Articulatory Movements During Vowels in Speakers With Dysarthria and Healthy Controls

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Purpose: This study compared movement characteristics of markers attached to the jaw, lower lip, tongue blade, and dorsum during production of selected English vowels by normal speakers and speakers with dysarthria due to amyotrophic lateral sclerosis (ALS) or Parkinson disease (PD). The study asked the following questions: (a) Are movement measures different for healthy controls and speakers with ALS or PD, and (b) Are articulatory profiles comparable for speakers with ALS and speakers with PD?

Method: Nineteen healthy controls and 15 speakers with dysarthria participated in this study. The severity of dysarthria varied across individuals and between the 2 disorder groups. The stimuli were 10 words (i.e., *seed, feed, big, dish, too, shoo, bad, cat, box,* and *dog*) embedded into sentences read at a comfortable reading rate. Movement data were collected using the X-ray microbeam. Movement measures included distances, durations, and average speeds of vowel-related movement strokes.

Results: Differences were found (a) between speakers with ALS and healthy controls and (b) between speakers with ALS and PD, particularly in movement speed. Tongue movements in PD and ALS were more consistently different from healthy controls than jaw and lower lip movements. This study showed that the effects of neurologic disease on vowel production are often articulator-, vowel-, and context-specific.

Conclusions: Differences in severity between the speakers with PD and ALS may have accounted for some of the differences in movement characteristics between the groups. These factors need to be carefully considered when describing the nature of speech disorder and developing empirically based evaluation and treatment strategies for dysarthria.

KEY WORDS: dysarthria, speech kinematics, amyotrophic lateral sclerosis, Parkinson disease

Dysarthria has been defined as a speech disorder resulting from damage to neural mechanisms that regulate speech movements (Netsell, 1986). Changes in articulatory movements associated with dysarthria lead to aberrant speech acoustics and a perceptually recognizable disorder. Most of what we know about the nature of articulatory impairment in dysarthria comes from a number of perceptual and acoustic studies (see Weismer, 1997, for review). These types of analyses, however, are focused on the composite result of multiple articulatory movements and cannot tell us with certainty whether and how neurological diseases affect the individual or collective movements of articulators such as the jaw, tongue, and lips. In broad terms, the relatively small number of speech movement studies in dysarthria seems to show that articulatory movements are slow and reduced in magnitude and may demonstrate interarticulator timing disturbances. A brief review of the relevant evidence follows.

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Movement Reduction

An early report by Kent, Netsell, and Bauer (1975) showed reduced movement spaces (i.e., mobility ranges) for the jaw, lips, and tongue during a variety of consonants and vowels produced by 4 speakers with dysarthria arising from various neurological disorders. Smaller-than-normal tongue movements, but not jaw movements, for specific sounds were reported for 1 speaker with dysarthria due to cerebellar disease and for 5 individuals with athetoid cerebral palsy (Kent & Netsell, 1975, 1978). Reduction in size was also noted in movements of the jaw and/or lower lip in groups of speakers with dysarthria due to Parkinson disease (PD; Ackerman et al., 1997; Connor et al., 1989; Forrest & Weismer, 1995; Forrest, Weismer, & Turner, 1989; Hirose, Kiritani, Ushijima, Yoshioka, & Sawashima, 1981). In addition to the reduced total movement space and movement amplitudes, dysarthric articulatory movements were noted to be less distinctive and occupied more central regions of the vocal tract than those produced by speakers without dysarthria due to PD (Kent & Netsell, 1978; Kent, Netsell, & Bauer, 1975).

Slowness

Speakers with dysarthria have been said to move more slowly than healthy speakers. Perceptual (Darley, Aronson, & Brown, 1969a, 1969b) and acoustic features of articulatory slowness (e.g., reduced F2 transitions; Weismer, 1991; Weismer, Martin, Kent, & Kent, 1992) have been reported as a characteristic of many speakers with dysarthria. Abnormalities in movement speed of individual articulators were documented in case studies of dysarthria associated with athetoid cerebral palsy, traumatic brain injury (TBI), cerebellar disease, and amyotrophic lateral sclerosis (ALS; Kent & Netsell, 1975, 1978; Kent et al., 1975; Hirose, Kiritani, & Sawashima, 1982a). Peak velocities of the jaw, and of the lower lip plus jaw, were shown to be reduced in groups of speakers with PD relative to those obtained from healthy controls (Caligiuri, 1987; Connor, Abbs, Cole, & Gracco, 1989; Forrest & Weismer, 1995; Forrest, Weismer, & Turner, 1989). Similar observations have been made for lower lip movements in speakers with cerebellar atrophy (Ackerman, Hertrich, & Scharf, 1995; Ackerman, Hertrich, Daum, Scharf, & Spieker, 1997).

Aberrant Movement Timing and Coordination

The most typical disturbance noted in dysarthric movements is increased durations (presumably due to slowing of the articulators). Findings of longer than normal CV and VC movements have been noted in individual cases of speech disorders associated with TBI, cerebellar disease, and athetoid cerebral palsy (Kent & Netsell, 1975, 1978; Kent et al., 1975). However, shorter closing (VC) movement durations were observed in one study of lip and jaw movements in dysarthria due to PD (Forrest & Weismer, 1995). These shorter VC movement durations may have been a result, in part, of the reduced amplitudes for the closing gestures studied by Forrest and Weismer (1995).

The timing relationship among different articulatory movements within the boundaries of a single segment (sometimes defined acoustically) has been referred to under the umbrella term of *coordination*. Presence of discoordination in dysarthric speech has been suggested based on perceptual observations of some dysarthria types (Darley et al., 1969a, 1969b) but has not been unequivocally documented for any dysarthria types using objective measures (Bartle, Goozée, Scott, Murdoch, & Kuruvilla, 2006; Hertrich & Ackermann, 1999; Kent et al., 1975; Tjaden, 2003). Existing data seem to suggest that as movements change due to disease, multiple movements get scaled proportionally in time, preserving interarticulatory timing relationships. Evidence for proportional changes in articulatory timing—and, hence, more or less "normal" interarticulator coordination—among speakers with ALS and PD was recently reported in a study of lip and tongue dorsum movements in the production of the vowel /u/ (Weismer, Yunusova, & Westbury, 2003). There were, however, a few examples of discoordination patterns reported by Weismer et al. (2003), particularly in speakers with ALS. Other examples of articulatory discoordination in dysarthria have been reported, including disordered timing of tongue and velar movements in individuals with cerebral palsy (Kent & Netsell, 1975) and overly synchronized movements with unusual sequencing of velocity peaks for lip and jaw in speakers with PD (Connor et al., 1989). Further study of discoordination in dysarthria is warranted to understand its role in this group of speech disorders. There is no a priori reason to exclude any neuropathology as being free of coordination difficulties in speech or limb movements. For example, Hausdorff et al. (2000) found changes in temporal organization of gait movements in ALS and PD. It is of continuing interest to know if changes in temporal organization—discoordination—are also found in the articulatory motions of speakers with ALS or PD.

Most observations of articulatory abnormalities associated with dysarthria, summarized in the previous paragraphs, have come from analyses of single articulator movements occurring in simplified phonetic material (e.g., nonsense monosyllables formed from bilabial consonants and open vowels, and alternating motion rate tasks [AMRs]). Moreover, many of these data have been obtained in case studies, for either very local (e.g., CV or VC motions) or gross (movement spaces across a large amount of speech material) speech motions. Absent from the literature on dysarthria are focused studies of different articulatory motions for specific sound classes collected from larger speaker groups. The present study reports movements of two flesh markers on the tongue together with jaw and lower lip movements collected during vowels embedded in sentences and produced by persons with PD and ALS, two neurological diseases in which dysarthria is a common symptom.

