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Research Article

Jaw Rotation in Dysarthria Measured With a Single Electromagnetic Articulography Sensor

Jeff Berry,[a] Andrew Kolb,[b] James Schroeder,[b] and Michael T. Johnson[b]

Purpose: This study evaluated a novel method for characterizing jaw rotation using orientation data from a single electromagnetic articulography sensor. This method was optimized for clinical application, and a preliminary examination of clinical feasibility and value was undertaken.
Method: The computational adequacy of the single-sensor orientation method was evaluated through comparisons of jaw-rotation histories calculated from dual-sensor positional data for 16 typical talkers. The clinical feasibility and potential value of single-sensor jaw rotation were assessed through comparisons of 7 talkers with dysarthria and 19 typical talkers in connected speech.
Results: The single-sensor orientation method allowed faster and safer participant preparation, required lower data-acquisition costs, and generated less high-frequency artifact than the dual-sensor positional approach. All talkers with dysarthria, regardless of severity, demonstrated jaw-rotation histories with more numerous changes in movement direction and reduced smoothness compared with typical talkers.
Conclusions: Results suggest that the single-sensor orientation method for calculating jaw rotation during speech is clinically feasible. Given the preliminary nature of this study and the small participant pool, the clinical value of such measures remains an open question. Further work must address the potential confound of reduced speaking rate on movement smoothness.

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The establishment of useful, objective measures of articulatory performance requires data-acquisition and analysis methods that are feasible for clinicians. Electromagnetic articulography (EMA) provides a means for characterizing tongue, lip, and jaw movements. EMA data may have unique clinical value in the assessment and treatment of motor speech disorders (Green, 2015; Green et al., 2013; Tilsen, Das, & McKee, 2015; Weismer, Yunusova, & Bunton, 2012). Although substantial work has developed methods for using EMA, nearly all EMA-based analyses rely exclusively on sensor-position data (cf. Henriques & van Lieshout, 2013; Kroos, 2009). Three-dimensional EMA systems provide sensor-orientation data in addition to position data (Berry, 2011a; Kolb, Johnson, & Berry, 2015; Kroos, 2009). Yet a lack of demonstrated methods for using sensor-orientation data has limited potential clinical applications. The current work presents a novel use of EMA sensor-orientation data to objectively characterize physiological aspects of jaw movement in dysarthria.

Physiological Measures in Dysarthria Assessment

The notion that physiological measures may be important for characterizing dysarthria has existed since well before the 1960s (Duffy, 2006). Yet the pioneering works of Hardy (1967), and Darley, Aronson, and Brown (1969a, 1969b, 1975) have provided the impetus for various approaches to physiological characterization of dysarthria (Abbs, Hunker, & Barlow, 1983; Ballard, Solomon, Robin, Moon, & Folkins, 2009; Barlow, 1998; Dietsch et al., 2014; Duffy, 2013; Folkins et al., 1995; Hirose, 1986; Kent, 1996, 2009, 2015; Kent & Rosen, 2004; Luschei, 1991; Murdoch, 2010; Netsell & Daniel, 1979; Robin, Somodi, & Luschei, 1991; Rosenbek & LaPointe, 1985; Solomon, Clark, Makashay, & Newman, 2008; Theodoros, Murdoch, & Horton, 1999; Weismer & Kim, 2010). The Mayo Clinic classification system for motor speech disorders (Darley et al., 1969a, 1969b, 1975; Duffy, 2013) focuses on perceptual assessment techniques and seeks to infer physiologic correlates of disordered speech signs and symptoms. This system supports the notion that physiologic information about the involved speech subsystems is

[a]Department of Speech Pathology & Audiology, Marquette University, Milwaukee, WI
[b]Department of Electrical & Computer Engineering, Marquette University, Milwaukee, WI
Correspondence to Jeff Berry: jeffrey.berry@marquette.edu

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clinically relevant. The widely embraced principle of targeting individually defined pathophysiologic features of the speech subsystems in dysarthria treatment is a common justification for physiologic assessment (DePaul & Abbs, 1989; Netsell & Rosenbek, 1985; Rosenbek & Jones, 2009; Theodoros et al., 1999).

Perceptual assessments of dysarthria are a mainstay of clinical practice (Duffy, 2006; Duffy & Kent, 2001; Kent, 2009; Simmons & Mayo, 1997). Yet there are noteworthy limitations on the use of perceptual assessments, reflecting the challenge of dissociating multiple, co-occurring dimensions (respiratory, phonatory, resonatory, articulatory, prosodic, etc.), variations in the procedures and scaling systems associated with different perceptual assessment tools, and limits on the availability and effectiveness of clinical training that affect reliability (Kent, 1996; Zeplin & Kent, 1996; Zyski & Weisiger, 1987). Moreover, research on dysarthria has frequently reported discrepancies between inferred and objectively measured physiologic features of dysarthria that may reflect limits on the adequacy of perceptual inference when used in isolation (Kent, Kent, Duffy, & Weismer, 1998; Weismer & Kim, 2010). Thus, measurement of physiologic aspects of speech that can objectively characterize pertinent features of sensorimotor performance may be critical to the accurate characterization of speech deficits in dysarthria.

Relatively many physiologic approaches have already been cited, but these systems differ conceptually and practically, particularly with respect to the level of analysis, assessment tasks, and instrumentation. A detailed discussion of these differences is beyond the scope of this article, but in general, pertinent physiologic processes are presumed to be characterized by measures of articulatory movement velocity, amplitude (range of motion), accuracy, smoothness, coordination, and muscle strength and tone (see Kent & Rosen, 2004). The phrase *articulatory kinematics* refers to measures of articulatory movement without information about the causal forces underlying those movements. These measures can be examined using various instruments. Whereas many such tools have been used primarily in research laboratories, because they are expensive and inefficient and require specialized training, direct measures of articulatory kinematics can now be obtained from talkers with dysarthria using instrumentation and methods that are increasingly cost effective and practical to implement within clinical environments.

Levels of Analysis and the Potential Value of Kinematic Measures

A distinct advantage of kinematic data is that some kinematic measures of performance are more directly interpretable than corresponding metrics from acoustic and perceptual levels of analysis. For example, articulatory-movement velocity and amplitude are direct measures of the speed and range of articulatory movements that have often been shown to differentiate healthy and disordered speech (Weismer et al., 2012). One might assume that perceived changes in speaking rate correspond to predictable changes in articulatory movements; however, the kinematic changes exhibited by typical, healthy talkers to change speaking rate are quite complex and idiosyncratic and only sometimes seem to follow such straightforward expectations (see review in Berry, 2011b). Moreover, there are clinical examples in which perceived reductions in speaking rate can sometimes be associated with increases in articulatory-movement velocity (Yunusova et al., 2010), as well as examples where articulatory-movement velocities are reduced despite perceived increases, or no differences, in speaking rate (Forrest, Weismer, & Turner, 1989; Walsh & Smith, 2012).

