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Research Article

Neurogenic Orofacial Weakness and Speech in Adults With Dysarthria

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Purpose: This study compared orofacial strength between adults with dysarthria and neurologically normal (NN) matched controls. In addition, orofacial muscle weakness was examined for potential relationships to speech impairments in adults with dysarthria.

Method: Matched groups of 55 adults with dysarthria and 55 NN adults generated maximum pressure (P_{max}) against an air-filled bulb during lingual elevation, protrusion and lateralization, and buccodental and labial compressions. These orofacial strength measures were compared with speech intelligibility, perceptual ratings of speech, articulation rate, and fast syllable-repetition rate.

Results: The dysarthria group demonstrated significantly lower orofacial strength than the NN group on all tasks. Lingual strength correlated moderately and buccal strength correlated weakly with most ratings of speech deficits. Speech intelligibility was not sensitive to dysarthria severity. Individuals with severely reduced anterior lingual elevation P_{max} (< 18 kPa) had normal to profoundly impaired sentence intelligibility (99%–6%) and moderately to severely impaired speech (26%–94% articulatory imprecision; 33%–94% overall severity).

Conclusions: Results support the presence of orofacial muscle weakness in adults with dysarthrias of varying etiologies but reinforce tenuous links between orofacial strength and speech production disorders. By examining individual data, preliminary evidence emerges to suggest that speech, but not necessarily intelligibility, is likely to be impaired when lingual weakness is severe.

Normal speech production requires low levels of orofacial muscle strength, generally less than 25% of maximum (Bunton & Weismer, 1994; Neel, Palmer, Sprouls, & Morrison, 2015; Searl, Evitts, & Davis, 2007; Searl, Knollhoff, & Barohn, 2017). Although not common, there are neurological disorders resulting from disease or injury that could reduce muscle strength to the extent that weakness would encroach on this low requirement. When weakness is severe, muscles may be required to perform near their maximal capacity to move, even for tasks such as speech that are typically effortless. Furthermore, muscle strength that is adequate but lower than normal results in a reduced functional reserve of muscle strength for the target task (DePaul & Brooks, 1993; Kent, Kent, & Rosenbek, 1987; Neel et al., 2015; Robbins, Levine, Wood, Roecker, & Luschei, 1995). This is likely an untenable situation that would quickly lead to fatigue and performance breakdown.

Weakness in skeletal muscles is associated with reduced speed of contraction, leading to the supposition that weak speech articulators would produce slow speech (Luschei, 1991; Palmer & Osborn, 1940). The available literature describes a complex relationship between orofacial muscle weakness and speech rate. Maximum rate performance on a syllable-repetition task, referred to as *speech diadochokinesis* or *alternating motion rate* (AMR), commonly assists in the differential diagnosis of the dysarthrias, some of which are accompanied by orofacial muscle weakness. Correspondence between AMR performance and muscle weakness has received mixed support in the literature (Dworkin & Aronson, 1986; Dworkin, Aronson, & Mulder, 1980; Langmore & Lehman, 1994; Neel & Palmer, 2012; Samlan & Weismer, 1995). Sentence-level speech tasks can also reveal associations between speech rate, dysarthria severity, and intelligibility, as evidenced in studies of adults with amyotrophic lateral sclerosis especially of the bulbar type (ALS-B; Ball, Willis, Beukelman, & Pattee, 2001; Shellikeri et al., 2016). ALS-B is well recognized for its preferential weakness of the tongue (DePaul & Brooks, 1993; Langmore

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& Lehman, 1994), but the specific contributions of lingual weakness to reduced AMR or speech rates are not clear.

Many researchers have examined speech and muscle strength for potential associations, and the evidence seems to trend in similar directions over time. Early literature provided compelling data associating orofacial muscle weakness with speech impairments in children and adults (Dworkin, 1979, 1980; Dworkin & Aronson, 1986; Dworkin et al., 1980; Palmer & Osborn, 1940; Sanders & Perlstein, 1965). On the basis of an analysis of speech and tongue strength in 94 children and adults with a variety of speech sound or fluency disorders, Palmer and Osborn (1940) concluded that "since speed and precision of motor movement are dependent upon efferent tonicities, for the most successful work in correction of these defects, a direct attempt must be made to improve the muscular strength of the tongue" (p. 139). This is perhaps the earliest known published endorsement of oral-motor exercises by speech-language pathologists, which are commonly incorporated in treatment programs for speech sound disorders (Lof & Watson, 2008).