Vowels were selected for the present analysis because of their central role in speech production theory and importance to speech intelligibility. Clearly, an understanding of articulatory motion differences for vowels produced by persons with dysarthria and healthy controls is one step to developing a theory of the speech production deficit in motor speech disorders. As a first step, the present study aims for an articulatory description of vowel segments drawn from real words in sentences, produced by relatively many speakers with dysarthria and by healthy control speakers. Moreover, in recognition of certain reported differences for healthy speakers between vowel gestures that precede versus follow consonants (e.g., Gracco & Löfqvist, 1994) and the theoretical treatment of vocalic gestures that comprise opening and closing gestures (Saltzman & Munhall, 1989), an analysis approach was adopted for the current study that treated vocalic gestures as consisting of two parts (see *Acoustic and Movement Segmentation* subsection of Method section). Finally, an understanding of vowel gestures in dysarthria will presumably shed more light on the strong association between perceptual–phonetic and acoustic characteristics of vowels on the one hand and the severity of speech intelligibility deficits on the other (Kent, Weismer, Kent, & Rosenbek, 1989; Weismer, Jeng, Laures, Kent, & Kent, 2001; Ziegler, Hartmann, & von Cramon, 1988).

The choice to study speakers with PD and ALS was made partially as a result of the frequent dysarthria in these disorders but also because there are previous suggestions in the literature that the two diseases may affect the articulators differently. For example, Connor et al. (1989) have suggested that the jaw, but not the lower lip, is affected in the speech of persons with PD, and DePaul and Brooks (1993) have argued for disproportionate involvement of the tongue, relative to other articulators, in the dysarthria associated with ALS. No study, however, has reported motions of the jaw, lip, and tongue in both diseases, using the same speech materials. The present study permits such a comparison. More generally, speakers with PD and ALS were chosen for this study because of the very different neuropathologies associated with the two diseases, which might be expected to yield very different results on vowel gesture characteristics. As noted previously, because the two diseases have been associated with limb discoordination in gait analysis, they seemed to be likely candidates for articulatory coordination analyses as well.

In summary, the present investigation focuses on the following questions: (a) Do the size, speed, and timing of articulatory movements differ between healthy control speakers and speakers with ALS and PD? and (b) if differences exist, what are the speech movement profiles in the two diseases, and is there evidence of differential articulatory impairment according to disease type?

Method

Speakers

A total of 34 speakers, including 19 healthy controls, 7 with a medical diagnosis of PD, and 8 diagnosed with ALS, were selected among speakers recorded over time for a large study of speech movements, speech acoustics, and intelligibility in dysarthria at the University of Wisconsin–Madison. All methods used in this study were approved by the university's Human Subject Review Committee, and informed consent was obtained from all participants. There were 10 men and 9 women in the healthy control group (hereafter, N group), 3 men and 4 women in the PD group, and 4 men and 4 women in the ALS group. Age of the participants ranged from 46 to 86 years among the N speakers (M = 59 years); 40 to 71 years among the speakers with PD (M = 56 years); and 43 to 71 years among the speakers with ALS (M = 49 years). The Ns in the PD and ALS group were determined by the series of patients studied under the protocol described below, agreement among the experimenters that the patients had a recognizable dysarthria, and the availability of full sets of data. No other selection criteria (such as type or severity of dysarthria) were imposed on participants with neurological disease. The dialect base for the majority of participants was the Upper Midwest region.

Table 1 summarizes pertinent information about medical diagnoses, dysarthria type, and speech severity for speakers in the disordered groups. All participants with ALS or PD were judged to have a perceptually recognizable speech disorder by three experienced speech-language pathologists (SLPs). Each of the three judges listened independently to three sentences read by each speaker in the D group and judged the dysarthria type following the system described by Darley et al. (1975). The judges were blind to the medical diagnosis. Table 1 displays all of the different labels given by the SLPs. For example, if each SLP provided a unique dysarthria type for a given speaker, three labels are reported in Table 1 (as in the case of Speaker 209). Dysarthria types are reported here for descriptive purposes only. Severity of dysarthria is represented by two types of intelligibility scores, one

Table 1. Demographics and disorder characteristics for speakers with dysarthria.

ID	Dx	Gender	Age	Type of dysarthria	Intelligibility scores
104	PD	F	50	Hypokinetic, flaccid	99.3/143.0
106	PD	M	66	Hypokinetic, flaccid	98.1/196.0
107	PD	M	53	Ataxic, spastic	98.5/229.3
113	PD	F	40	Spastic–flaccid, spastic	97.0/223.2
115	PD	F	50	Spastic, flaccid	96.6/225.8
135	PD	M	60	Hypokinetic	98.3/209
137	PD	F	71	Hypokinetic, ataxic	98.7/193.3
209	ALS	M	43	Flaccid, mixed, hypokinetic	98.1/158.7
210	ALS	M	55	Spastic–flaccid	69.3/13.6
220	ALS	M	44	Spastic–flaccid, flaccid	67.9/50.5
224	ALS	M	43	Spastic–flaccid, flaccid	70.5/51.2
227	ALS	F	71	Spastic–flaccid	88.5/105.8
233	ALS	F	47	Spastic–flaccid, flaccid–ataxic	66.8/40.3
241	ALS	F	41	Spastic–flaccid, ataxic	64.8/33.4
243	ALS	F	45	Ataxic	97.6/NA

Note. Participants whose ID begins with 1 had a medical diagnosis of Parkinson disease (PD); participants whose ID begins with 2 were diagnosed with amyotrophic lateral sclerosis (ALS). Severity of dysarthria is reflected in the intelligibility score: The first score shows results of the single word analysis, and the second score shows results of the sentence analysis. Speaker 243 has only a single word intelligibility score, an average of 5 listener judgments. The dysarthria type for this speaker was determined by agreement among the authors. Dx = diagnosis; M = male; F = female; NA = not available.

obtained using a single-word intelligibility test (Kent et al., 1989; the first number in the last column, expressed as a percentage) and the other from direct magnitude estimates of scaled sentences (the second number in the last column, expressed as the numerator of a ratio whose denominator is 100, where 100 is assigned to an utterance assumed to be representative of midrange intelligibility). A more detailed description of the intelligibility procedures can be found in Yunusova, Weismer, Kent, and Rusche (2005). One of the participants (Speaker 243) was recorded much later than the others, and only a single word intelligibility score, based on the responses of 5 listeners, was available for her (individual scores: 100, 100, 98, 96, and 94). Three independent judgments of dysarthria type were not available for this speaker, but the authors unanimously agreed that her speech was clearly dysarthric and would probably be described as primarily (and mildly) ataxic. The intelligibility data in Table 1 are also reported for descriptive purposes only, rather than being used as a variable in the main analyses of articulatory motions. The intelligibility data, however, are considered in a general way in the Discussion section.

Speech Tasks

The vowels /I/ (*big, dish*); /i/ (*seed, feed*); /ae/ (*bad, cat*); /u/ (*too, shoo*); /a/ (*box*); and /o/ (*dog*) were analyzed. These vowels are at or near the corners of, and hence span, the vowel articulatory space. The words containing these vowels were embedded in sentences (The other one is *too big*; The *bad* one is in the *box*; To *feed* the *cat* one must *shoo* the *dog*; I took a spoon and *dish*; A new *seed* will grow fast) and were read at self-selected, comfortable speech rates.

Eight of the words containing the selected vowels were in the form of CVC and hence included vowels in closed syllables. Two had vowels in open syllables followed by another word beginning with a consonant ("*too* big" and "*shoo* the"). All vowels, except /u/ in *too,* carried primary stress and, in many cases, the sentence prominence. The consonant environment varied across words. For each participant, between 5 and 10 repetitions of each word were used for the analyses, depending on availability. Missing data were mostly due to malfunctioning of the equipment, mistracking, and/or inability of a participant to complete the experiment.

Kinematic and Acoustic Data Acquisition and Processing

Kinematic and acoustic data were obtained using the X-ray microbeam technique, following procedures described in Westbury (1994). Movements of articulators were recorded by tracking the real time positions of up to 11 flesh-point markers (gold pellets, 2–3 mm in diameter). A typical complete marker array consisted of four tongue, two lip, and two jaw markers as well as three fiducial markers (one at the central maxillary incisors and two on the bridge of the nose). Sampling rates during tracking varied by marker and usually were

40 samples/s for the upper lip, mandibular, and reference markers and 80 samples/s for the lower lip and all tongue markers, except the one in the vicinity of the tongue blade (designated T1 and tracked at 160 samples/s). The raw sagittal-plane marker trajectories were subsequently smoothed and resampled at a uniform rate of 145 samples/s. Routine postprocessing steps also included head movement correction, synchronization of all channels, identification of mistracks, and re-expression of marker coordinates relative to a subject-specific, anatomic head-based coordinate system.

