Orofacial Movements Associated With Fluent Speech in Persons Who Stutter

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This study was intended to replicate and extend previous findings that (a) during fluent speech persons who stutter (PS) and those who do not (NS) differ in their vocal tract closing movements (L. Max, A. J. Caruso, & V. L. Gracco, 2003) and (b) ratios relating lip and tongue speed to jaw speed increase with stuttering severity (M. D. McClean & C. R. Runyan, 2000). An electromagnetic system was used to record movements of the upper lip, lower lip, tongue, and jaw of 43 NS and 37 PS during productions of a nonsense phrase and a sentence. Measurement and analysis of movement speeds, durations, and ratios of lip and tongue speed to jaw speed were performed on fluent productions of a nonsense phrase and sentence. Statistical comparisons were made between PS with low and high stuttering severity levels (LPS and HPS) and NS. Significant variations across groups in movement speed and duration were observed, but the pattern of these effects was complex and did not replicate the results of the two earlier studies. In the nonsense phrase, significant reductions in lower lip closing duration, jaw closing duration, and jaw closing speed were seen in PS. In the sentence task, HPS showed elevated tongue opening and closing durations. For tongue opening in the sentence, LPS showed elevated speeds and HPS showed reduced speeds. The elevated speeds for LPS are interpreted as a contributing factor to speech disfluency, whereas the reduced speeds and increased durations in HPS are attributed to adaptive behavior intended to facilitate fluent speech. Significant group effects were not seen for the speed ratio measures. Results are discussed in relation to multivariate analyses intended to identify subgroups of PS.

KEY WORDS: stuttering, orofacial movements, tongue, jaw, lips

Beginning primarily with the investigations of Zimmermann (1980a), there has been a continuing effort to characterize possible differences in the movements underlying the fluent speech of persons who stutter (PS) and those who do not (NS) (Caruso, Abbs, & Gracco, 1988; Kleinow & Smith, 2000; Max, Caruso, & Gracco, 2003; McClean & Runyan, 2000; Smith & Kleinow, 2000). This work has revealed moderate differences between PS and NS in a variety of kinematic measures. A central issue regarding interpretation of these findings was highlighted by Max et al., who pointed out that kinematic differences in PS and NS may reflect acquired behaviors intended to enhance speech fluency, or more general neuromotor mechanisms that are operative during speech and nonspeech movements. In support of the latter view, they presented data indicating differences between PS and NS in the characteristics of finger flexion movements and combined lip and jaw movements as they contribute to vocal tract closing for speech and nonspeech oromotor

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behaviors. Max et al. interpreted these various results as reflecting differences between PS and NS in basic properties of the general neuromotor system that are specific to vocal tract closing and limb flexion movements.

An alternative perspective on kinematic differences in speech between PS and NS is that they, in part, reflect processes specific to the speech motor system of PS that are intended to enhance speech fluency. Such processes are reflected in increased movement durations in the fluent speech of PS following some forms of speech therapy (McClean, Kroll, & Loftus, 1990; Samar, Metz, & Sacco, 1986; Story, Alfonso, & Harris, 1996). There is also modest evidence that more severe PS who have not undergone therapy tend to display increased movement durations and reduced velocities in their fluent speech (McClean, Kroll, & Loftus, 1991). This finding suggests that in some PS, childhood and/or adult experience with speech disfluency promotes acquired adaptive behaviors that enhance fluent speech.

In summary, initial findings on orofacial movements during fluent speech in adults suggest that differences between NS and PS may reflect general motor system properties and/or acquired motor processes intended to enhance speech fluency. However, we are far from understanding how these factors are realized in terms of inherited traits and experiences that shape the speech motor system in children and adults who stutter. It is our view that progress in this area will depend in part on more detailed information on differences in the kinematics of fluent speech in adult NS and PS. Due to the variable nature and modest size of reported differences, replication and refinement of certain studies are needed (Muma, 1993).

One result we see as particularly important is that of Max et al. (2003), which indicated differences between PS and NS in vocal tract closing but not opening movements. Specifically, they observed greater movement durations and extents in PS compared to NS for vocal tract closing movements and no significant differences in opening movements. This finding has broad implications for both theory and clinical approaches to stuttering. Insofar as vocal tract opening and closing movements involve distinct neuromotor mechanisms as suggested by Max et al. (see also Gracco, 1994), solidification of their findings could speak directly to the nature of central neural processes contributing to speech disfluency. Hence, the first major objective of this study was to replicate the observations of Max et al. regarding vocal tract closing movements in PS and to assess whether related trends vary with stuttering severity. Max et al. studied combined lip and jaw opening and closing movements associated with closure and release of bilabial stop consonants, where consonant position within utterances of varying length was systematically controlled. The speech sample used here was not specifically designed to replicate their method. Rather, the kinematic recordings from an existing dataset were used to evaluate the generality of their findings regarding group differences in vocal tract closing movements and the absence of differences in opening movements.

