAC	11.52	6	77.36
PALS13	68	Male	8	Speech	67.58	7	117.64
PALS14	61	Female	5	Speech	94.55	9	130.5
PALS15	69	Female	20	Speech	71.21	7	94.35
PALS16	67	Male	201	Speech	93.64	6	101.82
PALS17	64	Female	15	Speech	91.21	9	108.54
PALS18	64	Male	51	Speech	79.55	6	80.44
PALS20	64	Male	37	Speech	91.82	8	108.34
PALS21	71	Female	15	Speech	93.03	9	94.41
PALS22	76	Female	18	Speech	97.58	9	133.46
PALS23	48	Male	10	Speech	70.30	9	88.28

Table 2. *Tongue Body and Jaw Kinematic Correlation Coefficient Values of Speech Intelligibility and Speaking Rate*

Variable	Pearson r against Speech Intelligibility	Pearson r against Speaking Rate
Tongue Body 3D Euclidian Distance (mm)	0.186	0.283
Jaw Body 3D Euclidian Distance (mm)	-0.570**	-0.241
Tongue Body X Displacement (mm)	0.139	-0.097
Jaw X Displacement (mm)	-0.291	-0.113
Tongue Body X Distance (mm)	0.197	0.296
Jaw X Distance (mm)	-0.514*	-0.151
Tongue Body Y Displacement (mm)	0.381	0.247
Jaw Y Displacement (mm)	0.092	-0.043
Tongue Body Y Distance (mm)	0.443*	0.456*
Jaw Y Distance (mm)	-0.521*	-0.209
Tongue Body Displacement (mm)	0.156	0.210
Jaw Displacement (mm)	-0.491*	-0.233
Tongue Body X Range (mm)	0.257	0.424
Jaw X Range (mm)	-0.462*	-0.033
Tongue Body Y Range (mm)	0.672**	0.693**
Jaw Y Range (mm)	-0.397	-0.107
Tongue Body Duration (s)	-0.454*	-0.491*
Jaw Duration (s)	-0.454*	-0.491*

Tongue Body Speed (mm/s)	0.465*	0.704**
Jaw Speed (mm/s)	-0.356	0.094
Tongue Body Convex Hull 2D (mm)	0.422	0.682**
Jaw Convex Hull 2D (mm)	-0.615**	-0.085

*p<.05; **p<.01

Table 3. *Descriptive Information across Groups*

Variable	Mild Mean (SD)	Severe Mean (SD)	Control Mean (SD)
Tongue Body 3D Euclidian Distance (mm)	30.09 (10.82)	23.68 (8.32)	26.26 (8.20)
Jaw Body 3D Euclidian Distance (mm)	20.15 (6.79)	22.19 (11.38)	15.61 (9.85)
Tongue Body X Displacement (mm)	0.19 (2.21)	0.63 (2.61)	0.50 (1.25)
Jaw X Displacement (mm)	2.24 (2.27)	2.67 (2.32)	3.26 (2.54)
Tongue Body X Distance (mm)	17.22 (8.35)	12.32 (6.17)	15.04 (6.27)
Jaw X Distance (mm)	12.71 (4.02)	13.07 (7.13)	9.20 (6.13)
Tongue Body Y Displacement (mm)	3.58 (2.89)	3.42 (2.60)	4.43 (3.33)
Jaw Y Displacement (mm)	2.30 (1.22)	2.61 (1.97)	4.54 (2.98)
Tongue Body Y Distance (mm)	20.10 (6.53)	14.98 (5.11)	17.57 (6.52)
Jaw Y Distance (mm)	11.28 (2.84)	12.31 (5.28)	9.89 (5.88)
Tongue Body Displacement (mm)	4.81 (2.16)	4.94 (1.92)	5.38 (2.33)
Jaw Displacement (mm)	3.75 (1.97)	4.69 (2.08)	5.86 (3.67)
Tongue Body X Range (mm)	7.77 (3.24)	5.49 (2.50)	7.24 (2.89)
Jaw X Range (mm)	6.86 (2.74)	6.48 (3.17)	5.54 (3.54)
Tongue Body Y Range (mm)	10.48 (3.34)	7.58 (2.12)	9.33 (3.44)
Jaw Y Range (mm)	6.19 (1.70)	6.40 (2.22)	6.50 (3.57)
Tongue Body Duration (s)	0.739 (0.145)	0.926 (0.213)	0.499 (0.077)
Jaw Duration (s)	0.739 (0.145)	0.926 (0.213)	0.499 (0.077)
Tongue Body Speed (mm/s)	41.12 (13.50)	25.75 (6.96)	52.44 (13.17)
Jaw Speed (mm/s)	26.95 (5.15)	23.80 (10.87)	30.51 (16.89)