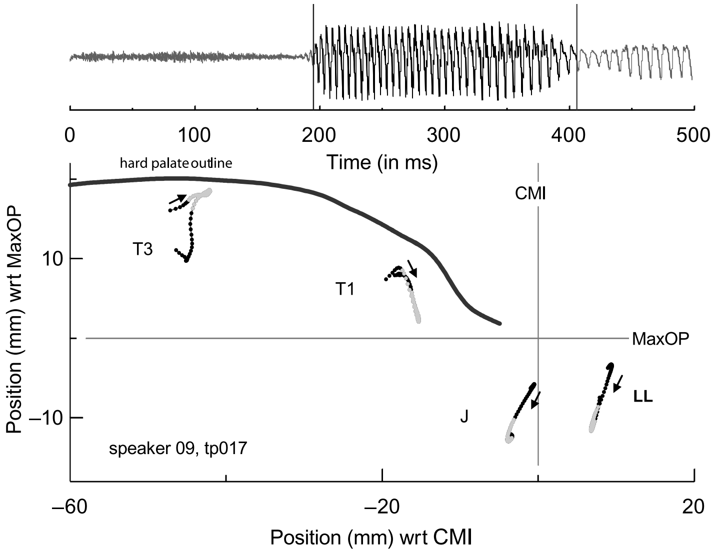
The marker array analyzed in this study, represented in the anatomic head-based frame of reference, is shown in Figure 1. The array consisted of four markers—one on the jaw (J), one on the lower lip (LL), and two on the tongue: T1 at the tongue blade (~1 cm back from the apex) and T3 in an area often referred as the *tongue dorsum* (~3–4 cm back from the apex). Marker positions in Figure 1 are expressed relative to an x-axis representing the maxillary occlusal plane (MaxOP) and a y-axis normal to the MaxOP and passing through the lower tips of the central maxillary incisors (CMI). In this coordinate system, lip and tongue movements include contributions from the jaw. For the purposes of this study, LL, T1, and T3 positions were subsequently re-expressed relative to the jaw following procedures outlined by Westbury, Lindstrom, and McClean (2002). In five sessions where the molar marker was missing during recording, the rotational component of jaw motion necessary for re-expression was estimated (see Westbury et al., 2002). Hereafter, all LL, T1, and T3 measures will be reported for the marker movements relative to, and hence independent of, the jaw.

Acoustic recordings were obtained simultaneously with the acquisition of kinematic data using a directional microphone (Shure SM81 Condenser) and a 15-bit resolution A/D converter, sampling the signal at a rate of 22 kHz. An analog anti-aliasing filter (–3dB at 7500 Hz) was applied prior to the digital conversion. A speech analysis program (TF32; Milenkovic, 2001) was used to display marker movement trajectories together with wide-band spectrograms and editable LPC-based formant tracks.

Acoustic and Movement Segmentation

The vowel-related movement intervals were identified acoustically based on vowel formant tracks beginning at the onset and ending at the offset of periodic energy in the region of the second formant, as determined from a combined spectrographic and waveform display. Vowel identification based on this criterion is often straightforward for individuals with normal speech but can be challenging for speakers with dysarthria. In cases where the initial criterion could not be applied for speakers with neurological disease, secondary criteria were used. They consisted of, in respective order, (a) change in intensity of the first and second formants; (b) onsets and offsets of F2 transitions; (c) changes in the energy of higher (above 4 KHz) formants; and (d) perceptual verification. After the vowel formants were tracked, kinematic and

Figure 1. Sagittal plane trajectories (with respect to cranial axes) traced by four articulator markers during *seed* produced by a healthy control speaker. The direction of the movement for each trajectory is indicted by an arrow. CMI = central maxillary incisors; MaxOP = maxillary occlusal plane; T1 = tongue blade; T3 = tongue dorsum; J = jaw; LL = lower lip.



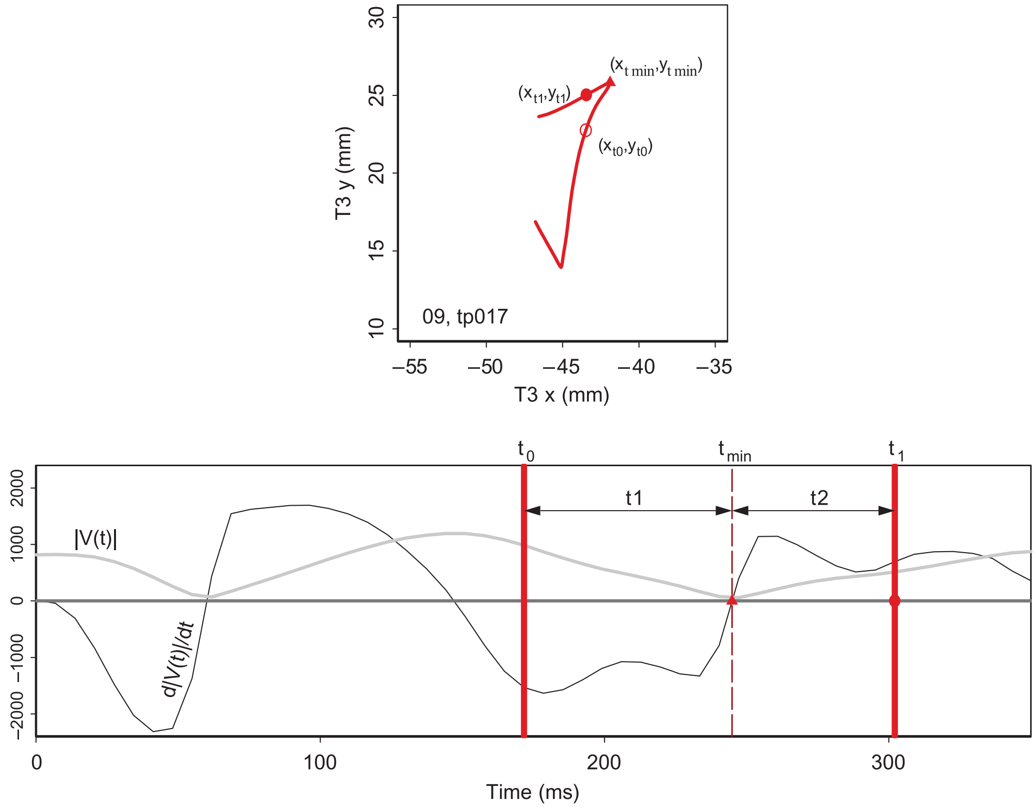
vowel-related acoustic channels for each word were extracted and transferred into the S-PLUS environment for further analyses (S-PLUS Version 6.2; Insightful Corporation, 2003).

Figure 1 shows the acoustic and movement signals during *seed* produced by a speaker in the N group. In the lower part of the figure, positions of the articulator markers during the vowel are marked in light gray. Positions during surrounding consonant segments are in black. Vertical lines intersecting the speech wave, shown above the movement trajectories, are drawn to indicate the operationally defined onset and offset of the vowel. Arrows indicate the direction of each movement. In this set of trajectories, the jaw (J) and lower lip (LL) move down and back and then forward and up from the beginning to the end of the vowel. At the same time, the tongue blade (T1) moves first forward and down, and then back and up, while the tongue dorsum (T3) moves forward and up toward the palate and then back and slightly downward.