Most studies over the past two decades have not supported the expected relationship between tongue weakness and impaired speech. Participants in these studies had dysarthria associated with several traumatic, genetic, or progressive neurological disorders (McHenry, Minton, Wilson, & Post, 1994; Neel et al., 2015; Solomon, Lorell, Robin, Rodnitzky, & Luschei, 1995; Solomon, Robin, & Luschei, 2000; Theodoros, Murdoch, & Stokes, 1995). McCauley, Strand, Lof, Schooling, and Frymark (2009) concluded from a systematic literature review that lip weakness and tongue weakness are not predictive of speech intelligibility. Two recent studies, however, may again reverse the trend to favor a relationship between orofacial weakness and speech impairment. First, Jones, Crisp, Asrani, Sloane, and Kishnani (2015) reported that patients with late-onset Pompe disease who had more severe dysarthria also had weaker tongues than those with less severe dysarthria. Second, Searl et al. (2017) documented a strong correlation between word-level intelligibility and lingual weakness in adults with ALS-B. As Searl et al. explained, skepticism toward using tongue strength as an indicator for speech deficits is rooted in variations across measurement approaches, insufficient data, and the submaximal requirements for executing speech. Additional research is clearly warranted.

If orofacial muscle weakness has an impact on speech production, it could manifest in a variety of ways depending on the speech task and the method of evaluating performance on the task. On the basis of the motor-control principle of task specificity, the articulatory movements associated with alveolar-lingual and bilabial English phonemes may best be assessed via anterior-tongue elevation and interlabial compression, respectively. Intelligibility testing, either from transcribing reading samples or rating spontaneous speech, is considered the most functional representation of motor speech because of its impact on communication. However, measures of intelligibility do not characterize features of speech disruption. During connected speech tasks, speech articulation is the primary contributor to reduced intelligibility (De Bodt, Hernandez-Diaz, & Van de Heyning, 2002; Lee, Hustad, & Weismer, 2014; Whitehill & Wong, 2006). To capture the overall "goodness" of speech that may be missed by rating intelligibility and specific parameters of speech articulation, recent studies have included ratings for overall severity (Solomon et al., 2000), naturalness (Makashay, Cannard, & Solomon, 2015; Scholderle, Staiger, Lampe, Strecker, & Ziegler, 2016), and listening effort (Landa et al., 2014; Whitehill & Wong, 2006). These parameters also correlate strongly with speech intelligibility and effectively represent the essence of disordered speech in a variety of neurogenic populations.

Maximum performance tasks are commonly included in motor speech evaluations to test the limits of the speech motor control system (Kent et al., 1987). Relevant to orofacial muscle function, syllabic AMR is a particularly useful task for assessing the dysarthrias. Although AMR tasks are not produced with maximum articulatory velocities (Westbury & Dembowski, 1993), Palmer and Osborn (1940) and Luschei (1991) have suggested that muscle weakness is likely to affect the speed of muscle contraction for speech. If true, then AMR and speech rates might reveal a quantifiable effect of weakness. This hypothesis has received mixed support in the literature (Dworkin & Aronson, 1986; Dworkin et al., 1980; Langmore & Lehman, 1994; Neel & Palmer, 2012; Neel et al., 2015). In short, as is true for other dimensions, the relationship between speech rate and orofacial strength is logical in theory but tenuous in practice.

The present study seeks to further elucidate relationships between orofacial weakness and dysarthria in a heterogeneous group of adults. To that end, the orofacial strength measures were expanded from the well-studied lingual-elevation task (Adams, Mathisen, Baines, Lazarus, & Callister, 2013) to include interlabial compression (Clark & Solomon, 2012). In addition, movements not expected to correlate with speech included buccodental compression, lingual protrusion, and lingual lateralization (Clark, O'Brien, Calleja, & Corrie, 2009). The first aim is to compare age- and sex-matched groups of neurologically normal (NN) adults and participants with acquired dysarthria to determine if they can be differentiated in terms of orofacial strength. If the groups differ as expected, then the next aim is to examine performance by the speakers with dysarthria on sentence-level speech and AMR tasks as they compare to orofacial weakness. The hypotheses are that articulatory precision, speech naturalness, and articulation rate and AMR will correlate with lingual-elevation and interlabial compression strength, especially in individuals demonstrating extreme weakness. Intelligibility is expected to be less sensitive to differences in orofacial muscle strength but may also correlate positively.

Method

Participants

Participants included 55 adults with dysarthria and 55 NN adults matched for sex (49 men and six women in each group) and age (range = 18–78 years; dysarthria: $M = 40.0$, $SD = 17.3$; NN: $M = 40.1$, $SD = 18.2$). Selected data from 44 of the participants with dysarthria and 31 of the NN participants were reported previously (Clark & Solomon, 2012; Solomon, Clark, Makashay, & Newman, 2008).

Participants with dysarthria were recruited from patient referrals to the Speech Pathology Clinic at the former Walter Reed Army Medical Center. Etiologies varied: 21 had a neurovascular event or neuroplasm, 18 sustained head/neck/brain injury (16 from combat injuries, three of whom also had strokes), 13 had progressive and/or generalized neurologic disease, and three had other neuropathies. Accordingly, dysarthria types were most often mixed, indeterminate, or complicated by concomitant injuries or disorders.

NN participants were recruited from the Walter Reed Army Medical Center and Appalachian State University and its surrounding community. They reported no history of neurologic or speech problems, with the exception of two participants who were briefly enrolled in speech therapy as children and reported no residual deficits. All participants consented to participate according to the policies and procedures of the institution at which they were enrolled.

