Research Note

Initial Observations of Lingual Movement Characteristics of Children With Cerebral Palsy

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Purpose: This preliminary study compared the speech motor control of the tongue and jaw between children with cerebral palsy (CP) and their typically developing (TD) peers.

Method: Tongue tip and jaw movements of 4 boys with spastic CP and 4 age- and sex-matched TD peers were recorded using an electromagnetic articulograph during 10 repetitions of “Dad told stories today.” The duration, path distance, average speed, and speech movement stability of the movements were calculated for each repetition.

Results: The children with CP had longer durations than their TD peers. Children with CP had longer path distances

and faster average speed as compared with their TD peers for both articulators. The TD group but not the CP group had longer path distances and faster average speeds for the tongue than the jaw. The CP group had reduced speech movement stability for the tongue as compared with their TD peers, but both groups had similar speech movement stability for the jaw.

Conclusions: Children with CP had impaired speech motor control of the tongue and jaw as compared with their TD peers, and these speech motor control deficits were more pronounced in the tongue tip than the jaw.

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Cerebral palsy (CP) is a group of disorders caused by perinatal damage to the central nervous system resulting in movement impairments with secondary disorders in sensory, cognitive, language, and speech domains (Rosenbaum et al., 2007). The motor impairment associated with the disorder may affect the speed, coordination, and accuracy of speech movements, resulting in dysarthria (Workinger, 2005). Many individuals with CP have dysarthria characterized by reduced speech intelligibility (e.g., Ansel & Kent, 1992; Hodge & Gotzke, 2014; Hustad, Schueler, Schultz, & DuHadway, 2012; Patel, 2002; Pennington, Smallman, & Farrier, 2006), increased production errors (Nordberg, Miniscalco, & Lohmander, 2014; Whitehill & Ciocca, 2000), slower speaking rates (Hodge & Gotzke, 2014; Hustad, Gorton, & Lee, 2010; Nip, 2012), impaired pitch control (Ciocca, Whitehill, & Yin, 2004), and prolonged syllable durations (Patel, 2002, 2003). A likely reason for some of these speech characteristics is impaired speech motor control (Hustad et al., 2012),

such as that observed in the lips and jaws of this group (e.g., Hong et al., 2011; Nip, 2012, 2017; Ward, Strauss, & Leitão, 2013). Although studies on these articulators provide some insight into impaired speech motor control of children with CP, there is little information about the lingual control of this group. The tongue is the primary articulator for many phonemes (Wang, Green, Samal, & Yunusova, 2013). Therefore, understanding how lingual control differs in children with CP from their typically developing (TD) peers may provide further insights into the mechanisms of intelligibility deficits of these children.

Acoustic Speech Characteristics in Speakers With CP Suggest Reduced Lingual Control

The hypothesis that the dysarthria secondary to CP is characterized by a lack of precise motor control of articulators (Hustad et al., 2012; Workinger, 2005), particularly the tongue, is indirectly supported by acoustic studies in this population. Articulatory control accounts for most of the variance of intelligibility in talkers with CP (Ansel & Kent, 1992; Lee, Hustad, & Weismer, 2014; Whitehill & Ciocca, 2000). In particular, talkers with CP have smaller vowel spaces as compared with TD peers (Higgins & Hodge, 2002; Hustad et al., 2010; Liu, Tsao, & Kuhl, 2005). Reduced vowel space in this population suggests that children with CP do not have the same lingual control as their peers to distinguish vowels acoustically (Higgins & Hodge, 2002; Hustad et al., 2010; Lee, Hustad,

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& Weismer, 2014). Furthermore, this reduction in vowel space, and resultant distinctiveness, is also shown in the increased overlap of F1 and F2 values between vowels produced by adults with CP (Kim, Hasegawa-Johnson, & Perlman, 2011). This increased overlap between vowels is more pronounced as the severity of the dysarthria increases (Kim, Hasegawa-Johnson, et al., 2011), suggesting that the degree of lingual impairment affects the severity of the intelligibility deficits.

Another relatively robust acoustic finding that suggests reduced lingual control in talkers with dysarthria (Kim, Kent, & Weismer, 2011) is the shallower slopes of F2 transitions (e.g., between a vowel and the preceding and/or following consonant) when compared with healthy controls. These shallow F2 slopes have been observed in both adult talkers with CP (Rong, Loucks, Kim, & Hasegawa-Johnson, 2012) and children with CP (Lee et al., 2014), suggesting a reduced ability to advance and retract the tongue. Taken together with the vowel space findings, acoustic studies of talkers with CP suggest that they have reduced lingual control.

Children With CP Have Impaired Speech Motor Control

Fine control of tongue movement is needed to produce different sounds (Wang et al., 2013), but tongue movements of children with CP have not yet been studied. Although acoustic findings suggest that there is reduced lingual control in this population, quantal or nonlinear relations between articulation and acoustics make it difficult to gauge how movements affect the speech signal (Mefferd, 2015; Stevens, 1989). Depending on where the movements happen, small movements may have large acoustic consequences, or large movements may have few acoustic consequences (Stevens, 1989). Direct observations of the speech movements themselves are critically needed to understand how impaired speech motor control may affect speech development in these children (Hustad et al., 2012).