At the acoustic level of analysis, articulatory-movement velocity and amplitude tend to correlate with measures of slope of the second formant (F2). Recent work examining the acoustics of dysarthria (Kim, Kent, & Weismer, 2011; Kim, Weismer, Kent, & Duffy, 2009; Lansford & Liss, 2014) demonstrates that, whereas acoustic metrics such as F2 slope may differentiate healthy and disordered speech and may be sensitive to changes in dysarthria severity, there is limited support for using such a measure to differentiate by disease or dysarthria subtype. Among several acoustic measures, Lansford and Liss (2014) found that only measures of F2 slope show statistically significant differences between patient groups, suggesting that both temporal and spectral aspects of speech may be pertinent to characterizing differential aspects of dysarthria subtypes.

F2 slope reflects time-varying aspects of articulatory movement and is therefore an intuitive correlate of articulator velocity and amplitude. However, because F2 slope reflects the concomitant influences of multiple articulators (i.e., tongue, lips, jaw), such a measure may not be optimal for dissociating articulator-specific deficits (e.g., relatively poorer lip-movement control than tongue) and would not necessarily be sensitive to the sort of interarticulatory compensatory responses that have been hypothesized on the basis of kinematic studies of talkers with dysarthria. Such compensatory, adaptive behaviors are unlikely to reflect explicit strategies used by talkers with disordered speech, because similar articulatory trading relations occur in typical speech across examples of the same phoneme produced in different phonetic environments, to minimize acoustic variability using strategic trade-offs between articulator movements (Guenther et al., 1999; Perkell, 2012; Perkell, Matthies, Svirsky, & Jordan, 1993). It stands to reason that compensatory articulatory changes that occur in response to speech impairment resulting from disease may also exploit existing sensorimotor control strategies if one articulator is more compromised than another. Because kinematic measures can be used to differentiate between multiple articulators, they would be sensitive to subtle movement trade-offs between articulators that may not be detectable acoustically or perceptually.

Another important consideration regarding the potential value of kinematic measures relates to the nature of the dysarthria being assessed. Certain examples of dysarthria are characterized by production deficits that are catastrophic for acoustic and perceptual measures. As an example, severe impairment in voice quality can substantially compromise typical methods for formant tracking, so although the phonatory component of a dysarthria may be readily characterized using acoustic and perceptual measures, the articulatory component of such a dysarthria may be best measured kinematically, because the detrimental effects of severe voice-quality impairment may mask articulatory deficits acoustically and perceptually.

Perceptual and acoustic measures are most certainly easier and more cost effective to obtain than kinematic measures. Moreover, they are able to reflect the net abilities of the speech mechanism, suggesting that they are more likely to provide a measure of overall disability and characterize how well the speech subsystems operate collectively. Thus, the limitations of not being able to characterize articulator-specific deficits or circumstances in which specific deficits may mask acoustic and perceptual assessments are certainly not reasons to justify only kinematic measures of performance. All three levels of analysis most certainly have value and contribute uniquely to the process of assessment.

Jaw Kinematics and Dysarthria

Characteristics of jaw kinematics offer a context for using sensor orientation, because jaw movements have substantial rotation reflecting an independent level of sensorimotor control (Edwards & Harris, 1990; Vatikiotis-Bateson & Ostry, 1995; Westbury, 1988). Despite the relative simplicity of jaw movement compared to other articulators, such as the tongue, jaw movements reflect an active sensitivity to both segmental and suprasegmental aspects of speech (Lim, Lin, & Bones, 2006; Mooshammer, Hoole, & Geumann, 2007). Moreover, within the available literature on the kinematics of dysarthria, a relatively large proportion has studied the jaw or the jaw-and-lower-lip complex, due to the accessibility of these structures.

In general, it is well established that jaw movements are affected in dysarthria. Movement velocities of the jaw (or jaw and lip) have been observed to be reduced in talkers with Parkinson's disease compared with neurologically healthy talkers (Caligiuri, 1987; Connor, Abbs, Cole, & Gracco, 1989; Forrest et al., 1989; Forrest & Weismer, 1995; Walsh & Smith, 2012). Reduced movement velocities have also been reported for talkers with cerebellar disease (Ackermann, Hertrich, Daum, Scharf, & Spieker, 1997; Hirose, Kiritani, & Sawashima, 1982b; Hirose, Kiritani, Ushijima, & Sawashima, 1978; Kent & Netsell, 1975), amyotrophic lateral sclerosis (ALS; Mefferd, Green, & Pattee, 2012; Yunusova, Weismer, Westbury, & Lindstrom, 2008), cerebral palsy (Kent & Netsell, 1978; Rong, Loucks, Kim, & Hasegawa-Johnson, 2012), and traumatic brain injury (TBI; Kent, Netsell, & Bauer, 1975; Loh, Goozée, & Murdoch, 2005; Murdoch & Goozée, 2003).

Increased amplitude of jaw movements has been reported for some talkers with ALS (DePaul, Abbs, Caligiuri, Gracco, & Brooks, 1988; Hirose et al., 1982a; Kent et al., 1975; Mefferd et al., 2012), in addition to context-specific increases or decreases in jaw-movement amplitude during word recitation coupled with generally reduced jaw-movement velocities (Yunusova et al., 2008). In a small-scale longitudinal study of disease progression in ALS, Yunusova et al. (2010) noted increases in jaw-movement amplitude and velocity despite continuous declines in speaking rate. Yunusova, Green, Lindstrom, Pattee, and Zinman (2013) also reported that jaw-movement amplitudes for talkers with ALS tended to increase with advancing disease severity. Such apparently conflicting findings may suggest a complex interplay between changes in speech ability and adaptive sensorimotor function and underscore the challenge of inferring physiological effects from perceptual data. Yunusova et al. (2010) have reported that measures of speaking rate were sensitive indices of bulbar decline in ALS, yet kinematic measures from these patients reflected unanticipated, potentially important information about the adaptive state of the sensorimotor system or the degenerative disease process that could not be gleaned from speaking rate alone. Moreover, in a much larger scale longitudinal study of ALS, Rong, Yunusova, Wang, and Green (2015) found that instrumental-based measures of articulatory and phonatory function predicted bulbar decline in ALS prior to notable changes in speech intelligibility and speaking rate.