Procedures

Orofacial Strength Evaluation

Orofacial strength was assessed with the Iowa Oral Performance Instrument (IOPI Medical LLC, Carnation, WA) and accessories (tongue bulbs, lateral tongue-bulb holders, surgical-grade double-sided tape, wooden tongue blades, 2-in.^{2} gauze). Strength was defined as the maximum pressure (P_{max}) generated against an air-filled bulb across three brief (1–3 s) trials.

Five tasks were presented in random order: (1) tongue-dorsum elevation, (2) tongue protrusion, (3) tongue lateralization, (4) buccodental (cheek) compression, and (5) interlabial (lip) compression. Task 1 included anterior and posterior elevations, and Tasks 3 and 4 were conducted on the right and left sides; the order of these variations was randomized. Procedures have been described and illustrated previously (Clark et al., 2009; Clark & Solomon, 2012; Solomon et al., 2008).

Speech Evaluation

Speech was recorded in a double-walled sound-attenuating booth onto a digital audio recorder (Marantz DAT PMD 670, Mahwah, NJ) via a head-mounted cardioid condenser microphone (AKG C420, Northridge, CA) positioned 4 to 5 cm from the lips.

Speech samples included an extemporaneous monologue, paragraph reading, speech AMRs, and the 22-item Sentence Intelligibility Test (SIT; Yorkston, Beukelman, & Tice, 1996). The monologue, prompted with a topic suggestion (e.g., vacation, family, or work), was the primary connected speech sample used in this study. Speech AMR involved several seconds of rapid and accurate productions of /pʌ/, /tʌ/, and /kʌ/ following a model by the examiner. The SIT was administered in accordance with the original test-manual instructions. Participants were instructed to speak clearly when reading the sentences aloud; they were allowed to repeat the sentence after hearing the examiner if reading or vision was an issue. Speech stimuli were transferred digitally to a laboratory computer and edited using Praat acoustic analysis software (Boersma & Weenink, 2009) for perceptual and acoustic analyses.

Data Reduction

English-speaking listeners with normal hearing transcribed SIT sentences after hearing each sentence twice under headphones in a sound-attenuating booth. The median percentage of correctly transcribed words (including inflectional suffixes) across three listeners was used for data analysis.

Segments of connected speech (20–80 s duration) were excerpted and edited to remove examiner interjections, long pauses, and unrelated noise, taking care to retain the natural flow of speech. To achieve adequate samples in four cases, segments of the reading task supplemented or replaced the monologue. Three certified speech-language pathologists, each with more than 3 years' experience working with adults, independently rated the speech after listening to each sample over headphones at a comfortable listening level as many times as desired. Listeners estimated the percentage of words understood from the monologue as an indicator of conversational speech intelligibility. In addition, they rated overall severity, articulatory precision, speech naturalness, and listening effort using visual analog scales (VAS) labeled at the extremes with *absolutely normal* to *profoundly abnormal, absolutely precise* to *profoundly imprecise, absolutely natural* to *profoundly unnatural,* and *easy to listen* to *takes all of my effort to listen,* respectively. Labels for mild (MI), moderate (MO), and severe (SE) appeared in gray font under each line at 10 mm, 35 mm, and 72 mm; this design is consistent with a validated voice-quality evaluation form (Karnell et al., 2007; Nagle, Helou, Solomon, & Eadie, 2014). Scores were expressed as a percentage of the abnormal dimension (millimeters from left end of 100-mm line). Median ratings of each perceptual dimension from the three speech-language pathologists were used for data analysis.

Articulation rate (also called interpause speech rate) for the connected speech samples was determined by one of four native English-speaking raters with normal hearing who transcribed each sample orthographically and counted the syllables produced. Using the Praat acoustic analysis software, raters removed pauses > 250 ms and divided the number of syllables by the remaining speaking duration. Raters also determined syllabic AMR by noting the duration of 10 sequential speech from a midsection of each AMR string. In trials with fewer than 10 syllables, all available syllables were used, excluding the final syllable. Temporal measures were semiautomated within the acoustic software program by marking spoken sections and pauses, concatenating the spoken portions, and thus determining the total duration of speech. One expert rater, who was also one of the original raters, remeasured 11% of all connected speech samples for reliability. Agreement for each sample was strong for intrarater reliability (1.9%–4.2% error). Interrater reliability was excellent for two of the three additional raters (1.1%–4.5% error) but was unacceptable for one rater (7.8%–13.5% error), primarily because of inaccurate syllable counts; data from this rater were recalculated and replaced by the expert rater.

Statistical Analysis

Two-sample *t* tests for independent means examined group differences for the eight orofacial strength tasks. An adjusted alpha level of .006 corrected for multiple comparisons. Spearman rank correlation analysis indicated strength of associations between orofacial P_{max} and characteristics of speech because of nonnormal distributions of several speech measures. For tasks involving right/left measures, data were sorted by weaker versus stronger side to highlight the potential relevance of muscle weakness to speech deficits. Pearson correlation was used to examine relationships between temporal measures and orofacial P_{max} results.

