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Perceptual and instrumental assessments of orofacial muscle tone in dysarthric and normal speakers

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Abstract—Clinical assessment of orofacial muscle tone is of interest for differential diagnosis of the dysarthrias, but standardized procedures and normative data are lacking. In this study, perceptual ratings of tone were compared with instrumental measures of tissue stiffness for facial, lingual, and masticatory muscles in 70 individuals with dysarthria. Perceptual and instrumental tone data were discordant and failed to discriminate between five dysarthria types. These results raised concerns about the validity of Myoton-3 stiffness measures in the orofacial muscles. Therefore, a second study evaluated contracted and relaxed orofacial muscles in 10 neurotypical adults. Results for the cheek, masseter, and lateral tongue surface followed predictions, with significantly higher tissue stiffness during contraction. In contradiction, stiffness measures from the superior surface of the tongue were lower during contraction. Superior-to-inferior tongue thickness was notably increased during contraction. A third study revealed that tissue thickness up to ~10 mm significantly affected Myoton-3 measures. Altered tissue thickness due to neuromuscular conditions like spasticity and atrophy may have undermined the detection of group differences in the original sample of dysarthric speakers. These experiments underscore the challenges of assessing orofacial muscle tone and identify considerations for quantification of tone-related differences across dysarthria groups in future studies.

Key words: dysarthria, motor speech assessment, muscle tone, Myoton, neurological disorders, orofacial muscles, rigidity, spasticity, stiffness, tissue thickness, tongue, viscoelastic properties.

INTRODUCTION

The dysarthrias are a group of motor speech disorders with a taxonomy based on clusters of speech characteristics [1–2]. These speech features are manifestations of underlying neuropathophysiologies within the lower motor neuron (LMN) system (flaccid), upper motor neuron (UMN) system (spastic), cerebellar motor control circuit (ataxic), and basal ganglia motor control circuit (hypokinetic and hyperkinetic). Sensorimotor impairments such as muscle weakness, incoordination, reduced or excessive movement, involuntary muscle activity, and altered tone occur across multiple dysarthria types, so clinicians must identify particular configurations of these abnormalities in order to differentiate among the disorders [3].

Muscle weakness and incoordination are straightforward concepts for most clinicians, but the nature of abnormal muscle tone may be less familiar and more

Abbreviations: ANOVA = analysis of variance, LMN = lower motor neuron, LSD = (Fisher) least significant difference, SLP = speech-language pathologist, UMN = upper motor neuron.

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complex. Muscle tone is the tonic or background activity of a resting muscle and arises from both peripheral and central mechanisms. Peripherally, muscle tone is modulated by muscle spindles, which are an integral component of the stretch reflex and act to maintain posture and joint integrity via low-level, relatively static isometric contractions [4]. If the LMN system is impaired, voluntary muscle contraction and muscle tone are abnormally reduced, leading to flaccidity. Centrally, the reticulospinal tract of the motor system [5] and the direct and indirect pathways of the basal ganglia contribute to increased tonic muscle activity [6]. Specifically, disruption of descending motor signals from indirect UMNs to the LMN pools [7] causes muscle spasticity and hyperreflexia because of reduced inhibition of peripheral reflexes [8]. Disturbances of the direct and indirect pathways of the basal ganglia can result in muscle rigidity, characterized by heightened tonic activity without hyperactive stretch reflexes [6,9–11]. To summarize, hypotonia is generally associated with flaccid dysarthria and damage to the LMN pathway, whereas hypertonia occurs with spastic, hypokinetic (when consistent), and hyperkinetic (when fluctuating) disorders, and is associated with damage to the indirect UMN pathway and/or the basal ganglia control circuit [3,12–13]. The accurate identification and typing of tone abnormalities can be an important confirmatory component in differentiating dysarthria types.

Compared with other characteristics associated with dysarthria, there is less agreement about how to assess muscle tone in orofacial musculature [3]. Muscle tone status may be reported by speech-language pathologists (SLPs) as part of a motor speech evaluation, but there are no published standardized procedures for its assessment. The few tests that address orofacial tone impairments instruct the clinician to passively stretch [14] or palpate [15] the muscles of interest and then rate whether resistance to the perturbation is lower or higher than normal. A paucity of normative data for perceptual measures of tone combined with poor correlation between clinical rating scale scores and physiologic measures of spasticity [16] limits the reliability and clinical utility of perceptual ratings of tone.

Several confounds to muscle tone measurement have been described. First, although muscle is of primary interest when assessing tone, tissue resistance is also influenced by nonmuscular epithelial, connective, vascular, and adipose tissues [4–5,17]. Second, certain components of tonic activity are regulated differently in the muscles of the orofacial system than in other skeletal muscles [18]. In limb musculature, the presence and function of muscle spindles and the associated stretch reflexes are consistent relative to muscle size [19–21]. In contrast, these features vary by site for the orofacial muscles, including the jaw-closing muscles [22], jaw-opening muscles [23], facial and labial musculature [24–31], tongue [32], pharynx and larynx [33–34], and soft palate [33–34]. Therefore, it is logical to expect tone impairments to manifest differently in muscles of the speech production mechanism than in limb and truncal muscles.

