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Research Article

Articulatory Correlates of Stress Pattern Disturbances in Talkers With Dysarthria

Daniel Kim,[a] Mili Kuruvilla-Dugdale,[b] Michael de Riesthal,[a] Robin Jones,[a] Francesca Bagnato,[c] and Antje Mefferd[a]

Purpose: Reduced stress commonly occurs in talkers with Parkinson's disease (PD), whereas excessive and equal stress is frequently associated with dysarthria of talkers with amyotrophic lateral sclerosis (ALS) and multiple sclerosis (MS). This study sought to identify articulatory impairment patterns that underlie these two impaired stress patterns. We further aimed to determine if talkers with the same stress pattern disturbance but different diseases (ALS and MS) exhibit disease-specific articulatory deficits.

Method: Fifty-seven talkers participated in the study—33 talkers with dysarthria and 24 controls. Talkers with dysarthria were grouped based on their medical diagnosis: PD (n = 15), ALS (n = 10), MS (n = 8). Participants repeated target words embedded in a carrier phrase. Kinematic data were recorded using electromagnetic articulography. Duration, displacement, peak speed, stiffness, time-to-peak speed, and parameter c were extracted for the initial lower lip opening stroke of each target word, which was either stressed or unstressed.

Results: Stress effects were significant for all kinematic measures across groups except for stiffness and time-to-peak speed, which were nonsignificant in ALS. For comparisons with controls, more kinematic measures significantly differed in the ALS group than in the PD and MS groups. Additionally, ALS and MS showed mostly similar articulatory impairment patterns.

Conclusions: In general, significant stress effects were observed in talkers with dysarthria. However, stress-specific between-group differences in articulatory performance, particularly displacement, may explain the perceptual impression of disturbed stress patterns. Furthermore, similar findings for ALS and MS suggest that articulatory deficits underlying similar stress pattern disturbances are not disease-specific.

Dysarthria is a neurogenic motor speech disorder with impairment in speech production due to neurological conditions that affect specific brain regions involved in speech motor control. Based on their seminal studies on perceptual speech characteristics, Darley et al. (1969a, 1969b, 1975) proposed that speech patterns of talkers with dysarthria vary systematically with their underlying neuropathology. As a result of their observations, dysarthria types that are associated with specific neuropathologies were established. For example, hypokinetic dysarthria is associated with basal ganglia pathology and commonly occurs in talkers with Parkinson's disease (PD). By contrast, spastic–flaccid dysarthria is associated with bilateral upper and lower motor neuron degenerations and frequently occurs in talkers with amyotrophic lateral sclerosis (ALS). Finally, spastic–ataxic dysarthria is related to bilateral corticobulbar tract lesions in combination with cerebellar lesions and is predominantly present in talkers with multiple sclerosis (MS).

Several studies have sought to identify potential speech acoustic features that could account for differences in perceptual speech characterization across talkers with dysarthria. Although various acoustic parameters have been examined, most studies failed to identify spectral features that could differentiate dysarthria types. Temporal features that characterize speech rhythm, however, could reliably distinguish between different dysarthria types (Liss et al., 2009). This finding aligns with previous auditory-perceptual observations that stress pattern disturbances can differ across talkers with dysarthria (e.g., Darley et al., 1969a, 1969b, 1975). Reduced stress, for example, commonly occurs in talkers

[a]Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, Nashville, TN
[b]Department of Speech, Language and Hearing Sciences, University of Missouri, Columbia
[c]Neuroimaging Unit, Neuroimmunology Division, Department of Neurology, Vanderbilt University Medical Center, Nashville, TN
Correspondence to Daniel Kim: daniel.kim.1@vanderbilt.edu

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with PD. By contrast, excessive and equal stress can be frequently observed in talkers with ALS and MS (Duffy, 2013).

Presumably, differences in articulatory constraints result in various stress pattern disturbances. Findings of acoustic studies by Liss et al. (2009) suggest that, particularly, the ability to vary segment durations to create stress patterns was impaired in specific ways depending on the underlying neuropathology. For example, segment durations were generally longer and stress-related variation in durations was reduced in talkers with ALS when compared to typical talkers. By contrast, segment durations of talkers with PD tended to be shorter than those of typical talkers and also varied less in response to stress. Finally, an acoustic study by Ziegler et al. (1993) investigated talkers with dysarthrias of a wide variety of underlying neuropathologies (e.g., traumatic brain injury, stroke, neurodegenerative disease). They found two deviant patterns: either prolonged segment durations or a trend toward shortened segment durations. Most importantly, the stress-related variation of segment durations was reduced in all talkers with dysarthria. This finding suggests that talkers with dysarthria who generally produced prolonged segment durations were unable to sufficiently shorten these durations to accommodate the durational demands of unstressed segments. Conversely, talkers who typically produced segment durations that were too short relative to typical talkers were unable to sufficiently prolong segment durations to accommodate stressed segments.

To vary segment durations, talkers need to modify their underlying speech movements. Within the framework of a mass-spring model, kinematic stiffness is thought to be the control parameter that regulates duration, displacement, and speed (Kelso et al., 1983). Kinematic stiffness is estimated based on the ratio of peak speed and displacement (Ostry et al., 1983). Although shorter movements are typically executed with smaller amplitudes and lower peak speed than longer movements, it is the change in the stiffness, or the ratio of peak speed and displacement, that results in a durational change (Munhall et al., 1985).

With regards to stress-related variation in movement duration, it has been shown that typical talkers produce stressed speech segments with lower longer durations and lower stiffness than unstressed segments (Munhall et al., 1985). Stressed segments also inherit larger displacements and greater peak speed than unstressed speech segments (Munhall et al., 1985). Interestingly, the velocity profiles of these articulatory movements show only subtle changes in their shape or their "peakedness" (indexed by parameter c), which suggests that typical talkers utilize similar strategies to generate speed during unstressed and stressed segments. However, the symmetry of the velocity profile (the time-to-peak speed relative to the total movement duration) differs across stress conditions, which suggest that typical talkers implement different articulatory control strategies during the production of stressed and unstressed segments (Ostry et al., 1987). Specifically, stressed segments are associated with more asymmetrical velocity profiles indicating shorter acceleration phases and prolonged deceleration phases than unstressed segments.

