

# Electropalatographic Assessment of Tongue-to-Palate Contacts Exhibited in Dysarthria Following Traumatic Brain Injury: Spatial Characteristics

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Consonant imprecision has been reported to be a common feature of the dysarthric speech disturbances exhibited by individuals who have sustained a traumatic brain injury (TBI). Inaccurate tongue placements against the hard palate during consonant articulation may be one factor underlying the imprecision. To investigate this hypothesis, electropalatography (EPG) was used to assess the spatial characteristics of the tongue-to-palate contacts exhibited by three males (aged 23–29 years) with dysarthria following severe TBI. Five nonneurologically impaired adults served as control subjects. Twelve single-syllable words of CV or CVC construction (where initial C = /t, d, s, z, k, g/, V = /i, a/) were read aloud three times by each subject while wearing an EPG palate. Spatial characteristics were analyzed in terms of the location, pattern, and amount of tongue-to-palate contact at the frame of maximum contact during production of each consonant. The results revealed that for the majority of consonants, the patterns and locations of contacts exhibited by the TBI subjects were consistent with the contacts generated by the group of control subjects. One notable exception was one subject's production of the alveolar fricatives in which complete closure across the palate was demonstrated, rather than the characteristic groove configuration. Major discrepancies were also noted in relation to the amount of tongue-to-palate contact exhibited, with two TBI subjects consistently demonstrating increased contacts compared to the control subjects. The implications of these findings for the development of treatment programs for dysarthric speech disorders subsequent to TBI are highlighted.

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Consonant imprecision has been found to be a common feature exhibited in the speech of individuals with dysarthria subsequent to traumatic brain injury (TBI). In a study conducted by Theodoros, Murdoch, and Chenery (1994), the speech of 20 sub-

jects with TBI was analyzed using perceptual-based measures. Consonant imprecision was exhibited by 95% of the sample. To effectively treat and improve consonant articulation in this population, an understanding of the physiological nature of the

articulatory disturbances is imperative (Theodoros et al., 1994) and, for this, instrumentation capable of directly and objectively assessing lingual movements and contacts during speech is required. There is a paucity of such physiological studies, however, despite the availability of a suitable and well-established instrumental assessment technique called electropalatography (EPG).

Electropalatography records the location and timing of tongue contacts against the hard palate during speech (Hardcastle, 1984; Hardcastle, Gibbon, & Jones, 1991; Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989). These spatial and temporal features are likely to be directly related to the level of consonant precision exhibited by an individual, as found by Hardcastle, Morgan Barry, and Clark (1985) and Morgan Barry (1995) in their EPG assessment of an individual with dysarthria following a cerebrovascular accident. In regard to dysarthria following TBI, only one study has used EPG to provide a detailed description of the associated articulatory disturbances. This study, conducted by the present authors (Goozée, Murdoch, & Theodoros, 1999), focused on the tongue-to-palate timing characteristics exhibited by three individuals with dysarthria following TBI, each of whom exhibited consonant imprecision. Timing disturbances were found to be demonstrated by all three individuals and were proposed to have contributed to the consonant imprecision exhibited. To gain a comprehensive understanding of the nature of the articulatory disturbances underlying the consonant imprecision, however, it would be important to complement the timing results with information regarding the spatial characteristics of the tongue-to-palate contacts, a feature also expected to influence consonant precision. The present study, therefore, forms a follow-up to the previous article on timing characteristics (Goozée et al., 1999) and uses EPG to investigate the spatial characteristics of the tongue-to-palate contacts produced by the same three individuals with dysarthria following TBI. The results are presented in a series of individual case discussions.

## METHODS

### Subjects

Three males with dysarthria following severe TBI participated in the study. The subjects ranged in age from 23 to 29 years and were at least 20 months post-TBI. The medical and biographical de-

tails of each of the three subjects are presented in detail in the case discussions that follow.