Emerging portable and handheld devices for instrumental measurement of muscle tone [35] may offer clinically useful alternatives [36–38] to perceptual ratings if their reliability and validity across various muscle sites and populations can be demonstrated. For applications involving the orofacial system, such a tool should isolate relatively small muscles and access difficult-to-reach areas such as the tongue and the velum. To our knowledge, three instruments have been used to assess orofacial muscle tone. The OroSTIFF (Epic Medical Concepts & Innovations; Mission, Kansas) measures resistance to a dynamic stretch applied to the perioral tissues by incrementally stretching the corners of the mouth laterally [39–41]. Preliminary data support its reliability and validity for neurologically normal adults and the presence of increased stiffness (rigidity) in an adult with hypokinesia associated with Parkinson disease [39–40]. The Myotonometer (Neurogenic Technologies, Inc; Missoula, Montana) measures tissue compliance in response to incrementally depressing muscle tissue [42–43]. Clark and Solomon demonstrated differences in compliance between relaxed and contracted submental musculature, but not with therapeutic interventions that were expected to increase (vibration) or decrease (ice) resting tone in persons with neurological abnormalities [44]. The latter result suggested a lack of therapeutic benefit, insufficient sensitivity of the Myotonometer to detect small changes in this region, or both. Neither of these instruments can be applied to the less accessible tongue or to the smaller muscles of the cheeks and jaw.

A third instrument, the Myoton (Müomeetria; Tallinn, Estonia), briefly deforms a small tissue site with a narrow probe and generates an acceleration curve analyzed according to a damped oscillation model [45]. The Myoton was originally developed to measure muscle tone in large muscles of the torso and limbs, and recent reports

indicate good reliability over time for individuals with stroke and healthy older people [46–47]. Investigations using an earlier version of the Myoton demonstrated greater stiffness and lesser elasticity of the tongue and velum in middle-aged adults with obstructive sleep apnea than in adults who did not snore [48–50]. The acceleration curve, generated via an 8 ms perturbation, yielded two outcome variables: frequency of oscillation (in hertz; an indicator of stiffness) and logarithmic decrement of damped oscillation (reflecting elasticity). Subsequently, the instrument was reconfigured to deliver a 25 ms pulse perturbation with stiffness as an additional output variable [51]. Stiffness (in newtons per meter) was calculated from the linear displacement of tissue per force of the perturbation and corresponds, in theory, to the calculated frequency of oscillation from the acceleration curve. Solomon and Clark used the Myoton-3 to quantify tissue stiffness of the lateral tongue and midcheek in 10 participants with UMN or LMN disorders and 4 neurologically normal adults [51]. Participants with LMN disorders exhibited reduced stiffness/decreased tone as predicted, but no significant changes in stiffness were identified in those with UMN lesions [51]. Investigators and the manufacturers of the Myoton-3 subsequently identified concerns with the perturbation setting and internal analysis algorithm of the device. Despite acceptable test-retest reliability [51], these issues may have negatively affected data collection and thus the validity of study findings. The Myoton-3 manufacturer modified the analysis algorithm for improved outcomes, and preliminary testing on orofacial musculature within the research laboratory indicated adequate reliability with a pulse perturbation of 10 ms. The present investigation applied the revised instrumentation to a larger disordered population.

The purpose of the primary study in this report was to compare orofacial stiffness (and the associated parameters of oscillation frequency and decrement) as an indicator of muscle tone across groups of participants that differed based on dysarthria diagnosis. Procedures were modified from our previous investigation to achieve clinically feasible and efficient data collection. Orofacial stiffness measures were predicted to be lower than normal in individuals with flaccid, mixed flaccid-spastic, and possibly ataxic dysarthrias and higher than normal in those with hypokinetic and spastic dysarthrias [3,39,51–52]. Unanticipated results led to study 2, which was designed to validate the ability of the Myoton-3 to detect stiffness in the tongue, cheek, and jaw muscles by comparing relaxed and contracted muscles in neurotypical adults. Finally, study 3 tested the ensuing hypothesis that tissue thickness influences Myoton-3 stiffness measures.

STUDY 1

Methods

Participants

Participants with dysarthria were recruited from patients referred to the Speech Pathology Division at the Mayo Clinic (Rochester, Minnesota) for a diagnostic motor speech assessment from December 2010 to June 2011. Speech and speech-like tasks within a standard motor speech assessment included spontaneous speech, oral reading, sustained phonation, and fast syllable repetitions (alternating and sequential motion rates) [3]. SLPs from the Mayo Clinic (authors J. D., E. S., or H. C.), each of whom had at least 14 yr of clinical experience in motor speech diagnostics and participated in ongoing intra- and interrater reliability testing for such evaluations, performed these assessments and determined the presence, type, and severity (mild, moderate, marked, or severe) of motor speech disorders. Ninety-seven patients agreed to participate in additional tasks for the study and provided written informed consent in accordance with the Mayo Clinic Institutional Review Board. Of these, 70 individuals were diagnosed with flaccid, mixed flaccid-spastic, ataxic, hypokinetic, or spastic dysarthria and therefore were included in this analysis. Summary demographic information for participants is shown in **Table 1**.

Instrumentation

Tissue stiffness was assessed with the Müomeetria Myoton-3 (V6.7, 2005). A 7 cm cylindrical probe (3 mm diameter) was lowered slowly to the surface of each tissue site at approximately a right angle until the instrument triggered a 10 ms pulse perturbation. An accelerometer sensed the tissue's response and generated an acceleration curve. Using the Myoton-3's "triplescan" option, three trials yielding curves each with two positive phases were obtained from each site. If a curve failed to meet measurement parameters, an error message cued the examiner to repeat the trial. A liquid-crystal screen displayed numeric values for the three outcome variables. Oscillation *frequency* correlates to tissue stiffness such that higher frequency of oscillation is associated with stiffer tissue. Logarithmic *decrement* is a damping ratio reflecting the ability of the tissue to return to its original shape after

Table 1.
Demographic information for participants in study 1.