Although acoustic studies have shown that the modulation of segment durations in response to stress demands is constrained in talkers with dysarthria (e.g., Liss et al., 2009; Ziegler et al., 1993), the underlying articulatory mechanisms have not been delineated. That is because kinematic studies that are presently available on talkers with dysarthria mainly focus on stressed segments and rarely include unstressed segments. The main rationale for the focus on stressed segments is that talkers with dysarthria experience more difficulty with the production of more extreme vocal tract shapes, which are often associated with stressed segments and tense vowels (Tjaden et al., 2005; Turner et al., 1995). Indeed, it has been suggested that the production of unstressed segments and lax vowels is less affected in talkers with dysarthria because they are associated with less extreme vocal tract shapes (Turner et al., 1995). However, acoustic findings only supported this assertion for talkers with dysarthria due to PD; not for talkers with dysarthria due to ALS (Tjaden et al., 2005). Specifically, talkers with PD demonstrated an acoustic vowel space area for lax vowels that was comparable to that of controls suggesting that talkers with dysarthria due to PD had no difficulty achieving less extreme vocal tract configurations. By contrast, talkers with ALS exhibited a significantly smaller acoustic vowel space area for lax vowels when compared to that of controls. Most importantly, between-group differences in acoustic vowel space area for tense vowels reported by Turner et al. (1995) were comparable to between-group differences reported for the lax vowels reported by Tjaden et al. (2005). These findings suggest that talkers with ALS may be equally challenged with the production of more extreme vocal tract shapes required for stressed segments as with the production of less extreme vocal tract shapes required for unstressed segments. However, to this day, the articulatory impairment patterns that underlie these challenges remain elusive because direct side-by-side comparisons are still lacking for most talkers with dysarthria.

One of the few kinematic studies that did include stressed and unstressed segments found that, during both stress conditions, talkers with PD had reduced displacements, reduced speeds, and shorter durations relative to controls (Forrest et al., 1989). These findings were explained by elevated levels of articulatory stiffness in this clinical group. By contrast, several studies have shown that articulatory displacements of talkers with ALS are often comparable to those of typical talkers while segment durations are prolonged, suggesting relatively low levels of articulatory stiffness in this clinical group (e.g., Kuruvilla-Dugdale & Chuquilin-Arista, 2017; Lee et al., 2017; Mefferd, 2015). Relatively low articulatory stiffness was also suggested for talkers with MS, at least during stressed segments, as these talkers demonstrated comparable or even larger articulatory displacements and prolonged segment durations relative to their healthy peers (Mefferd et al., 2019).

Based on previous kinematic findings for talkers with dysarthria, it is conceivable that a reduced stress pattern in talkers with PD may be explained by a constrained ability to decrease stiffness levels to particularly accommodate stressed segments. Furthermore, it is conceivable that equal and excessive stress patterns of talkers with ALS and MS may be driven by a constrained ability to increase stiffness levels, which is required for the production of unstressed segments. Constraints in stiffness regulation across all dysarthria groups may be further explained by an impaired ability to generate speed in a timely fashion (Barlow & Abbs, 1986). Therefore, it is also important to examine movement performance characteristics such as the time-to-peak speed and parameter c (i.e., speed generation normalized for displacement as a function of time = the shape of the velocity profile or the "peakedness" of the velocity profile, Ostry et al., 1987).

In addition, previous studies have rarely compared articulatory performance patterns directly across multiple clinical groups with dysarthria. It is rather typical for studies to report findings of comparisons between a single clinical group and typical talkers (e.g., Caligiuri, 1989; Forrest et al., 1989; Kearney et al., 2017; Kuruvilla-Dugdale & Chuquilin-Arista, 2017; Lee et al., 2017; Whitfield et al., 2018; Wong et al., 2010; Yunusova et al., 2012). Comparisons across various clinical groups with dysarthria are, however, needed to better understand how talkers with different speech perceptual characteristics such as distinct stress pattern disturbances differ in their articulatory performance patterns. Furthermore, it is unknown if talkers with similar stress pattern disturbances, but different underlying etiologies, also show similar articulatory impairments. Such insights are important for our conceptual understanding of dysarthria types.

The current study aimed to identify potential differences in lower lip articulatory performance patterns of stressed and unstressed segments in talkers with PD, ALS, and MS. Based on previous kinematic findings, we sought to specifically test the hypothesis that regardless of the underlying neuropathology, all talkers with dysarthria will show a limited ability to vary stiffness and hence duration in response to stress demands relative to controls. Therefore, we expected to find significant stress condition effects on stiffness only for controls. Furthermore, we expected to find significantly greater stiffness levels in talkers with PD (particularly during stressed segments) and significantly lower stiffness levels in talkers with ALS and MS (particularly during unstressed segments) relative to controls.

To further characterize the articulatory performance deficits that are associated with deviant stiffness levels in talkers with dysarthria, we also examined displacement and peak speed measures. Based on previous literature, we expected reduced displacements particularly in talkers with PD (e.g., Forrest et al., 1989; Yunusova et al., 2008) as well as reduced peak speeds across all three disease groups (e.g., Forrest et al., 1989; Mefferd et al., 2012, 2019; Yunusova et al., 2008). Finally, we explored potential disease-specific mechanisms that underlie speed constraints by examining the velocity profiles of stressed and unstressed segments (i.e., time-to-peak speed, parameter c). No predictions were made for these measures because they have rarely been studied in talkers with dysarthria.

Method

Participants

The study was approved by the institutional review board committee of Vanderbilt University Medical Center. All participants consented to the study prior to data collection. Data included in this study were collected as part of a larger project on articulatory performance in talkers with dysarthria. All participants with a neurological condition were diagnosed by a board-certified neurologist. Exclusion criteria for all participants were as follows: (a) difficulty with saliva management; (b) a prescription for hearing aids; (c) a history of speech, language, or hearing impairments; and (d) wearing a pacemaker (per safety regulations of the articulography). Furthermore, to be eligible to participate, participants had to score at least 24 points (out of 30) on the Mini-Mental Status Examination (Folstein & Folstein, 2012). Talkers with dysarthria were also not eligible if they reported a history of any neurological conditions other than PD, ALS, or MS, and talkers with PD were not eligible if they had received surgical treatment (i.e., deep brain stimulation). Finally, healthy controls were not eligible if they reported a history of any neurological conditions.

All participants completed the Sentence Intelligibility Test (Yorkston et al., 2007) prior to kinematic data collection to document speech severity. The Sentence Intelligibility Test recordings were presented to a speech-language pathologist with expertise in motor speech disorders who was not blinded to the medical diagnosis of the participants. The speech-language pathologist was asked to complete the Mayo Clinic dysarthria rating scale (Darley et al., 1969a) for each talker with dysarthria. For the purpose of the current study, only talkers with dysarthria who were rated to have perceptible stress pattern disturbances (i.e., reduced stress, equal/excessive stress) were included in this study.

Based on these inclusion and exclusion criteria, a total of 57 participants were included in the current study—33 talkers with dysarthria and 24 controls (15 men, nine women; M_{age} = 61.3, SD = 9.3). Talkers with dysarthria were grouped based on their medical diagnosis: 15 talkers with PD (10 men, five women; M_{age} = 68.6, SD = 6.6), 10 talkers with ALS (three men, seven women; M_{age} = 59, SD = 7.4), eight talkers with MS (three men, five women; M_{age} = 52.9, SD = 4.8). Controls were sex- and age-matched (± 5 years of age) to participants in the experimental groups. Some healthy participants matched by age and sex with participants of multiple experimental groups (e.g., one control matched one talker with ALS and one talker with MS; see Table 1).

Experimental Tasks

As part of a larger experimental protocol, all participants were asked to complete five repetitions of four target words embedded in a short carrier phrase ("Say _ again") at their habitual rate and loudness. Two of the selected target words had an unstressed initial syllable (i.e., meticulous, metropolis), the other two had a stressed initial syllable (i.e., mantis, manicure). These target words were selected

Table 1. Demographic and speech characteristics of participants with dysarthria.