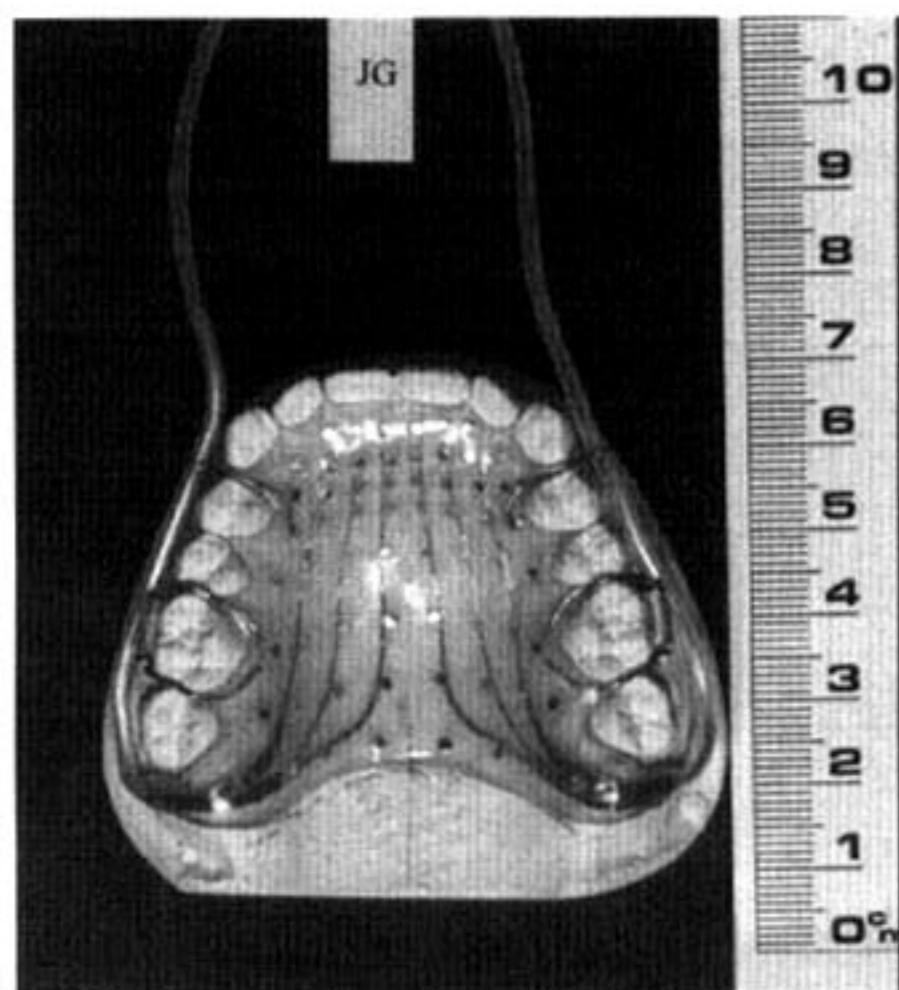
Perceptual assessments, including the Assessment of Intelligibility of Dysarthric Speech (Yorkston & Beukelman, 1981) and a speech sample analysis using the perceptual rating scale outlined by FitzGerald, Murdoch, and Chenery (1987), were conducted prior to the EPG assessment. On the basis of the results obtained using the perceptual rating scale and in accordance with the classification system developed by Darley, Aronson, and Brown (1975), each subject's speech disturbance was differentially diagnosed by two qualified speech-language pathologists. Two subjects presented with mild spastic dysarthria, and with respect to articulatory functioning, were perceived to exhibit mild consonant imprecision. The third subject presented with moderate spastic-ataxic dysarthria and exhibited a moderate level of consonant imprecision and phoneme prolongation. All three subjects' vowel productions were judged as perceptually acceptable. Complete details regarding the administration of the perceptual assessments and the results obtained by the three TBI subjects were presented in Goozée et al. (1999).

Five nonneurologically impaired adult subjects (2 males, 3 females) aged 22–48 years (mean age 28.2 years;  $SD = 11.14$ ) served as control subjects for the EPG component of the study. The control subjects presented with perceptually normal speech as judged by a qualified speech-language pathologist.

Each of the TBI subjects and control subjects were native speakers of English and had not undergone tongue, jaw, or palatal surgery. In addition, each TBI subject had a negative history of speech disturbance prior to the onset of TBI.