Group	*n*	Sex (Female:Male)	Age, yr (Mean ± SD)	BMI (Mean ± SD)	Dysarthria Severity* (Mean ± SD)
Flaccid	13	5:8	56.5 ± 22.8	27.3 ± 3.9	1.0 ± 0.0
Flaccid-Spastic	25	13:12	57.9 ± 12.4	30.2 ± 8.0	1.9 ± 1.2
Ataxic	11	4:7	56.6 ± 10.8	31.4 ± 5.8	1.4 ± 0.6
Hypokinetic	14	2:12	63.5 ± 11.3	26.2 ± 5.7	1.6 ± 0.6
Spastic	7	3:4	64.9 ± 8.23	25.7 ± 3.8	2.3 ± 1.1
Total	70	27:43	59.3 ± 14.2	28.7 ± 6.25	1.6 ± 0.9

*Dysarthria severity ranged from 0 (normal speech) to 4 (severely deviant).
BMI = body mass index, SD = standard deviation

deformation as demonstrated by the reduction in amplitude of an oscillation from one wave peak to the next (e.g., if the second peak was half the size of the first, ln(2/1) = 0.693). Decrement is inversely proportional to elasticity. The magnitude of the *stiffness* coefficient (also described in the "Introduction" section) correlates with tissue tension relative to the Myoton-3's known deformation force. For each site of data acquisition, an internal algorithm determined which trial was closest to the arithmetic mean of the three pulse perturbations. The data from that trial were internally saved and downloaded to a laboratory computer.

Procedures

In addition to any tone-related impressions recorded by the treating clinician as part of the motor speech assessment, participants underwent a perceptual evaluation of muscle tone by an experienced research SLP (H. C.) at the Mayo Clinic. The appearance of facial muscles at rest (droop and lip retraction) was rated on a scale of 0 to 4 (normal to severe). In addition, tissue bulk and resistance to passive stretch were rated on a scale of –4 to 4 (severely low to severely high). The investigator rated tongue and cheek bulk (thickness) by palpating the tissue between the forefinger and thumb, and passive resistance of the tongue, cheeks, and upper and lower lips by grasping the tissue and slowly elongating it. To confirm reliability of these perceptual ratings, they were compared with those reported in the medical record by the Mayo Clinic SLP conducting the motor speech evaluation (e.g., facial droop, dystonic jaw, abnormal resting tongue posture or movement).

Instrumental measures of tissue stiffness were obtained from all participants by using the Myoton-3 in the following sequence: left cheek, left masseter, left superior surface of tongue, right cheek, right masseter, right superior surface of tongue, right upper lip, right lower lip, left upper lip, and left lower lip. Participants were seated upright in a comfortable chair with feet flat on the ground and remained relaxed throughout data collection. The head was in a neutral position for lip and tongue measures; for cheek and masseter measures, the head was tilted to the left or right so that the Myoton-3 probe was angled no more than 45° toward the ground as it approached the tissue surface. During data acquisition, a wooden tongue blade was positioned under the relevant area of tissue, excluding masseter and lower lip. Measurements from the superior surface of the tongue were obtained with the mouth open and the Myoton-3 probe tip placed ~5–7 mm posterior to the tongue tip and ~3–4 mm lateral to midline (**Figure 1(a)**). For the upper lip, the probe tip was placed on the vermillion border ~5–7 mm lateral to midline (**Figure 1(b)**). Lower lip measures were taken from the middle of the vermillion, ~5–7 mm lateral to midline (**Figure 1(c)**). The probe tip was placed on the cheek ~10–15 mm lateral to the lip angle, avoiding natural creases in the skin when the underlying muscles (risorius, buccinator, platysma) contracted (**Figure 1(d)**). The masseter test site was selected by identifying the center of the most prominent palpable bulge during contraction (**Figure 1(e)**).

Data Analysis

Perceptual data were categorized for abnormally low tone, normal tone, and abnormally high tone. Ratings of –1, 0, and 1 were considered to be within normal limits. Facial droop from 2 to 4 and tissue bulk and passive resistance from –2 to –4 were considered indicative of low muscle tone. Resting lip retraction of 2 to 4 and bulk and passive resistance of 2 to 4 were interpreted as high muscle tone. Cheek tissue bulk was removed from consideration because ratings appeared to reflect assessment