Results

Orofacial Strength

For every structure and task, P_{max} was significantly lower for the dysarthria group than the NN group (Table 1). Across all tongue tasks, P_{max} averaged 47.0 kPa for the dysarthria group and 67.8 kPa for the NN group; tongue protrusion provided the highest P_{max} for both groups. Facial muscles generated P_{max} averaging 24.5 kPa for the dysarthria group and 33.3 kPa for the NN group, with P_{max} for buccodental compression exceeding that for interlabial compression.

Table 1. Summary and inferential statistical results for maximum pressure (P_{max}, in kPa) generated by orofacial muscles for the dysarthria and neurologically normal (NN) participant groups.

	Dysarthria		**NN**				
Task	***M***	***SD***	***M***	***SD***	***t***	***df***	***p***
Tongue							
Elevation							
Anterior	43.6	19.0	61.8	13.0	5.87	108	<.001*
Posterior	44.0	18.2	57.4	13.1	4.29	100	<.001*
Lateralization							
Right	47.0	21.7	69.1	19.8	5.52	105	<.001*
Left	45.1	22.6	70.2	20.8	5.98	105	<.001*
Protrusion	55.2	23.1	80.7	16.7	6.62	107	<.001*
Cheek compression							
Right	27.4	9.9	36.5	9.0	4.98	106	<.001*
Left	27.5	10.9	35.0	9.0	3.89	105	<.001*
Lip compression	18.7	6.5	28.5	12.5	4.97	103	<.001*

*Statistically significant between-groups difference, $p < .006$.

Perceptual Characteristics of Connected Speech

Figure 1 illustrates results for the connected speaking task. Estimated conversational intelligibility was 90% to 100% for 43 of 55 speakers, resulting in a median of 100% and an extremely unbalanced distribution with 10 outliers (note that the values on the ordinate are reversed to represent increasing severity in a positive direction). Of the VAS ratings, overall severity provided the highest median (33%, indicating moderate severity) and the most normally balanced distribution. Articulatory precision and naturalness yielded similar distributions, and listening effort was positively skewed; medians were in the mild-to-moderate range.

Table 2 lists Spearman rank correlation coefficients between orofacial P_{max} and ratings of connected speech. Estimated conversational intelligibility was weakly to moderately correlated with P_{max} (r_s = .227–.519). Other perceptual characteristics of speech were significantly correlated with tongue P_{max} measures ($r_s = -.365$ to $-.588$) and less strongly correlated with facial muscle P_{max} ($r_s = -.128$ to $-.288$). Figure 2 illustrates the relationship between median ratings for articulatory precision (higher percentages = greater severity) and anterior-tongue elevation P_{max} ($r_s = -.493$).

Sentence Intelligibility

The median SIT score was 97.8%; 47 of 54 speakers with dysarthria (missing data for one highly intelligible participant) scored better than 85% on this test. Figure 3 illustrates individual dysarthria participant data for the SIT plotted against anterior-tongue elevation P_{max}. For comparison,

Figure 1. Ratings of connected speech for individual participants in the dysarthria group according to estimated intelligibility (left plot; note reversal of values so that upward indicates lower intelligibility) and visual analog scales (right plot) ranging from *absolutely normal* (0) to *profoundly abnormal* (100) on the basis of the median scores from three experienced listeners.

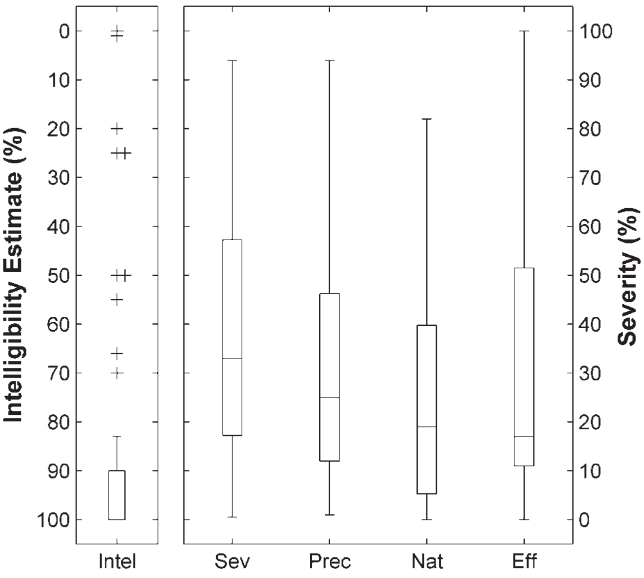


Table 2. Spearman rank correlation coefficients (r_s) between orofacial strength (P_{max}) and speech measures.