Small but increasing numbers of studies have demonstrated that talkers with CP have reduced speech motor performance and control as compared with healthy peers; however, these studies have primarily focused on lip and jaw movement (e.g., Hong et al., 2011; Nip, 2012, 2017; Ward et al., 2013). A small study of adults with CP showed that some of these talkers demonstrate slower tongue speeds and reduced amplitude of tongue movement, whereas jaw movements are increased to compensate for the tongue movement differences (Rong et al., 2012). However, even the jaw movements of talkers with CP differ in comparison with their TD peers. Children with CP have increased lip and jaw speeds and displacements (Nip, 2012; Nip & Wilson, 2014; Ward et al., 2013), resulting in slower speaking rates (Nip, 2012). In addition, spatial and temporal coordination of the tongue and jaw (Rong et al., 2012) and lip and jaw (Hong et al., 2011; Nip, 2017) is reduced for talkers with CP. Furthermore, the coordination of lip and jaw movements in this population is highly correlated with severity, as indexed by intelligibility (Nip, 2017). On the basis of

findings from other oral articulators, it would be expected that similar differences in tongue speed, amplitude, and stability would be observed in this population.

Little is known about tongue motor control during speech production in TD children or in children with speech disorders. Despite this lack of information about tongue movements in children with CP, insights from studies of other groups with dysarthria further support the hypothesis of reduced lingual control in dysarthria secondary to CP. For example, the lingual movements of talkers with amyotrophic lateral sclerosis (ALS) differ from healthy controls, which affects their intelligibility (Mefferd, 2015; Yunusova, Weismer, Westbury, & Lindstrom, 2008).

However, merely identifying that lingual movements are impaired in talkers with dysarthria is not adequate to better design interventions for these talkers. Kinematic findings from other populations with dysarthria have revealed that not only do tongue movements of talkers with dysarthria differ from healthy controls, they also differ between clinical populations. For example, talkers with ALS have smaller movement amplitudes and reduced speeds of the tongue tip and jaw as compared with healthy controls or talkers with Parkinson's disease (PD; Yunusova et al., 2008). However, tongue blade movements are larger for talkers with ALS than talkers with PD (Mefferd, 2015). In addition, there are stronger associations between tongue speed and intelligibility for talkers with ALS than for talkers with PD (Yunusova et al., 2008). Despite group differences in movements, some of the acoustic consequences of their impaired speech movements, such as reduced vowel space, are similar between the two groups. Taken together, these findings further underscore the need for direct observations of tongue movements in any given population with dysarthria, including children with CP, to better specify intervention targets. In addition, kinematic data can be used to explicate the ways in which articulatory differences affect more integrative measures of speech production, such as intelligibility (Mefferd, 2015; Nip, 2017; Rosenbek & Jones, 2009; Weismer & Kim, 2010). This information may allow clinicians to determine a more accurate prognosis of the child's speech development, allowing for more specific timing and selection of intervention approaches (Rong, Yunusova, Wang, & Green, 2015).

Theoretical and Clinical Implications

Theoretical frameworks, including dynamic systems (e.g., Green & Nip, 2010; Smith & Goffman, 2004; Thelen, 1991), suggest that multiple domains, including language, cognition, and speech motor control, affect speech movements and ultimately affect speech production. Domains may act as a rate-limiting factor (Green & Nip, 2010; Thelen, 1991) that prevents additional speech development until that domain develops further (Green & Nip, 2010; Thelen & Smith, 1994). Children with CP demonstrate speech motor control deficits (Hustad et al., 2012; Lee & Hustad, 2013; Nip, 2012, 2017; Ward et al., 2013), which may be used to predict changes in intelligibility (Green, 2015; Green, Yunusova et al., 2013). For example, interarticulator

coordination is shown to significantly affect intelligibility in children with CP and may be a rate-limiting factor in their development of intelligibility (Nip, 2017). At present, our understanding of the speech motor control deficits in this group is incomplete for all the oral articulators (jaw, lips, tongue). Speech motor control deficits differ in severity among articulators for children with CP. For example, the jaw movements of speakers with CP appear to be relatively unaffected compared with the lips (Nip, 2012); however, no similar information about the tongue exists in this group. Identification of rate-limiting factors may lead to better specification of intervention targets for this group.

Research Question and Hypothesis

The purpose of this study is to provide initial observations of the tongue tip and jaw movements of children with CP and their TD peers. On the basis of previous acoustic and kinematic findings, we hypothesize that children with CP will (a) have more variable movement patterns, greater articulatory excursions, and different speeds than their TD peers, and (b) tongue tip movements of children with CP will be more impaired than their jaw movements.