Patient ID	Sex	Age	Dysarthria severity
PDF16	Female	61	Mild
PDF19	Female	70	Mild
PDF20	Female	66	Mild
PDF21	Female	68	Mild–Moderate
PDF22	Female	66	Mild
PDM14	Male	84	Mild
PDM15	Male	75	Moderate
PDM17	Male	72	Mild
PDM19	Male	66	Mild–Moderate
PDM21	Male	73	Mild
PDM23	Male	63	Mild
PDM25	Male	66	Moderate
PDM26	Male	58	Mild
PDM27	Male	76	Mild
PDM28	Male	65	Mild
AF12	Female	59	Moderate–Severe
AF13	Female	52	Moderate–Severe
AF14	Female	72	Mild–Moderate
AF15	Female	48	Moderate–Severe
AF16	Female	64	Moderate
AF17	Female	58	Moderate
AF18	Female	69	Moderate–Severe
AM13	Male	56	Moderate–Severe
AM14	Male	57	Moderate
AM16	Male	55	Moderate
MSF03	Female	51	Moderate
MSF04	Female	49	Mild
MSF06	Female	61	Mild
MSF07	Female	56	Mild
MSF10	Female	53	Moderate
MSM02	Male	45	Mild–Moderate
MSM05	Male	53	Moderate
MSM06	Male	55	Mild

Note. PD = Parkinson's disease; F = female; M = male; A = amyotrophic lateral sclerosis; MS = multiple sclerosis.

from a larger pool of stimuli because they elicit the same articulatory movement patterns (i.e., bilabial opening strokes) within a similar phonetic environment (i.e., bilabial consonant—stressed/unstressed vowel—alveolar consonant). It should be noted that vowels during stressed and unstressed segments differ in height (i.e., the stressed vowels are more open than the unstressed vowels), which likely impacts displacement and peak speed. Nevertheless, previous kinematic studies reported no significant vowel effects on duration, stiffness, time-to-peak speed, and parameter c in typical talkers (e.g., Kent & Moll, 1969; Kuehn & Moll, 1976; Ostry et al., 1983). Because the primary aim of the current study is to determine the extent to which talkers with dysarthria are able to modify their stiffness levels to accommodate stressed and unstressed segments, the difference in vowel height across the target words was not a concern.

Data Acquisition

Speech kinematic data were captured using three-dimensional (3D) electromagnetic articulography (AG501, Carstens) at a sampling rate of 250 Hz. Five small sensors were affixed to the orofacial region with dental adhesive: two sensors to the sagittal midline of the tongue, two sensors to the midline of the upper and lower lips, and one sensor at the lower incisors (jaw). Three head reference sensors were placed on fitted goggles, which each participant wore during the data collection. These head reference sensors were used to correct all kinematic data for head movements during the speech task. A bite plate with bite plate reference sensors was used to record a rest file and to create a local coordinate system to express movement from each of the orofacial sensors relative to the head.

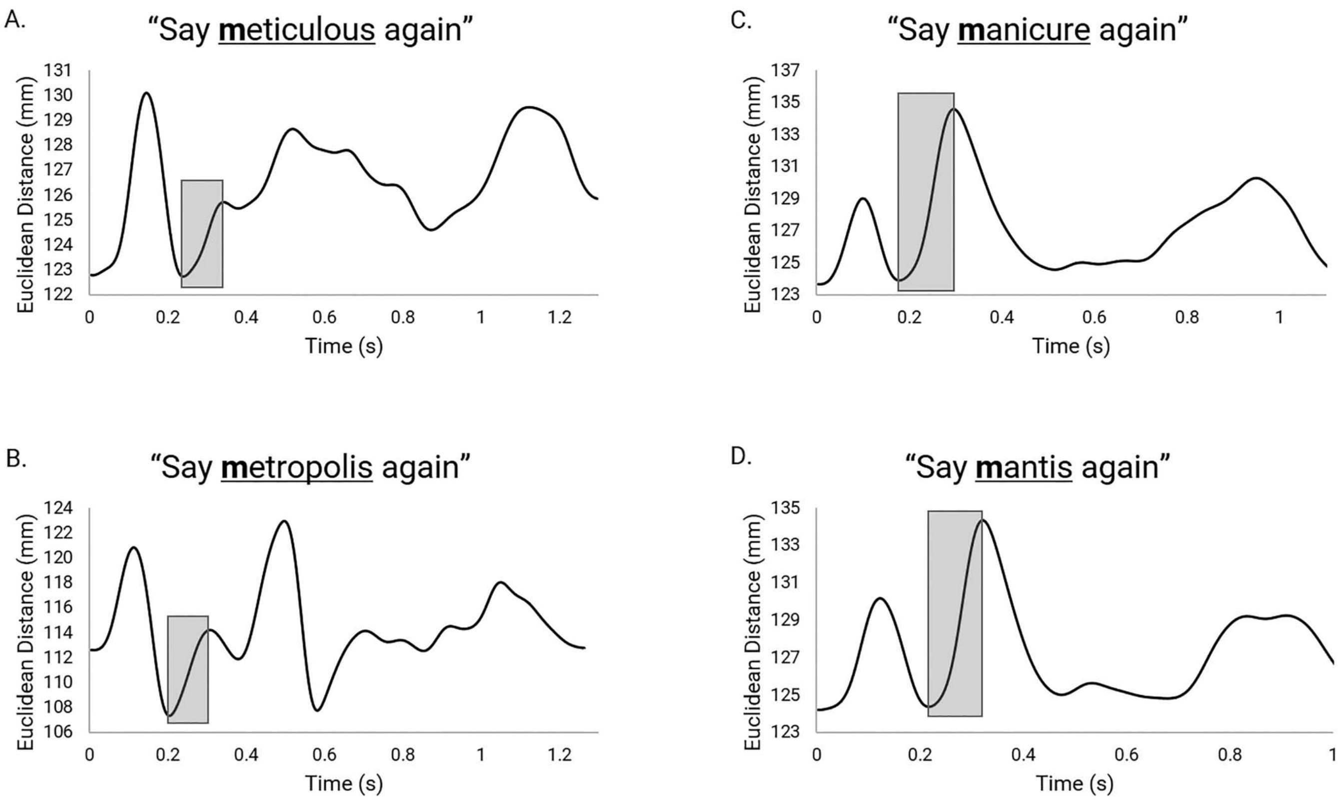
For the purpose of this study, we specifically examined the kinematics of the lower lip sensor. The raw data were converted into positional data using the *CalcPos* software, and the head movements were corrected using the *NormPos* software (Carstens, Bovenden, Germany). All the kinematic data were then low-pass filtered at 15 Hz in *SMASH* (Green et al., 2013).