### Procedure

The Reading Electropalatograph (EPG3) system was used to record the tongue-to-palate contacts and acoustic output produced by the three TBI subjects and the five control subjects. Each subject was fitted with his or her own artificial acrylic palate, which had been molded to fit over the hard palate (see Figure 1). The artificial palate contained an array of 62 miniature touch-sensitive disk electrodes (1.4 mm in diameter) that detected tongue contact. The electrodes were arranged in eight rows and eight columns according to a predetermined scheme based on anatomical landmarks (see Hardcastle, Gibbon, & Jones, 1991), and, as such, permitted comparisons between different subject's contact



**Figure 1.** Photograph of an artificial EPG palate placed on a dental impression of the hard palate and teeth. The EPG palate covers the hard palate from the central incisors anteriorly, to the junction of the hard and soft palates posteriorly, and the side teeth laterally. Each row of electrodes contains 8 electrodes, except for the anterior row (row 1), which contains 6 electrodes.

patterns to be made (Hardcastle & Gibbon, 1997). Along each row the electrodes were equally spaced, with the spacing between the anterior four rows half that of the posterior four rows (Hardcastle, Gibbon, & Jones, 1991).

Changes in tongue-to-palate contacts were sampled at 10 millisecond time intervals (sampling rate 100 Hz) and recorded as a series of EPG frames or tongue-to-palate contact diagrams. Acoustic data were collected from a microphone, which was positioned at a set distance of 10 cm from the mouth and connected to the EPG3 main unit. The acoustic signals were sampled at a rate of 10,000 Hz. For a review of the Reading EPG hardware and software refer to Hardcastle et al. (1989) and Hardcastle, Gibbon, and Jones (1991).

Twelve single-syllable real words consisting of a CV or CVC construction were read aloud three times by each subject while wearing the EPG palate. The word-initial consonants included the oral alveolar stops /t, d/, the alveolar fricatives /s, z/, and the velar stops /k, g/. This array of lingual consonants was chosen so that differences in place, manner, and voicing could be examined. The consonants were produced in two different vowel environments, the low /a/ vowel and the high front /i/ vowel. Each of the target words was preceded by the neutral schwa (see the Appendix). The words were printed on flash cards and presented in ran-

dom order. Each subject was instructed to use a comfortable speaking rate and loudness level when reading the words aloud.

Prior to the recording stage of the assessment, a 45-minute desensitization period was provided to allow each subject to become accustomed to speaking with the EPG palate in his or her mouth. An independent speech-language pathologist listened to each subject read aloud a standard passage prior to wearing the palate and again after the desensitization period and verified there was no significant change in speech production with the palate in situ following the desensitization period. In addition, each subject was familiarized with the list of words prior to recording to ensure that intelligibility and speech rate were not adversely affected by reading difficulties. The EPG assessments were conducted by a qualified speech-language pathologist who listened to each word produced by the subjects. Any productions in which the target word was read aloud incorrectly (as verified by the subjects themselves) were rejected. In the event that a word was misread, the subject repeated the word after the speech-language pathologist. Errors in reading occurred infrequently, but were noted for the words "Sarge" (e.g., produced as /sag/) and "quiche," words not likely to be commonly used by the subjects.

The EPG assessments were conducted in an electrically shielded, quiet room. During the assessments, the subjects were seated in a straight-backed chair and were not presented with a visual display of their tongue-to-palate contacts. The recording samples were set at a duration of 5 sec, with two words elicited during each 5-sec period.

Each word read aloud during the EPG assessment was phonetically transcribed from the high-quality acoustic signals recorded by the EPG3 system by two qualified speech-language pathologists (one who was unrelated to the study, the other a researcher in the study). The phonetic transcriptions were used to examine the "outcome" of the tongue-to-palate contacts, that is, how the consonants produced were perceived.

### EPG Analysis Procedures

The EPG and acoustic files were loaded into an analysis program called EMA Tools, which runs in Matlab<sup>®</sup> (Nguyen, 1996). To investigate and compare the tongue-to-palate contacts produced by the TBI subjects and control subjects, a single EPG frame (i.e., tongue-to-palate contact diagram) was selected for analysis from each series of EPG frames (i.e., raw data) recorded for the target word-

initial consonants. The particular frame chosen for analysis was the (first) frame of maximum contact, which captures one important articulatory feature of the consonant produced (Gibbon, 1990).

Within the EMA Tools program, the raw EPG data were depicted in the form of totals displays, which are graphs in which the number of contacted electrodes within a particular region of the palate is plotted as a function of time (i.e., over consecutive frames) (Byrd, Flemming, Mueller, & Tan, 1995; Hardcastle, Gibbon, & Jones, 1991; Hardcastle, Gibbon, & Nicolaidis, 1991). Using the totals displays, the first frame to exhibit the greatest or "maximum" number of contacted electrodes could be readily identified. For the alveolar consonants, the totals displays were generated from the number of contacted electrodes within the anterior region of the palate (i.e., anterior four rows of electrodes), and for the velar consonants, the posterior region (i.e., posterior four rows of electrodes) of the palate.