Method

Participants

Four boys with spastic CP ranging in age from 9 to 14 years and four age- and sex-matched TD peers with no history of speech, language, hearing, or motor disorders were recruited for this study. All participants passed a hearing screening at 0.5, 1, 2, and 4 kHz at 20-dB hearing level (ASHA, 1997) and an oral mechanism screening, the Oral Speech Mechanism Screening Examination—Third Edition (St. Louis & Ruscello, 2000). Language was assessed using the Clinical Evaluation of Language Fundamentals—Fourth Edition (Semel, Wiig, & Secord, 2003). Speech intelligibility at the sentence level was assessed with the Test of Children's Speech + (Hodge, Daniels, & Gotzke, 2009) or the Speech Intelligibility Test (Yorkston, Beukelman, Hakel, & Dorsey, 2007). Gross motor deficits were classified using the Gross Motor Function Classification System (Palisano et al., 1997). Speech characteristics were judged by two speech-language pathologists. Results and additional participant information are shown in Table 1.

Kinematic Recordings

Tongue and jaw movements were recorded with an electromagnetic articulograph (WAVE; Northern Digital, Waterloo, ON, Canada). Sensors were placed in and around the mouth using U.S. Food and Drug Administration–approved dental glue (Glustitch; Delta, BC, Canada) at 1 cm behind the tongue tip, just above the central incisors on the maxilla, and just below the central incisors on the mandible. One six-dimensional sensor (*x*, *y*, *z*, pitch, yaw, roll) was placed on the forehead to subtract head movement. Participants were then asked to produce 10 repetitions of

the sentence “Dad told stories today” at their typical rate and volume. This sentence was chosen to parallel the sentence “Buy Bobby a puppy” in the number of syllables and alveolar (rather than bilabial) consonants. Acoustic recordings were made with a condenser microphone placed on each participant's forehead.

Data Analysis

Movement traces for the tongue tip and jaw for each repetition of the sentence were parsed using the acoustic signal by the second, third, and fourth authors. Head movements were subtracted from the jaw and tongue sensor data to obtain three-dimensional Euclidean movement traces. Jaw movements were not subtracted from the tongue. Published algorithms to subtract the jaw signal from the tongue can introduce error (Henriques & van Lieshout, 2013). At present, no algorithm exists that allows for subtraction of the jaw signal from the tongue while allowing for jaw rotation (Shellikeri et al., 2016). Jaw movements were used to parse each utterance. The beginning of the utterance was defined by jaw closure for the alveolar stop and jaw opening for the diphthong at the end of “today.” Only utterances with no phonemic errors were included in the final analysis. One participant (Speaker 3) exhibited disfluencies; however, utterances included for the final analysis were made without blocks, part-word repetitions, or marked prolongations. Sample movement traces of the jaw and tongue tip sensors for speakers with mild and severe spastic dysarthria secondary to CP and a TD peer are shown in Figure 1.

Measurements of duration, range of movement, maximum speed of the tongue tip, and maximum speed of the jaw were obtained (Green, Moore, & Reilly, 2002) using Speech Movement Analysis for Speech and Hearing research (SMASH; Green, Wang, & Wilson, 2013). Univariate analyses revealed that the kinematic data were skewed, so the data were log-transformed. Zero-lag correlations were also obtained from SMASH to obtain a measure of speech movement stability (Green et al., 2002) similar to the spatiotemporal index (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). All repetitions for an articulator and participant were time- and amplitude-normalized. The first repetition of an articulator's movement for each participant was cross-correlated with the average signal of the remaining trials for that given articulator (e.g., the first tongue repetition with the remaining tongue repetitions), with the lag value set at 0. A similar procedure was completed with all repetitions.

Separate multilevel models examining the effect of Group (CP, TD) and Articulator (tongue tip, jaw) while controlling for Age as a covariate were conducted using SAS PROC MIXED (SAS Institute Inc., 2014) on each kinematic variable (distance, average speed, stability). A multilevel model examining the effect of Group while controlling for Age as a covariate was conducted on duration. Age was included as a covariate in all models because previous studies have demonstrated that articulatory control changes with age well into adolescence (Walsh & Smith, 2002).

Table 1. Speaker characteristics, including age, sex, cerebral palsy (CP) type, Gross Motor Function Classification System (GMFCS) rating, sentence intelligibility, Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) core language standard score, dysarthria type, and speech characteristics.

Speaker	Age (years; months)	Sex	CP type	GMFCS	Sentence intelligibility (%)	CELF-4 score	Age of typically developing peer (years; months)	Dysarthria	Speech characteristics
1	9;11	M	Spastic quadriplegia	III	66.3	106	10;0	Spastic	Strain-strangled voice, slow rate, hypernasal, imprecise articulation, short breath groups
2	11;6	M	Spastic hemiplegia	II	95.7	109	11;11	Spastic	Strain-strangled voice, mild hypernasality
3	12;8	M	Spastic diplegia	III	66.7	66	12;0	Spastic	Strain-strangled voice, prolonged phonemes, slow rate, hypernasal, imprecise articulation, disfluencies
4	14;10	M	Spastic hemiplegia	III	97.2	120	14;3	Spastic	Mild hypernasality, glottal fry

Figure 1. Example of a movement trace for the jaw (top panel) and tongue tip (bottom panel) of a child with mild dysarthria, a child with severe dysarthria, and a typically developing (TD) peer. Note the increased duration for the child with severe dysarthria. 3D indicates three-dimensional.