Data Analysis

The lower lip opening stroke of the initial syllable was the specific interest in this study because talkers produce stress-related temporal and spatial changes primarily during the opening strokes (rather than the closing strokes) of speech segments (De Jong, 1995). For lower lip kinematic measures, the 3D Euclidean distance signals between the center head reference sensor and the lower lip sensor were calculated in *SMASH*. The 3D positions of the lower lip sensor were extracted at the onset and offset of each segment defined as the positional minimum of the lower lip distance signal associated with /m/ of each target word and the following positional maximum of the lower lip distance signal associated with the vowel (see Figure 1). Lower lip kinematics were not decoupled from the jaw displacements because the purpose of the study is to examine the overall lower lip displacement pattern, not the independent contributions of the lower lip and jaw.

Based on the defined segment boundaries for the lower lip opening stroke, the following kinematic measures were extracted: duration, displacement, peak speed, parameter c, time-to-peak speed, and articulatory stiffness. Segment durations were defined as the time between the onset and offset of each lower lip opening stroke. Lower lip displacement was defined as the relative change in the 3D Euclidean distance between the onset (positional minimum) and offset (positional maximum) for each lower lip opening stroke. Peak speed was defined as the maximum value of the first derivative of the change in displacement over the change in time during the lower lip opening stroke. Parameter c indexes the "peakedness" of velocity profiles, and it was determined by the ratio of peak speed over displacement in relation to duration (Munhall et al., 1985). That is, a higher value for the parameter c indicates a sharper peak in the velocity profile (i.e., triangular shape). In contrast, a lower value indicates a flattened velocity profile (i.e., trapezoidal shape; see also Nelson, 1983). Time-to-peak speed describes the

Figure 1. The panels display the 3D Euclidean distance signals calculated between the central head sensor and lower lip sensor during the sentence productions of unstressed (panels A and B) and stressed (panels C and D) conditions of a control subject. The gray sections indicate the lower lip opening stroke of the initial syllable of our specific target words.



acceleration phase of movements (i.e., time from movement onset to peak speed) and is commonly used to index the symmetry of velocity profiles. When acceleration and deceleration phases are similar in duration, the velocity profile is symmetrical. A shortening or lengthening of the acceleration phase will result in an asymmetrical velocity profile that is positively or negatively skewed. Time-to-peak speed is expressed as the percent of the time relative to the total movement duration. Finally, articulatory stiffness was defined as the ratio of peak speed over displacement.

Based on findings by Adams et al. (1993), it is known that talkers who volitionally slow their speaking rate produce articulatory movements with multiple velocity peaks. Because talkers with dysarthria can also produce speech at a slow rate, we inspected each velocity profile and documented the number of peak velocities in addition to all kinematic parameters described above. 13.7% of all movements were associated with multiple velocity peaks. These productions were excluded for further analysis. The rationale for this decision was that the relations between the selected kinematic parameters are only interpretable when their velocity profiles are single peaked (e.g., Nelson, 1983; Munhall et al., 1985). The exclusion of movements with multiple velocity peaks was also necessary to compare the kinematic parameters across talkers. The detailed report on the excluded repetitions is shown in Table 2.

Table 2. The number of multiple lower lip velocity peaks (excluded from the analysis).

Group	Participants with repetitions excluded (participants in sample) *n (n)*	Number of repetitions excluded %
Control	6 (24)	18/289 (6.2)
PD	5 (15)	6/169 (3.6)
ALS	5 (10)	31/117 (26.5)
MS	7 (8)	38/100 (38)

Statistical Analysis

To test our research hypothesis, we examined within-group differences (stressed and unstressed conditions) as well as between-group differences (Control, PD, ALS, and MS). We performed linear mixed model analysis on each kinematic parameter using R (R Core Team, 2019) and lme4 (Bates et al., 2012). The groups, stressed conditions, and the Group × Stress condition interaction were submitted as the fixed effects and the participants were submitted as the random effects into the model. The effects were tested by obtaining *p* values using likelihood ratio tests of the full model with the effect of our specific interest against the model without the effect. For all statistical tests performed, the critical α level was set at .05. If the effect of interaction was significant ($p < .05$), we conducted post hoc analyses using Tukey adjusted critical alpha-level for multiple comparisons. Potential aging- and sex-effects on all kinematic measures were considered (e.g., Simpson, 2002; Goozée et al., 2005); however, within the control group, the effect of age and sex were nonsignificant for all kinematic measures. Therefore, age and sex were not included as covariates in the statistical model.

Data results are presented as group means (95% confidence intervals) unless otherwise specified. The data of one control and one talker with ALS were excluded from this statistical analysis because they did not have complete sets of both stressed and unstressed segment repetitions. Per recommended criterions by Osborne and Overbay (2004), we excluded two repetitions (out of a total of 675 repetitions across all participants), which were produced by one talker with PD and one talker with MS, with kinematic stiffness that were 3 SDs above and below their group means.

Results

Duration

Panel A of Figure 2 presents the mean total durations (± 95% CI) of talkers across all groups and stress conditions. The likelihood ratio test findings in Table 3 shows that the main effects of group, $\chi^2(3) = 66.4$, $p < .001$, and stress condition, $\chi^2(1) = 440.56$, $p < .001$, for total duration were significant. The interaction between the group and stress conditions also had significant effects on the total durations, $\chi^2(3) = 18.03$, $p < .001$. Tables 4 and 5 provide the results of pairwise multiple comparisons for duration. Within each group, durations were significantly longer during the production of stressed segments than the production of unstressed segments (all $p < .001$).

For between-group comparisons, durations of controls and talkers with PD in stressed conditions were significantly shorter than those of talkers with ALS and MS (all $p < .01$). In the unstressed condition, however, durations of controls and talkers with PD were significantly shorter than only those of talkers with ALS ($p < .001$). In contrast, durations of talkers with MS were comparable to those of talkers with PD and controls. For the group comparisons between the talkers with ALS and MS, the durations of talkers with ALS were significantly longer than those of

Figure 2. Group means (± *SE*) for lower lip kinematic measures. PD = Parkinson's disease; ALS = amyotrophic lateral sclerosis; MS = multiple sclerosis.