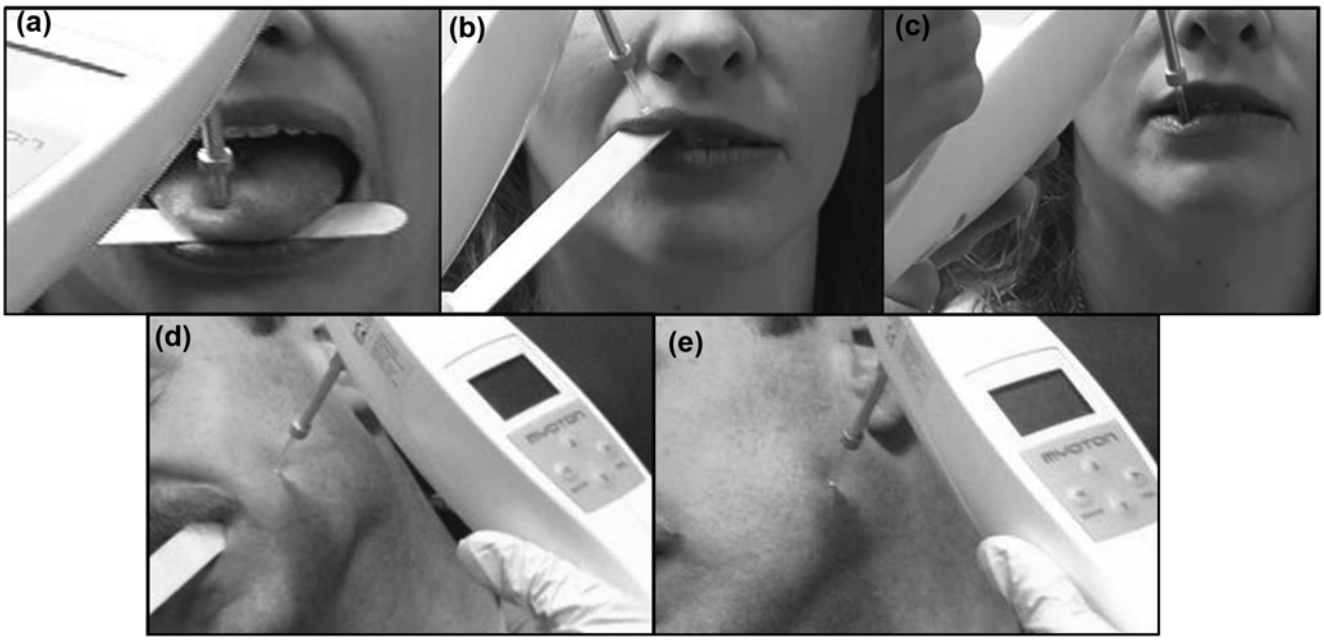

Figure 1.
Procedures for Myoton-3 data collection from **(a)** superior surface of tongue, **(b)** upper lip, **(c)** lower lip, **(d)** cheek, and **(e)** masseter.

of adipose tissue (fat pads) more so than muscle. Perceptual ratings for five tasks (resting appearance, tongue thickness, cheek resistance, upper-lip resistance, lower-lip resistance) were analyzed descriptively.

Instrumental determination of stiffness, frequency, and decrement from each tissue site were downloaded from the Myoton-3 and imported to SPSS (version 21, IBM Corporation; Armonk, New York) for further analysis. After testing the requisite assumptions, analyses of variance (ANOVAs) with diagnostic category as a between-subjects factor were calculated to assess participant characteristics and for Myoton-3 measures by side, site, and outcome variable. For any significant main effects pertaining to the instrumental data, pairwise comparisons were assessed with post hoc Fisher least significant difference (LSD) tests. An alpha level of 0.05 was established for statistical significance.

Results and Interpretation

Preliminary Analysis

Participant characteristics across groups were compared using one-way ANOVAs. Neither age ($F_{4,65}$ = 0.851, p = 0.50) nor body mass index ($F_{4,58}$ = 1.893, p = 0.12) differed across groups. For dysarthria severity, post hoc tests indicated that the statistically significant ANOVA result ($F_{4,64}$ = 3.357, p = 0.02) was attributable to differences between the mixed flaccid-spastic and flaccid groups (p = 0.003) and between the spastic and flaccid groups (p = 0.005), wherein individuals with flaccid dysarthria had significantly lower severity scores than either of these groups. Additionally, the spastic group had significantly more severe dysarthria than the ataxic group (p = 0.049).

Perceptual Ratings

A summary of the perceptual evaluation of muscle tone is provided in **Table 2**. Muscle tone was judged to be abnormal for at least one rating for 13 (19%) of all participants, with the highest prevalence in the flaccid (31%) followed by the flaccid-spastic (24%) and hypokinetic (21%) dysarthria groups. No participants in the ataxic or spastic groups had discernible muscle tone abnormalities. Ratings indicated abnormally low tone, but only for a single task, for two participants in the flaccid group (unilateral), three in the flaccid-spastic group (bilateral), and one in the hypokinetic dysarthria group (bilateral). Muscle tone was judged to be abnormally high, again only for a single task, for one participant in the flaccid group (unilateral), three in the flaccid-spastic

Table 2.
Number of participants with perceptual ratings of abnormal muscle tone by dysarthria type.

Dysarthria Group	*n*	≥1* Abnormal Rating, *n* (%)	Resting Facial Posture, *n*	Cheek Resistance, *n*	Upper-Lip Resistance, *n*	Lower-Lip Resistance, *n*	Tongue Thickness, *n*
Flaccid	13	4 (31)	↓ 2	↓ 1	↓ 1	↓ 2	↑ 1
Flaccid-Spastic	25	6 (24)	↑ 2, ↓ 3	↑ 1	—	—	—
Ataxic	11	0	—	—	—	—	—
Hypokinetic	14	3 (21)	—	↑ 1	↑ 1	↓ 1	—
Spastic	7	0	—	—	—	—	—

*One participant with flaccid dysarthria had >1 abnormal rating.
↑ = higher than normal, ↓ = lower than normal.

group (bilateral), and two in the hypokinetic (bilateral) dysarthria group. Only one participant in the study had ratings of abnormal muscle tone for more than one task: an 18 yr-old female with mild flaccid dysarthria due to myotonic dystrophy received 4 out of 5 abnormally low tone ratings, all bilaterally. Given the low number of abnormal ratings, these data were inappropriate for inferential statistical evaluation or for correlational analysis with the instrumental results.