Figure 2. Individual *M* and *SD* (bars) of movement duration for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

Results

Duration

Figure 2 shows the duration data for each participant. The two participants with lower intelligibility (1 and 3) showed a marked increase in duration as compared with their TD peers. The participants with higher intelligibility (2 and 4) only showed slightly longer durations compared with their age-matched peers. The durations of the jaw movements were significantly longer for participants with CP than for their TD peers, $F(1, 43) = 45.99, p < .001$. A significant effect of Age was also found, $F(1, 44) = 39.50, p < .001$.

Path Distance

The path distance data for the jaw and the tongue tip of each participant are shown in Figures 3 and 4, respectively.

Participants 1, 2, and 3 showed greater path distances of the tongue tip as compared with their age-matched TD peers. Participant 4 had slightly smaller path distances as compared with his age-matched peer. All four participants had larger jaw path distances as compared with their TD peers. A significant effect of Age was found for path distance, $F(1, 120) = 13.04, p < .001$. Significant main effects were also found for Group, $F(1, 111) = 68.58, p < .001$, and Articulator, $F(1, 109) = 14.27, p < .001$. A significant Group $\times$ Articulator interaction for path distance was found, $F(1, 109) = 4.1, p < .05$. Post hoc analyses revealed that jaw and tongue tip movements were significantly larger for the participants with CP than for their TD peers. In addition, tongue tip movements had significantly larger path distances than the jaw for the TD peers; similar articulator differences were not observed for the children with CP.

Figure 3. Individual *M* and *SD* (bars) of the jaw path distance for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

Figure 4. Individual *M* and *SD* (bars) of the tongue tip path distance for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

Average Speed

The individual data for average speed of the tongue tip, as shown in Figure 5, show that the oldest three participants with CP demonstrated faster jaw speeds when compared with their age-matched peers. In contrast, only the younger participants (1 and 2) had faster tongue speeds as compared with their TD peers, as shown in Figure 6. The older two participants showed slightly slower speeds. Significant main effects for average speed were found for Group, $F(1, 151) = 14.16$, $p < .001$, and Articulator, $F(1, 151) = 26.87$, $p < .001$. Children with CP had significantly faster average speeds than their TD peers for both articulators. In addition, the average speeds for the tongue tip were faster than for the jaw for both groups. A significant Group $\times$ Articulator interaction, $F(1, 151) = 9.07$,

$p < .01$, was found, and post hoc analyses revealed that children with CP had significantly faster jaw speed than their TD peers. Similar to path distance, the TD group had faster tongue tip speeds than for the jaw, but no articulator differences were observed for the CP group. There was no significant effect of Age.

Speech Movement Stability

The individual speech movement stability data for each participant can be seen in Figures 7 and 8. For both articulators, all the participants with CP had reduced speech movement stability as compared with their age-matched TD peers. A significant main effect of Group was found, $F(1, 109) = 22.57$, $p < .001$, with the TD group

Figure 5. Individual *M* and *SD* (bars) of the jaw average speed for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

Figure 6. Individual *M* and *SD* (bars) of the tongue tip average speed for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

having greater overall movement stability than the CP group. A significant main effect of Articulator was observed, $F(1, 107) = 5.09, p < .05$, with the jaw having a significantly greater degree of speech movement stability as compared with the tongue for both groups. There was no significant main effect of Age or a significant Group $\times$ Articulator interaction.

Discussion

The current investigation provides initial observations of tongue and jaw movements of children with CP and their TD peers. Overall, children with CP differ in their speech motor performance and control of the tongue tip and jaw as compared with their TD peers. In particular, children

Figure 7. Individual *M* and *SD* (bars) of the zero-lag cross-correlation coefficient of the jaw for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

Figure 8. Individual *M* and *SD* (bars) of the zero-lag cross-correlation coefficient of the tongue tip for each participant with cerebral palsy (CP) and his age-matched typically developing (TD) peer.

with CP have larger path distances of the tongue tip and jaw, faster jaw speeds, and reduced speech movement stability of the tongue tip.