Partitioning of the vowel-related movement trajectories of each articulator marker into two parts is illustrated in Figure 2. The top portion of the figure shows the T3 trajectory during *seed* produced by a male with normal speech. During the vowel, the marker travels from its position at vowel onset (x_{t0}, y_{t0}) to a position that corresponds to the local minimum in the speed history ($x_{t\ min}$, $y_{t\ min}$) and then to its position at vowel offset (x_{t1}, y_{t1}). For convenience, we take the entire vowel movement of T3 to consist of two straight-line strokes, one initial between t_0 and t_{min}, and one final between t_{min} and t_1. The time of the local minimum in the speed history was located as a zero-crossing in the first time-derivative of the marker's speed history (see bottom portion of Figure 2). The velocity vector (dx/dt, dy/dt) at each position sample along a trajectory was estimated using a three-point central difference formula. Movement speed, represented by |V(t)| in the figure, was then the magnitude of the velocity vector at each sample.

In cases involving multiple zero-crossings in |V(t)| during the vowel interval from t_0 to t_1, only the time of the zero-crossing for which the corresponding speed was the lowest was picked for measurement. In some Vowel × Marker × Speaker conditions, no speed minimum occurred during the vowel (e.g., when a marker moved only in one direction throughout a vowel). These cases were relatively infrequent across participants, occurring in 10% of cases for J, 11% for LL, 8% for T1, and 5% for T3 movements among individuals with normal speech.

Figure 2. T3 trajectory expressed relative to the jaw-based coordinate system during *seed* (top panel) and the corresponding speed history and its first time derivative (bottom panel). Note that for ease of visualization, the speed history was multiplied by 10.



Comparable figures were 13%, 11%, 11%, and 4%, respectively, among the PD group, and 8%, 7%, 5%, and 2%, respectively, among the ALS group. In these cases, only the marker positions at the onsets and offsets of the vowel were used for analysis, and kinematic measures were based only on the total trajectory.

Measurements

Nine measures were used to describe the vowel-related movements for each marker trajectory partitioned into initial and final strokes: (a) Euclidian distance for the first stroke, between the position at vowel onset and at speed minimum (d1); (b) Euclidian distance for the second stroke, between the position at speed minimum and at the vowel offset (d2); (c) total distance (dtot = d1 + d2); (d) duration of the initial stroke (t1); (e) duration of the final stroke (t2); (f) total duration (tdur = t1 + t2); (g) proportional timing of occurrence of the local speed minima within the vowel duration (t1p), calculated as the ratio between t1 and tdur (t1p = t1/tdur); and (h) the values of average speeds s1 and s2, for the initial and final strokes, respectively, given by the ratios of distance moved to movement duration (i.e., s1 = d1/t1, s2 = d2/t2).

Because d1 and d2 were calculated as the straight-line distances between marker positions at the vowel onset and minimum speed, and at minimum speed and vowel offset, these measures could underestimate the actual distance traveled by the marker during the relevant intervals. The size of the error depends on the extent to which a particular trajectory has a curved path. In order to estimate an average error for approximating movements in this simplified way, 3 speakers—Speakers 16 (N group), 106 (PD group), and 220 (ALS group)—were randomly selected from the pool of participants, and the total distances moved by each marker along its trajectory during each vowel were calculated. The average difference between the total distance traveled and estimated Euclidean distance across all words varied across markers. Jaw movement distances were underestimated by 3.0%, 2.8%, and 4.8 % for the 3 participants, respectively. Lower lip movements were underestimated by 13.0%, 8.0%, and 15.6 %. T1 movements were underestimated by 11.0%, 11.0%, and 10.0%, and T3 movements by 3.0%, 2.4%, and 9.8%, respectively. Given errors of this relatively small size, straight-line representations of movement strokes are probably a reasonable first approximation in a description of marker movements during vowels.

Reliability

Intrajudge reliability for a single handmade measure in this study—total (vowel) durations—was estimated by re-measuring a selected 10% of vowels (76 utterances) produced by speakers with dysarthria. Only dysarthric productions were selected because they should produce the most conservative estimates of intrajudge reliability. Five words were randomly chosen from each speaker with dysarthria (except 1 speaker who contributed six words), and vowel durations were re-measured following the criteria described previously. The averaged absolute difference between the original and repeated measures was 12 ms (*SD* = 13, range = 0–70 ms) across words.

Statistical Treatment of Data

Five to 10 repetitions of each word were used to estimate average participant performance for each measure. An analysis of within-speaker *SD*s for 5 N speakers and 5 D speakers revealed that the averages represented the movements reasonably well across repetitions for both N and D groups (see Yunusova, 2005, for detailed analysis). The summary impression of this analysis was that errors about the mean appeared to be related to the magnitude of the mean across measures and groups, suggesting that the data violated the heteroscedasticity assumption. To alleviate the effect of the nonuniform error, all across-repetition data were log- or square-root transformed prior to the calculation of their averages, depending on distribution shape. After speaker averages were calculated for transformed data, they were back-transformed into the original scales and used for the descriptive analyses.

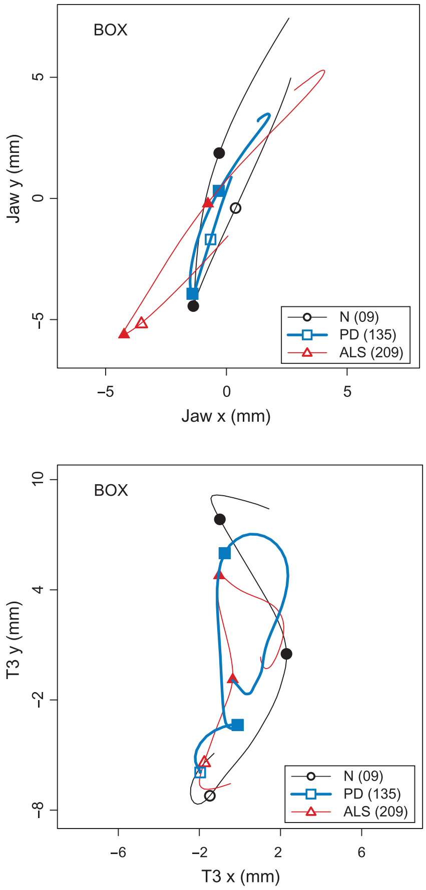
For each of the measures (dependent variables) and each of the four markers, a nested analysis of variance (ANOVA) was performed to assess the effect of group, word, and their potential interaction. Three different transformations (log-, cube-root, and square-root) were used to obtain approximately normally distributed residuals, depending on the variable. Group was a between-subjects effect; word effect and the Word × Group interaction were within-subject effects. If the Word × Group interaction was significant at $p < .05$, Tukey's honestly significant difference (HSD) method was used to perform pairwise comparisons on the groups for each word. If the interaction was not significant—and the group effect was—Tukey's HSD was used to compare groups averaged over words. Main word effects were not of interest in this analysis, and pairwise comparisons between words were not pursued.

Results

Movement Trajectories in N and D Productions: An Example

Figure 3 illustrates a comparison of three exemplar movement trajectories of J (top) and T3 (bottom) markers

Figure 3. J (top panel) and T3 (bottom panel) marker trajectories in x–y head space during the word *box* produced by 1 speaker from each of the three groups. Note that different scales on the two plots are used to maximize the plotting region. The open symbols (circle, square, and triangle) identify the onset of vowel-related movements for speakers in the N, PD, and ALS groups, respectively, whereas the first closed symbol along each trajectory shows the time of the local speed minima (the end of the first stroke), and the second closed symbol shows the end of the vowel.



recorded during a single repetition of the word *box* produced by 1 speaker from the N group (continuous thin line), 1 from the PD group (continuous thick line), and 1 from the ALS group (dotted line). Along each marker trajectory, the vowel begins at the open symbol. Tracing each trajectory from the vowel onset, the time of the local speed minimum is marked by the first closed symbol, and the time of the vowel offset is marked by the second closed symbol. The marker trajectories from different talkers were mean corrected (i.e., the mean of each position vector was subtracted from the original vector) to facilitate their comparison but otherwise were not scaled. The top panel shows that the speaker with PD (d1 = 2.8 mm and d2 = 3.2 mm) produced a scaled-down version of the N jaw movement (d1 = 4.4 mm and d2 = 6.4 mm). The speaker with ALS produced a very small initial movement stroke (d1 < 1 mm) but a large final stroke (d2 = 6.5 mm). T3 marker trajectories (bottom) were similar in shape for the speaker with ALS and the healthy control speaker, with both d1 and d2 movements being somewhat reduced in the speaker with ALS (cf. 4.7 vs. 7.6 mm for d1 and 5.7 vs. 8.8 mm for d2). The speaker with PD moved T3 less than the other speakers during the first part of the vowel (about 3 mm) and had a large movement (9.4 mm) for the second part.