To aid comparisons between the tongue-to-palate contacts produced by the TBI subjects and the control subjects, "representative" frames of maximum contact were generated for each target consonant. This was achieved by combining the frames of maximum contact for a consonant over the three repetitions that were elicited, depicting an electrode as "contacted" if it had been activated at least twice within the three repetitions. The representative tongue-to-palate contact diagrams each closely resembled the individual EPG frames from which they were composed.

Three parameters were chosen to be analyzed from the representative frames of maximum contact: location, pattern, and amount of tongue contact against the hard palate. It was envisioned that, together, these parameters would provide a comprehensive profile of the spatial characteristics of the tongue-to-palate contacts.

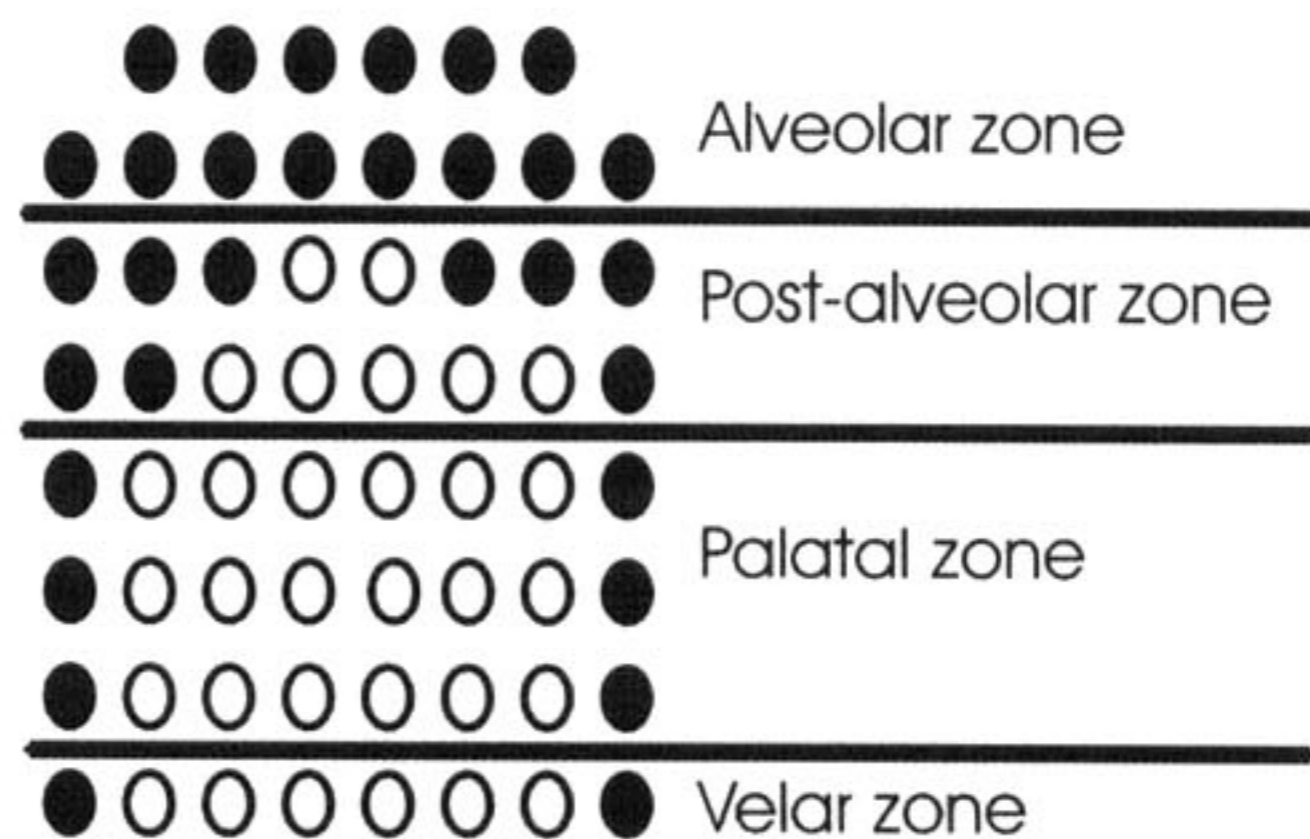
### *Location and Pattern of Tongue-to-Palate Contacts*

To investigate the location and pattern of tongue-to-palate contacts, the representative frames of maximum contact were visually inspected in regard to the following features:

1. Anterior-to-posterior location of contact along the midline of the palate (identified for the stop consonants, /t, d, k, g/)
2. Anterior-to-posterior location of maximum constriction or the point on the palate where the groove width is narrowest (identified for the fricatives, /s, z/)
3. Lateral contact (i.e., complete or incomplete contact along the outermost left and right electrode columns; length of contact measured in terms of number of electrodes along the outermost electrode columns).