Tongue Body Convex Hull 2D (mm)	38.23 (23.06)	18.34 (11.66)	29.94 (19.38)
Jaw Convex Hull 2D (mm)	10.75 (5.01)	10.13 (9.63)	8.88 (11.57)

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ACADEMIC VITA

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EDUCATION

- B.S., Communication Sciences and Disorders, 2017, The Pennsylvania State University, University Park, PA
- The Schreyer Honors College, University Park, PA
  - Fall 2013-Present
  - Thesis Topic: Tongue and jaw movements in "Iowa" between speakers with and without dysarthria secondary to ALS
  - Expected thesis publication submission: Summer 2017
    - Thesis Advisor: Jimin Lee, Ph. D., CCC-SLP
- Paul-Valéry Université, Montpellier, France
  - September 2015-December 2015

WORK EXPERIENCE

- **Bucks County Intermediate Unit #22, Doylestown, PA**
  - **July 2016-August 2016**
  - *Instructional Assistant*
    - Supported and assisted students with a variety of behavioral and educational needs
    - Instructed students in academic subjects and socially appropriate behavior
    - Maintained a positive and encouraging learning environment
    - Encouraged students to utilize their AAC devices throughout the school day
    - Responsible for helping students who needed one-on-one assistance
- **Ecole St. Jean-Baptiste, Montpellier, France**
  - **September 2015-December 2015**
  - *Instructional Assistant*
    - Helped teachers with their lessons and created activities for the children that helped facilitate learning needs
    - Created and taught English lessons to five-year-old children
    - Observed and participated in weekly speech therapy sessions

ACTIVITIES

- **National Student Speech Language Hearing Association (NSSLHA), The Pennsylvania State University, University Park, PA**
    - **January 2014-Present**
    - *Member*
        - Partake in five community service events every semester
        - Update current understanding of disorders, programs, and research in Communication Sciences and Disorders
- **THON Committee: Rules and Regulations, The Pennsylvania State University, University Park, PA**
    - **October 2014-February 2017**
    - *Committee Member*
        - Raise money for the Four Diamonds at Penn State Hershey Children's Hospital to provide emotional and financial support, spread awareness, and increase research funding
        - Promote the Penn State IFC/Panhellenic Dance Marathon, THON, and motivate others to participate

RESEARCH & TEACHING

- **Speech Production Laboratory, The Pennsylvania State University, University Park, PA**
    - **January 2015-Present**
    - *Lab Member*
        - Analyze kinematic and acoustic data of speakers with and without dysarthria secondary to ALS
        - Write an honors thesis about the tongue and jaw movements of speakers with and without dysarthria secondary to ALS
        - Recruit listeners to participate in the study
        - Review the kinematic data collected by other members in the lab
- **CSD 146 Teaching Assistant, The Pennsylvania State University, University Park, PA**
    - **January 2015-Present**
    - *Teaching Assistant*
        - Helped students with course material by answering questions and holding weekly office hours
        - Assisted the teacher with grading, participation points, and monitoring the class

COMMUNITY INVOLVEMENT

- **Hearts of Hope, Perkasie, PA**
    - **January 2015-Present**
    - *Intern*

        - Craft the hearts that are sent to people in need of a symbol of hope
        - Manage the inventory and assist in national and international deliveries and events
- **Race Across America: Team Revolution**
    - **May 2012-October 2016**
    - *Crew Member*
        - Spread awareness of the lack of funds going towards pediatric brain tumor research through social media
        - Arranged fundraising events at local businesses and restaurants to raise funds for the Christopher Court Foundation and the Children's Hospital of Philadelphia
        - Participated in the bicycle competition, Race Across America, in June 2016 to encourage others to donate to the cause
        - Raised $120,000 to give to the Children's Brain Tumor Tissue Consortium (CBTTC) at the Children's Hospital of Philadelphia

AWARDS

- Dean's List
    - Fall 2013-Present
- Alumni Recognition for Student Excellence Award
    - College of Health and Human Development Alumni Society
    - December 2016
- Margaret Decker Scholarship
    - College of Health and Human Development
    - August 2016
- Eve Willard Jordan Trustee Scholarship
    - The Schreyer Honors College
    - August 2013-Present
- Academic Excellence Scholarship
    - The Schreyer Honors College
    - August 2013-Present

INTERNATIONAL EDUCATION

- Paul-Valéry Université, Montpellier, France
    - September 2015-December 2015
    - Instructional Assistant at Ecole St. Jean-Baptiste

LANGUAGE SKILLS

- Proficient at speaking, writing, and reading French (9 years of study)