Changes in jaw-movement amplitude have been hypothesized to reflect compensatory, adaptive changes in response to relatively more impaired tongue movements in ALS (DePaul & Abbs, 1987; Langmore & Lehman, 1994; Mefferd et al., 2012; Yunusova et al., 2008), but may alternatively be a reflection of pathological changes associated with degenerative disease processes (Yunusova et al., 2013). It should be noted that whereas the term "compensatory" is often used to imply that behavioral changes are adaptive (working to support functional behaviors by helping compensate for breakdowns), compensatory behaviors may also be maladaptive, or working antagonistically to further undermine the achievement of functional behaviors. Differential impairment between articulators has been reported for people with TBI (Jaeger, Hertrich, Stattrop, Schönle, & Ackermann, 2000) and talkers with cerebral palsy (Rong et al., 2012); as a consequence, the hypothesis that dysarthria-related articulatory changes may reflect a degree of secondary response to primary impairment of other articulators has also been used to explain articulatory-movement differences observed in people with TBI (Murdoch & Goozée, 2003). Loh et al. (2005) also found generally reduced jaw-movement velocity and amplitude for children with TBI, but noted substantial talker differences with regard to movement variability that may have reflected different compensatory strategies. By contrast, Bartle, Goozée, Scott, Murdoch, and Kuruvilla (2006) found that three of their nine participants with TBI demonstrated increased ranges of jaw-movement amplitude, a finding that mimicked earlier results from Netsell and Kent (1976) for a talker with ataxic dysarthria. In general, although the broader literature suggests that articulatory-movement amplitudes are generally reduced in dysarthria, kinematic studies of jaw movement seem to characterize a wide range of idiosyncrasy that has often been interpreted as reflecting adaptive efforts either to stabilize the other articulators by reducing jaw-movement amplitudes or to increase jaw-movement amplitudes to compensate for restricted ranges of motion in the tongue or lips.

Concerns about differential articulatory impairments within talkers with dysarthria has motivated work examining the relative (interarticulatory) timing of tongue, lip, and jaw movements. Weismer, Yunusova, and Westbury (2003) found similar relative timing patterns among talkers with Parkinson's disease, talkers with ALS, and healthy older adults. Bartle et al. (2006) also found little evidence of noteworthy differences in tongue, lip, and jaw timing for participants with TBI, although they suggested that substantial variability within and across participants (both the control group and participants with TBI) may have washed out any statistically significant differences between groups in the study. It is interesting that although there is a long-standing expectation that some talkers with dysarthria are affected by a lack of coordination (Darley et al., 1975; Duffy, 2013), efforts to objectively characterize coordinative breakdowns associated with dysarthria have been largely equivocal. Connor et al. (1989) observed apparent increases in movement synchrony in participants with Parkinson's disease rather than the reduced synchrony that one might anticipate as a reflection of discoordination. Such a finding may be another example of adaptive changes, in this case with regard to interarticulatory timing, that occur to stabilize the disordered sensorimotor control system and help compensate for coordination difficulties. Identifying these sorts of differences in sensorimotor control is important for understanding dysarthria and devising individualized treatment strategies on the basis of a thorough understanding of both primary and secondary features of disordered speech.

In addition to concerns about interarticulatory coordination, many studies of articulatory kinematics have examined the relations among different kinematic parameters within the movements of an articulator. A particularly common focus has been the ratio of articulatory-movement velocity to amplitude. These two parameters are typically linearly related. The scaling of movement velocity with amplitude ("move farther, move faster") is a pervasively observed feature of movement kinematics that may be altered for some talkers with motor speech disorders (Ackermann et al., 1997; Ackermann, Hertrich, & Scharf, 1995; Jaeger et al., 2000), though reports for talkers with Parkinson's disease (Forrest et al., 1989; Forrest & Weismer, 1995) have indicated no differences.

Closing and opening movements of the jaws may differ, with oral closure faster than release (Gracco, 1994). Speaking-rate changes may further these differences, resulting in distinct changes in movement form (Adams, Weismer, & Kent, 1993). Because speaking rate is known to affect aspects of articulatory kinematics, the reduced speaking rate that is typically associated with dysarthria may complicate the interpretation of certain kinematic measures, particularly those associated with the smoothness and stability of movements. Measures of movement smoothness and stability have been used to characterize the process of motor recovery following stroke (see Balasubramanian, Melendez-Calderon, Roby-Brami, & Burdet, 2015; Rohrer et al., 2002) and have been used in a wide range of speech studies to examine the variability of movement patterns (Smith, Johnson, McGillem, & Goffman, 2000).

Reductions in speaking rate have been observed to increase the spatial and temporal variability (decrease smoothness) of articulator movements for talkers with dysarthria (Kleinow, Smith, & Ramig, 2001). Increasing speech intensity, however, may actually reduce the variability of articulator movements for talkers with Parkinson's disease (Dromey, 2000; Kleinow et al., 2001). The mechanisms underlying this intensity effect are not entirely clear, but substantial work has focused on the treatment benefits of increased speech intensity (e.g., Dromey, Ramig, & Johnson, 1995; Ramig, Bonitati, Lemke, & Horii, 1994; Sapir, 2014; Sapir, Spielman, Ramig, Story, & Fox, 2007; Solomon, McKee, & Garcia-Barry, 2001). Healthy talkers typically tend to increase articulatory-movement velocity and amplitude with increases in speech intensity (Huber & Chandrasekaran, 2006; McClean & Tasko, 2002; Schulman, 1989; Tasko & McClean, 2004). Talkers with Parkinson's disease may also follow a similar pattern of kinematic change when increasing speech intensity (Dromey, 2000), though the manner by which intensity modifications are elicited from a talker affects the form of kinematic changes (Darling & Huber, 2011). Darling and Huber (2011) have suggested that talkers with Parkinson's disease may implement different articulatory strategies for changing speech intensity due to differential subsystem impairments, possibly using greater respiratory modification to increase intensity in compensation for a relatively restricted capacity to alter jaw-movement amplitude. Such an interpretation (again) underscores the potential need for assessing talkers with dysarthria at multiple levels and within different subsystems of the speech mechanism to have a stronger basis for evaluating the possibility of compensatory and adaptive changes in sensorimotor function.

In summary, jaw-movement kinematics are subject to both segmental and suprasegmental factors and may be particularly affected by variables such as speaking rate and speech intensity, which are commonly altered in dysarthria. A relatively large proportion of the kinematic literature on dysarthria has examined jaw movements and established that dysarthria may be associated with differences in the jaw-movement velocity, amplitude, and variability. Many studies have speculated that altered jaw movements may reflect compensatory or adaptive changes in sensorimotor control in response to differential impairments across articulators or subsystems.

Toward the Use of Physiological Data in Dysarthria Assessment

The preceding review supports the position that there is a strong historical basis and substantial clinical motivation for the complementary use of physiological measures in the assessment of dysarthria. Different levels of analysis (perceptual, acoustic, physiologic) provide distinct information about the nature of dysarthria. Taken together, data from these different levels allow the clinician a more complete view of the individual with dysarthria and provide a stronger basis for treatment planning and outcome assessment. Movement toward broader clinical use of physiologic measures is partially dependent on the development of methods that are valid, reliable, and cost and time effective for clinicians to implement.

In the current work, a single EMA sensor was used to register orientation data and quantify jaw rotation during speech. The methods for sensor placement, data acquisition, and data analysis were developed with the goal of making them easy and efficient to implement in order to optimize clinical feasibility. To evaluate whether such an approach may have value, the current work examines the adequacy of the signal-processing methods used and the potential for measures that are based on the current method to provide insights about articulatory movements in dysarthria. The adequacy of the proposed single-sensor (orientation) method was evaluated by comparison with data calculated using a position-based, dual-sensor method. The potential clinical value of single-sensor jaw rotation was evaluated by comparing data from talkers with dysarthria with data from typical talkers reading *The Caterpillar* (Patel et al., 2013). A variety of measures were used to provide a preliminary appraisal of the potential clinical value of jaw-rotation measures. Taken together, the two experiments presented in this article aim to provide a proof of concept regarding the single-sensor method for characterizing jaw movement.