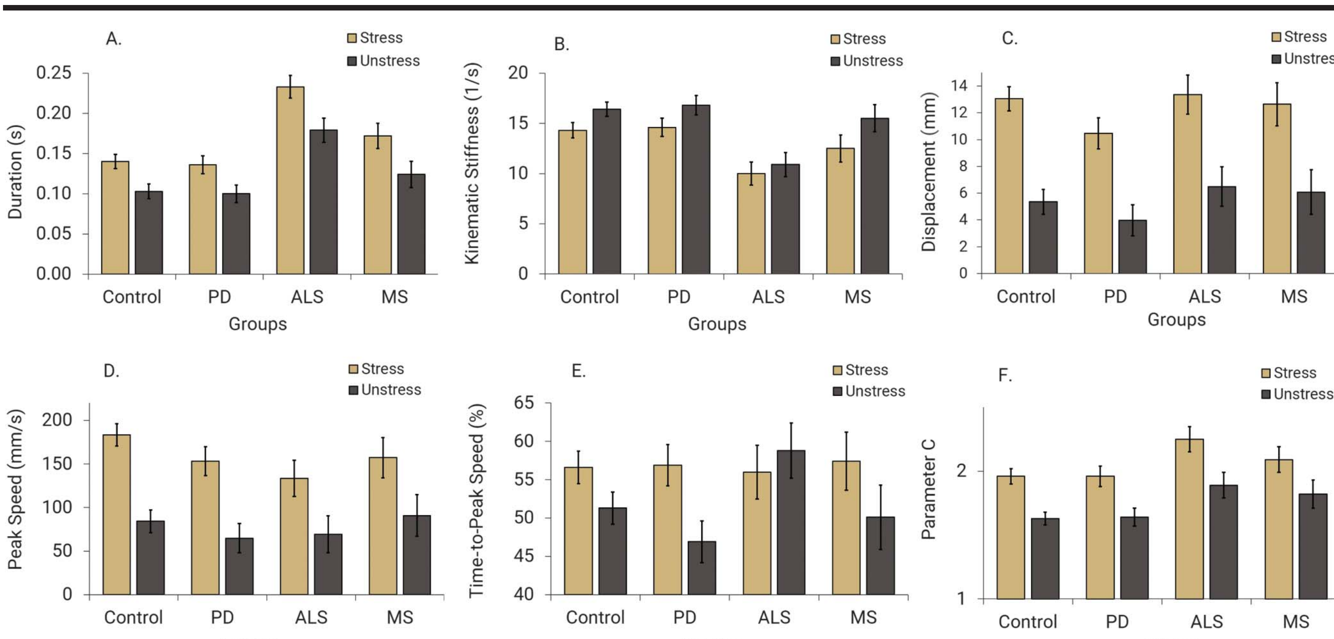


Table 3. Findings of the Likelihood Ratio Tests for linear mixed-effects models with participants as a random effect.

Kinematic measures	Fixed effects	*df*	χ^2	*P*
Stiffness				
	Group	3	41.05	< .001*
	Stress Condition	1	157.93	< .001*
	Group by Condition	3	13.57	.004*
Duration				
	Group	3	66.4	< .001*
	Stress Condition	1	440.56	< .001*
	Group by Condition	3	18.03	< .001*
Displacement				
	Group	3	10.41	.015*
	Stress Condition	1	820.89	< .001*
	Group by Condition	3	12.41	.006*
Peak speed				
	Group	3	9.84	.02*
	Stress Condition	1	665.33	< .001*
	Group by Condition	3	33.86	< .001*
Time-to-peak speed				
	Group	3	5.99	.112
	Stress Condition	1	66.3	< .001*
	Group by Condition	3	37.53	< .001*
Parameter c				
	Group	3	27.91	<.001*
	Stress Condition	1	343.27	<.001*
	Group by Condition	3	1.87	.6

*Level of statistical significance for interaction effect using *p* value of < .05.

Table 4. Pairwise comparisons of each kinematic measure across stress versus unstress conditions within each experimental group that showed significant Group × Stress condition interaction effects.

Kinematic measure	Group	*M* difference	*SE*	*P*
Duration				
	Control	0.037	0.002	< .001*
	PD	0.036	0.003	< .001*
	ALS	0.054	0.004	< .001*
	MS	0.048	0.005	< .001*
Stiffness				
	Control	−2.16	0.22	< .001*
	PD	−2.16	0.28	< .001*
	ALS	−0.88	0.39	.329
	MS	−3.06	0.48	< .001*
Displacement				
	Control	7.7	0.23	< .001*
	PD	6.48	0.3	< .001*
	ALS	6.86	0.42	< .001*
	MS	6.56	0.51	< .001*
Peak speed				
	Control	99.22	3.39	< .001*
	PD	88.38	4.36	< .001*
	ALS	63.97	6.08	< .001*
	MS	66.37	7.44	< .001*
Time-to-peak speed				
	Control	5.288	0.94	< .001*
	PD	9.997	1.22	< .001*
	ALS	−2.881	1.69	.681
	MS	7.301	2.06	.009*

Note. PD = Parkinson's disease; ALS = amyotrophic lateral sclerosis; MS = multiple sclerosis.

*$p < .05$ (corrected for multiple comparisons using Tukey adjusted critical alpha-level).

talkers with MS in both the stressed and unstressed conditions (all $p < .001$).

Stiffness

Panel B of Figure 2 presents the group means for stiffness (± 95% CI) for both stress conditions. The likelihood ratio test findings from Table 3 shows that the main effects of group, $\chi^2(3) = 41.05$, $p < .001$, and stress condition, $\chi^2(1) = 157.93$, $p < .001$, for stiffness were significant. The interaction between group and stress condition also had significant effects on stiffness, $\chi^2(3) = 13.57$, $p = .004$. Tables 4 and 5 provide the results of pairwise multiple comparisons for stiffness. For within-group comparisons, stiffness was significantly greater during the production of unstressed segments than the production of stressed segments for controls, talkers with PD, and talkers with MS (all $p < .001$). However, there was no significant difference between the stiffness of stressed and unstressed conditions for talkers with ALS ($p = .329$).

For between-group comparisons, stiffness of controls and talkers with PD was significantly greater than those of talkers with ALS in both stressed and unstressed conditions (all $p < .001$). However, there were no significant differences when stiffness values of controls and those of talkers with PD were compared to those of talkers with MS in both stressed and unstressed conditions. Finally, stiffness values of talkers with ALS were significantly lower than those of talkers with MS; however, only in the unstressed condition ($p < .001$), and not in the stressed condition.

Displacement

Panel C of Figure 2 presents the mean displacement (± 95% CI) of talkers across all groups and stress condition. The likelihood ratio test findings from Table 3 shows that the main effects of group, $\chi^2(3) = 10.41$, $p = .015$, and stress condition, $\chi^2(1) = 820.89$, $p < .001$, for displacement were significant. The interaction between group and stress condition also had significant effects on displacement, $\chi^2(3) = 12.41$, $p = .006$. Tables 4 and 5 provide the results of pairwise multiple comparisons for displacement. For within-group comparisons, displacement was significantly greater during the production of stressed segments than the production of unstressed segments for all four groups (all $p < .001$).

For between-group comparisons, displacements of controls were significantly greater than those of talkers with PD during the stressed condition ($p = .013$), but not during the unstressed conditions. In addition, displacements of talkers with PD during the stressed condition were significantly smaller than those of talkers with ALS ($p = .048$), but not in the unstressed condition. No significant differences

Table 5. Pairwise comparisons of each kinematic measure across all experimental groups that showed significant Group × Stress condition interaction effects.