Movement Extents (d1, d2, dtot)

Summary statistics in Table 2a, computed across words for each marker, show no consistent pattern of differences between speakers with dysarthria as compared with healthy control speakers. Results differed depending on the measure, marker, and word. A two-way ANOVA revealed significant Word × Group interactions for the d2 measure for J, $F(18, 263) = 2.25$, $p = .003$; T1, $F(18, 263) = 2.93$, $p < .001$; and T3, $F(18, 269) = 1.79$, $p = .03$; and for the dtot measure for J, $F(18, 263) = 1.85$, $p = .02$; T1, $F(18, 263) = 3.5$, $p \leq .001$; and T3, $F(18, 269) = 2.01$, $p = .01$.

Figure 4 shows an interaction plot between group and word conditions for distance traveled by J during the final movement stroke (d2). Group means are represented by the center of the plotted symbols, and symbol size shows relative across-speaker variability expressed as a percentage of the largest *SD* in the plotted data. For example, the largest across-speaker variability in d2 was found for the ALS group in the word *cat* (*SD* = 3.5 mm). For the same word, the N and PD groups have smaller *SD*s (1.9 and 2.6 mm, respectively)—hence, the smaller size of their respective symbols. Post hoc comparisons showed significantly smaller d2 movements for the J marker in speakers with PD as compared to speakers with ALS in *big* ($p = .03$) and in speakers with ALS as compared to healthy control speakers in *bad* ($p = .006$) and *cat* ($p = .03$).

Tukey's HSD comparisons for the total distance (dtot) traveled by J during vowels revealed statistically significant differences between ALS and N, and ALS and PD groups for *feed* and *too* ($p < .04$). On average, speakers with ALS showed larger movements in these words than speakers with PD and healthy controls. For example, average total J movements for speakers from the ALS, N, and PD groups, respectively, in *feed* were 5.0, 2.0, and 1.0 mm, and in *too* were 2.0, 1.0, and 0.9 mm.

For the T1 marker, the words *shoo, bad,* and *cat* had the largest movements among all words (≥6 mm) among N speakers and showed a tendency to have reduced amplitudes in speakers with dysarthria, more often in speakers with ALS. For example, for the d2 measure, words *shoo,*

Table 2. Group averages and standard deviations computed across words for (a) distance (d1, d2, and dtot), (b) average speed (s1 and s2), and (c) timing (t1, t2, and t1p) measures for the jaw (J), lower lip (LL), tongue blade (T1), and tongue dorsum (T3).

(a)

	d1 (mm)			d2 (mm)			dtot (mm)		
Marker	**N**	**PD**	**ALS**	**N**	**PD**	**ALS**	**N**	**PD**	**ALS**
J	0.93 (1.8)	0.80 (1.5)	1.43 (1.9)	1.46 (3.6)	1.24 (2.5)	1.57 (2.8)	2.58 (5.5)	2.02 (2.5)	3.52 (4.7)
LL	1.75 (3.4)	1.02 (3.1)	1.37 (3.1)	0.95 (1.8)	0.91 (2.1)	1.03 (2.6)	3.44 (3.4)	2.66 (3.2)	3.73 (3.1)
T1	1.23 (1.9)	1.44 (1.9)	1.30 (2.0)	3.23 (4.3)	2.84 (4.6)	1.94 (3.2)	5.65 (5.4)	5.29 (4.5)	4.46 (3.7)
T3	1.76 (2.2)	1.46 (2.3)	1.58 (2.1)	3.31 (4.4)	2.41 (2.8)	2.01 (2.9)	6.07 (6.3)	5.05 (4.9)	4.50 (3.6)

(b)

	s1 (mm/s)			s2 (mm/s)		
Position	**N**	**PD**	**ALS**	**N**	**PD**	**ALS**
J	19.9 (12.2)	14.2 (16.5)	16.5 (6.5)	23.2 (17.9)	16.5 (10.5)	17.3 (8.4)
LL	26.5 (17.0)	20.4 (14.3)	16.7 (7.1)	19.8 (12.0)	16.8 (10.7)	14.3 (6.7)
T1	28.5 (14.8)	26.0 (7.2)	18.8 (5.8)	40.7 (19.9)	35.1 (15.6)	21.9 (7.1)
T3	32.3 (10.4)	25.4 (9.3)	18.8 (4.3)	41.5 (14.9)	31.6 (11.0)	22.5 (6.9)

(c)

	t1 (ms)			t2 (ms)			t1p (ms)		
Position	**N**	**PD**	**ALS**	**N**	**PD**	**ALS**	**N**	**PD**	**ALS**
J	77.9 (30.5)	90.1 (34.4)	122.7 (24.8)	96.4 (34.6)	96.8 (41.7)	124.9 (34.6)	0.44 (0.13)	0.49 (0.14)	0.48 (0.07)
LL	87.1 (32.7)	94.5 (34.2)	120.9 (46.3)	79.2 (28.4)	91.3 (39.2)	124.3 (45.7)	0.50 (0.09)	0.50 (0.15)	0.48 (0.14)
T1	77.2 (30.5)	84.7 (39.8)	118.8 (43.7)	91.0 (31.7)	99.8 (33.4)	128.4 (39.7)	0.44 (0.09)	0.44 (0.13)	0.47 (0.15)
T3	76.9 (25.1)	85.6 (34.4)	116.9 (34.0)	91.6 (33.6)	96.6 (39.9)	128.0 (32.6)	0.44 (0.07)	0.45 (0.12)	0.46 (*0.07)

Note. N = healthy control.

bad, and *cat* showed average tongue blade movements of 6.0, 8.1, and 6.3 mm, respectively, across the N group, and 4.1, 4.5, and 3.6 mm across speakers with ALS. The means derived from ALS productions were significantly smaller than the normal means (p values ranging between .01 and .05). Although similar trends for across-word differences in T1 were noted for the dtot measure, only *cat* showed significantly smaller T1 movements among ALS speakers as compared to N ($p = .002$) and PD groups ($p = .02$), with respective means of 3.2, 5.9, and 6.0 mm.

For the T3 marker, the only statistically significant group difference for the d2 measure was in *dog* between ALS and N group averages, with the former moving only 2.6 mm and the latter moving 8.7 mm ($p = .003$). Figure 5 shows an interaction plot for the dtot measure for the T3 marker. Smaller T3 movements can be noted for speakers with ALS as compared with healthy control speakers across the four words with low vowels and for speakers with PD as compared with normal speakers in *bad* and *box*. For this measure, statistically smaller-than-normal movements were observed in *bad* for speakers with PD ($p = .04$) and in *dog* for speakers with ALS ($p = .05$).

Average Speed of Articulator Marker Movements (s1, s2)

Summary statistics in Table 2b show that vowel-related movements of the L, T1, and T3 markers tended to be slower in ALS as compared with N and PD productions. Significant Group × Word interactions were noted for the s1 measure for the LL marker, $F(18, 257) = 2.3$, $p = .003$. Average LL speeds during the initial stroke were significantly lower in speakers with ALS as compared with healthy control speakers in *feed* (*M*s = 17.3 and 41.2 mm/s, respectively; $p = .0007$), *big* (*M*s = 13.4 and 30.7 mm/s, respectively; $p = .006$), *shoo* (*M*s = 8.7 and

Figure 4. Group × Word interaction plot showing across-speaker averages in movement sizes traveled by J during the final stroke. The size of the symbol represents variability around each mean expressed relative to the largest standard deviation. Asterisk denotes words that showed statistically significant contrasts.