Method

EMA Data

All EMA data were collected using the NDI Wave Speech Research System (Wave system). The Wave system can track sensors with either 5 or 6 degrees of freedom (DOF) in a 300 mm cube, and includes internal motion correction relative to a primary designated reference sensor, typically used for head-movement correction. Because 6-DOF sensors are bulky and can interfere with articulation, a typical configuration uses a single head-mounted reference sensor and all other sensors with 5 DOF.

The Wave system returns positional data (X, Y, Z positions) as well as orientation data from sensors, expressed in quaternions. In computer graphics and visualization, quaternions are often used to represent rotations and orientations, due to their compactness compared with Euler matrices and avoidance of gimbal lock (Hanson, 2005). Formally defined, a quaternion is a complex number of the form

$$q = \left[q_0, q_x\boldsymbol{i}, q_y\boldsymbol{j}, q_z\boldsymbol{k}\right], \qquad (1)$$

where q_0, q_x, q_y, and q_z are real numbers and $\boldsymbol{i}$, $\boldsymbol{j}$, and $\boldsymbol{k}$ are imaginary numbers satisfying the equation

$$i^2 = j^2 = k^2 = ijk = -1. \qquad (2)$$

Normalized quaternions ($\|q\| = 1$) are used exclusively when doing rotations, because they preserve the lengths of the vectors being rotated and have the desirable property that their conjugate is their inverse (Hart, Francis, & Kauffman, 1994). A quaternion can be thought of as an angle–axis pair, representing rotation by angle θ about an axis v:

$$q = \left[\cos(\theta/2), \sin(\theta/2)\left(q_x i + q_y j + q_z k\right)\right], \qquad (3)$$

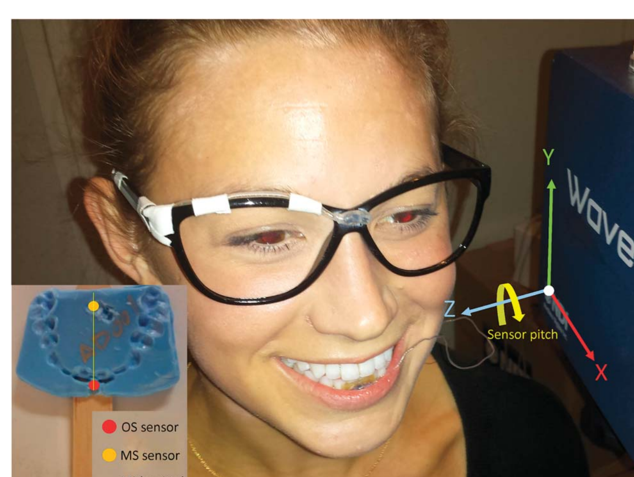
where $v = \sin(\theta/2)(q_x i + q_y j + q_z k)$. To rotate from a vector b_i to a new vector b_f, a quaternion (detailed in Hart et al., 1994) is required of the form

$$b_f = q b_i q^*, \qquad (4)$$

where q represents the desired quaternion rotation from Equation 3 and q* is its conjugate. Using Equations 3 and 4, a quaternion can be used to represent the rotation required to derive an object's current orientation vector from a predetermined baseline orientation vector.

In the Wave system the 6-DOF reference sensor registers X, Y and Z positions as well as $[q_0, q_x, q_y, q_z]$ quaternion orientation information representing rotation relative to a baseline orientation predefined by the system. The 5-DOF sensors also register $[q_0, q_x, q_y, q_z]$ quaternion data, but with $q_z = 0$. This approach represents the sensor plane (the plane of the internal sensor toroid) but provides no information about the yaw (twist) of this plane. The choice of $q_z = 0$ is arbitrary but allows for consistent representation of a planar orientation with a three-dimensional quaternion. For the current experiments, the reference sensor was rigidly attached to the nose bridge of glasses worn by the participants, centered in the midsagittal plane. Figure 1 shows a participant

Figure 1. Experimental setup, bite plate, and coordinate system.



seated next to the Wave field generator and wearing reference glasses. The 6-DOF sensor is placed to mimic the axes defined by the global coordinate system of the Wave system.

To calibrate the position and orientation data for a given participant's articulatory working space, a bite-plate record was taken, with the purpose of establishing the maxillary occlusal plane as the XZ plane and the midsagittal plane as the XY plane. A bite plate was formed from two softened pieces of bite-registration wax sandwiched around a tongue depressor. Participants were required to bite down on the warm wax. The resulting dental impression was used to identify the locations of two 5-DOF sensors that were embedded within the wax and to define the necessary anatomical reference points (see Figure 1, lower left). A short EMA recording was then taken with the sensor-embedded bite plate returned to the mouth. One 5-DOF sensor was positioned in the bite plate anteriorly abutting the juncture of the central maxillary incisors and the second 5-DOF sensor was positioned to bisect the (transverse) distance between the maxillary first and second molars. Taken together, the sensor locations were used to define the midsagittal and maxillary occlusal planes in a local coordinate space with its origin at the central maxillary incisors.

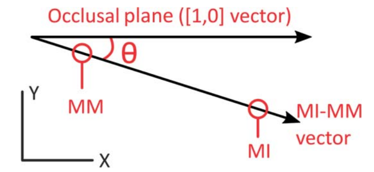
Figure 1 shows an approximation of the local coordinate system used in the ensuing analysis, with the x-axis reflecting anterior–posterior sensor position, the y-axis reflecting inferior–superior sensor position, and the z-axis characterizing deviation from the midsagittal plane (Z = 0). Also visible in Figure 1 is the anterior jaw sensor, affixed to the labial surface of the midline juncture of the mandibular incisors (MI) with the sensor lead orientated laterally. This placement allows registration of sensor rotation about the z-axis, which is most relevant to characterizing jaw movement. Although not explicitly analyzed in the current work, this sensor placement will also register translational movements of the sensor along all three axes, which may be useful for making a more complete characterization of jaw movement (Edwards & Harris, 1990).

Jaw-Rotation Calculations

For the first experiment in this study, jaw rotation was calculated using two methods: a dual-sensor calculation using only positional data and a single-sensor method using orientation data. The second experiment, examining the clinical relevance of EMA-based jaw-rotation measurement, used only the single-sensor method of calculation, with a sensor-adhesion approach that was optimized for safe, fast, reliable data acquisition.

The dual-sensor calculation determined the angle between the x-axis (the [1,0] vector) and the vector pointing from the mandibular molar (MM) sensor to the MI sensor, $v_{\mathrm{MI-MM}}$. Because the angle of interest is defined in the XY plane, all vectors were projected onto that plane. The x-axis vector represents the maxillary occlusal plane. The vector $v_{\mathrm{MI-MM}}$ represents the mandible and changes direction as the mandible is elevated and depressed (see Figure 2).