Task	SIT	Estimated intelligibility	Overall severity	Precision	Naturalness	Listening effort
Tongue						
Elevation						
Anterior	**.349***	**.519***	**–.493***	**–.468***	**–.398***	**–.520***
Posterior	**.271**	**.470***	**–.455***	**–.400***	**–.365***	**–.503***
Lateralization						
Weaker	**.387***	**.415***	**–.485***	**–.460***	**–.406***	**–.467***
Stronger	**.366***	**.443***	**–.464***	**–.403***	**–.376***	**–.470***
Protrusion	**.500***	**.479***	**–.524***	**–.506***	**–.476***	**–.588***
Cheek compression						
Weaker	**.324**	**.293**	**–.246**	–.166	–.198	**–.275**
Stronger	**.239**	**.292**	**–.284**	**–.229**	–.194	**–.288**
Lip compression	.187	.227	–.128	–.185	–.146	–.193

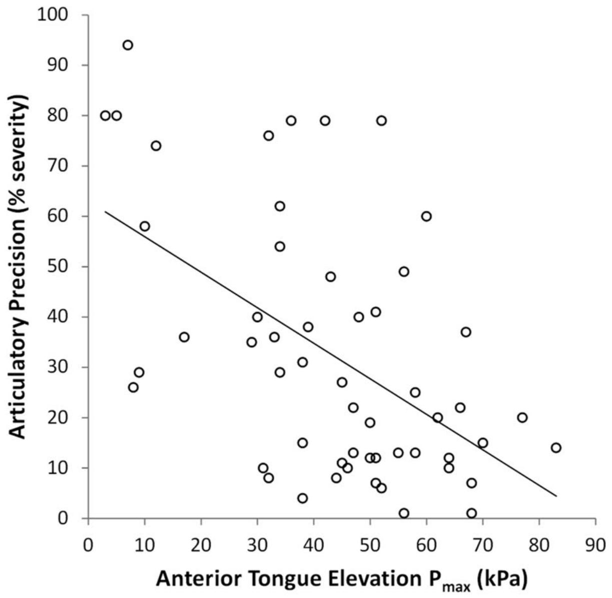
Note. Intelligibility was determined at the sentence level with the Sentence Intelligibility Test (SIT; Yorkston et al., 1996) and during connected speech by estimation (in percentages). Remaining parameters were rated (via visual analog scales) from connected speech. Bold font indicates r_s with $p < .05$; bold font plus * indicates r_s with $p < .01$ (one-tailed).

Figure 3 also includes anterior-tongue elevation P_{max} for the NN group in a box-and-whisker format; all NN speakers were highly intelligible. Spearman correlation tests revealed weak correlations between SIT scores and orofacial P_{max} measures for the dysarthria group (Table 2).

Speech Rate

Table 3 lists summary statistics for articulation rate and AMR for the participants with dysarthria. On average, the rate was slower than normal (cf. Dworkin et al., 1980; Jacewicz, Fox, O'Neill, & Salmons, 2009). Statistically significant Pearson correlation coefficients between the rate measures and anterior-tongue elevation P_{max} (Table 4) were weak (r = .247–.268); few other correlations between orofacial strength and rate were significant. Figure 4 illustrates the relationship between /tʌ/ AMR and anterior-tongue elevation P_{max} (r = .247).

Figure 2. Ratings of articulatory precision for connected speech (from 0 = *absolutely normal* to 100 = *profoundly abnormal*; median of three experienced listeners) plotted against anterior-tongue elevation strength (maximum pressure, P_{max}, across three trials, in kPa). The line is the linear regression (r = .534).



Discussion

This study demonstrated reduced lingual and facial strength in adults with dysarthria as compared with NN

Figure 3. Sentence Intelligibility Test scores (percentage words correct, median of three listeners) plotted against anterior-tongue elevation strength (maximum pressure, P_{max}, across three trials, in kPa) for individual participants with dysarthria. (Top) Box-and-whisker plot of P_{max} for neurologically normal participants (center line = median; box = 25–75 percentiles; whisker = 1.5 times the interquartile range; + = outlier).

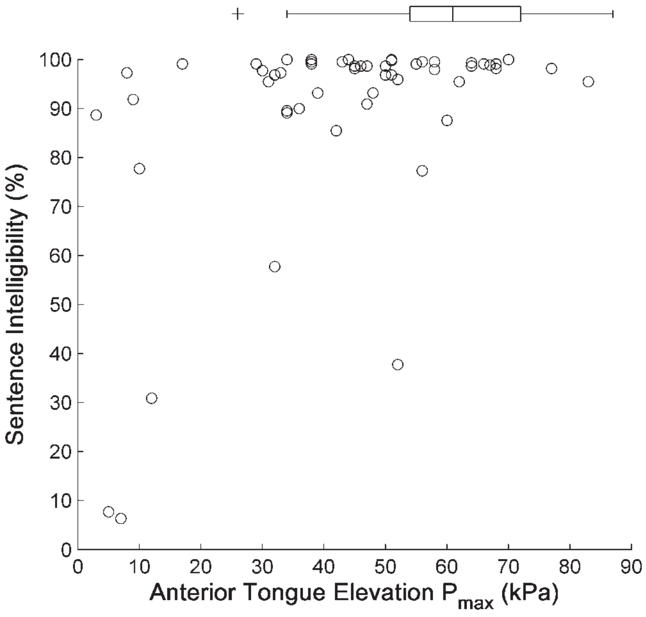
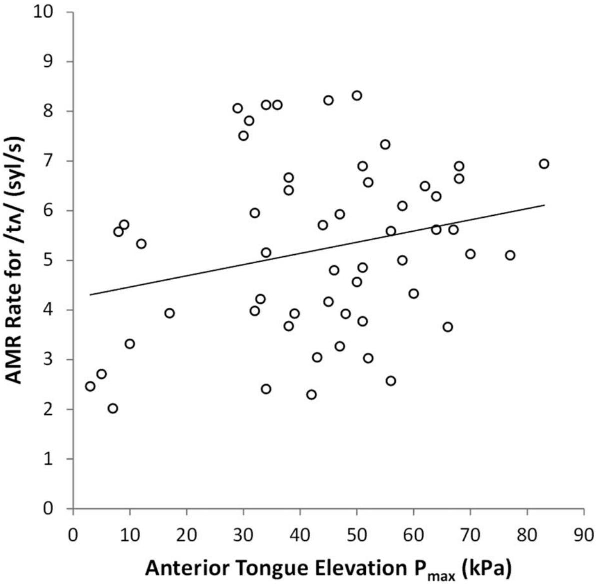