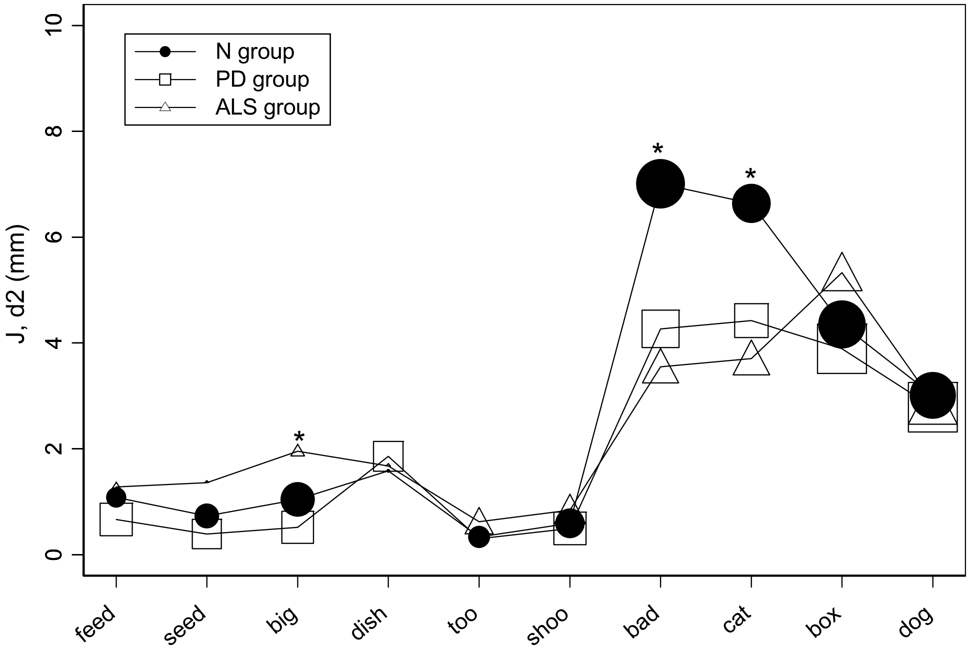
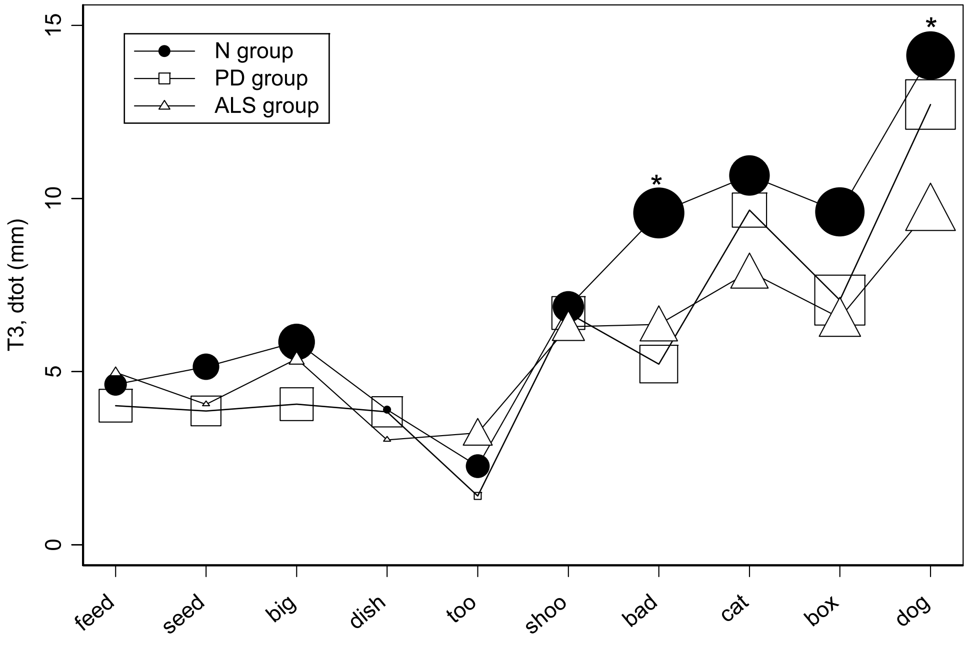


Figure 5. Group × Word interaction plot showing across-speaker averages in total distance traveled by the tongue dorsum during the vowels. The size of the symbol represents variability around each mean expressed relative to the largest standard deviation. Asterisk denotes words that showed statistically significant contrasts.



19.3 mm/s, respectively; $p = .03$), and *bad* (*M*s = 40.6 and 52.4, respectively; $p = .007$).

A main effect of group without a Group × Word interaction was found for the s1 measure in T1 and T3 markers (see Table 2b), $F(2, 23) = 4.4$, $p < .03$, and $F(2, 26) = 8.1$, $p < .002$, respectively. T1 marker movements in ALS were slower than in N ($p < .0001$) and PD ($p = .0009$) productions. T3 marker movements were slower in the ALS group as compared with both N and PD groups ($p < .006$) and were slower in the PD group as compared with the N group ($p = .02$).

Significant Group × Word interactions were seen for the s2 measure for T1, $F(18, 263) = 3.0$, $p < .001$, and T3 markers, $F(18, 269) = 2.0$, $p = .01$. Significantly slower T1 average speeds were recorded for ALS speakers as compared with N and PD speakers in the words *seed, dish, bad,* and *cat*. The means were 15.4 and 43.0 mm/s for *seed* ($p = .008$), 12.7 and 37.4 for *dish* ($p = .0008$), 19.2 and 56.3 mm/s for *bad* ($p < .0001$), and 18.6 and 55.4 mm/s for *cat* ($p < .0001$) in the ALS and N groups, respectively. Average speeds recorded for the T1 marker from speakers with PD were similar to those produced by N speakers.

Figure 6 shows a Group × Word interaction plot for the s2 measure obtained for the T3 marker. Significant reduction in average speed was found for the ALS group as compared with the N group in *feed, seed, shoo, cat, box,* and *dog* (p values ranging between .0003 and .04). T3 movements for speakers with ALS were also significantly slower than those for speakers with PD, although only for *seed* ($p = .015$).

Total Durations

Figure 7 shows an interaction plot for the total (vowel) duration measure. N speakers produced vowels with an average duration of 178 ms (*SD* = 58.6) across all words. The across-word average duration for the PD group was 188 ms (*SD* = 70.8). The average duration for the ALS group was 256 ms (*SD* = 88.9). Statistical testing revealed a significant Group × Word interaction for this measure, $F(18, 269) = 2.5$, $p < .001$. Post hoc contrasts showed that all comparisons of ALS and N total durations were statistically significant (p values ranging between < .0001 and .043). Moreover, ALS vowels were longer than PD vowels in all words but *cat, box,* and *dog* ($p < .04$).

Stroke Durations and Proportional Timing (t1, t2, t1p)

A summary of the results presented in Table 2c shows J marker movements for speakers with ALS being, on average, approximately 45 ms longer than normal in the initial stroke and 29 ms in the final

Figure 6. Group × Word interaction plot showing across-speaker averages in the s2 measure for T3 marker. The size of the symbol represents variability around each mean expressed relative to the largest standard deviation. Asterisk denotes words that showed statistically significant contrasts.