Another recent finding that may have broad implications for models of stuttering is the reported increases in lip–jaw and tongue–jaw speed ratios in more severe PS (McClean & Runyan, 2000). These elevated ratios were a consequence of higher lip and tongue speeds and a reduction in jaw speeds in more severe PS. In general, this result points to the importance of bringing greater focus in kinematic studies of PS to the independent actions of different speech articulators, particularly the jaw relative to the lower lip and tongue. The initial speed ratio results were based on mean speeds across opening and closing movements. In light of the results of Max et al. (2003), the question arises as to whether the association of speed ratios with stuttering severity differs for vocal tract opening and closing movements. Thus, in addition to replication of Max et al., a second major goal of the present study was to replicate the previous findings on speed ratios in a new group of PS using a more refined analysis in which ratios are broken out in terms of opening and closing movements.

Method

Participants

Participants were 80 adults: 43 NS (mean age = 26 years) and 37 PS (mean age = 23 years). There was 1 female in the NS group and 2 in the PS group. The PS were at the Walter Reed Army Medical Center to participate in a stuttering treatment program. Twelve of the 37 PS had previously received speech therapy that focused in part on modification of the motor aspects of speech production. In two cases the therapy program was intensive in nature, but it had been more than 6 years since their participation. The remaining 10 participants with therapy history had less than 2 hr of clinician–client contact per week. As described later in the Results section, statistical analysis indicated that the therapy history of these 12 participants was not a significant source of variance in the kinematic measures.

Speech Sample

Analyses were carried out on two distinct speech samples in order to assess the generality of results. One sample involved repetition of a simple nonsense phrase. The other involved reading a lengthy meaningful sentence. The data used in the present studies were a component of a larger dataset involving a number of different speech tasks. In the initial speech task of this larger procedure, participants produced the nonsense phrase "a bad daba" (/əbæd dæbə/) at their habitual loudness and speech rate, pausing at a comfortable rate between each token. This speech utterance was selected primarily because it involves large-amplitude orofacial movements that are amenable to automated software measurement of specific movements and because there is symmetry in the phonetic structure between the initial and final portion of the utterance. For the purposes of this study, analyses were performed on the first five fluent tokens recorded in a 30-s time interval. At least five fluent productions were obtained in all participants.

In the second speech task, participants read the following sentence: "In late fall and early spring the short rays of the sun call a true son of the out-of-doors back to the places of his childhood." This is the first sentence of a long passage that was read near the end of the physiologic recording procedure.

Stuttering Severity

During a two-day pretreatment period, PS were videotaped in a studio while producing a monologue and reading a brief passage. These recordings were used to assess stuttering severity using the Stuttering Severity Instrument (SSI; Riley, 1994). Separate SSI scores were obtained for the monologue (SSI-M) and reading (SSI-R). Two certified speech-language pathologists, experienced with stuttered speech, carried out SSI measurement procedures using a consensus judgment format. That is, when both judges agreed on the occurrence of an instance of stuttering being present, it was appropriately marked. When discrepancies occurred, the judges watched the speech sample repeatedly until agreement was reached and scored as to the instances of stuttered or fluent speech. At least 6 months subsequent to this original scoring procedure, a second consensus judgment task was performed by the senior judge (the third author) and a second experienced judge. During this second task, judges had access to the original scoring sheets. The videotape was watched again and the judges resolved any discrepancies between themselves and the original data by watching the tape as frequently as needed and discussing the sample until agreement was reached.

The SSI-M scores were used to assign PS to a high or low severity group (HPS and LPS) for analysis of the nonsense phrase. Individuals with SSI-M less than 25 were assigned to the low severity group (LPS) and those equal to or above 25 to the high severity group (HPS). A cutoff of 25 represents the division between the mild and moderate categorization on the SSI (Riley, 1994). This cutoff resulted in 23 participants in the LPS group (mean SSI-M = 17, range = 7–24) and 14 in the HPS group (mean SSI-M = 30, range = 25–34). This grouping was used in analysis of participants' repetitions of the nonsense phrase, where severity was treated as a three-level ordinal factor (NS: 0, LPS: 1, HPS: 2). Use of the SSI-M with the nonsense phrase analysis was based on the assumption that the nonsense phrase was well rehearsed and therefore approximated spontaneous speech.