Table 3. Summary statistics for temporal speech results (in syllables/s) for participants with dysarthria.

Task	*M*	*SD*
Articulation rate	4.09	1.16
Alternating motion rate		
/pʌ/	5.37	1.68
/tʌ/	5.29	1.80
/kʌ/	4.66	1.69

Note. Pauses exceeding 0.25 s were omitted from connected speech samples for articulation rate.

Figure 4. Individual participant data for alternating motion rate (AMR) for /tʌ/ plotted against maximum anterior-tongue elevation pressure. The line is the linear regression (*r* = .247). syl = syllables.



participants, supplementing existing literature on tongue-elevation strength in healthy and disordered populations (Adams et al., 2013; Jones et al., 2015; Lazarus et al., 2013; Neel et al., 2015). Although many of the present NN participants were included in the meta-analysis conducted by Adams et al. (2013), this article adds to the existing literature by reporting data from NN participants who were age- and sex-matched to the participants with dysarthria and by comparing the groups on tongue protrusion, tongue lateralization, and lower facial muscle strength tasks. Overall, accumulating evidence indicates that adults with dysarthria are likely to demonstrate orofacial weakness. Given that orofacial weakness was confirmed when comparing groups in this study, the data were relevant to the aim of relating reduced muscle strength to impaired speech.

The diverse group of adults with dysarthria in the present study revealed moderate relationships between lingual weakness and speech at best (r_s = −.365 to −.588). There was no clear distinction in correlations between the various lingual tasks, indicating either that task specificity was not a critical feature or that maximum anterior-tongue elevation was not specific enough to speech to matter. Buccal strength correlated weakly and labial strength did not correlate significantly with any of the perceptual variables despite the lips' more obvious role in speech production. Similarly, Hartelius and Lillvik (2003) reported greater impairment of the tongue than the lips in individuals with dysarthria associated with multiple sclerosis.

Table 4. Pearson correlation coefficients between orofacial strength and rate during a connected speech task and fast-syllable repetitions (alternating motion rate).

Task	Articulation rate	Alternating motion rate		
		/pʌ/	/tʌ/	/kʌ/
Tongue				
Elevation				
Anterior	**.254**	**.266**	**.247**	**.268**
Posterior	.038	.119	.153	.188
Lateralization				
Weaker	.215	.193	.138	.137
Stronger	**.242**	.196	.169	.183
Protrusion	**.310**	**.236**	.197	.199
Cheek compression				
Weaker	**.231**	.110	.017	−.069
Stronger	.142	.162	.098	.012
Lip compression	−.010	.214	.097	.031

Note. Bold font indicates *r* with $p < .05$.

These results are relevant to the recent literature examining the functional impact and extent of orofacial weakness on speech in adults with dysarthria. Neel et al. (2015) reported perceptually normal speech in 12 adults with oculopharyngeal muscular dystrophy despite lingual-elevation strength averaging 42% of normal (24.7 kPa). Jones et al. (2015) documented lingual-elevation strength (mean of three trials) averaging 51% of published Iowa Oral Performance Instrument norms (maximum of three trials) in 30 individuals with late-onset Pompe disease, 87% of whom had slight to moderate dysarthria. Those with no to slight dysarthria had significantly greater anterior-tongue elevation P_{max} (*M* = 38.2 kPa) than those with mild to moderate dysarthria (*M* = 25.3 kPa), providing general support for an association between lingual weakness and speech deficits. Searl et al. (2017) used a small pressure transducer to document that anterior-tongue elevation P_{max} in adults with ALS-B averaged 53% of NN controls (35.7 kPa) and that word intelligibility scores correlated strongly with anterior-tongue elevation P_{max} for the ALS group (*r* = .852). Interestingly, in people with ALS-B, the proportion of strength used to produce coronal consonants was the same as healthy people, indicating that the weakness did not affect their functional reserve for speech. Furthermore, the authors speculated that speakers with ALS-B may maintain an internal representation of effort rather than targeting a particular output level, resulting in the avoidance of fatigue despite degraded articulatory precision.