Children With CP Differ in Their Speech Motor Control Compared With TD Peers

The current findings of overall reduced speech motor performance and control are similar to previous kinematic findings in this population. In the current study, the children with CP have increased durations as compared with their TD peers, mirroring previous findings of slower speaking rates in this group (Hustad et al., 2010; Nip, 2012). The CP group also demonstrated increased path distances of the tongue tip and jaw, similar to previous findings of increased lip and jaw amplitudes in children with CP during speech production (Hong et al., 2011; Nip, 2012; Ward et al., 2013). This finding can be observed at both the group and individual level; all the children with CP had larger path distances for the tongue and jaw compared with their age-matched TD peers. Speaker 3 had particularly large path distances in comparison with the other speakers. Although we included only fluent utterances from this speaker in the final analysis, Speaker 3 took more time to produce the utterance, had more prolonged phonemes than the other participants, and had two instances of brief prolongations. The increased duration and prolonged segments may have increased the tongue and jaw movements for this participant. Previous research has hypothesized that children with CP may have a reduced ability to grade the force of their jaws, resulting in larger path distances for the jaw in this group (Kent & Netsell, 1978; Nip, 2012; Ward et al., 2013). The increased path distance of the tongue tip for the CP group may reflect similar impairments in lingual force control.

In the current study, the children with spastic CP had faster jaw speeds, similar to prior studies of people with CP (Hong et al., 2011; Nip, 2012; Rong et al., 2012; Ward

et al., 2013). This finding suggests that these talkers use more ballistic movements of the jaw when talking, which may indicate more immature speech motor control (Kent, 1992). Somewhat surprisingly, the pattern of speed differences for the tongue tip was more mixed. Only the two youngest participants with CP had faster tongue speeds than their TD peers; the older two participants had very similar tongue speeds to their TD peers. Tongue tip speed findings appear to differ for children with CP compared with adults with CP, whose tongue tip speeds are slower or the same as neurotypical adults (Rong et al., 2012). However, the current study did not decouple tongue movements from the jaw, whereas the study by Rong et al. (2012) did so. Therefore, the tongue tip speeds from the CP group, which were not decoupled from the jaw in the current study, may be overestimated because of the faster jaw speeds in this group. Future studies should examine tongue movements decoupled from the jaw in a larger number of participants to determine how tongue movements may differ across development in this population.

Tongue Tip Movements of Children With CP Are More Impaired Than Jaw Movements

Lingual-movement deficits are expected in children with CP because of the association between the F2 slope and intelligibility in talkers with dysarthria secondary to various etiologies (Kim, Kent, et al., 2011), including CP (Kim, Hasegawa-Johnson, et al., 2011; Lee et al., 2014). F2 is highly dependent on independent lingual movements, whereas changes to F1 can be accomplished with lingual and/or jaw movement (Rong et al., 2012). Articulator differences observed in the current study suggest that children with CP have more difficulty with tongue tip movements as compared with their jaw movements, which would support the above hypotheses. First, the CP group did not show a significant difference in the path distance of the tongue tip

and the jaw, whereas the TD group did move their tongue tips significantly more than the jaw. The lack of path distance differences between the tongue tip and jaw sensors suggests that the tongue tip did not move independently from the jaw for the CP group.

The speech movement stability findings also show articulator differences between the jaw and tongue tip for children with CP. The CP group had reduced speech movement stability for both the jaw and the tongue tip as compared with the TD group. Both groups demonstrated significantly reduced speech movement stability for the tongue tip compared with the jaw. One reason for this difference in speech movement stability may be due to anatomical and biomechanical differences between the two articulators (Green, Moore, Higashikawa, & Steeve, 2000). The tongue functions as a muscular hydrostat (Kier & Smith, 1985) and has considerably more movement flexibility than the bony jaw, which is relatively more constrained due to its bilateral anatomic connection to the skull at the temporomandibular joints (Green et al., 2000).

The lack of differences between the tongue tip and jaw in path distance and speech movement stability in the CP group may also represent the compensatory strategy of using the jaw to help the tongue reach articulatory targets, a finding similarly reported in speakers with ALS (Kuruvilla, Green, Yunusova, & Hanford, 2012; Mefferd, 2015). However, these movement differences may also represent immature speech motor control. During early toddler speech production, a reliance on articulators with fewer degrees of freedom (i.e., jaw) versus articulators with greater degrees of freedom (e.g., lips, tongue) has been reported (Green et al., 2000). In theory, the current findings may suggest that the tongue is a rate-limiting factor in the development of speech intelligibility in children with CP. Because there are no longitudinal data on the development of tongue movements for speech production in either TD children or children with CP, longitudinal studies of tongue motor control may be needed to determine whether the articulatory differences between the tongue tip and the jaw in this population represent compensatory strategies or delayed development. Determining the mechanism for these articulatory patterns may be useful in developing new treatment strategies for this population.

Toward a Descriptive Model of Speech Motor Control in Children With CP

Overall, children with CP seem to have decreased lingual and mandibular motor control as compared with their TD peers. For some variables, such as speech movement stability, the tongue appears to be more impaired than the jaw. These findings suggest that speech motor control may affect the intelligibility of these children and that articulators may differ in their relative contribution to the intelligibility deficits (Rong et al., 2012; Wang, Samal, Rong, & Green, 2016). Further work is needed to specify the relative contribution of each articulator to the intelligibility deficits in this population. This information may be

used to prioritize treatment targets (e.g., articulators that are shown to have the greatest impact on intelligibility) during intervention.