Kinematic measure	Groups	Stressed condition	*M* difference	*SE*	*P*
Duration					
	Control–PD	S	0.003	0.007	.999
		US	0.003	0.007	1.000
	Control–ALS	S	–0.09	0.009	< .001*
		US	–0.08	0.009	< .001*
	Control–MS	S	–0.03	0.009	.012*
		US	–0.02	0.01	.321
	PD–ALS	S	–0.1	0.01	< .001*
		US	–0.08	0.01	< .001*
	PD–MS	S	–0.04	0.01	.009*
		US	–0.02	0.01	.257
	ALS–MS	S	0.06	0.01	< .001*
		US	0.05	0.01	< .001*
Stiffness					
	Control–PD	S	–0.35	0.6	.999
		US	–0.35	0.61	.999
	Control–ALS	S	4.22	0.71	< .001*
		US	5.5	0.73	< .001*
	Control–MS	S	1.8	0.76	.259
		US	0.9	0.8	.949
	PD–ALS	S	4.57	0.77	< .001*
		US	5.85	0.78	< .001*
	PD–MS	S	2.16	0.82	.144
		US	1.25	0.85	.819
	ALS–MS	S	–2.42	0.9	.125
		US	–4.6	0.93	< .001*
Displacement					
	Control–PD	S	2.59	0.75	.013*
		US	1.36	0.76	.616
	Control–ALS	S	–0.3	0.87	1.000
		US	–1.15	0.89	.904
	Control–MS	S	0.4	0.94	.999
		US	–0.74	0.97	.995
	PD–ALS	S	–2.89	0.95	.048*
		US	–2.51	0.96	.153
	PD–MS	S	–2.19	1.01	.375
		US	–2.1	1.04	.465
	ALS–MS	S	0.7	1.11	.998
		US	0.41	1.14	1.000
Peak speed					
	Control–PD	S	30.22	10.71	.09
		US	19.38	10.78	.622
	Control–ALS	S	50.01	12.49	.002*
		US	14.76	12.74	.943
	Control–MS	S	26.36	13.48	.512
		US	–6.49	13.9	.999
	PD–ALS	S	19.79	13.53	.827
		US	–4.62	13.75	1.000
	PD–MS	S	–3.86	14.45	1.000
		US	–25.87	14.84	.659
	ALS–MS	S	–23.65	15.81	.81
		US	–21.25	10.84	.9

(*table continues*)

in displacements were found for any other between-group comparisons for either stress condition.

Peak Speed

Panel D of Figure 2 presents the mean peak speed (± 95% CI) of talkers across all groups and stress condition. The likelihood ratio test findings from Table 3 shows that the main effects of group, $\chi^2(3) = 9.84$, $p = .02$, and stress condition, $\chi^2(1) = 665.33$, $p < .001$, for peak speed were significant. The interaction between group and stress condition also had significant effects on peak speed, $\chi^2(3) = 33.86$, $p < .001$. Tables 4 and 5 provide the results of pairwise multiple comparisons for peak speed. For within-group comparisons, peak speed was significantly greater during the production of stressed segments

Table 5. *(Continued).*

Kinematic measure	Groups	Stressed condition	*M* difference	*SE*	*P*
Time-to-peak speed					
	Control–PD	S	−0.34	1.73	1.000
		US	4.37	1.76	.203
	Control–ALS	S	0.62	2.07	1.000
		US	−7.55	2.15	.011*
	Control–MS	S	−0.84	2.23	.999
		US	1.17	2.43	.999
	PD–ALS	S	0.96	2.24	.998
		US	−11.92	2.31	< .001*
	PD–MS	S	−0.51	2.39	1.000
		US	−3.21	2.57	.918
	ALS–MS	S	−1.47	2.64	.999
		US	8.72	2.85	.047*

Note. PD = Parkinson's disease; S = stressed condition; US = unstressed condition; ALS = amyotrophic lateral sclerosis; MS = multiple sclerosis.

*$p < .05$ (corrected for multiple comparisons using Tukey adjusted critical alpha-level).

than the production of unstressed segments for all four groups (all $p < .001$).

For between-group comparisons, peak speeds of controls were significantly greater than those of talkers with ALS during the stressed condition ($p = .002$), but not during the unstressed condition. No significant differences in peak speed were found for any other between-group comparisons for either stress condition.

Time-to-Peak Speed

Panel E of Figure 2 presents the mean time-to-peak speed (± 95% CI) of talkers across all groups and stress conditions. The likelihood ratio test findings from Table 3 shows that the main effects of group for time-to-peak speed were not significant. However, the main effects of stress condition were significant, $\chi^2(3) = 66.3$, $p < .001$. Furthermore, the interaction between group and stress condition was also significant, $\chi^2(3) = 37.53$, $p < .001$. Tables 4 and 5 provide the results of pairwise multiple comparisons for time-to-peak speed. For within-group comparisons, time-to-peak speed was significantly longer during the production of stressed segments than the production of unstressed segments for controls, talkers with PD, and talkers with MS (all $p < .01$). However, there was no significant difference between the time-to-peak speed of stressed and unstressed conditions for talkers with ALS.

For between-group comparisons, the time-to-peak speed of controls, talkers with PD, and talkers with MS during unstressed condition were significantly shorter than those of talkers with ALS (all $p \leq .047$). No significant differences in time-to-peak speed were found for any other between-group comparisons for either stress condition.

Parameter C

Panel F of Figure 2 presents the mean parameter c (± 95% CI) of talkers across all groups and stress conditions. The likelihood ratio test findings from Table 3 shows that both the group, $\chi^2(3) = 27.91$, $p < .001$, and stress condition, $\chi^2(1) = 343.27$, $p < .001$, had significant main effects on parameter c. That is, regardless of the stress condition, talkers with ALS and talkers with MS each had greater parameter c than both controls and talkers with PD (all $p < .02$). Furthermore, regardless of the group, parameter c was significantly greater in the stressed condition than in the unstressed condition ($p < .001$). The interaction between group and stress condition was not significant.

Discussion

The purpose of this study was to identify potential differences in lower lip articulatory performance patterns of stressed and unstressed segments across talkers with PD, ALS, and MS to better understand the articulatory mechanisms that underlie stress pattern disturbances in talkers with dysarthria. Based on the kinematic findings of existing literature, we predicted that relative to the controls, all talkers with dysarthria would show a limited ability to vary stiffness, and hence, durations across stress conditions (within-group comparisons). Furthermore, we examined displacement and peak speed to better understand the articulatory deficits that are associated with deviant stiffness levels in talkers with dysarthria. We predicted that peak speed would be lower between talkers with dysarthria and controls (regardless of the disease type), whereas displacement would be predominantly reduced in talkers with PD and controls (particularly during the stressed segment). Finally, we examined time-to-peak speed and parameter c to better understand the articulatory factors that contribute to between-group differences in peak speed.

With regards to within-group comparisons, a restricted ability to vary stiffness in response to stress was observed in talkers with ALS, but not in talkers with PD and MS. Stress effects on duration, however, were significant in all disease groups. With regards to between-group comparisons, relative to controls significantly reduced peak speeds were only observed in talkers with ALS during the stressed condition and significantly reduced displacements were observed in talkers with PD during the stressed segment. The following sections will first discuss the findings of kinematic measures for each disease group in the context of the available literature. We will then use the current findings to outline potential articulatory mechanisms that may underlie the stress pattern disturbances of talkers with PD, ALS, and MS.