Instrumental Measures

Instrumental measures of stiffness, frequency, and decrement also failed to reveal significant differences between diagnostic categories. ANOVAs for each tissue site and outcome measure yielded *p*-values ranging from 0.06 to 0.78. Summary descriptive statistics for instrumental measures of stiffness, frequency, and decrement are presented in **Appendices 1**, **2**, and **3**, respectively (available online only). Tissue stiffness values tended to be higher in individuals with flaccid dysarthria than in those with spastic or hypokinetic dysarthria. For example, **Figure 2** illustrates actual stiffness measures obtained from the superior surface of the tongue, as well as predicted values based on diagnostic criteria for the various dysarthrias and what is known of their neurological underpinnings. Left-right differences were observed for virtually all structures and diagnostic groups across outcome measures (*p*-values ranged from <0.001 to 0.03, with two exceptions: masseter decrement [$p = 0.72$] and upper-lip stiffness [$p = 0.07$]).

Interpretation of Study 1 Results

Results of the perceptual assessment of orofacial muscle tone did not detect the abnormalities expected based on previous literature and classification systems for the dysarthrias [3,39,51–53]. Furthermore, there was

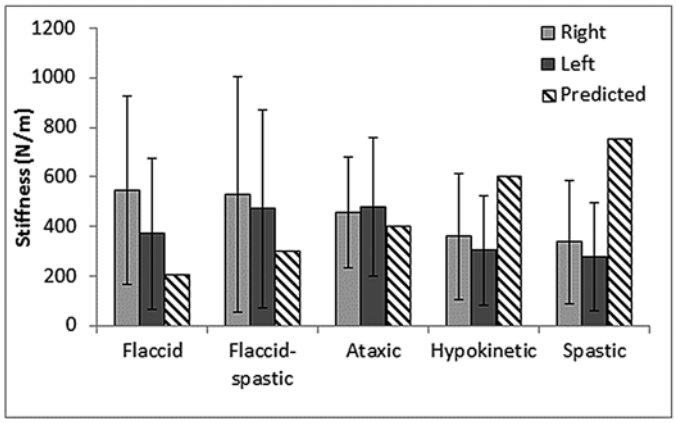

Figure 2.
Predicted and actual Myoton-3 stiffness measures from right and left superior tongue surfaces by dysarthria type in study 1. Predicted values were developed using presumed neuromuscular characteristics associated with neuropathophysiology for each dysarthria type. Error bars: ±1 standard deviation.

no clear relationship between dysarthria type and orofacial muscle stiffness as assessed with the Myoton-3 and some results were contradictory.

Perceptual tone abnormalities were difficult to ascribe with confidence and were recorded in a small minority of participants from all groups and structures. Only one participant, with myotonic dystrophy and mild flaccid dysarthria, had clear and consistent ratings of abnormal muscle tone, including bilateral facial droop and lower than normal cheek and lip resistance. Incidentally, assessment of tongue and lip strength also yielded abnormally low values for this participant (13 and 7 kPa, respectively, using the Iowa Oral Performance Instrument [IOPI Medical; Redmond, Washington]; normal averages for young women are 55.8 and 27.5 kPa, respectively

[54]). Instrumental assessment of muscle tone (stiffness at rest) for this participant did not correspond with the perceptual ratings or the differences in tone that would be expected based on this participant's medical diagnosis, except perhaps for the tongue. Stiffness values from Myoton-3 testing fell within ~25 percent of the mean for the flaccid dysarthria group for all measures except the superior surface of the tongue, which was 2.5 times lower. As described in studies 2 and 3, however, this assessment for the tongue is suspect.

By definition, spasticity is associated with higher contractile properties within muscle tissue while at rest and therefore should yield higher stiffness and lower compliance values, whereas flaccidity is associated with lower resting muscle activity, lower tissue stiffness, and higher tissue compliance. In the present study, Myoton-3 results were contrary to predictions and exhibited unexplainable asymmetries. In particular, measurements taken from the superior surface of the tongue revealed stiffness values that were highest for the flaccid and flaccid-spastic dysarthria groups and lowest for the hypokinetic and spastic dysarthria groups. This is opposite the expected pattern and begs explanation. Previous studies using instrumental measures of muscle tension have confirmed lower than normal tissue compliance in spastic muscles as well as in volitionally contracted muscles. The Myotonometer identified statistically significantly increased resistance to stretch in the involved versus uninvolved biceps brachii muscles of individuals with spasticity due to UMN disorders [43] and in contracted versus relaxed biceps of healthy adults [43,55]. In orofacial musculature, the Myotonometer also detected significantly lower tissue compliance in contracted versus relaxed submental musculature [44].

A second study was developed to establish whether the unexpected results from study 1 were related to the Myoton-3's ability to detect orofacial stiffness, confounds associated with the complex nature of a dysarthric population, or both. On the basis of previous studies that demonstrated predictable differences in muscle stiffness for contracted versus relaxed musculature, investigators evaluated orofacial muscle stiffness in the masseter, cheek, and tongue. Stiffness measures were anticipated to be greater during contraction than relaxation.

STUDY 2

Methods

Participants

Ten adults (5 women, 5 men; age: range 26–58 yr, mean 42.1 yr) were recruited from volunteers at the Walter Reed National Military Medical Center. Participants in study 2 were at least 18 yr of age with no history of neurological insult or disease, speech or swallowing disorders, or structural anomalies of the mouth.