Limitations and Future Directions

This preliminary study presents the first observations of the lingual motor control of children with CP and has various limitations. First, the data set only includes four children with CP and four age- and sex-matched peers. Future studies should include a larger number of participants with a narrower range in age. Although age was not a significant predictor for two variables (average speed, speech movement stability), it was a significant predictor for duration and path distance. In addition, only boys were included in the current study, and future work should include girls to determine if there are any potential sex-related differences. Future studies may also focus on explicating the articulatory-acoustic relations in this population to better understand how these altered speech movements affect the speech characteristics in this population. Last, decoupling the tongue from the jaw may provide more specific insights into the relative contribution of the jaw and the tongue to speech production.

Conclusion

This initial examination of the tongue and jaw movements of children with CP demonstrated that these children have impaired speech motor control of both articulators. For the CP group, sentences took longer to produce, articulators moved more inefficiently, as indexed by the increased path distances and average speeds for both articulators, and movements were produced with less stability than their TD peers.

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References

- American Speech-Language-Hearing Association. (1997). Guidelines for audiologic screening. In *ASHA Practice Policy*. Retrieved February 17, 2012, from <http://www.asha.org/docs/html/GL1997-00199.html>
- Ansel, B. M., & Kent, R. D. (1992). Acoustic-phonetic contrasts and intelligibility in the dysarthria associated with mixed cerebral palsy. *Journal of Speech and Hearing Research*, 35, 296–308.