In the extreme, muscle paralysis prevents movement and disallows function. Therefore, it is logical to assume that severely or profoundly paretic orofacial muscles would affect speech articulators' ability to reach spatial targets accurately and swiftly. The current study's cohort included eight participants who generated anterior-tongue elevation P_{max} values that were lower than the lowest P_{max} for the NN group (see Figure 1). Table 5 lists their demographic and diagnostic information, and Table 6 includes their anterior-tongue elevation P_{max} and speech test results. Examination of these data reveals that these weakest speakers demonstrated moderately to severely impaired articulatory precision (26%–94% severity on VAS) and that half of them had moderately to profoundly reduced sentence intelligibility (6%–78%). The fact that some of these very weak speakers maintained high sentence intelligibility (89%–99%) indicates that other muscles and structures may act to compensate. Indeed, even patients with total glossectomy can have acceptable speech intelligibility (Dziegielewski et al., 2013). In the present cohort, structural damage from gunshot wounds and blast explosions also affected speech intelligibility and other speech features.

With regard to sentence intelligibility, all but seven of the 54 participants with dysarthria scored at least 85% on the SIT according to the median of three independent raters; remaining scores ranged from 6% to 78%. In addition, the strong ceiling effect and tightly clustered data rendered the intelligibility data unsuitable for parametric correlational analyses. In contrast, ratings of speech samples were broadly dispersed for the other perceptual characteristics of speech evaluated by VAS. Although studies have identified articulatory inaccuracies as the primary contributor to reduced intelligibility (De Bodt et al., 2002; Lee et al., 2014; Whitehill & Wong, 2006), prosodic, semantic, morphosyntactic, and other cues certainly aid in the interpretation of connected speech (De Bodt et al., 2002; Hustad & Beukelman, 2001; Riddel, McCauley, Mulligan, & Tandan, 1995; Whitehill & Wong, 2006).

Slow speech is common in most types of dysarthria (Duffy, 2013). This study found that articulation rate, or speech rate without the influence of pauses, was approximately 20% slower than normal (cf. Jacewicz et al., 2009). In addition, associations between articulation rate and lingual strength were weak, perhaps in part because speech was produced at self-selected rates that could either be inherent to the disorder or compensatory for other impairments. Rates on the AMR task were also approximately 20% slower than normal (cf. Dworkin et al., 1980). The only orofacial strength task that correlated significantly, albeit weakly, with articulation rate and each of the three AMR tasks was anterior-tongue elevation.

Given the weak associations between articulation rate and AMR with orofacial strength, it appeared that no relationship existed. However, examination of the weakest subgroup of participants revealed markedly slow articulation and syllable-repetition rates for the majority, but these rates were within normal limits for the remainder (cf. Dworkin et al., 1980; Jacewicz et al., 2009). Upon further examination of the AMR data for /tʌ/ (Figure 4), none of the eight weakest participants exceeded 5.8 syllables/s, whereas 44.6% of the remaining participants with dysarthria (with

Table 5. Demographic and diagnostic information about participants with dysarthria with severe tongue weakness (maximum anterior-tongue elevation pressure, $P_{max} < 18$ kPa); participants listed in order of ascending tongue strength (see Table 6).

ID	Age	Sex	Etiology/diagnosis	Dysarthria (type, severity)	Speech characteristics
D52	34	M	Blast explosion (loss of right mandible, teeth, lower lip)	Flaccid, severe, plus structural damage	Imprecise speech, hypernasal, nasal emission, slow rate
D04	21	M	Blast explosion (traumatic brain injury, jaw fracture)	Spastic, severe	Slow, absent consonants, harsh-strained voice quality, continuous voicing, hypernasal, short phrases
D29	48	M	Amyotrophic lateral sclerosis	Spastic, severe	Slow, undiscernible phonemes, hypernasal, harsh-strained voice quality, continuous voicing, short phrases, emotional lability
D58	23	M	Gunshot wound (through neck; bilateral paresis of lower face, tongue, velopharynx, larynx)	Flaccid-spastic, moderate	Hypernasal, nasal emission, strained and breathy voice quality, mild imprecision
D71	52	F	Iatrogenic right CN XII sectioning during neck resection	Flaccid, moderate	Imprecise consonants, distorted vowels, rough voice quality
D69	73	F	Amyotrophic lateral sclerosis	Flaccid-spastic, severe	Imprecise consonants, hypernasal, inspiratory stridor, slow, excess and equal stress, short phrases
D09	24	M	Gunshot wound (through neck; left tongue and face paresis); blast explosion (parietal bone loss; intracranial shrapnel)	Spastic-hypokinetic-flaccid, moderate	Imprecise consonants, blurred, short rushes of speech, slow rate, strained and breathy voice quality, short breath groups, emotional lability
D40	52	M	Amyotrophic lateral sclerosis	Spastic, moderate	Strained and harsh voice quality, continuous voicing, slow rate, monoloud, imprecise consonants

Table 6. Speech results for participants with dysarthria who have severely reduced anterior tongue-elevation strength (P_{max}; refer to Table 5); participants listed in order of ascending tongue strength.