The analysis of stuttering severity in relation to the kinematic measures of the read sentence used the SSI-R rather than the SSI-M to classify LPS and HPS. This was done primarily because it is our view that speech motor processes and mechanisms of disfluency are likely to differ markedly for monologue and reading. Support for this perspective is provided, for example, by evidence that frequency-altered auditory feedback has marked group effects on percent stuttering during reading but not monologue (Armson & Stuart, 1998). Because, on average, SSI-R values were lower than their corresponding SSI-M values, a different cutoff level was used to distinguish the LPS and HPS groups. The cutoff level for the SSI-R was derived from a linear regression analysis in which SSI-R was treated as the dependent variable and SSI-M as the predictor. This analysis showed a significant association between the reading and monologue measures ($p < .0005$, slope = 0.77, intercept = 0.11, R^2 = 34%). The predicted value of SSI-R from the SSI-M level of 25 was 19, and PS with SSI-R levels less than 19 were assigned to the LPS group in analyses of the sentence data. Excluding 10 participants who were disfluent during sentence production, the SSI-R cutoff of 19 yielded a total of 27 PS, 16 LPS (mean SSI-R = 9, range = 0–18), and 11 HPS (mean SSI-R = 26, range = 19–36). Three NS were disfluent on the reading, resulting in 40 NS. This grouping of participants into discrete categories was used in analysis of participants' reading of the test sentence, again with severity being treated as a three-level ordinal factor (NS: 0, LPS: 1, HPS: 2). The use of SSI-R scores to distinguish LPS and HPS groups resulted in 9 of 27 PS being classified differently than with the use of the SSI-M, 5 going from HPS to LPS and 4 going from LPS to HPS.

Data Acquisition

Participants were seated in a sound-treated room and prompted to produce a wide range of speech tasks while orofacial movement and speech acoustic recordings were obtained. Speech activities were recorded over 15–20 thirty-second recording sweeps. All physiologic testing on PS occurred within the first 2 days of their stay at Walter Reed prior to any speech therapy. Recordings were obtained of the two-dimensional positions of the upper lip, lower lip, tongue blade, and jaw within the midsagittal plane by means of a Carstens AG100 Articulograph (Carstens Medizinelektronik GmbH, Lenglern, Germany), an electromagnetic movement analysis system (Tuller, Shao, & Kelso, 1990). Sensor coils (3 × 2 × 2 mm) were attached to the bridge of the nose, upper-lip vermilion, and lower-lip vermilion with biomedical tape, and to the tongue blade (1 cm from the tip) and base of the lower incisors with surgical adhesive (Isodent). The acoustic speech signal was transduced with a Shure M93 miniature condenser microphone (Shure, Inc., Niles, IL) positioned 7.5 cm from the mouth. The orofacial kinematic signals and the audio signal were, respectively, digitized to computer at 250 Hz per channel and 16 kHz.