Figure 2. Schematic of jaw angle defined with respect to the maxillary occlusal plane with electromagnetic articulography sensors mandibular molar (MM) and mandibular incisor (MI).



Using the two vectors, and defining opening of the jaws as a negative angle, the angle can be calculated as follows:

$$\theta = -\cos^{-1}[(\mathrm{x} \cdot v_{\mathrm{MI-MM}})/(||x||||v_{\mathrm{MI-MM}})], \tag{5}$$

where x is the x-axis vector and θ is the jaw-opening angle. Because the MM and MI sensors were difficult to place exactly parallel to the XZ plane, the zero jaw angle would actually be registered as a small offset from zero. To correct for the offset and report an absolute jaw angle, the position-derived angles were corrected using

$$\theta_{\mathrm{p}}' = \theta_{\mathrm{p}} - \max(\theta_{\mathrm{p}}), \tag{6}$$

where θ_{p}' is the absolute jaw angle. This method requires that the participant completely occlude the jaws at some point during the data record.

The single-sensor method for calculating jaw rotation uses the quaternion orientation data from the MI sensor. The same maxillary vector (the [1,0] vector) is used as in the dual-sensor method, but the lower-jaw vector is calculated differently. It is obtained using Equation 4 along with the quaternion data from the MI sensor:

$$v_{\mathrm{L}} = q_{\mathrm{MI}} v_{\mathrm{b}} q_{\mathrm{MI}}^{*}, \tag{7}$$

where v_{L} is the lower-jaw vector, q_{MI} is the quaternion obtained from the MI sensor, and v_{b} is the baseline orientation vector. During bite-plate correction, average sensor orientation is computed and used as a baseline reference, so that future calculations are done relative to this base orientation. The baseline orientation vector is enforced to be along the z-axis [0,0,1] (pointing toward the participant's right side). Using Equation 7, the lower-jaw vector is calculated and the final jaw angle is solved for using

$$\theta = -\cos^{-1}[(\mathrm{x} \cdot v_{\mathrm{L}})/(||x||||v_{\mathrm{L}}||)]. \tag{8}$$

The sensor is affixed such that its orientation-norm vector is approximately perpendicular to the lower incisors.

The jaw angle is determined by taking the current sensor angle relative to the jaw-closed sensor angle by subtracting a baseline offset from the quaternion data. As with the position-derived angles, the orientation-derived angle offset was chosen to be the greatest recorded angle in a given record. The new angles were

$$\theta_o' = \theta_o - \max(\theta_o), \qquad (9)$$

where θ_o' represents the absolute jaw angle.

Time-varying changes in jaw rotation were determined via the two methods already described. Calculations were corrected such that the maximum jaw rotation was 0, and all corresponding jaw angles of rotation were negative with respect to this baseline. This approach characterizes depression of the mandible through increasingly negative angles.

Participants, Jaw-Sensor Placements, and Speaking Tasks

Experiment 1

The single-sensor orientation method and the dual-sensor position method of calculating jaw rotation were compared on the basis of data from 16 typical talkers with two 5-DOF EMA sensors attached to the lower teeth—one to the midsagittal juncture of the central MI and another on the buccal surface of the first or second MM—using Iso-Dent cyanoacrylate dental adhesive (Ellman International, Oceanside, NY). Participants in this experiment were asked to repeatedly say the word "buttercup" and to repeat a sequence of vowel sounds as well as hold the jaws closed in a static position.

Experiment 2

The potential clinical value of single-sensor jaw rotation was examined on the basis of data from 26 adult participants (ages 19–52 years). Nineteen of these participants were typical talkers (eight female and 11 male) and seven were people with dysarthria (four female and three male). Talkers with dysarthria had a range of severity (mild to profound), age, etiology and perceived features of dysarthria and sensorimotor impairment (see Table 1). Although all of these individuals had acquired, chronic dysarthria secondary to stroke or other nondegenerative brain injury, the participant group was quite diverse. Such diversity may be critical to determining how different assessment measures may reflect different aspects of dysarthria. This perspective seems reasonable, given the historical challenges of finding predictable correlations among measures at different levels of analysis or predicting physiological deficits exclusively on the basis of perceptual subtyping (Weismer & Kim, 2010).

For Experiment 2, a single 5-DOF EMA sensor was attached to the midsagittal juncture of the central MI (as before; see Figure 1). To optimize the clinical feasibility of data acquisition, a method for sensor adhesion was used that increased the safety and efficiency of sensor placement. MI sensors were prepared in advance of data acquisition. For each sensor, a rectangle 5 × 15 mm was cut from Stomahesive gum (ConvaTec, Princeton, NJ). The EMA sensor was pressed into the center of the rectangle, creating an impression. This impression was filled with Periacryl 90 Oral Tissue Adhesive (Glustitch, Delta, British Columbia, Canada). The EMA sensor was then repositioned in the glue-filled impression and a weighted tongue depressor was placed on top to assure that the sensor was tightly fitted to the Stomahesive while the glue dried. Once the glue was dry, the prepared sensor was ready for use. To prepare a participant for the experiment, the labial surface of the lower front teeth was dried with gauze and then the Stomahesive-backed EMA sensor was pressed onto the dental surface of the MI. Care was taken to ensure that the Stomahesive gum contacted only dental surfaces, because it does not adhere to oral tissues. This sensor-adhesion technique proved extremely effective and efficient (typically requiring less than 5 min), eliminated the need for direct use of cyanoacrylate adhesives on the oral tissues (which increased participant safety), and reduced data-acquisition costs.

Participants in the second experiment were asked to read *The Caterpillar* (Patel et al., 2013). The text for the script was displayed on a computer monitor. The total script was segmented on the basis of the (17) average breath groups used by typical talkers. Four segments of the script were then extracted for analysis. These specific segments were identified on the basis of the average number of directional changes in jaw movement (analogous to strokes; see Tasko & Westbury, 2002) exhibited by typical talkers for each segment. To be specific, the four segments extracted for further analysis were (a) the segment with the fewest typical strokes, (b) the segment with the highest number of typical strokes, and (c) two segments with nearly equivalent stroke numbers occurring near the beginning and end of the script. It was assumed that the number of jaw strokes within a segment roughly reflected the movement complexity. In consequence, the segments selected for analysis were assumed to represent (a) a relatively low-complexity jaw-movement sequence (Segment 11), (b) a relatively high-complexity jaw-movement sequence (Segment 17), and (c) two sequences of relatively comparable complexity occurring early and late in the read passage (Segments 1 and 15) that could reveal performance differences across the time course of the speech task (e.g., fatigue).

Several parameters associated with jaw rotation were measured for each participant in each of the four extracted segments of the reading script. These parameters were chosen to explore different aspects of the kinematics of jaw rotation and were not driven by explicit hypotheses regarding the possible form of jaw kinematic differences between typical talkers and talkers with dysarthria. Table 2 summarizes the various parameters that were measured (see also Takada, Yashiro, & Takagi, 2006). These parameters were not mutually exclusive, but were assumed to variously reflect three general aspects of jaw rotation: movement amplitude, movement smoothness, and movement velocity.