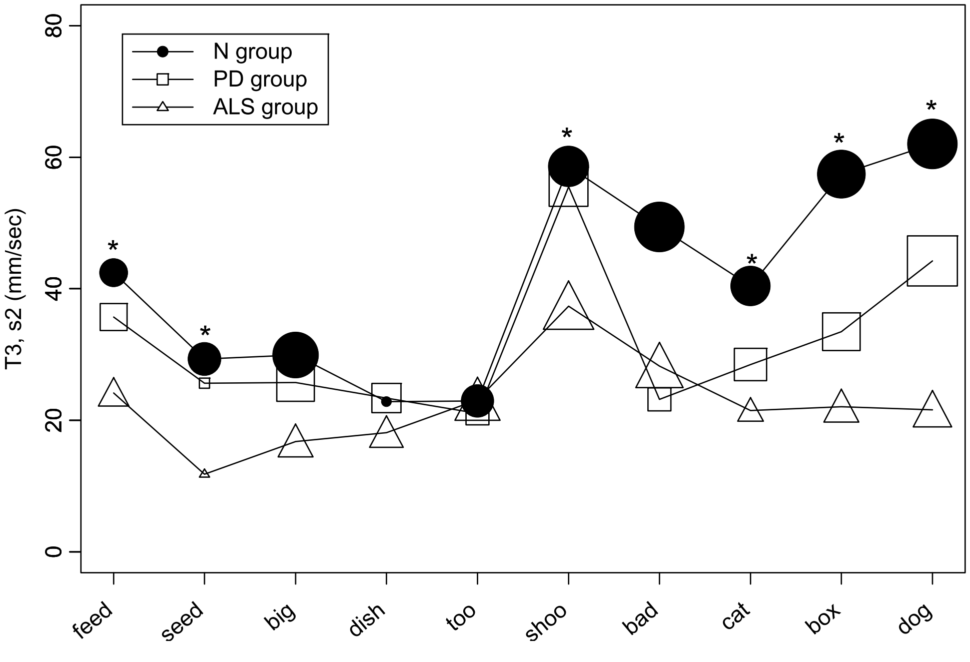
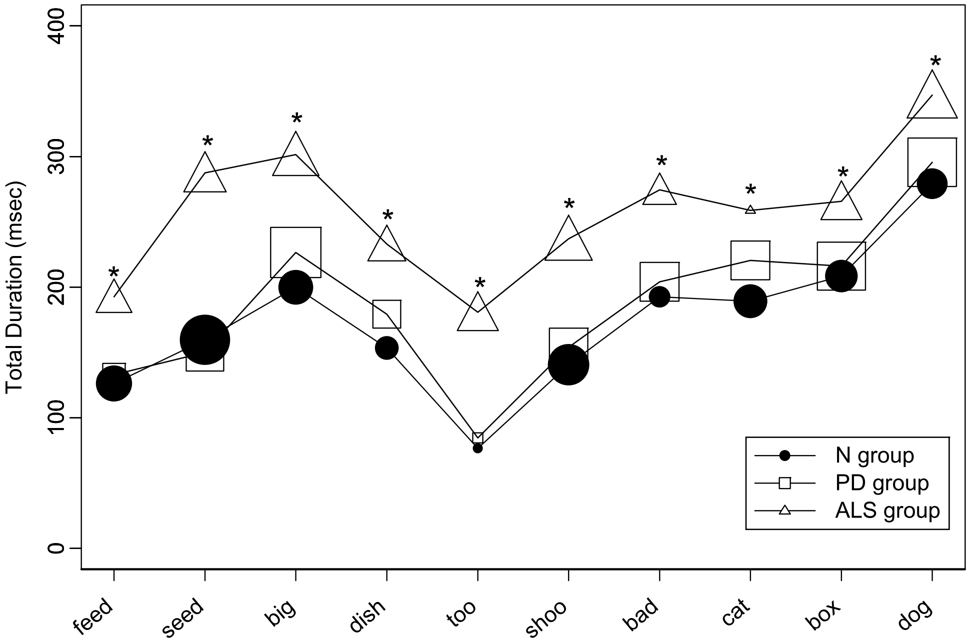


Figure 7. Group × Word interaction plot showing across-speaker averages in total (vowel) durations. The size of the symbols represents variability around each mean expressed relative to the largest standard deviation. Asterisk denotes words that showed statistically significant contrasts.



stroke. A one-way ANOVA revealed a significant effect of group but no Group × Word interaction for the t1 measure for J, $F(2, 24) = 10.4, p = .0006$. Post hoc tests showed that the ALS group differed in this measure from both the N ($p < .0001$) and PD ($p = .003$) groups. For t2, a Group × Word interaction was significant, with group differences (ALS vs. N and PD) found for *seed, big,* and *dish,* with p values ranging between .0002 and .02.

LL marker movements were approximately 34 and 45 ms longer than normal in ALS productions of initial and final movement strokes, respectively. This effect was similar across all words for t1, with results showing a significant main effect of group, $F(2, 24) = 8.0, p = .002$, but no Word × Group interaction. There was a significant Word × Group interaction for the t2 measure for this marker, $F(18, 257) = 1.9, p < .02$, with *seed, dish, too, shoo,* and *cat* showing significant differences between ALS and PD, and ALS and N groups (p values ranging between .0005 and .04). Words beginning with labial consonants (i.e., *feed, big, bad,* and *box*) did not show group differences on this measure.

For T1, movements in *dish, too, shoo, bad,* and *dog* were, on average, 66 ms longer for the initial stroke and 12 ms longer for the final stroke in ALS as compared with N speakers. For the remaining words, the ALS productions were, on average, 17 ms and 63 ms longer compared with N speakers for the t1 and t2 measures, respectively. Statistical tests showed significant Group × Word interactions, with differences between ALS and N, and ALS and PD for *seed, dish, too, shoo, bad,* and *dog* for the t1 measure (p values ranging between < .0001 and .04) and *feed, seed, cat,* and *box* for the t2 measure (p values ranging between < .01 and .045).

T3 marker movements were longer for speakers with ALS, as compared with normal-speaking participants, by 40 ms and 36 ms in the initial and final movement strokes, respectively. This effect was relatively uniform in different words. The main effect of group without a Group × Word interaction was seen for both t1 and t2 measures, $F(2, 26) = 6.2, p = .006$, and $F(2, 26) = 9.8, p < .0006$, respectively, with ALS productions being different from both N and PD productions (p values ranging between < .001 and .006).

When expressed as proportional time relative to vowel duration (t1p), time to the local speed minimum within the vowel interval was statistically different only in a few cases. Speakers with ALS showed earlier occurrences of speed minima for the LL marker in *shoo* as compared to speakers with PD and healthy controls ($p = .0003$). Speakers with ALS also showed a significantly delayed occurrence of local speed minima for the T1 marker, as compared with speakers in the N and PD groups, in *dish* and *bad* ($p = .04$ and .01).

Discussion

This study compared movement characteristics of markers attached to the jaw, lower lip, tongue blade, and dorsum during production of selected vowels in sentences by individuals with normal speech and speakers with dysarthria due to ALS or PD. The articulator marker movements were examined for evidence of reduction in movement size and changes in duration and average speed. In addition to evaluating some of the general expectations related to understanding the nature of the movement deficit in dysarthria (e.g., reduced movement size, slower-than-normal movement speed), the study compared group differences in movements of the four potentially independent articulators and provided a description of conditions in which the movement deficits were most notable as far as vowel production is concerned. These topics are discussed in more detail in the sections that follow.

Articulatory Movements in Dysarthria

Movements of markers attached to the jaw, lower lip, and tongue were rarely reduced in size during vowels in speakers with dysarthria as compared with healthy controls. Of 120 possible Word × Articulator combinations (3 Distance Measures × 10 Words × 4 Articulator Markers = 120), only 12 showed statistically significant group differences between either of the dysarthria groups and the N group. In the majority of significant cases (8 of 12 differences), the movements of articulator markers (2 jaw and 6 tongue) were smaller in speakers with ALS as compared to individuals with normal speech. In three cases, jaw marker movements were larger in ALS as compared to individuals with normal speech. There was only one comparison between the PD and N groups that revealed smaller tongue blade marker movements for the former as compared with the latter. These findings largely differ from the reports of notable movement reduction associated with dysarthria, particularly in ALS. However, this might be due to differences in movement intervals examined in this and other studies (i.e., vowel-related movements versus CV transitions; see Ackerman et al., 1997; Connor et al., 1989; Forrest et al., 1989). Speaking tasks also differed between studies, with the majority of published observations based on measures obtained in monosyllables and AMRs.

Differences between speakers with dysarthria and healthy controls were seen more consistently in the average speed and duration measures. Movements of the articulator markers were significantly slower for speakers with ALS as compared with N speakers in 4 of 20 possible comparisons (2 Average Speed Measures × 10 Words) for the lower lip, 14 of 20 for T1, and 16 of 20 for T3. No differences were seen in the speed of jaw movements. The notable group differences in the derived measure of average speed between ALS and N productions are not surprising, considering the finding of significantly longer movement stroke durations across words for the speakers with ALS. Speakers in the PD group showed movement stroke durations similar to those of healthy control participants. Their tongue dorsum marker (T3) movements, however, were significantly slower than normal in the initial stroke, indicating that even though there were not significant PD–N magnitude differences, some combination of distance and time produced the significant s1 effect in T3.