For purposes of examining and describing the location of contact, the tongue-to-palate contact diagrams were divided into four zones, which delineated phonetically relevant regions of the palate: alveolar (rows 1–2), postalveolar (rows 3–4), palatal (rows 5–7), and velar (row 8) (Gibbon & Nicolaidis, in press) (Figure 2).

In addition to the contact features described, two numerical indices were calculated to further characterize the location and pattern of contact exhibited at the frames of maximum contact. These indices comprised a center of gravity index and a lateral asymmetry index and were calculated automatically by the EMA Tools analysis program. The center of gravity (COG) index expresses, as a single numerical value, the location of the main concentration of electrode contacts along the anterior-to-posterior axis of the palate, whereby progressively higher weightings are given toward anterior elec-



**Figure 2.** Example representative frame of maximum contact with phonetically relevant zones delineated. The top row (row 1) designates the anterior region of the palate at the alveolar ridge, and the bottom row (row 8) designates the posterior region of the palate at the junction of the hard and soft palates. Contacted electrodes are depicted as filled circles.

trode contacts (Hardcastle, Gibbon, & Nicolaidis, 1991; Jones & Hardcastle, 1995).

The lateral asymmetry index expresses the degree of contact asymmetry between the right and left sides of the palate (Jones & Hardcastle, 1995). On the basis of the formula used in the EMA Tools program, a positive lateral asymmetry value indicates a greater number of contacts on the left side of the EPG frame or tongue-to-palate contact diagram, whereas a negative value indicates more contacts on the right side of the frame. Further, contacts displayed on the left side of the EPG frame were in fact made on the right-hand side of the actual EPG palate, and vice versa. The COG and lateral asymmetry numerical indices were first calculated for the individual frames of maximum contact recorded for each word-initial consonant and then averaged over the three repetitions.

#### *Amount of Tongue-to-Palate Contact*

The amount of tongue-to-palate contact or "contact area" at the frame of maximum contact was quantified by calculating the number of electrodes contacted within particular regions of the palate. For the alveolar consonants, the total number of contacted electrodes in the anterior zone (anterior four rows) of the palate were calculated (maximum number of electrodes = 30). For the velar consonants, the total number of contacted electrodes in the posterior zone (posterior four rows) of the palate were calculated (maximum number = 32). As with the numerical indices, the number of contacts were calculated individually for each frame of maximum contact and then averaged over the three consonant repetitions.

In addition to determining the overall amount of contact, the representative frames of maximum contact were visually inspected to examine the nature of the contact area. The contact features that were investigated included:

1. Anterior-to-posterior length of contact along the midline of the palate (stop consonants)
2. Anterior-to-posterior length of lateral contact along the outermost right and left electrode columns (particularly relevant for velar stops, /k, g/)
3. Width of lateral contact (i.e., referring to electrode contacts on the left and right margins of the palate)
4. Width of groove at maximum constriction (fricatives)
5. Length of constriction for fricatives (i.e., referring to the number of rows over which the groove is formed).

Many of the contact features listed were based on those proposed by Hardcastle (1984), Hardcastle, Gibbon, and Nicolaidis (1991), and Dagenais, Lorendo, and McCutcheon (1994).