- Ciocca, V., Whitehill, T. L., & Yin, J. M. K. (2004). The impact of cerebral palsy on the intelligibility of pitch-based linguistic contrasts. *Journal of Physiological Anthropology and Applied Human Science*, 23(6), 283–287. <http://doi.org/10.2114/jpa.23.283>
- Green, J. R. (2015). Mouth matters: Scientific and clinical applications of speech movement analysis. *Perspectives on Speech Science & Orofacial Disorders*, 25, 6–16.
- Green, J. R., Moore, C. A., Higashikawa, M., & Steeve, R. W. (2000). The physiological development of speech motor control: Lip and jaw coordination. *Journal of Speech, Language, and Hearing Research*, 43, 239–255.
- Green, J. R., Moore, C. A., & Reilly, K. J. (2002). The sequential development of jaw and lip control for speech. *Journal of Speech, Language, and Hearing Research*, 45, 66–79.
- Green, J. R., & Nip, I. S. B. (2010). Some organization principles in early speech development. In B. Maassen & P. H. H. M. Van Lieshout (Eds.), *Speech motor control: New developments in basic and applied research* (pp. 171–188). Oxford, United Kingdom: Oxford University Press.
- Green, J. R., Wang, J., & Wilson, D. L. (2013). SMASH: A tool for articulatory data processing and analysis. In F. Bimbot, C. Cerisara, C. Fougere, G. Gravier, L. Lamel, F. Pellegrino, & P. Perrier (Eds.), *14th Annual Conference of the International Speech Communication Association (Interspeech 2013)*, Lyon, France (pp. 1331–1335). Red Hook, New York: Curran Associates.
- Green, J. R., Yunusova, Y., Kuruvilla, M. S., Wang, J., Pattee, G. L., Synhorst, L., Zinman, L., ... Berry, J. D. (2013). Bulbar and speech motor assessment in ALS: Challenges and future directions. *Amyotrophic Lateral Sclerosis and Frontotemporal Degeneration*, 14, 494–500.
- Henriques, R. N., & van Lieshout, P. (2013). A comparison of methods for decoupling tongue and lower lip from jaw movements in 3D articulatory. *Journal of Speech, Language & Hearing Research*, 56, 1503–1516.
- Higgins, C. M., & Hodge, M. M. (2002). Vowel area and intelligibility in children with and without dysarthria. *Journal of Medical Speech-Language Pathology*, 10, 271–277.
- Hodge, M., Daniels, J., & Gotzke, C. L. (2009). *TOCS+ intelligibility measures* (Version 5.3) [computer software]. Edmonton, Canada: University of Alberta.
- Hodge, M. M., & Gotzke, C. L. (2014). Construct-related validity of the TOCS measures: Comparison of intelligibility and speaking rate scores in children with and without speech disorders. *Journal of Communication Disorders*, 51, 51–63.
- Hong, W.-H., Chen, H.-C., Yang, F. G., Wu, C.-Y., Chen, C.-L., & Wong, A. M. (2011). Speech-associated labiomandibular movement in Mandarin-speaking children with quadriplegic cerebral palsy: A kinematic study. *Research in Developmental Disabilities*, 32, 2595–2601. <http://doi.org/10.1016/j.ridd.2011.06.016>
- Hustad, K. C., Gorton, K., & Lee, J. (2010). Classification of speech and language profiles in 4-year-old children with cerebral palsy: A prospective preliminary study. *Journal of Speech, Language, and Hearing Research*, 53, 1496–1513. [http://doi.org/10.1044/1092-4388\(2010/09-0176\)](http://doi.org/10.1044/1092-4388(2010/09-0176))
- Hustad, K. C., Schueler, B., Schultz, L., & DuHadway, C. (2012). Intelligibility of 4-year-old children with and without cerebral palsy. *Journal of Speech, Language, and Hearing Research*, 55, 1177–1189. [http://doi.org/10.1044/1092-4388\(2011/11-0083\)](http://doi.org/10.1044/1092-4388(2011/11-0083))
- Kent, R. D. (1992). The biology of phonological development. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 65–90). Timonium, MD: York Press.
- Kent, R., & Netsell, R. (1978). Articulatory abnormalities in athetoid cerebral palsy. *Journal of Speech and Hearing Disorders*, 43, 353–373.
- Kier, W., & Smith, K. K. (1985). Tongues, tentacles and trunks: The biomechanics of movement in muscular-hydrostats. *Zoological Journal of the Linnean Society*, 83, 307–324.
- Kim, H., Hasegawa-Johnson, M., & Perlman, A. (2011). Vowel contrast and speech intelligibility in dysarthria. *Folia Phoniatrica et Logopaedica*, 63, 187–194. <http://doi.org/10.1159/000318881>
- Kim, Y., Kent, R. D., & Weismer, G. (2011). An acoustic study of the relationships among neurologic disease, dysarthria type, and severity of dysarthria. *Journal of Speech, Language, and Hearing Research*, 54, 417–429. [http://doi.org/10.1044/1092-4388\(2010/10-0020\)](http://doi.org/10.1044/1092-4388(2010/10-0020))
- Kuruvilla, M. S., Green, J. R., Yunusova, Y., & Hanford, K. (2012). Spatiotemporal coupling of the tongue in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, 55, 1897–1909. [http://doi.org/10.1044/1092-4388\(2012/11-0259\)](http://doi.org/10.1044/1092-4388(2012/11-0259))
- Lee, J., & Hustad, K. C. (2013). A preliminary investigation of longitudinal changes in speech production over 18 months in young children with cerebral palsy. *Folia Phoniatrica et Logopaedica*, 65, 32–39. <http://doi.org/10.1159/000334531>
- Lee, J., Hustad, K. C., & Weismer, G. (2014). Predicting speech intelligibility with a multiple speech subsystems approach in children with cerebral palsy. *Journal of Speech, Language, and Hearing Research*, 57, 1666–1678. http://doi.org/10.1044/2014_JSLHR-S-13-0292
- Liu, H.-M., Tsao, F.-M., & Kuhl, P. K. (2005). The effect of reduced vowel working space on speech intelligibility in Mandarin-speaking young adults with cerebral palsy. *The Journal of the Acoustical Society of America*, 117(6), 3879–3889. <http://doi.org/10.1121/1.1898623>
- Mefferd, A. (2015). Articulatory-to-acoustic relations in talkers with dysarthria: A first analysis. *Journal of Speech, Language, and Hearing Research*, 58, 576–589. http://doi.org/10.1044/2015_JSLHR-S-14-0188
- Nip, I. S. B. (2012). Kinematic characteristics of speaking rate in individuals with cerebral palsy: A preliminary study. *Journal of Medical Speech-Language Pathology*, 20, 88–94.
- Nip, I. S. B. (2017). Interarticulator coordination in children with and without cerebral palsy. *Developmental Neurorehabilitation*, 20(1), 1–13.
- Nip, I. S. B., & Wilson, E. M. (2014). Jaw kinematics of chewing in children with cerebral palsy. *Developmental Medicine and Child Neurology*, 56(S5), 77–78.
- Nordberg, A., Miniscalco, C., & Lohmander, A. (2014). Consonant production and overall speech characteristics in school-aged children with cerebral palsy and speech impairment. *International Journal of Speech-Language Pathology*, 16, 386–395.
- Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine and Child Neurology*, 39, 214–223.
- Patel, R. (2002). Prosodic control in severe dysarthria: Preserved ability to mark the question–statement contrast. *Journal of Speech, Language, and Hearing Research*, 45, 858–870. [http://doi.org/10.1044/1092-4388\(2002/069\)](http://doi.org/10.1044/1092-4388(2002/069))
- Patel, R. (2003). Acoustic characteristics of the question–statement contrast in severe dysarthria due to cerebral palsy. *Journal of Speech, Language, and Hearing Research*, 46, 1401–1415.
- Pennington, L., Smallman, C., & Farrier, F. (2006). Intensive dysarthria therapy for older children with cerebral palsy: Findings