An additional question was whether there is evidence for discoordination between the four articulators in our vowel data. The stroke durations and the proportional timing measure were examined for this purpose. The present results showed that for ALS productions, the increase in movement duration was largely proportional between the two movement strokes of all articulator markers except the jaw, for which the initial movement stroke seemed to lengthen somewhat more than the final stroke. The proportional time measure revealed only a small number of contrasts (3 of 40) in tongue blade and lower lip trajectories, whereas the occurrence of speed minima within vowel duration was different for ALS as compared with N and PD groups. All timing measures were similar between the PD and N groups. Thus, our findings can be interpreted to indicate largely preserved intra-articulator coordination during vowels in dysarthria due to ALS or PD, assuming that these measures capture an aspect or the essence of coordination. Similar conclusions were reached by Weismer et al. (2003) for a different type of analysis but for several of the same speakers. In both studies, however, a few speakers were found for whom coordination patterns were notably different from normal (see Yunusova, 2005, for a detailed analysis of movements obtained from such individuals). At this time, it is difficult to speculate why some speakers would exhibit timing patterns so different from those of other speakers. One possible explanation might lie in the severity of speech impairment of each individual speaker, since only speakers with the lowest intelligibility scores showed interarticulatory relationships different from normal in Yunusova (2005) and Weismer et al. (2003). Based on these preliminary findings, it might be fair to suggest that coordination could be one of the speech features that is relatively resistant to mild neurologic damage but deteriorates with greater severity. The relationship between measures of coordination and severity of speech impairment will be explored in the future.

Movement-Based Dysarthria Profiles

Some differences were observed between vowel-related movements in speakers with ALS and PD, although for most measures, ALS movements were not as consistently different from PD as from movements produced by healthy controls. At the same time, PD movements were neither consistent nor large enough to be reliably different from the control data. Those differences observed between speakers with ALS and PD might be attributed as easily to differences in severity of speech impairment as to disease type. Our measures of speech intelligibility (see Table 1) indicated that severity was moderate for the majority of speakers with ALS and mild for the majority of speakers with PD.

Some data summaries published by others seem to show that kinematic differences between dysarthria types/etiologies are less pronounced than perceptual differences and that different neurologic diseases have similar speech movement characteristics (see Ackerman et al., 1997; Hirose, 1986). Had group differences between the two disease types surfaced in our study, they could have been revealed in two possibly interdependent ways. First and most obviously, both groups could have generated articulatory characteristics different from normal but also different from each other. This result could arise from the same types of articulatory abnormalities but ones differing in magnitude depending on disease type rather than severity (i.e., intelligibility). Alternatively, group differences could be reflected not in the magnitude of articulatory deficits but in which articulators showed deficits. This is the alternative outlined in the introduction, where tongue motions seem to have been disproportionately affected in ALS (DePaul & Brooks, 1993), and jaw movements seem to have been disproportionately affected in PD (Connor et al., 1989). Our results seem to be more consistent with the first possibility, although this interpretation must be considered somewhat weak because we cannot yet determine the extent to which severity differences across the two groups predict observed articulatory differences. Comparisons of groups of speakers with different disease/dysarthria types closely matched on speech intelligibility measures are necessary to obtain a clear answer.

Differential Impairment Between Articulators

A comparison of movement characteristics between articulators suggested that for both dysarthria groups, tongue marker movements tended to differ more from normal than from jaw or lip marker movements, across all kinematic measures. The size of movements of the lower lip marker were comparable to healthy controls in speakers with either ALS or PD, but their durations were longer (hence, their speeds were slower) than normal in speakers with ALS. This fact may reflect a compensatory response in the lip, to preserve timing (synchrony) between movements of the lip and tongue. Weakening of the lip musculature due to ALS could also result in slower-than-normal movements (see Goldfarb & Simon, 1984, linking slowing and muscle weakness in limb musculature in ALS), although the first possibility is more likely, given our informal observations of adequate lip function in the majority of ALS speakers producing other speech sounds involving the lips (e.g., the plosive consonants).

As did the lower lip, the jaw marker showed vowel-related movements that were often similar to normal in distance and speed for the two dysarthria groups but consistently of greater duration for speakers with ALS. In the study of articulatory movement in ALS by Hirose, Kiritani, and Sawashima (1982b), jaw movements in 2 speakers with ALS repeating syllables /ta/ and /ka/ were notably larger than jaw movements of their 1 control speaker. Our CVC words with low vowels (*box* and *dog*), however, showed the opposite effect. However, it is difficult to compare speech movements from AMR sequences (Hirose et al., 1982b) to those from words (current study), especially because speech movements in AMR sequences have been shown to be so variable across speakers (Westbury & Dembowski, 1993). At the same time, larger-than-normal jaw marker movements for speakers with ALS were seen in words with high vowels (e.g., *feed, big, too*). Average speed of jaw marker movements for speakers with ALS was comparable to normal across words even when the movement durations were longer for speakers with ALS. These results, considered together, might suggest a compensatory-type jaw response to ongoing reduction in movement amplitude of tongue markers. However, tongue marker movements were not found to be significantly smaller in the three words with significantly larger-than-normal jaw marker movements. Furthermore, jaw vertical positions at the moment of maximum elevation during these vowels revealed identical positions to those observed for normal speakers rather than the higher positions that might have been expected if the jaw was being used to support weak upward tongue movements. It is important to consider that compensatory responses in the articulatory system might not be easily identifiable and separable from disease effects, unless parallel analyses of premorbid movement and acoustics can be compared with the same measures following onset of disease.

Overall, our results seem to show modest evidence of differential impairment across articulators, hinting that movements of the tongue are more different from normal than movements of the jaw and lower lip in both neurogenic conditions. At the same time, there is no clear evidence of differential articulatory impairment across disease types. Speakers with ALS or PD show movement "profiles" similar to each other in most respects. The differences that were observed may reflect severity of the speech disorder rather than differences in underlying neuropathology. We plan to investigate this possibility in future research.

Word/Vowel Effects

The apparent effects of neurogenic disease on articulator movement parameters heavily depended on word and vowel, at least for distance, duration, and speed measures. Words with low vowels were consistently more affected across speakers with dysarthria. Stated alternatively, words and vowels requiring larger, longer, and faster movements showed more significant associations with disease. Changes associated with the presence of dysarthria were also seen in movements of the lips in vowels preceded by bilabial consonants and for the tongue blade in words with alveolar contexts. Thus, phonetic context effects cannot be separated from vowel effects. In future work, we would be interested to see if, for example, high vowels placed in consonant environments requiring larger articulatory motions would also exhibit patterns of reduction in movement extent, duration, and speed similar to ones we observed for low vowels embedded in bilabial and alveolar contexts.

Conclusions

An overall impression from our work is that during vowels, articulator markers do not necessarily move less in speakers with dysarthria due to ALS or PD, as compared to healthy controls, but tend to take longer to move the same distances. We showed that different articulators seem to be affected disproportionately, with the tongue experiencing a more significant impact of neurologic condition regardless of the two types of diseases considered. The observed effects, however, were often vowel- and phonetic context–specific. We can therefore argue that our results might not generalize to speech movements for other sounds in different phonetic contexts. Additionally, our results might not generalize to the populations of speakers with ALS or PD due to relatively small speaker groups studied. Based on our limited speech sample, we can hypothesize for future studies that some articulatory events might be more affected in dysarthria than some other events. Specifically, speech events requiring large articulator movements (e.g., specific CV combinations, diphthongs, glides) should be more strongly affected by disease and are therefore ideal targets to study in dysarthria. Weismer et al. (1992) reached a similar conclusion based on acoustic analyses of vowel formant trajectories. Functional effects of changes in kinematic parameters need to be focused on in the future, showing changes in segment-related movements and their predicted effects on speech acoustics and intelligibility.

Acknowledgments

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