Table 1. Participants with dysarthria: Demographics, documented pathophysiology, and perceptual features of speech.

Participant	Age (years)	Pathophysiology	Features of speech
Women			
D04F	32	12.5 years post TBI secondary to MVA and 1.5-month coma. Presented with bilateral vocal folds paresis, velopharyngeal insufficiency, right lingual paresis, and bilateral upper-limb and trunk spasticity.	Profound dysarthria with 15% word-level intelligibility, nonfunctionally intelligible conversational speech characterized by chronic hypernasality, severely reduced speaking rate, and severe phoneme distortions.
D91F	38	3 years post CVA.	Presented with mild expressive aphasia and mild dysarthria characterized by mild phoneme distortions, intermittently atypical phrasing, intermittent speaking-rate variation, and excessive pitch variation. Conversational speech intelligibility was within functional limits.
D92F	46	2.5 years post CVA.	Presented with right orofacial paresis with mild expressive aphasia, mild dysarthria, and possible mild apraxia of speech. Speech characterized by mild–moderate and intermittently irregular phoneme distortions, reduced pitch variation, and mildly reduced speaking rate. Conversational speech intelligibility was within functional limits.
D93F	28	8 years post ruptured right-sided sylvian-choroidal AVM.	Residual mild expressive (crossed) aphasia and mild dysarthria characterized by mildly reduced speaking rate, mildly reduced prosodic variation, and intermittent phoneme distortions, particularly with increased speaking rate. Conversational speech intelligibility was within functional limits.
Men			
D08M	53	2 years post hyponatremic encephalopathy and 2-week coma. Presented with orofacial spasticity and bilateral upper- and lower-limb spasticity.	Severe dysarthria and intermittent disfluencies with severe phoneme distortions and 70% word-level intelligibility (achieved in part through explicit efforts to hyperarticulate word-level speech). Conversational speech was severely unintelligible, but borderline functional due to frequent, hyperarticulated word repetitions and other compensatory repairs for communication breakdowns.
D09M	25	2 years post TBI (MVA) and 3.5-month coma, as well as recent history of seizures. Presented with orofacial spasticity and severely reduced breath support.	Severe dysarthria with 76% word-level intelligibility and severely reduced intelligibility during conversational speech. Speech was characterized by severe phoneme distortion, moderately reduced loudness, moderately reduced speaking rate, mildly reduced pitch variation, and intermittent, mild hypernasality.
D94M	24	10.5 years post multiple intracerebral hemorrhages secondary to left basal-ganglia AVM and a large left MCA infarction.	Presented with right orofacial paresis, mild–moderate expressive aphasia and mild dysarthria. Speech was characterized by intermittently reduced loudness, intermittent, mild hypernasality, and intermittent, mildly reduced speaking rate. Conversational speech intelligibility was mildly reduced intermittently, particularly with increased speaking rate.

Note. TBI = traumatic brain injury; MVA = motor-vehicle accident; CVA = cerebrovascular accident; AVM = arteriovenous malformation; MCA = middle cerebral artery.

Table 2. Measures of jaw rotation.

Measure type	Measure	Definition
Movement amplitude	Mean percent angle (MnPA)	$\frac{\text{mean } angle}{talker\ global\ \max\ angle}$
	Median percent angle (MdPA)	$\frac{\text{median } angle}{talker\ global\ \max\ angle}$
	Maximum percent angle (MxPA)	$\frac{\max\ angle}{talker\ global\ \max\ angle}$
Movement smoothness	Coefficient of variation (CV)	$\frac{100 \times std.dev.}{mean}$
	Strokes	*# of changes in direction of jaw rotation*
	Normalized jerk cost—scaled (NJCs)	$\frac{\left(0.5\int_{T_1}^{T_2}(x'''(t))^2+(y'''(t))^2+(z'''(t))^2dt\right)\times t^5}{\left(\int_{T_1}^{T_2}\sqrt{\left(\frac{dx(t)}{dt}\right)^2+\left(\frac{dy(t)}{dt}\right)^2+\left(\frac{dz(t)}{dt}\right)^2}dt\right)^2}$
Movement rate of change	Peak angular velocity—elevate (PAVe)	$\max\lvert\omega\rvert^{deg.}/_{sec.}$ where the angular velocity $\omega = \frac{d\phi}{dt}$
	Peak angular velocity—depress (PAVd)	$\max\lvert-\omega\rvert^{deg.}/_{sec.}$ where the angular velocity $\omega = \frac{d\phi}{dt}$

Results

Experiment 1

Figure 3 shows a series of jaw movements from a single participant calculated using the orientation (single-sensor) method (shown in red) and the position (dual-sensor) method (shown in blue). The talker elevates the mandible briefly near the beginning of the recording and then depresses the mandible before repeating a sequence of vowel sounds. The two methods of calculation produce slight differences in the shape and magnitude of jaw-angle variation. More frequent, small-magnitude oscillations are apparent in the position-based time series compared with the orientation-based data. The position time series also registers somewhat larger movement amplitudes, with offsets from the orientation data that vary over the time course of the record. Nonetheless, the correlation between the two methods across the data records for all 16 participants was .981.

Experiment 2

Table 3 provides summary statistics for the various measured parameters across all typical talkers (divided by sex). Aside from some sex differences in relative variance, the only notable sex differences appear to be that women tend toward higher angular velocities than men for both jaw elevation and depression, and men tend toward peak jaw openings that reflect a large proportion of their maximum opening. In both regards, participants exhibit relatively high standard deviations in these data. For all talkers, mean and median jaw opening is approximately 30% of the global maximum. In addition, jaw-depression velocities tend to be higher than jaw-elevation velocities for Segments 11 and 17, with the reverse pattern for Segments 1 and 15.

Table 4 provides summary statistics for the various measured parameters for each of the participants with dysarthria. Boldface indicates values that are more than 2 *SD*s from the mean for the typical talkers of the same sex. This approach is intended to be descriptive and help highlight participant-specific differences, rather than serve as an indicator of inferential statistical analysis. Robust statistical analysis was simply not feasible, given the paucity of participants in this preliminary study.

Several participant-specific observations can be made from these data. Two talkers with dysarthria exhibit obvious differences in relative jaw opening and angular

Figure 3. Comparison of orientation (single sensor) and position (dual sensor) measures of jaw rotation.

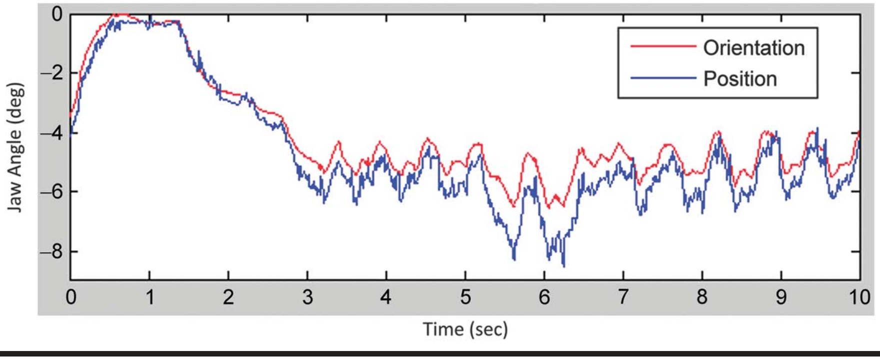


Table 3. Jaw-rotation measures for typical talkers: *M* (*SD*).