Findings on Typical Talkers

Findings revealed significant within-group effects for all kinematic measures, which indicate systematic modifications of speech movements to accommodate stress demands. Our findings for duration, displacement, peak speed, and kinematic stiffness are consistent with those of previous studies that have investigated articulatory performance changes in response to stress manipulations in typical talkers (e.g., Adams et al., 1993; Munhall et al., 1985; Ostry et al., 1983). As in previously reported findings, the controls in the current study displayed longer duration, greater displacement and peak speeds, as well as lower stiffness for stressed segments than for unstressed segments. Furthermore, the parameter c was significantly greater during stressed segments than unstressed segments in typical talkers of our study, as well as in those of previous studies (e.g., Munhall et al., 1985). It is important to note that these findings are congruent despite methodological differences across studies (e.g., stress manipulation during syllable repetitions versus elicitation of stressed and unstressed segments during pseudoword or real word production). However, the differences in the parameter c for stressed and unstressed segments are thought to be too small to indicate a change in the underlying speed generation strategies (Munhall et al., 1985).

Our findings for time-to-peak speed during the lip opening strokes of controls, however, did not align with those of previous studies. Specifically, we found prolonged acceleration phases (i.e., longer time-to-peak speeds) for lip opening movements during stressed segments than during unstressed segments. By contrast, previous studies that examined opening strokes reported a shortening of the acceleration phase as durations increased (e.g., Adams et al., 1993; Munhall et al., 1985; Ostry et al., 1983). Interestingly, findings for acceleration phases of closing strokes aligned with our findings (e.g., Hertrich & Ackermann, 1997). It has been speculated that differences in the shape of velocity profiles of opening and closing strokes indicate different motor control strategies (Gracco, 1994). However, findings of comparable acceleration times for opening and closing strokes of controls in the study by Forrest and Weismer (1995) undermine this assertion. Although the underlying reasons for the mixed findings for the acceleration durations during stressed and unstressed segments are currently unclear, differences in time-to-peak speeds across speech conditions are frequently interpreted to indicate a reorganization of the articulatory control mechanisms (Adams et al., 1993).

Findings on Talkers With PD

With regard to stress effects, our findings on talkers with PD did not support the prediction that these talkers are constrained in their ability to alter stiffness to accommodate stress demands. However, our findings are congruent with those of Forrest and Weismer (1995) for all kinematic measures except for time-to-peak speed and parameter c. Talkers with PD performed stress condition with greater movement duration, displacement, peak speed, and lower stiffness than the unstressed condition. These findings suggest that the ability to modify stiffness is intact in talkers with PD and that the perceived reduced stress cannot be explained by a lack of contrast between stressed and unstressed segments. We will further discuss articulatory factors that may explain the stress pattern disturbances in a separate section (see “Potential Articulatory Mechanisms That Underlie Stress Pattern Disturbances in Talkers With Dysarthria”).

With regard to time-to-peak speed and parameter c values, talkers with PD in our study had significantly greater time-to-peak speed and parameter c values for stressed segments than for unstressed segments. The stress effects on time-to-peak speed in our study are in the opposite direction to those reported previously (e.g., Munhall et al., 1985; Ostry et al., 1983), which is a finding that is difficult to explain and will require further investigations. Our findings for parameter c, however, are congruent with those of previous studies (Munhall et al., 1985; Ostry et al., 1983). It should be noted that the differences in parameter c values between the two stress conditions are considerably larger in the current study than in the previous studies. Larger differences in parameter c values may be explained by methodological differences (e.g., nonspeech vs. speech stimuli) and may indicate that typical talkers and talkers with PD do change their activation patterns of antagonistic muscle groups to optimize energy expenditure and economize motor effort for larger, longer, and faster movements of stressed segments relative to smaller, shorter, and slower movements during unstressed segments (e.g., Nelson, 1983; Perkell et al., 2002).

With regards to comparisons between talkers with PD and controls, our findings for stressed and unstressed segments were consistent with those of previous studies reporting a general downscaling of articulatory performance in PD regardless of the stress condition (e.g., Ackermann et al., 1997; Forrest & Weismer, 1995). That is, relative to controls, talkers with PD tended to produce reduced peak speed and significantly lower displacement while having comparable durations, stiffness, and time-to-peak speed. The downscaling of peak speed and displacement explains why kinematic stiffness and duration did not differ between talkers with PD and controls. The trend of a more asymmetric velocity profile as indicated by a relatively shorter acceleration phase during the unstressed segments in talkers with PD, however, may suggest differences in the timing of force generation between talkers with PD and controls. Due to the relatively small sample size of talkers with PD in the current study, however, these findings need to be interpreted with caution until they are replicated in future studies.

Findings on Talkers With ALS

To our knowledge, studies have not examined dynamic measures such as stiffness, time-to-peak speed, and parameter c in talkers with ALS. These measures are, however, interesting because they are related to movement durations, which have been shown to be abnormally long in talkers with ALS (e.g., Liss et al., 2009; Mefferd et al., 2012; Shellikeri et al., 2016; Tjaden & Turner, 2000). Studies on typical talkers have shown that stiffness is inversely related to duration (e.g., Kelso et al., 1983; Ostry et al., 1983). Based on these findings, talkers with ALS should exhibit significantly lower kinematic stiffness during stressed and unstressed segments. Indeed, findings of the current study confirmed this prediction. However, although significant stress effects were found on duration in these talkers, stress effects were not evident in the stiffness measure. It is possible that relations between duration and stiffness are less predictable in talkers with abnormally long movement durations. Indeed, a modeling study by Fuchs et al. (2011) suggests that estimations of stiffness based on movement durations become less accurate when articulatory movement durations are extremely long.

Based on findings by Liss et al. (2009), talkers with ALS were expected to show limited stress effects on duration. Our current findings, however, suggest that talkers with ALS can achieve shorter durations during unstressed segments than stressed segments, although durations were in general significantly longer for both stress conditions relative to those of controls. Similarly, talkers with ALS were able to produce significantly larger displacements and greater peak speeds during the stressed segments than unstressed segments. These findings do not support the notion that a constrained ability to modify duration underlies the stress pattern disturbances of talkers with ALS (excess and equal stress). These observations further raise the question if talkers with ALS base their overall articulatory rate on their ability to accommodate the temporal demands of unstressed segments or on the spatial demands of stressed segments. The observed reduced stiffness and prolonged time-to-peak speed during the unstressed segments of talkers with ALS relative to controls suggest that the temporal demands of unstressed segments may pose an equal or even greater articulatory challenge than the spatial demands of stressed segments for these talkers. This notion is interesting as it contrasts longstanding speculations that talkers with ALS produce speech at a slowed articulatory rate to achieve their targeted vocal tract configurations (but see discussion in Weismer et al., 2000).

Relative to controls, talkers with ALS produced significantly lower peak speeds in both stress conditions. In general, these findings are consistent with those of previous studies examining talkers with ALS (e.g., Hirose et al., 1982) and pseudobulbar palsy (e.g., Ackermann et al., 1997). Reduced peak speeds are typically associated with a delayed and constrained force generation (Barlow & Abbs, 1986; Mefferd et al., 2012), and explain the generally prolonged movement durations, prolonged time-to-peak speed, and increased parameter c values during both stress conditions in talkers with ALS when compared to controls.