- from six cases. *Child Language Teaching and Therapy*, 22(3), 255–273.
- Rong, P., Loucks, T., Kim, H., & Hasegawa-Johnson, M. (2012). Relationship between kinematics, F2 slope and speech intelligibility in dysarthria due to cerebral palsy. *Clinical Linguistics & Phonetics*, 26(9), 806–822. <http://doi.org/10.3109/02699206.2012.706686>
- Rong, P., Yunusova, Y., Wang, J., & Green, J. R. (2015). Predicting early bulbar decline in amyotrophic lateral sclerosis: A speech subsystem approach. *Behavioural Neurology*, 2015, e183027. <http://doi.org/10.1155/2015/183027>
- Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., . . . Jacobsson, B. (2007). A report: The definition and classification of cerebral palsy April 2006. *Developmental Medicine & Child Neurology*, 49(S2), 8–14.
- Rosenbek, J. C., & Jones, H. N. (2009). Principles of treatment for sensorimotor speech disorders. In M. R. McNeil (Ed.), *Clinical management of sensorimotor speech disorders* (2nd ed., pp. 269–286). New York, NY: Thieme Medical Publishers.
- SAS Institute Inc. (2014). SAS PROC MIXED (SAS Version 9.4) [Computer software]. Cary, NC: SAS Institute Inc.
- Semel, E., Wiig, E. H., & Secord, W. A. (2003). *Clinical Evaluation of Language Fundamentals—Fourth Edition*. San Antonio, TX: PsychCorp.
- Shellikeri, S., Green, J. R., Kulkarni, M., Rong, P., Martino, R., Zinman, L., & Yunusova, Y. (2016). Speech movement measures as markers of bulbar disease in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, 59, 887–899. https://doi.org/10.1044/2016_JSLHR-S-15-0238
- Smith, A., & Goffman, L. (2004). Interaction of language and motor factors in speech production. In B. Maassen, R. D. Kent, H. F. M. Peters, P. H. H. M. van Lieshout, & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech* (pp. 225–252). Oxford, United Kingdom: Oxford University Press.
- Smith, A., Goffman, L., Zelaznik, H. N., Ying, G., & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. *Experimental Brain Research*, 104, 493–501.
- St. Louis, K. O., & Ruscello, D. M. (2000). *Oral Speech Mechanism Screening Examination—Third Edition*. Austin, TX: Pro-Ed.
- Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics*, 17, 3–45.
- Thelen, E. (1991). Motor aspects of emergent speech: A dynamic approach. In N. A. Krasnegor, D. M. Rumbaugh, R. L. Schiefelbusch, & M. Studdert-Kennedy (Eds.), *Biological and behavioral determinants of language development* (pp. 339–362). Mahwah, NJ: Lawrence Erlbaum.
- Thelen, E., & Smith, L. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.
- Walsh, B., & Smith, A. (2002). Articulatory movements in adolescents: Evidence for protracted development of speech motor control processes. *Journal of Speech, Language, and Hearing Research*, 45, 1119–1133.
- Wang, J., Green, J. R., Samal, A., & Yunusova, Y. (2013). Articulatory distinctiveness of vowels and consonants: A data-driven approach. *Journal of Speech, Language, and Hearing Research*, 56, 1539–1551. [http://doi.org/10.1044/1092-4388\(2013/12-0030\)](http://doi.org/10.1044/1092-4388(2013/12-0030))
- Wang, J., Samal, A., Rong, P., & Green, J. R. (2016). An optimal set of flesh points on tongue and lips for speech-movement classification. *Journal of Speech, Language, and Hearing Research*, 59, 15–26. https://doi.org/10.1044/2015_JSLHR-S-14-0112
- Ward, R., Strauss, G., & Leitão, S. (2013). Kinematic changes in jaw and lip control of children with cerebral palsy following participation in a motor-speech (PROMPT) intervention. *International Journal of Speech-Language Pathology*, 15, 136–155.
- Weismer, G., & Kim, Y. (2010). Classification and taxonomy of motor speech disorders: What are the issues? In B. Maassen & P. H. H. M. Van Lieshout (Eds.), *Speech motor control: New developments in basic and applied research* (pp. 229–242). Oxford, United Kingdom: Oxford University.
- Whitehill, T. L., & Ciocca, V. (2000). Perceptual-phonetic predictors of single-word intelligibility: A study of Cantonese dysarthria. *Journal of Speech, Language, and Hearing Research*, 43, 1451–1465.
- Workinger, M. S. (2005). *Cerebral palsy: Resource guide for speech-language pathologists*. Clifton Park, NJ: Thomson-Delmar Learning.
- Yorkston, K. M., Beukelman, D. R., Hakel, M., & Dorsey, M. (2007). *Speech Intelligibility Test* [Computer software]. Lincoln, NE: Institute for Rehabilitation Science and Engineering at Madonna Rehabilitation Hospital.
- Yunusova, Y. Y., Weismer, G., Westbury, J. R., & Lindstrom, M. J. (2008). Articulatory movements during vowels in speakers with dysarthria and healthy controls. *Journal of Speech, Language, and Hearing Research*, 51, 596–611.