Procedures

Stiffness assessment was conducted on the tongue (superior and lateral aspects), cheek, and jaw muscles bilaterally in relaxed and contracted states. With the participant seated and a wooden tongue blade positioned under the tongue for support, the superior aspect of the tongue was tested in a relaxed state as described in study 1 and illustrated in **Figure 1(a)**. Subsequently, measures were taken while the participant contracted the tongue by pressing downward against the blade. For the remaining measures, the participant assumed a sidelying position on a fully reclined examination chair, as described and illustrated previously [51]. Each structure was assessed in the relaxed followed by the contracted state in this order: tongue, cheek, masseter; left then right sides. The sequence was fixed to facilitate data-collection efficiency with the Myoton-3, and the relaxed condition was always conducted first to avoid residual tension from the contracted trials. The wooden blade was positioned vertically between the teeth on the opposite side to support the tongue body during relaxation and to provide a stable surface to press the tongue against during contraction. Myoton-3 measures were obtained from the thickest part of the lateral aspect of the tongue, taking care to avoid contacting the teeth or lips with the probe. The target sites for the cheek and jaw were determined by palpating the contracted muscles and marking the overlying skin with a washable skin pen. For the cheek, the wooden tongue blade was placed between the cheek and lateral teeth, and the target site was 15–30 mm lateral to the lip angle, avoiding natural creases during contraction. For the masseter, the target site was in the center of the most prominent bulge during contraction. The probe approached the tissue as perpendicularly as possible at all sites.

Data Analysis

Stiffness, frequency, and decrement values from the Myoton-3 were imported to SPSS. A two-way repeated-measures ANOVA, with contraction status (relaxed, contracted) and side (left, right) as the within-subjects factors, tested for differences in each of the three Myoton-3 outcome measures.

Results and Interpretation

No significant right-left differences or interaction effects between side and contraction status were observed for any of the measurement sites ($p > 0.05$). Each site exhibited statistically significant differences in stiffness, frequency, and decrement across contraction status (ranges of $F_{1,36} = 6.056$ to 62.166 and $p < 0.001$ to 0.02). **Figure 3** illustrates mean values by structure and contraction status. Post hoc pairwise comparisons revealed significant differences ($p < 0.05$) across contraction status for each of the 12 pairs. For the lateral tongue, cheek, and masseter, stiffness and frequency were significantly greater during contraction than in the relaxed condition. In contrast, superior tongue surface values for stiffness and frequency were greater during relaxation versus contraction. Decrement measures were significantly smaller in the contracted condition for all four sites.

Stiffness, frequency, and decrement values for the lateral tongue, cheek, and masseter changed in the expected manner, with increased stiffness and frequency and decreased decrement during observable contraction of the target muscles. In contrast, measures of stiffness and frequency from the superior tongue surface were significantly smaller during contraction, even though muscle contraction was obvious per observation and palpation by experienced clinicians. This paradoxical result supported methodological considerations as a potential cause for the unpredicted results in study 1.

During data collection, tongue thickness in the lateral plane appeared to be minimally affected by contraction state on visual inspection, but changed perceptibly in the superior-inferior plane. To confirm these observations, digital calipers (CP9806-TF, Carrera Precision; Padova, Italy) were positioned at the thickest portions of the tongue and cheek during relaxed and contracted states in a subgroup of three participants. Tissue thickness increased 116 percent from the relaxed to the contracted state for the superior-to-inferior tongue dimension (mean = 6 and 13 mm, respectively) and 25 percent for the external-to-internal dimension of the cheek (mean = 8 and 10 mm, respectively). The thickness of the tongue across the lateral dimension did not differ substantially between the relaxed and contracted conditions (mean = 36 and 33 mm, respectively, an 8% decrease).

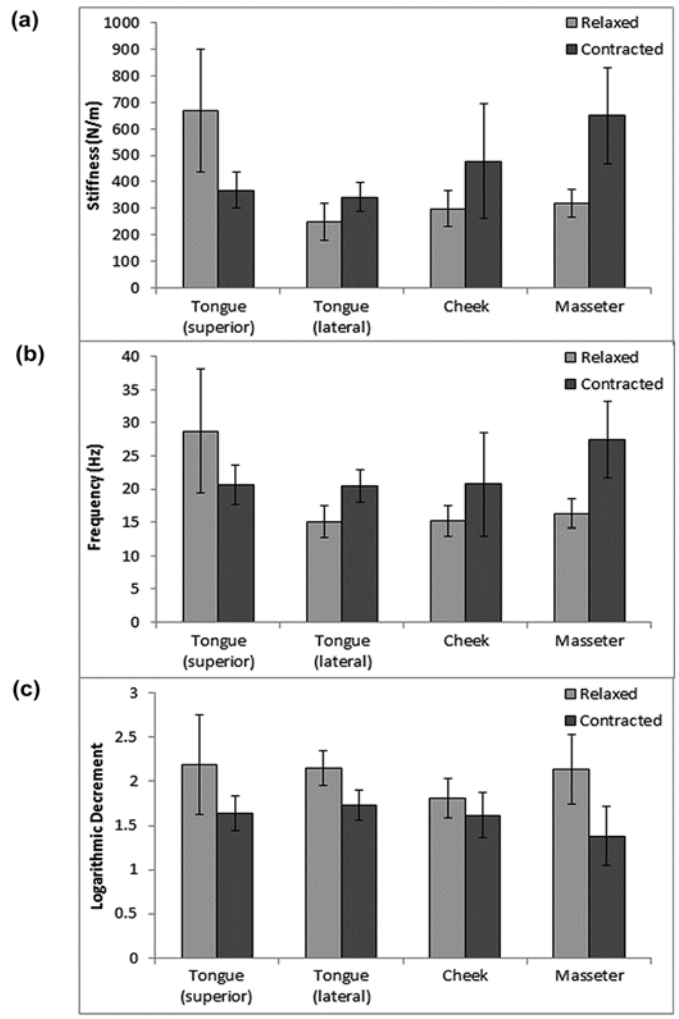

Figure 3.
Myoton-3 **(a)** stiffness, **(b)** frequency, and **(c)** decrement measures at each tissue site from neurotypical adults during contraction and relaxation in study 2. Each pairwise comparison was statistically significant at $p < 0.05$. Error bars: ±1 standard deviation.