## RESULTS AND DISCUSSION

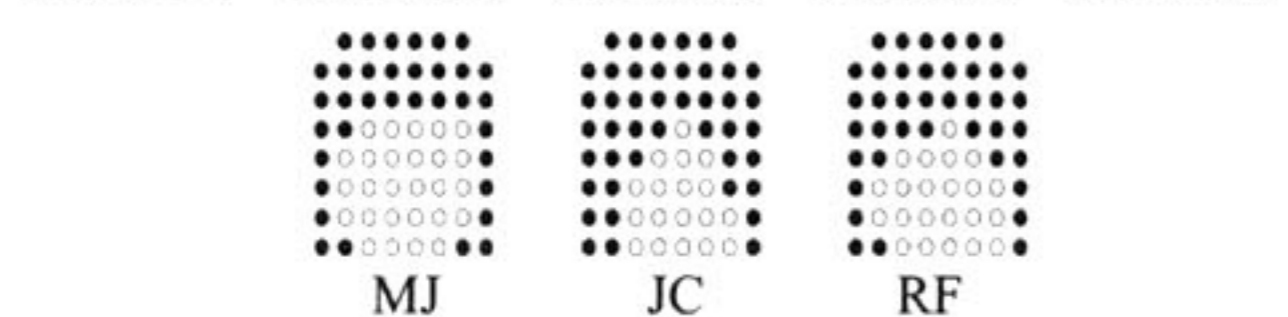
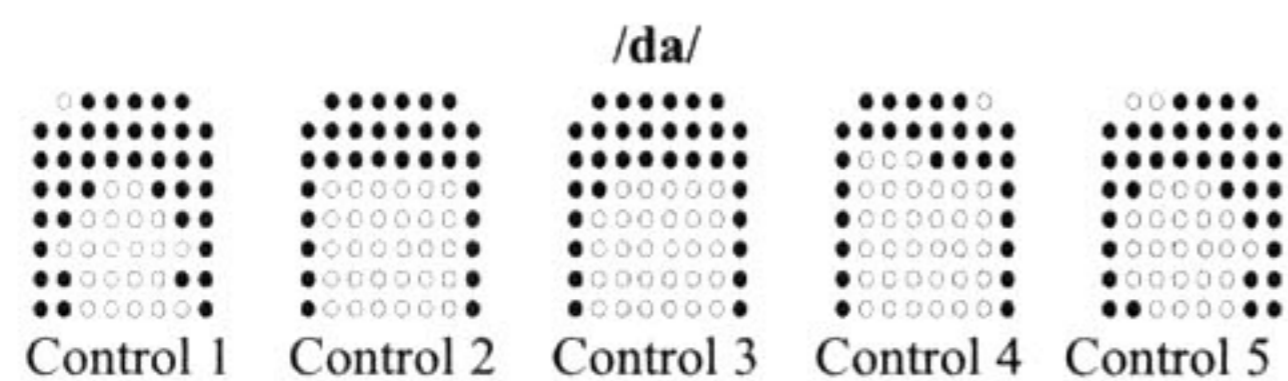
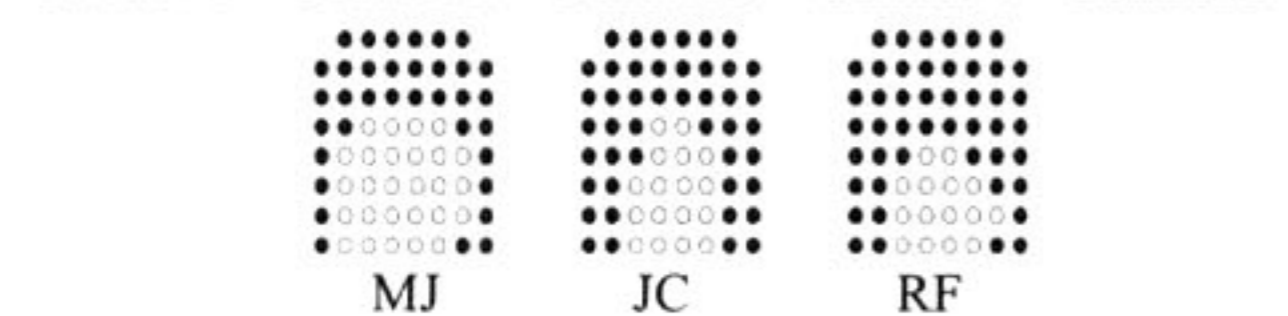
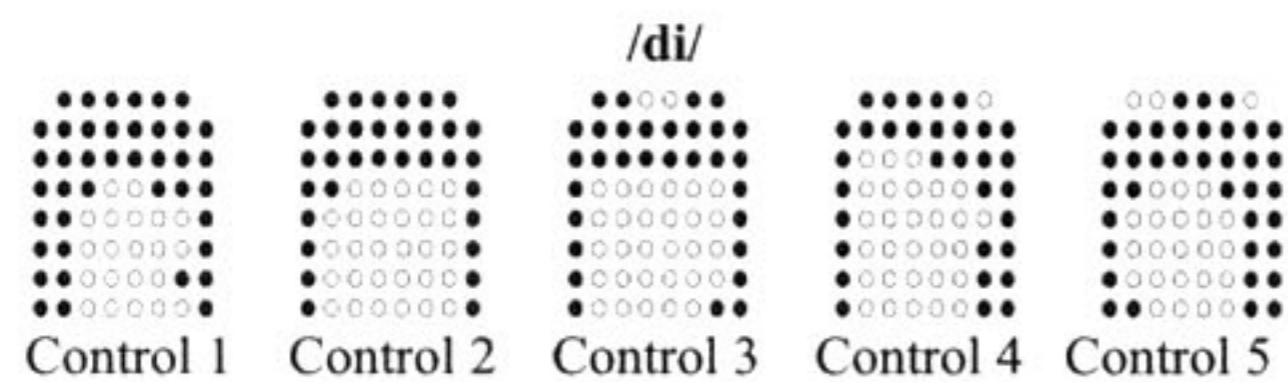
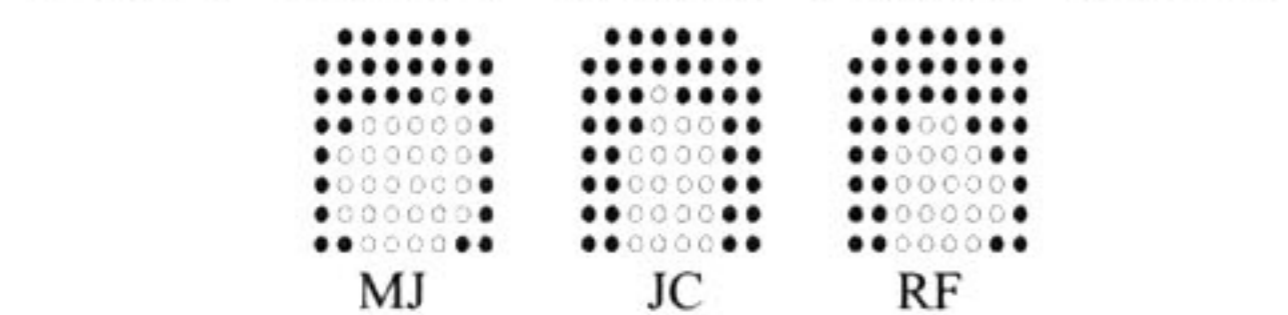
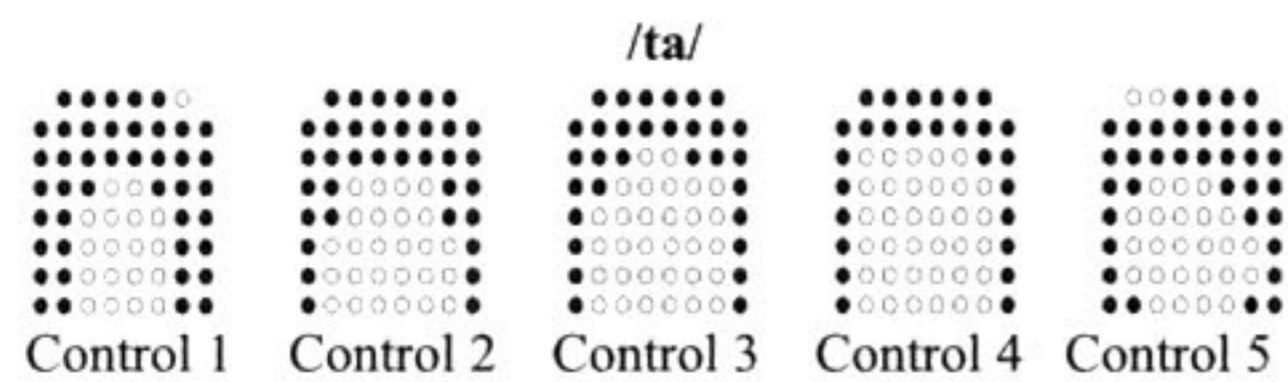
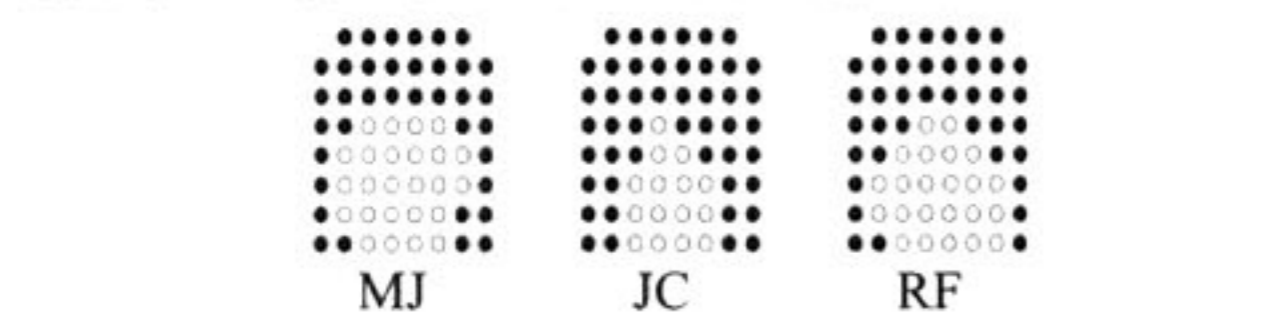
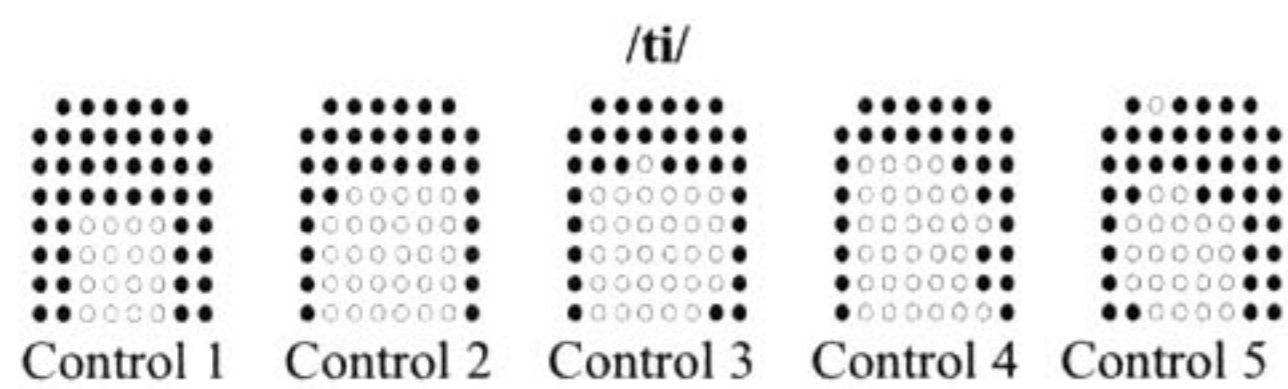
In the following section, the spatial characteristics of the tongue-to-palate contacts produced by the five control subjects are reported. Three case discussions follow, presenting details of the spatial characteristics of the tongue-to-palate contacts exhibited by the three subjects with dysarthria following TBI, compared to the control subjects' data.