			Connected speech						AMR (syl/s)		
ID	**P_{max} (kPa)**	**SIT (%)**	**Intel (%)**	**Sev (%)**	**Prec (%)**	**Nat (%)**	**Eff (%)**	**Rate[a] (syl/s)**	**/pʌ/**	**/tʌ/**	**/kʌ/**
D52	3	89	50	77	80	71	76	2.64	4.57	2.46	1.75
D04	5	8	1	86	80	48	85	2.69	2.44	2.71	1.84
D29	7	6	0	94	94	82	100	2.55	1.91	2.02	1.94
D58	8	97	85	33	26	4	23	4.90	6.12	5.57	4.86
D71	9	92	90	40	29	30	34	4.15	5.66	5.72	3.68
D69	10	78	50	58	58	58	64	2.55	3.43	3.32	3.32
D09	12	31	25	81	74	68	70	4.60	5.83	5.33	5.36
D40	17	99	100	46	36	22	20	3.74	4.50	3.94	3.37

Note. Severity is greater with lower values for intelligibility (SIT and Intel) and with higher values for the remaining extemporaneous speech parameters (Sev, Prec, Nat, Eff, Rate). AMRs are for syllables produced as quickly as possible (syl/s). P_{max} = maximum pressure; SIT = Sentence Intelligibility Test; Intel = estimated intelligibility; Sev = overall severity; Prec = precision; Nat = naturalness; Eff = listening effort; Rate = articulation rate; syl/s = syllables per second; AMR = alternating motion rate.

[a] Pauses > 0.25 s excluded.

$P_{max} \geq 29$ kPa) did. This observation suggests that extremely weak tongue muscles may be limited in terms of speed of contraction during speech. Previous studies have reported conflicting results regarding tongue strength and the speed of tongue movement for speech. Correlations have ranged from weak (Langmore & Lehman, 1994) to moderate to strong (Dworkin et al., 1980) in individuals with ALS; no significant correlations were reported for persons with oculopharyngeal muscular dystrophy (Neel et al., 2015). Neel and Palmer (2012) asserted that maximum tongue strength plays "at most, a small role" (p. 244) in articulation rate in connected speech and AMR tasks.

The ultimate goal of this line of research is to answer the elusive question of the minimum level of lingual strength required for speech purposes. Various levels have been suggested from diverse patient populations (Jones et al., 2015; Lazarus et al., 2013; Neel et al., 2015; Searl et al., 2017). The present study contributes a small amount of data toward that end such that the eight weakest participants on the anterior-tongue elevation task (P_{max} = 3–17 kPa) had moderately to severely impaired speech. In addition, there were exceptions to the observation that severe tongue weakness was associated with markedly impaired speech, indicating that the speech production system has the capacity to compensate for and adapt to severe neuromuscular weakness. Future studies are needed to fill gaps in tongue-strength data and add larger and more diverse populations to help clarify functional associations with tongue weakness. Studies that track patients with degenerative disorders over time may be best situated to address the fundamental question of a critical strength threshold to support normal speech function (Searl & Knollhoff, 2016). Conversely, studies could implement muscle-training protocols to strengthen weak orofacial muscles without directly training speech and examine outcomes with sensitive measures of speech accuracy and speed. Of the perceptual dimensions included in this study, ratings of overall severity and articulatory precision appear best suited to detect speech deficits associated with dysarthria.

This exploratory investigation included a large mix of etiologies in the neurogenic group to demonstrate the orofacial muscle-strength deficits of a clinical population in a medical setting. Admittedly, the patients seen at this military treatment facility are not typical of civilian settings because 30% sustained injuries in combat situations, many with polytraumatic injuries (for an interesting historical account of combat injuries involving the tongue and speech, see Peacher, 1950). Because of their often-complicated injuries and disorders, other factors, such as disrupted muscle tone, incoordination, structural damage, and other communication impairments (e.g., aphasia, apraxia of speech), may have affected performance and confounded attempts to isolate relationships between orofacial muscle strength and speech. Future research should examine specific categories of dysarthria types that are disproportionately affected by orofacial muscle weakness.

In conclusion, orofacial muscle strength was significantly reduced in persons with various types of dysarthria compared with a group of NN controls. Correlations between orofacial weakness and speech deficits were weak to moderate. Individuals with extremely weak tongues were likely to demonstrate moderate to severe speech deficits despite some having good intelligibility. Although existing evidence is insufficient to support an association between orofacial weakness and dysarthria, future research should explore a possible weakness threshold for affecting functional speech, especially as it relates to the different types of dysarthria. The difficulty with demonstrating clear associations between tongue strength and speech-related variables is undoubtedly a tribute to the redundancy, adaptability, and submaximal requirements for speech built into the orofacial neuromuscular system.

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