Segment	MnPA (%)	MdPA (%)	MxPA (%)	CV	Strokes	NJCs	PAVe (°/s)	PAVd (°/s)
Women								
Segment 11	28 (4)	28 (3)	63 (17)	63 (11)	6 (1)	1 (1)	43 (25)	−49 (8)
Segment 17	29 (5)	27 (6)	70 (12)	53 (11)	41 (3)	537 (143)	58 (33)	−63 (21)
Segment 1	22 (5)	20 (6)	57 (15)	64 (17)	17 (3)	27 (17)	44 (11)	−38 (17)
Segment 15	30 (6)	30 (7)	73 (15)	58 (12)	18 (3)	44 (14)	62 (46)	−57 (14)
Men								
Segment 11	30 (7)	31 (10)	62 (12)	62 (12)	7 (2)	1 (1)	33 (16)	−43 (16)
Segment 17	35 (9)	34 (11)	79 (11)	49 (13)	39 (8)	591 (314)	39 (15)	−53 (21)
Segment 1	29 (9)	27 (10)	67 (17)	56 (13)	19 (5)	47 (43)	40 (10)	−31 (8)
Segment 15	29 (6)	28 (8)	69 (13)	56 (10)	19 (3)	44 (22)	40 (14)	−40 (15)

Note. MnPA = mean percent angle; MdPA = median percent angle; MxPA = maximum percent angle; CV = coefficient of variation; NJCs = normalized jerk cost—scaled; PAVe = peak angular velocity—elevate; PAVd = peak angular velocity—depress.

velocity, with values larger than typical, indicating faster and larger changes in jaw rotation. Participant D04F, in particular, exhibits jaw depressions at angular velocities nearly twice that of her jaw elevations. All talkers with dysarthria produced jaw-rotation histories characterized by an increased number of strokes and increased normalized jerk cost. For most talkers with dysarthria these differences were evident even for the shortest-breath groups, and the magnitudes of these differences were further increased for longer-breath groups. In addition, most of these talkers showed increases in both measures for comparable segments (Segments 1 and 15) from the beginning and end of the passage.

Discussion

Experiment 1

Results of Experiment 1 show that single-sensor, orientation-based registration of jaw rotation provides information about jaw movement that is comparable to data obtained using a dual-sensor, positional approach but with lower measurement error. Overall, the methods produce very similar jaw-rotation time series. Frequent, small-magnitude oscillations were apparent in the position-based time series compared with the orientation-based data, suggesting an increase in high-frequency artifact as a result of dual sensor use. From a signal-processing perspective, the position-derived angle is based on the difference of two sensor measurements, an operation that acts as a mathematical differentiator and therefore amplifies high-frequency noise. The orientation-derived angle does not require such a difference to be calculated. In consequence, the single-sensor method shows less sensitivity to high-frequency artifact. The dual-sensor method tended to produced somewhat larger magnitude estimates of movement amplitude, which did not reflect a constant offset from the single-sensor data over time. Such an effect may reflect a compounding of the sensor tracking error of the EMA system, suggesting that the single-sensor, orientation-based approach is more reliable.

Given the relative ease of participant preparation for the single-sensor method, the findings of Experiment 1 support the goal of developing an approach that is more feasible within clinical settings without compromising the accuracy of the physiological measurements. All told, the process of participant preparation typically takes less than 10 min and requires minimal effort from the talker. Although the current study used read, connected speech, the approach could be adapted for a variety of tasks, from nonspeech oral movements (e.g., Ballard et al., 2009) to conversational speech (e.g., Rosen, Kent, Delaney, & Duffy, 2016). Only the process of segmenting the resulting data to demarcate the pertinent time intervals over which measures are made would be affected by task changes. All other aspects of data postprocessing and analysis are effectively automated.

Because the proposed method successfully uses quaternion rotation data, it establishes a basis for expanding the use of such data in kinematic analysis. Whereas the jaw offers an obvious context for using orientation data, due to the large rotational component of jaw movement, rotational data may also be useful in characterizing other aspects of articulation, such as tongue movement. Preliminary work in our lab has explored a method for estimating surface contours on the tongue using only two or three EMA sensors (Kolb et al., 2015). Successful development of such an approach could substantially expand the value of EMA data by effectively improving the spatial resolution of EMA data and providing a more complete characterization of tongue shapes and movements.

Experiment 2

The current results indicate that typical female talkers exhibit higher angular velocities of jaw movement than male talkers, and male talkers exhibit proportionally larger peak jaw opening. However, the relatively high standard deviations in these data suggest notable overlap across sex. As a consequence, although sex differences may be possible, further work will most certainly be required to examine these differences in a more robust fashion. Consistent with previous findings, data from Segments 1 and 15 indicated relatively higher jaw-elevation velocities than depression velocities for typical talkers (Gracco, 1994). However, an

Table 4. Jaw-rotation measures for talkers with dysarthria: *M* (*SD*).

Segment	MnPA (%)	MdPA (%)	MxPA (%)	CV	Strokes	NJCs	PAVe (°/s)	PAVd (°/s)
Women								
D04F								
Segment 11	35	**36**	60	41	**24**	**136**	85	–64
Segment 17	**43**	**48**	72	40	**69**	**23,100**	110	**–183**
Segment 1	**63**	**72**	**100**	43	**54**	**11,900**	**104**	**–215**
Segment 15	39	**47**	63	45	**55**	**5,490**	100	**–135**
D91F								
Segment 11	**40**	**42**	**100**	56	**12**	**7**	76	–45
Segment 17	**42**	**45**	91	46	**62**	**5,800**	55	–68
Segment 1	28	27	60	54	**26**	**281**	39	–32
Segment 15	37	35	82	56	**42**	**1,280**	57	–46
D92F								
Segment 11	20	**19**	44	62	8	2	13	**–25**
Segment 17	24	22	78	50	**87**	**22,800**	25	–37
Segment 1	20	15	61	83	**27**	122	24	–31
Segment 15	20	18	70	62	**57**	**4,190**	16	–41
D93F								
Segment 11	28	28	56	57	**11**	**4**	28	–38
Segment 17	20	19	74	63	**126**	**65,100**	50	–65
Segment 1	23	20	69	74	27	**237**	29	–52
Segment 15	22	23	54	54	43	**997**	41	–43
Men								
D08M								
Segment 11	32	30	75	68	**44**	**1,310**	29	–45
Segment 17	36	35	82	45	**131**	**122,000**	38	–41
Segment 1	39	42	76	42	**37**	**835**	38	–38
Segment 15	38	36	92	53	**66**	**12,000**	48	–70
D09M								
Segment 11	26	25	48	45	**17**	**12**	30	–38
Segment 17	32	30	65	46	**110**	**22,600**	42	–31
Segment 1	33	33	62	33	**40**	**343**	22	–19
Segment 15	24	21	67	61	**71**	**2,180**	26	–32
D94M								
Segment 11	37	38	73	52	8	**4**	**73**	–56
Segment 17	37	36	100	52	**69**	**4,810**	61	–76
Segment 1	26	22	67	56	28	**137**	60	–26
Segment 15	30	29	79	51	**37**	**691**	56	–43