Findings on Talkers With MS

Acoustic studies have shown that variability of segment duration is reduced in talkers with MS (e.g., Ackermann et al., 1997; Hartelius et al., 2000). Findings of the current study, however, show that talkers with MS are able to vary their movement durations to accommodate stress demands. It is possible that methodological differences between the current and previous acoustic studies contribute to the discrepant findings.

Findings of the other speech kinematic measures included in the current study are difficult to compare to previous studies because, so far, talkers with MS have rarely been studied kinematically. However, a previous study that has examined speech kinematics of talkers with ataxic dysarthria (which included some talkers with MS) found reduced stiffness, comparable peak speed, and comparable time-to-peak speed during stressed segments relative to controls (Ackermann et al., 1997). Our findings of the stressed condition are consistent with those of talkers with ataxic dysarthria.

Based on the specific stress pattern disturbances that are exhibited by talkers with MS, particularly, the articulatory performance of unstressed segments should differ between talkers with MS and controls, but not between talkers with MS and ALS. However, our findings only partially support this notion. Although certain speech kinematic measures such as displacement and peak speed of talkers with MS were comparable to those of talkers with ALS, other kinematic measures such as stiffness and time-to-peak speed differed more often during the unstressed condition from those of talkers with ALS than during the stressed condition. One reason for the differences between talkers with MS and ALS may be the severity of the impaired ability to generate speed. Secondly, intertalker variability in articulatory performance was greater within the MS group than within the other groups, which may have impacted our ability to detect significant between-group differences for comparisons between talkers with MS and controls regardless of the stress condition. As can be seen in Figure 2, duration tended to be prolonged in talkers with MS and stiffness tended to be reduced regardless of the stress condition relative to those of controls. Given that these trends were observed for both stress conditions, our prediction of more abnormal articulatory performance of talkers with MS during the unstressed condition could not be confirmed.

Potential Articulatory Mechanisms That Underlie Stress Pattern Disturbances in Talkers With Dysarthria

Stressed segments are characterized by relatively long movement durations and large displacements whereas unstressed segments are characterized by relatively short movement durations and small displacements (e.g., Munhall et al., 1985; Ostry et al., 1983). All talkers with dysarthria exhibited significant stress effects for duration and displacement. However, relative to controls, talkers with PD failed to achieve adequate displacements due to their downscaling of displacement and peak speed while durations were adequate. The downscaling resulted in significantly reduced displacements during the stressed segment. Therefore, particularly the large displacements as a key feature of stressed segments were missing in these talkers. By contrast, talkers with ALS and MS failed to achieve adequate movement durations during the stressed segments due to their difficulty with speed generation. Relative to controls, however, their displacements were adequate. Similarly, prolonged movement durations were observed during the unstressed segments. However, this comparison only reached significance in talkers with ALS and not in talkers with MS (likely due to the high variability and small sample size). Therefore, short durations as a key feature of unstressed segments were missing in these talkers. These differences in articulatory performance patterns between talkers with PD and talkers with ALS and MS may explain the perceived differences in stress pattern disturbances across these talkers with dysarthria. Although differences were observed between talkers with ALS and MS for duration (both stress conditions), stiffness (unstressed condition), and time-to-peak speed (unstressed condition), both groups exhibited in general similar impairment patterns in comparison to controls. Thus, the observed significant differences between talkers with ALS and MS may be explained by differences in impairment severity rather than disease-related differences.

Findings on Number of Velocity Peaks Across Talkers With Dysarthria

It is important to note that we excluded lower lip opening movements with multiple velocity peaks. Such velocity profiles were more frequently observed in talkers with MS than in any other group in this study. These talkers exhibited considerably longer movement durations when compared to the reported average movement durations of talkers with MS in this study. Interestingly, multiple velocity peaks were less frequently observed in talkers with ALS than in talkers with MS despite the fact that talkers with ALS tended to produce longer movement duration than talkers with MS regardless of the stress condition. This suggests that, in contrast to findings of typical talkers (Adams et al., 1993), movement duration itself may not necessarily determine the number of velocity peaks.

Although we can only speculate at this point, it is possible that articulatory control strategies may explain the different frequencies of multiple velocity peak occurrences across talkers with dysarthria who exhibit prolonged movement durations. That is, an impaired cerebellar function in talkers with MS may disturb feedforward loops (Ackermann et al., 1997; Guenther, 1995), whereas multiple peaks in talkers with ALS may be associated with peripheral muscle pathology (e.g., fasciculations). However, more research is warranted to specifically test these assertions.

Multiple peak velocities have also been observed in talkers with PD as well as controls. These talkers did not exhibit prolonged movement durations. Our findings for talkers with PD are consistent with those of previous studies. Specifically, Forrest and Weismer (1995) found multiple peak velocities for talkers with PD. The underlying reasons for the multiple peak velocities in talkers with relatively short movement durations, such as those with PD and controls, are currently unknown.

Limitations and Future Directions

The findings of the current study should be interpreted with caution due to the relatively small number of talkers within each group. Although there are known effects of both sex and age on speech kinematics (Simpson, 2002; Goozée et al., 2005), no significant age or sex effects on speech kinematic measures were found in the current study. However, our sample size of the control group was relatively small (females, n = 9; males, n = 15). Therefore, future studies are needed to replicate the current findings with larger sample size and more balanced ratios of age and sex across the experimental groups. Furthermore, the ability to vary articulatory performance in response to stress demands was examined in words that had similar phonetic contexts; however, the phonetic context was not identical. However, findings of control talkers aligned with those of previous studies that examined articulatory performance during stressed and unstressed segments (Forrest & Weismer, 1995). In future studies, articulatory performance could be investigated in target words that allow stress manipulation. For example, the word *conflict* would allow the manipulation of stress within the same word (CON-flict vs. con-FLICT). Finally, the current study had an exclusive focus on the contribution of the articulatory subsystem to stress production. However, dysarthria can affect all speech subsystems (respiration, phonation, articulation) and contribution of the other subsystems (i.e., changes in vocal intensity, fundamental frequency) to stress patterns in talkers with dysarthria should also be considered in future studies.

Conclusions

Studies that compare articulatory performance during stressed and unstressed segments across talkers with dysarthria are critically needed. This study was a first step to shed light on the articulatory impairments that contribute to different stress pattern disturbances across talkers with various neurological conditions. Findings of the current study suggest that although talkers with dysarthria were able to alter their articulatory performance in response to stress demands, the performance deficits observed during specific stress conditions may drive the perceptual impression of disturbed stress patterns. Specifically, the impression of reduced stress in talkers with PD may have been driven by the downscaling of displacement during stressed segments. By contrast, the perceptual impression of equal and excessive stress in ALS and MS may have been driven by the prolonged durations and increased displacements during unstressed speech segments. Ultimately, these findings provide the early empirical groundwork that will facilitate the development of explanatory models for articulatory mechanisms that underlie various stress pattern disturbances exhibited by talkers with dysarthria.

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