We speculated that the marked difference in tissue thicknesses for the tongue in the sagittal plane might account for the unexpected results from the superior tongue site in study 1, as well as in study 2. Specifically, thinner tissues might allow interference from the wooden tongue blade used as a platform for the tissue during

measurement. This would explain greater stiffness values than expected in persons with neurological disorders associated with low muscle tone and atrophied muscles and from the superior surface of the tongue despite an obviously softer (more compliant) structure when relaxed than when contracted. This suspicion led to a third experiment designed to assess the effects of tissue thickness on stiffness, frequency, and decrement measures obtained with the Myoton-3 using a surrogate for in vivo muscle tissue.

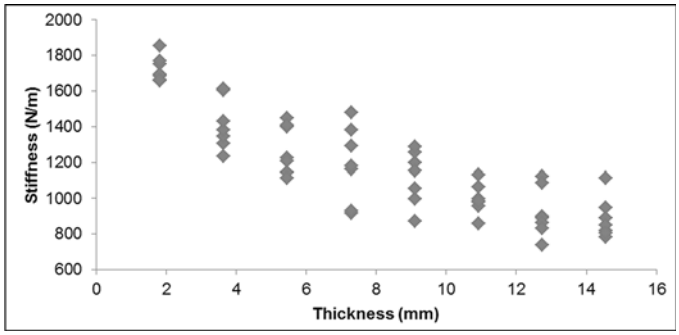

Figure 4.
Myoton-3 stiffness measures of sliced roast beef by tissue thickness in study 3. Stiffness was tested for six trials, plotted individually, at eight thicknesses.

STUDY 3

Methods

Procedures

Sliced roast beef from a delicatessen was selected as an experimental material because of similarities between bovine and human muscle tissue [56], relatively consistent thickness (mean = 1.8 mm/slice), and an absence of neuromuscular innervation or vascularization. The elasticity and shear resistance properties of heat-exposed meat are more similar to those of in vivo muscle tissue because of the communal aggregation induced by the cooking process [57], whereas raw meat was unable to maintain its structure during thin slicing and repeated poking from the Myoton-3 probe. The beef slices were laid flat on a table and stacked/removed individually to achieve eight different thicknesses of material six times each in a variety of orders. Myoton-3 measures of stiffness, frequency, and decrement were obtained with each replication of each stack thickness.

Data Analysis

Tissue thickness and mean stiffness, frequency, and decrement values from the Myoton-3 were imported to SPSS. Differences in each of the outcome variables across material thicknesses were assessed via one-way ANOVA and post hoc LSD tests.

Results and Interpretation

Stiffness differed significantly across thickness ($F_{7,48}$ = 29.123, $p < 0.001$). As illustrated in **Figure 4**, stiffness generally decreased as thickness increased. Post hoc tests confirmed that stiffness differed significantly from increments between 1.8 mm (one slice) to 9.1 mm (five slices) (**Table 3**), but failed to reach significance for thicker stacks. Frequency ($F_{7,48}$ = 41.040, $p < 0.001$) and decrement ($F_{7,48}$ = 3.887, p = 0.002) also differed significantly. Post hoc testing (**Tables 4** and **5**) revealed that frequency values differed significantly for 1–4 slices (up to 7.3 mm) and decrement values did not exhibit a clear pattern of differences across tissue thickness.

Trials using sliced roast beef enabled researchers to isolate muscle tissue thickness from other factors such as changes in vascularity and innervation that could influence tissue stiffness. Results from this experiment supported the hypothesis that tissue thickness directly affected Myoton-3 results. For the tested material, stacked tissue that totaled less than 10 mm exhibited significantly different stiffness values that could only be attributed to the hardness of the supporting table. The results for the stiffness and frequency parameters stabilized for tissue thickness exceeding 10 mm.

DISCUSSION

The Myoton instrument was originally designed for assessing tone in larger limb and truncal muscles. Indeed, studies have reported high reliability, symmetry, and validity for Myoton measures in the rectus femoris, biceps femoris, and gastrocnemius muscles [58–60]. Additionally, the Myoton-3 has successfully discriminated between on-off responses to medication and subthalamic stimulation in individuals with Parkinson disease for relaxed arm and hand muscles [61–62] and compared with healthy, matched controls [12,63]. Based on this

Table 3.
Post hoc comparisons (Fisher least significant difference) of stiffness by tissue thickness from study 3. Statistically significant results ($p < 0.05$) are italicized.

Thickness (mm)	Thickness (mm)						
	3.6	**5.5**	**7.3**	**9.1**	**10.9**	**12.7**	**14.6**
1.8	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
3.6		0.07	*0.004*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
5.5			0.24	*0.03*	*<0.001*	*<0.001*	*<0.001*
7.3				0.32	*0.01*	*0.001*	*<0.001*
9.1					0.11	*0.01*	*0.003*
10.9						0.29	0.14
12.7							0.67
14.6							

Table 4.
Post hoc comparisons (Fisher least significant difference) of frequency by tissue thickness from study 3. Statistically significant results ($p < 0.05$) are italicized.