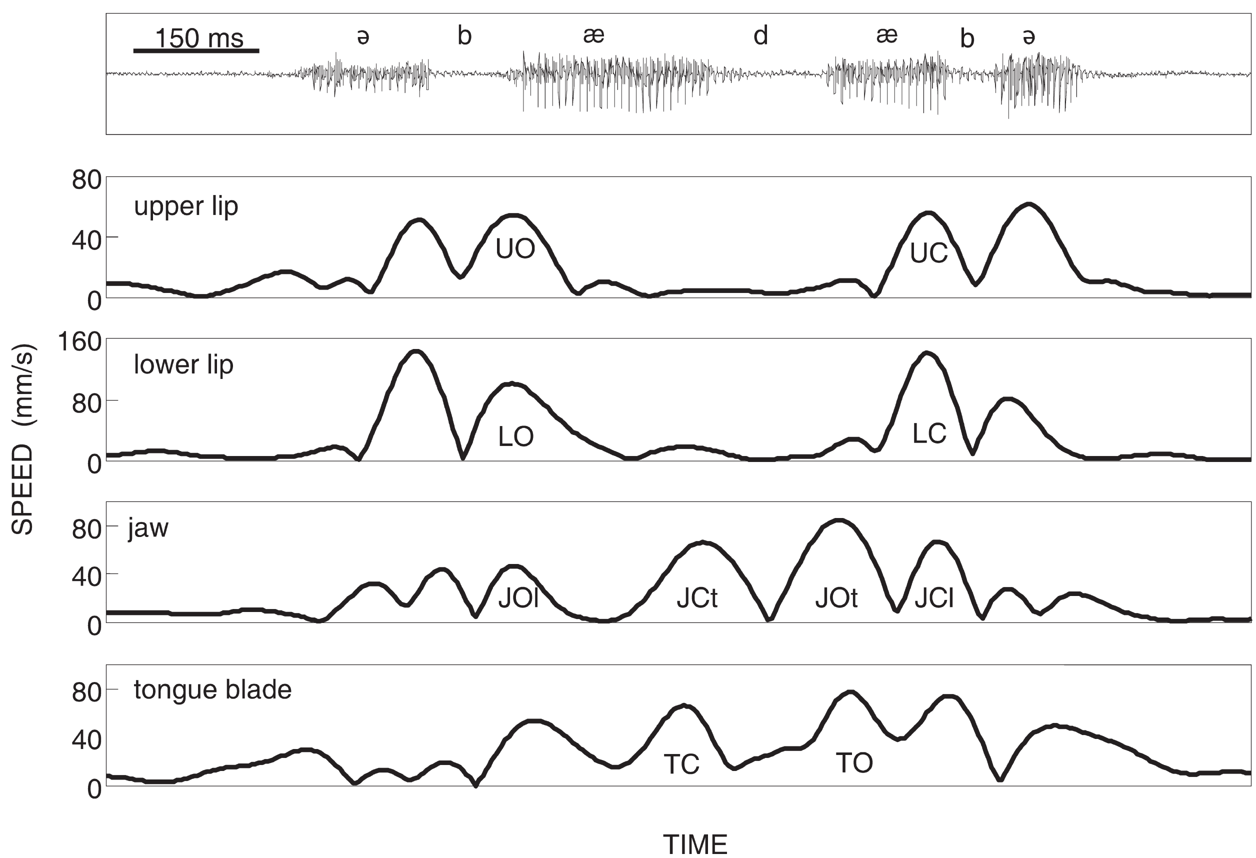
Signal Processing

The upper lip, lower lip, jaw, and tongue movement signals were low-pass filtered at 8 Hz and the nose signal at 3 Hz. All filtering was performed with a zero phase distortion fifth-order Butterworth filter. While head movements during recording were slight (<1.0 mm), nose sensor movements were subtracted from the upper lip, lower lip, tongue, and jaw movement signals in the X and Y dimensions in order to minimize any head movement contributions. The lower lip and tongue signals were then decoupled from the jaw using a method that takes into account the pitch rotation of the jaw (Westbury, Lindstrom, & McClean, 2002). Speed histories for the upper lip, lower lip, jaw, and tongue blade were derived from the X and Y velocities, as obtained with a three-point central method for differentiation.

Measurement of the Nonsense Phrase

As illustrated in Figure 1 for the nonsense utterance, speed histories showed well-defined peaks associated with the movements of various structures as they contribute to vocal tract opening and closing. Hereafter, these are referred to as opening and closing movements for particular structures (e.g., jaw closing). Labels in Figure 1 show speed peaks for lip and jaw opening in /bæd/ (UO, LO, JOl), tongue and jaw closing in /bæd/ (TC, JCt), tongue and jaw opening in /dæb/ (TO, JOt), and lip

Figure 1. Acoustic speech signal (top trace) and orofacial speed histories associated with a single production of the test utterance. The duration and peak speed were measured for each labeled movement. Labels show speed peaks for lip and jaw opening in /bæd/ (UO, LO, JOl), tongue and jaw closing in /bæd/ (TC, JCt), tongue and jaw opening in /dæb/ (TO, JOt), and lip and jaw closing in /dæb/ (UC, LC, JCl), where *l* and *t* in the abbreviations indicate that the jaw speed peak is synchronous with the lip or tongue movement.



and jaw closing in /dæb/ (UC, LC, JCl), where *l* and *t* in the abbreviations indicate that the jaw speed peak is synchronous with the lip or tongue movement. Measures of duration and peak speed were obtained on the 10 individual movements indicated. Interactive software was used to identify individual speed peaks and speed minima bounding each peak. These minima were associated with a change in the movement direction, and therefore the intervening period corresponded to a closing or opening movement. The interval defined by the minima on either side of a peak was taken as the measure of movement duration.

Twenty measures were obtained on each production of the nonsense phrase (duration and speed of 10 movements). The mean of each measure over the first five productions of the phrase was treated as a distinct response variable in statistical analyses. Additionally, lower-lip-to-jaw and tongue-to-jaw speed ratios were calculated. The means of the individual movements were first taken, and these mean speeds were used to calculate the speed ratios for vocal tract opening and closing movements. Speed ratio values were log transformed prior to statistical analysis.

Measurement of the Sentence

Orofacial movements associated with the read sentence were measured using automated procedures recently described by Tasko and Westbury (2002). The signal processing software parsed the speed records for each articulator into a series of strokes across the duration of the sentence. A stroke was defined as the period between two successive local minima in the speed history. Measures of speed and duration were then obtained for each stroke in the same manner as for the nonsense phrase. Additionally, the spatial orientation of the stroke's trajectory was estimated by a line that passes through the spatial positions at the stroke's onset and offset. This orientation is represented as the angle of the stroke's orientation line within the coordinate system. For the upper lip and jaw, this angle measurement was made relative to a line projected from the nose sensor and the jaw sensor during occlusion (i.e., a cranial-based system), with the direction of the nose sensor corresponding to 90°. This type of angle measurement was not possible for the lower lip and tongue blade since their motion was decoupled from the jaw (Westbury et al., 2002). As a result, for the lower lip and tongue, the angle measurement was made using a mandibular-based (i.e., not cranial-based) coordinate system. Although this transformation is necessary to represent lower lip and tongue blade movement independent of the jaw, it did not dramatically change the orientation of the movements relative to the cranial-based coordinate system. In other words, the superior–inferior and anterior–posterior dimensions were largely preserved in this mandibular-based coordinate system. Movements with angle values of 0°–180° were defined as vocal tract closing movements for the lower lip, tongue, and jaw, and as opening movements for the upper lip. Depending on the structure, opening or closing movements were accordingly defined as those with angles of 180°–360°. The validity of this general approach to defining movement direction was verified by examining histograms of the angular values across all strokes within a sentence production. These histograms consistently showed bimodal distributions with a distinct valley near the 180° point. The summary statistics used for each participant's sentence production were the median stroke speed and duration for the opening and closing movements. The median was used because the distribution of kinematic events in sentence material is not normal (Tasko & Westbury, 2002).