Note. Boldface indicates values that are more than 2 *SD*s from the mean for typical talkers of the same sex. MnPA = mean percent angle; MdPA = median percent angle; MxPA = maximum percent angle; CV = coefficient of variation; NJCs = normalized jerk cost—scaled; PAVe = peak angular velocity—elevate; PAVd = peak angular velocity—depress.

opposite pattern was observed for Segments 11 and 17, for which jaw-depression velocities tended to be higher than jaw-elevation velocities. These results suggest that linguistic factors specific to the segments analyzed influence movement patterns. In part, this difference between current results and previous findings may reflect our use of relatively long (breath-group-based) segments for analysis in this study, compared with the substantially shorter analysis segments (e.g., phonemes or gestures within phonemes) that have been more typically used in prior work. The use of breath-group-based segments may be justified on the basis of the fact that such units can be useful in characterizing the intelligibility of connected speech (Yunusova, Weismer, Kent, & Rusche, 2005). As a result, such units may have practical value at multiple levels of analysis, allowing corresponding perceptual, acoustic, and physiological measurements. Another practical benefit of using relatively long segments, such as breath groups, is that the time burden of manually segmenting assessment data is reduced, because fewer intervals must be manually demarcated by the clinician during the process of data analysis.

The results obtained for talkers with dysarthria reveal wide idiosyncrasy with little evidence of general patterns. Measures of jaw-rotation velocity in particular revealed highly idiosyncratic results among talkers with dysarthria. As suggested earlier, Segments 1 and 15 of the script elicited jaw-velocity effects that were generally consistent with expectations on the basis of the literature. In particular, jaw elevations were typically faster than depressions (Gracco, 1994). This pattern appeared to be true for participants D91F and D94M. On the other hand, participants D04F, D92F, and D08M all exhibited an opposite pattern for these segments, with depressions occurring at higher velocities than jaw elevations. Participant D09M exhibited a mixed pattern with relatively faster jaw elevations than depressions for Segment 1 and the opposite result for Segment 15. For Segments 11 and 17 of the reading script, which tended to elicit faster depressions than elevations for typical talkers, two participants with dysarthria (D92F and D93F) exhibited patterns consistent with the tendencies of typical talkers. All other participants with dysarthria (D04F, D91F, D94M, and D09M) exhibited mixed patterns across Segments 11 and 17, evincing no consistent relationship between the velocity and directionality of jaw movement. In general, there appeared to be little evidence of notable differences in jaw-movement velocities for talkers with dysarthria compared with typical participants, except in the case of participant D04F, who tended toward much faster rates of jaw movement than typical.

With regard to jaw-movement amplitude, only participants D04F and D91F showed sizable differences in movement amplitude compared with typical talkers for more than one segment and measure. In both cases, differences suggest a tendency toward somewhat larger jaw movements than typical. These two participants were quite different with regard to the perceptual features of dysarthria and severity, with D04F exhibiting quite profound impairment and being nonfunctional at the conversational level, and D91F presenting with conversational speech intelligibility within functional limits. Solely on the basis of this very limited data set, there does not appear to be a predictable relationship between the severity of dysarthria and jaw-movement amplitude.

All participants with dysarthria showed apparently reduced movement smoothness compared with the typical talkers for multiple segments for measures of strokes and normalized jerk costs. None showed differences in smoothness on the basis of the coefficient of variation measure. For most talkers with dysarthria these differences were evident even for the shortest breath groups, and the magnitudes of these differences were further increased for longer breath groups. In addition, most of these talkers showed notable increases in both measures between Segments 1 and 15 from the beginning and end of the passage, suggesting movement changes over time. Such an observation might be taken as an indication of fatigue, but the lack of corresponding changes in other kinematic parameters (i.e., changes in velocity or amplitude of movement over time) makes such an interpretation seem highly speculative. Only participant D04F exhibited apparent declines in movement velocity between Segments 1 and 15, and these were observed only for jaw depression. Another consideration is that talkers with dysarthria may have reduced speaking rate over time, resulting in a potential confound for measures of smoothness.

Reduced speaking rate is known to affect speech kinematics. In particular, reduced speaking rate alters movements such that the typically singular acceleration and deceleration components of a movement (often described as a unimodal velocity profile) become multiple within a movement pattern (Adams et al., 1993). Movements characterized by multiple velocity peaks will undoubtedly result in decreased measures of smoothness. As a consequence, the relatively less-smooth movements found in the current work for talkers with dysarthria may be confounded by the typically reduced speaking rates observed for these talkers.

Conclusions

Preliminary analyses of jaw rotations during connected speech suggest that there may be some measurable differences between talkers with dysarthria and typical talkers, particularly for metrics characterizing the number of directional changes in a movement and the smoothness of the movement pattern. However, the wide range of idiosyncrasy apparent in both typical talkers and talkers with dysarthria suggests that the value of these measures should be interpreted with great caution. Similar conclusions may be drawn regarding the finding that most talkers with dysarthria showed increases in the number of strokes and normalized jerk costs over the course of the reading passage. Such results may suggest that there may be value in exploring the possibility that such changes are a reflection of differences in speech abilities, such as increased fatigability compared with typical talkers, but the idiosyncrasy of these results and very modest number of participants suggest that such conclusions would be highly speculative. Moreover, given that the measures that tended to differentiate talkers with dysarthria from typical talkers were primarily related to movement smoothness, these measures are likely sensitive to reduced speaking rate, which was affected to some degree for all participants with dysarthria.

Follow-up work will need to directly examine the effects of speaking rate to determine whether or not the influence of speaking rate on movement smoothness can be dissociated from other factors. One approach would be to compare measures of smoothness across gradations of speaking rate for typical talkers as a basis for evaluating the magnitude of smoothness changes for talkers with dysarthria. Ensuing analyses will also need to focus on data from a larger cohort of participants to provide a more substantial normative data set and allow for a statistically robust appraisal of whether kinematic measures may differentiate talkers with dysarthria by type, severity, and etiology. Also, although the current study examined movements of a single articulator for the purposes of appraising a method for using EMA sensor orientation data, the analysis of a single articulator, such as the jaw, is insufficient to meet the needs of physiologic assessment in dysarthria. An important motivation for the development of clinically feasible methods of physiologic assessment is to bolster the capacity to characterize differential impairments within and across speech subsystems and foster the capacity to identify and differentiate primary and secondary features of dysarthria. The capacity to collect and analyze physiologic data from multiple articulators and subsystems in conjunction with perceptual and acoustic data may be critical to this endeavor.

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