Thickness (mm)	Thickness (mm)						
	3.6	**5.5**	**7.3**	**9.1**	**10.9**	**12.7**	**14.6**
1.8	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
3.6		0.08	*0.004*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
5.5			0.24	*0.04*	*0.001*	*<0.001*	*<0.001*
7.3				0.37	*0.03*	*0.01*	*0.006*
9.1					0.17	0.08	0.05
10.9						0.72	0.57
12.7							0.83
14.6							

Table 5.
Post hoc comparisons (Fisher least significant difference) of decrement by tissue thickness from study 3. Statistically significant results ($p < 0.05$) are italicized.

Thickness (mm)	Thickness (mm)						
	3.6	**5.5**	**7.3**	**9.1**	**10.9**	**12.7**	**14.6**
1.8	*<0.006*	*<0.001*	*<0.001*	*0.003*	*0.001*	0.06	0.17
3.6		0.35	0.25	0.76	0.49	0.33	0.15
5.5			0.83	0.53	0.81	0.06	*0.02*
7.3				0.40	0.65	*0.04*	*0.01*
9.1					0.70	0.20	0.08
10.9						0.10	*0.04*
12.7							0.62
14.6							

previous work, we hypothesized that measures of tissue stiffness obtained with the Myoton-3 would reflect differences in orofacial muscle tone typically associated with specific dysarthria types. Instead, the data from study 1 suggested the opposite; individuals with spastic and hypokinetic dysarthria, typically considered to have abnormally high tone, had lower orofacial stiffness values on average than did individuals with flaccid dysarthria,

which is characterized by abnormally low tone. Individuals with mixed flaccid-spastic dysarthria also had higher-than-predicted stiffness values, given that all but two of them had a medical diagnosis of amyotrophic lateral sclerosis, a disease that often presents with markedly weak, atrophied tongue muscle.

Two additional studies were developed to explore possible causes for these perplexing results. Study 2 compared stiffness during muscle relaxation and contraction in neurotypical individuals. The cheeks, masseters, and tongue when measured in the lateral aspect exhibited the predicted pattern of higher stiffness measures during contraction, whereas the tongue when measured from the superior surface did not. A paradoxical finding was that contraction of the tongue yielded lower values when stiffness was measured in the lateral dimension, but higher values when measured in the superior-inferior dimension. The apparent difference was that of tissue thickness, which led to study 3. This study used nonviable (bovine) muscle tissue and identified a tissue thickness threshold of approximately 10 mm above which Myoton-3 measures stabilized. The results of study 3 facilitate a reasonable interpretation of study 2's results (contraction vs relaxation), particularly with regard to differences across measurement sites. For the cheek, stiffness measures differed in the anticipated direction during contraction. Although cheek thickness during relaxation fell below the 10 mm threshold for three neurotypical adults, it increased by only 2 mm on average during contraction and then only averaged 10 mm. It is possible that because there was relatively little contraction-related difference in thickness at the cheek site, any contribution to the stiffness measures that was attributed to the underlying wooden tongue blade affected the relaxation and contraction stiffness measures similarly. Thus, the thickness-related confound identified during study 3 may not have affected Myoton-3 stiffness measures for the cheek. On the other hand, tongue thickness in the superior-inferior plane more than doubled during contraction, straddling the 10 mm cutoff. Thus, measures taken during relaxation were probably contaminated by the underlying stick, whereas stiffness data obtained from the superior tongue while contracted likely reflected muscle tissue properties alone.

The implications from studies 2 and 3 lend further insights to the interpretation of the results from study 1. Spastic and hypokinetic dysarthria are presumably characterized by spasticity and rigidity, respectively, both of which are considered to involve abnormally high muscle contraction/tone at rest. Caliper measures for a few participants and visual observation for all participants in study 2 confirmed that orofacial tissue is thicker when contracted. If, as expected, the resting state contractile properties of orofacial muscles in individuals with spasticity and rigidity are greater than normal, then their muscles might be thicker than in neurologically normal individuals and in people with lower muscle tone. Thus, Myoton-3 measures from the orofacial tissues of these dysarthria groups may experience less interference due to tissue thickness confounds. Flaccid dysarthria is linked to LMN damage, which can lead to abnormally low resting muscle tension ("floppiness") and eventually muscle atrophy; therefore, those in the flaccid dysarthria group may have thinner tissue than the other cohorts [64] and thus stiffness measures may be artificially inflated at some thin muscle sites. Individual variation in age-related sarcopenia, general body composition, and disease severity may also have affected stiffness values in these relatively small diagnostic cohorts. The SLP's perceptual judgments of tongue thickness from participants in study 1 were not predictive of Myoton-3 results, but calipers or ultrasound could be used in future studies to better quantify tissue differences.

CONCLUSIONS

Taken together, this series of experiments highlights challenges in obtaining reliable and clinically meaningful subjective and objective data about tissue stiffness as a correlate of muscle tone and offers a potential explanation for the unexpected stiffness measures obtained with the Myoton-3 from groups of dysarthric speakers. Stiffness measurements from the superior tongue surface appear to be vulnerable to thickness-related confounds, so future investigations of tongue stiffness would benefit from a lateral approach. Using the principles outlined here, further assessment of orofacial muscle tone in clinical populations may help guide the eventual quantification of orofacial muscle tone across diagnostic groups.

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