Statistical analyses initially involved multivariate analyses of variance (MANOVAs) to determine whether movement speeds and durations for particular structures or speed ratios varied significantly, with stuttering severity represented as a three level factor (NS, LPS, HPS). In cases where significant MANOVAs were obtained, one-way analyses of variance (ANOVAs) with post hoc Fisher tests were then applied to individual speed, duration, or speed ratio measures, again with stuttering severity as a single between-groups factor. Repeated-measures two-way ANOVAs were applied to a portion of the dataset to test for significant interactions between group and movement direction. All statistical analyses were carried out using Minitab 12.0.

Results

Nonsense Phrase Kinematics

For the nonsense phrase, six MANOVAs were carried out to evaluate whether significant variations in movement speed and duration were associated with stuttering severity. Distinct MANOVAs were associated with the various articulators and speed ratios. The classes of measures included in the six MANOVAs and their corresponding response variables are summarized in Table 1. Stuttering severity based on the SSI-M measure was the single three-level factor. The results of the MANOVAs indicated statistically significant Wilks's lambdas for the lower lip (p = .001) and the jaw when synchronous with lip movement (p = .005). No significant effects were obtained for the upper lip, jaw synchronous with the tongue, tongue, or the speed ratio measures. Recall that 12 PS had a prior history of some speech therapy. Speech therapy was never significant when treated as a covariate in the MANOVAs.

Based on the MANOVA results, one-way ANOVAs with post hoc Fisher comparisons at a 5% error rate were

Table 1. Summary of the classes of variables associated with each multivariate analysis of variance (MANOVA) and their corresponding response variables. Four response variables were involved in each MANOVA.

Variable class for MANOVA	Response variables
Upper lip	Opening and closing movement speeds and durations
Lower lip	Opening and closing movement speeds and durations
Jaw synchronous with lower lip	Opening and closing movement speeds and durations
Jaw synchronous with tongue	Opening and closing movement speeds and durations
Tongue	Opening and closing movement speeds and durations
Speed ratio	Lower-lip-to-jaw and tongue-to-jaw speed ratios for opening and closing movements

performed on the four response variables for the lower lip and jaw. The results of these analyses and the mean levels associated with the three groups are summarized in Table 2. There it may be seen that significant effects for stuttering severity ($p \leq .05$) were obtained for lower lip closing duration, jaw closing duration, and jaw closing speed. The mean levels of lower lip and jaw closing duration decreased monotonically with stuttering severity, but statistical significance was reached only in post hoc comparisons with the NS and not between the LPS and HPS. Lower lip and jaw speed did not vary monotonically with stuttering severity. Rather, the LPS tended to show the highest average speeds and the HPS the lowest. This trend was statistically significant only for the HPS who showed significant reductions in jaw closing speed relative to LPS.

Sentence Kinematics

As in the analysis of the nonsense phrase data, a series of MANOVAs was performed on the sentence data to determine whether significant variations in movement speed and duration were associated with stuttering severity. Five MANOVAs were performed, one for each articulator and one for the speed ratio data. Only a single MANOVA for the jaw was performed, because the measurement procedure did not identify individual jaw movements as being synchronous with the lower lip or tongue. The response variables were the same as those indicated in Table 1, and stuttering severity based on the SSI-R served as the single three-level factor. The results of the MANOVA indicated statistically significant Wilks's lambdas for the tongue ($p < .0005$) and speed ratios ($p = .046$), but not for other articulators. Again, therapy history was not significant when included as a covariate in these MANOVAs.

Considering the MANOVA results, one-way ANOVAs with post hoc Fisher tests were performed on the four response variables for the tongue and speed ratios. The results of these analyses and the mean levels associated with the three groups are summarized in Table 3.

Table 2. Results of analyses of variance (ANOVAs) for lower lip and jaw movement in the nonsense phrase.

	NS (n = 43)		LPS (n = 23)		HPS (n = 14)			
Response	*M*	*SD*	*M*	*SD*	*M*	*SD*	$F(2, 77)$	*p*
				Lower lip				
Open speed (mm/s)	75.3	29.5	86.3	22.1	69.7	18.1	2.11	.128
Open duration (ms)	163.5	22.0	176.8	38.7	178.8	24.1	2.53	.087
Close speed (mm/s)	78.8	34.0	93.4	24.6	87.0	38.1	1.57	.214
Close duration (ms)	131.7	15.3	123.5^{NS}	10.6	118.6^{NS}	8.9	6.43	.003*
				Jaw (lip)				
Open speed (mm/s)	40.4	19.4	39.8	18.2	28.3	10.7	2.56	.084
Open duration (ms)	163.1	28.9	162.9	23.0	174.8	32.0	1.02	.364
Close speed (mm/s)	40.7	18.7	50.4	22.3	33.0^{LPS}	17.9	3.63	.031*
Close duration (ms)	162.6	46.4	141.9^{NS}	27.1	138.8	31.1	3.11	.050*

Note. Superscripts (NS = nonstutterers, LPS = people who stutter with low stuttering severity levels) indicate cases where post hoc Fisher's comparisons showed that the mean level differed significantly from the group indicated.

*$p \leq .05$.

Table 3. Results of ANOVAs for the tongue and speed ratio measures on the sentence task.

Response	NS (n = 40)		LPS (n = 16)		HPS (n = 11)			
	M	*SD*	*M*	*SD*	*M*	*SD*	$F(2, 64)$	*p*
Tongue								
Open speed (mm/s)	69.5	16.4	83.0^{NS}	19.3	60.1^{LPS}	7.0	7.22	.001*
Open duration (ms)	131.7	12.4	136.7	10.1	144.8^{NS}	9.8	5.73	.005*
Close speed (mm/s)	78.4	18.3	83.2	17.6	77.7	12.4	0.50	.608
Close duration (ms)	125.0	10.6	122.9	9.7	146.6^{LPS,NS}	16.5	17.21	<.0005*
Speed ratios								
Lower lip /jaw open	1.67	0.52	1.59	0.45	2.05	0.85	1.82	.170
Lower lip/jaw close	1.76	0.55	1.82	0.79	2.17	1.12	1.02	.366
Tongue/jaw open	3.99	1.50	4.26	1.97	5.75	5.09	1.03	.364
Tongue/jaw close	4.99	2.39	4.43	14.3	8.19	9.14	2.89	.063

Note. HPS = people who stutter with high severity levels. ANOVA results for the speed ratios are based on log transformed data, but the means and standard deviations given in the table are based on untransformed data. Superscripts indicate cases where post hoc Fisher tests showed that the mean level differed significantly from the group indicated.

*$p \le .05$.

There it may be seen that significant effects for stuttering severity ($p \le .05$) were obtained for tongue opening duration, tongue closing duration, and tongue opening speed. Post hoc tests indicated significant increases in tongue opening speed for LPS and significant decreases in tongue opening speed for HPS. Durational effects involved increased movement durations in HPS.

In spite of a significant MANOVA, significant ANOVA results were not obtained for any of the speed ratio measures. Examination of Table 3 does show that the maximum speed ratio levels were associated with the HPS in all four cases, and this also occurred in the nonsense phrase data.

Overall Pattern of Speed and Duration Effects

In order to summarize the overall pattern of kinematic effects related to the three participant groups, bar graphs of the mean levels of movement speed and duration are provided, respectively, in Figures 2 and 3 for those cases showing significant ANOVAs in Tables 2 and

Figure 2. Bar graphs based on data presented in Tables 2 and 3 showing the mean movement speeds for the lower lip and jaw in the nonsense phrase and the tongue in the sentence. A label above a bar indicates a group with which a significant post hoc test difference was obtained.

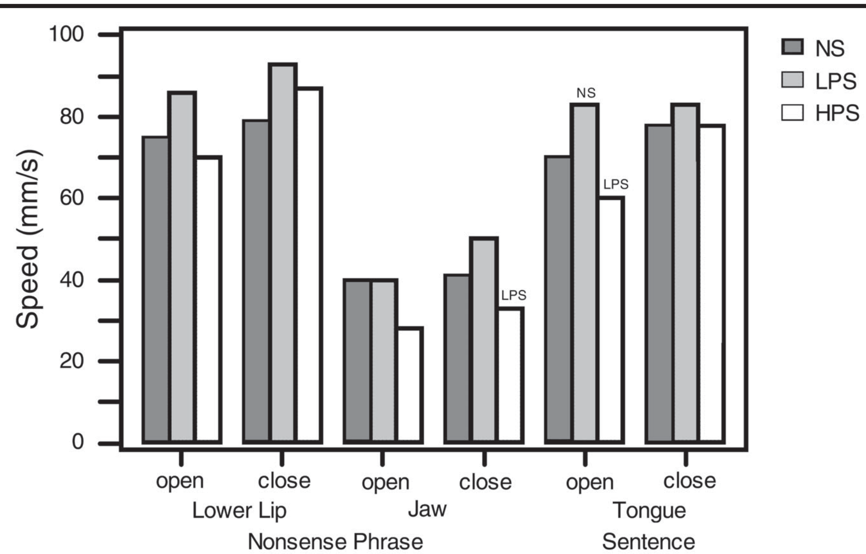
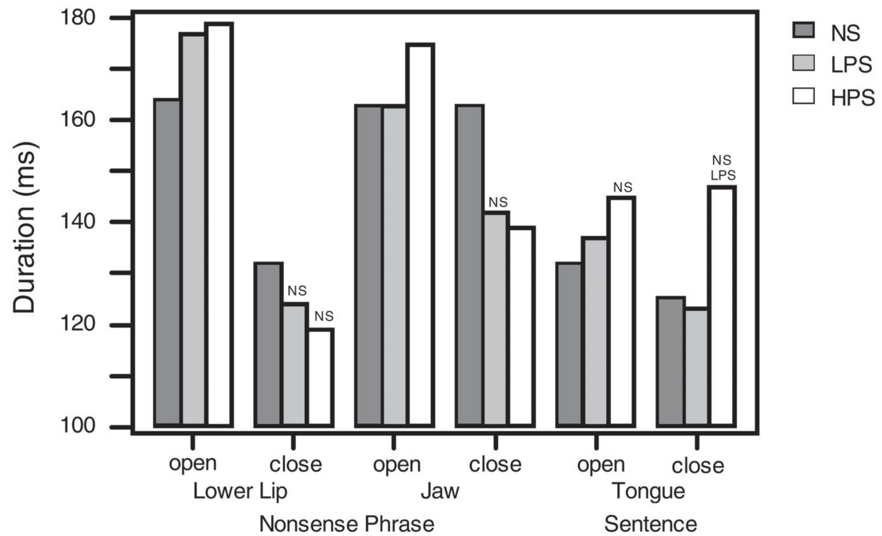


Figure 3. Bar graphs based on data presented in Tables 2 and 3 showing the mean movement durations for the lower lip and jaw in the nonsense phrase and the tongue in the sentence. A label above a bar indicates a group with which a significant post hoc difference was obtained.



3. In each figure, the lower lip and jaw data on the left are based on the nonsense phrase data as given in Table 2 and the tongue data on the right are based on the sentence data as given in Table 3. Cases showing significant post hoc differences with one or more of the groups with lower severity are indicated with labels over the bar.

Considering the pattern of effects for movement speed in Figure 2, LPS showed a significant elevation in speed for tongue opening in the sentence. HPS showed significant reductions in jaw closing speed in the nonsense phrase and tongue opening speed in the sentence. Figure 3 indicates markedly different patterns of significant duration effects for the nonsense phrase and sentence. In the nonsense phrase, LPS showed reduced durations for lower lip and jaw closing, and a similar difference was observed in HPS for the lower lip. In the sentence, HPS showed significantly longer tongue opening and closing movements.

In contrast with the results of Max et al. (2003), significant group differences were seen for opening as well as closing movements. In order to assess whether differences in opening and closing movements varied significantly with stuttering severity, two-way repeated-measures ANOVAs were performed on speed and duration for all four articulators, with severity as the between-groups factor and movement direction as the within-group factor. These analyses indicated significant interactions between stuttering severity and movement direction only for cases where significant one-way ANOVA had been obtained as described above. For the nonsense phrase, significant Group × Direction interactions occurred for jaw speed ($p = .01$), lower lip duration ($p = .001$), and jaw duration ($p = .019$). For the sentence, significant interactions occurred for tongue speed ($p = .008$) and duration ($p = .01$). The nature of these interactions can be seen in Figures 2 and 3 by examining the patterns of variation in mean levels across the three groups for the opening and closing movements within particular structures. The significant interaction seen for jaw speed in the nonsense phrase appears to be largely due to elevated closing speed in the LPS. A similar effect can be seen for tongue opening speed in the sentence, but additionally in this case the interaction was conditioned by equivalent closing speeds across the three conditions. Considering the duration data, Figure 3 shows a similar pattern of variation in group means contributing to the significant interactions for the lower lip and jaw in the nonsense phrase. In each case, with increased stuttering severity opening movement duration tended to increase, while closing movement duration decreased. In the case of tongue duration in the sentence, the significant interaction was due principally to equivalent closing movement durations for the NS and LPS, whereas opening movements showed a monotonic increase with severity.

Discussion

The two major objectives of this study were to replicate and extend (a) the previous report of Max et al. (2003) that speech kinematic differences between NS and PS are most evident for vocal tract closing versus opening movements, and (b) the finding of McClean and Runyan (2000) showing increased lip–jaw and tongue–jaw speed ratios with increases in stuttering severity. To address these goals, the speeds and durations of the upper lip, lower lip, tongue, and jaw were quantified in speaker productions of a simple nonsense phrase and a sentence. Although significant differences between NS and PS were observed in movement speeds and durations, the patterns of these effects were complex, and in general they do not provide a clear replication of either of the two previous studies. The nature and extent of significant effects varied with stuttering severity level, speech task, and movement direction.

Group differences in speed and duration in the nonsense phrase were seen only for lower lip and jaw closing movements, while group differences in the sentence task were restricted to the tongue, with significant effects being seen for both opening and closing movements. This difference between speech tasks in the structures showing significant group variations may be related to one or more of several factors. These include differences in phonetic structure, nature of the speech task (i.e., reading vs. repetition of a rehearsed phrase), overall utterance duration, and participant selection criteria for the LPS and HPS groups. With respect to phonetic structure, the phrase involved primarily bilabial consonants, and the sentence was heavily weighted with lingual consonants. It is reasonable to expect that particular speech samples will be more effective in evaluating statistical tendencies in the kinematics of particular articulators and therefore be more sensitive to kinematic differences in NS and PS for particular orofacial structures.

Given their parallel observations on speech and nonspeech orofacial closing movements and finger flexion, Max et al. (2003) interpreted their speech results as reflecting anomalies in the general motor system of PS. The present results pertain exclusively to speech movements and therefore cannot address this issue. Contrary to what would be expected from the results of Max et al., strong group differences were observed for tongue opening speed and duration in the sentence task, and widely varying patterns of two-way interaction between stuttering severity and movement direction were obtained. It is consistent with the results of Max et al. that significant group differences were seen only for lower lip and jaw closing movements in the nonsense phrase, but the direction of these effects was reversed in the two studies. Here we noted reduced lip and jaw closing movement durations and reduced jaw speeds in PS in the nonsense phrase, whereas Max et al. reported increased closing movement durations in PS. This difference in the direction of duration effects may be related to utterance position. In the nonsense phrase in the present study, lip opening movements occurred early and lip closing movements occurred late in the utterance, whereas in the Max et al. study both opening and closing movements occurred early in their short and intermediate test utterances where group differences were most apparent.

Orofacial speeds did not vary monotonically with stuttering severity in either the nonsense phrase or sentence task. This was most evident for tongue opening in the sentence where significantly higher speeds were seen for LPS and significantly lower speeds for HPS. The differences in the direction of movement speeds for LPS and HPS, in conjunction with the elevated movement durations in the sentence productions of HPS, suggest that qualitatively distinct control processes were operating in the two groups during the production of fluent speech. Our tentative interpretation is that the fluent sentence productions of HPS were characterized by learned adaptive behaviors intended to enhance speech fluency, because reduced movement speeds and prolonged durations are characteristic of the speech of PS following some forms of therapy (McClean et al., 1990; Samar et al., 1986; Story et al., 1996). Reduced speeds and prolonged durations also would be consistent with reduced levels of muscle activity (McClean & Tasko, 2003) and decreased levels of reflex gain that might enhance speech fluency (Zimmermann, 1980b). These interpretations of the reduced speeds in HPS suggest that the elevated speeds in LPS represent a contributing factor to speech disfluency and that LPS tend to rely less than HPS on adaptive speech motor processes.

Ratios relating the speeds of the lower lip and tongue to the jaw did not show statistically significant variations with stuttering severity for either speech task. Thus, the results of McClean and Runyan (2000) were not replicated. It is notable that the highest speed ratios were obtained for the HPS group for each of the four ratio measures for both the nonsense phrase and sentence. This is consistent with the McClean and Runyan results. These findings suggest that a subset of HPS tends to display elevated lip–jaw and tongue–jaw speed ratios. This may be relevant in future efforts to identify subgroups of PS where kinematic measures serve as predictor variables. That is, for a particular subgroup of PS, the relative speeds of the lower lip and tongue to the jaw may be especially important predictors.

It is our view that the etiology of stuttering is likely to vary widely across individual PS in terms of the degree of anomaly in the speech neuromotor system and how it interacts with linguistic and emotional–motivational systems in the brain (McClean, 1997). It may be that optimal treatment strategies need to assess individual characteristics in each of these areas. With respect to the speech neuromotor system, this and earlier studies of orofacial movement in PS during fluent speech identify a number of measures that could serve as useful predictor variables in multivariate studies aimed at identifying valid subgroups of PS. These measures include the speeds and durations of vocal tract opening and closing movements of different orofacial structures. However, the patterns of variation in orofacial kinematic measures across NS and PS appear to depend on level of stuttering severity, nature of the speaking task, and direction of movement. The successful use of kinematic measures in multivariate analyses intended to identify subgroups of PS may need to consider this broad range of factors.

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