### Control Group

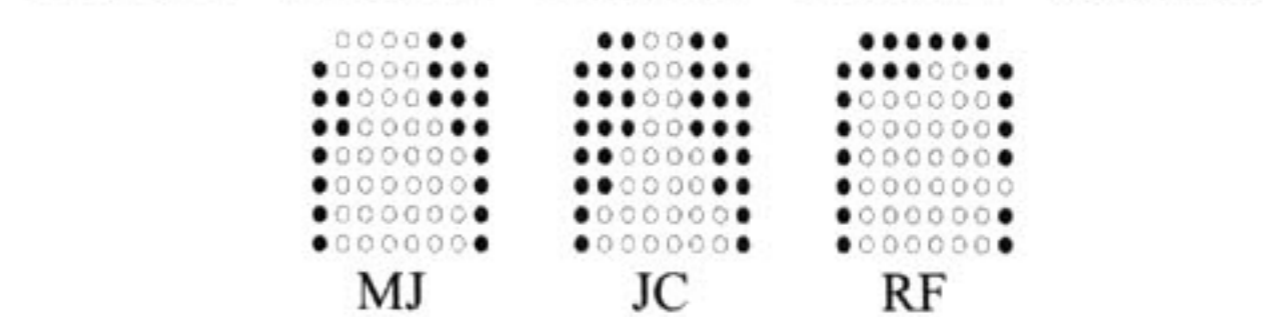
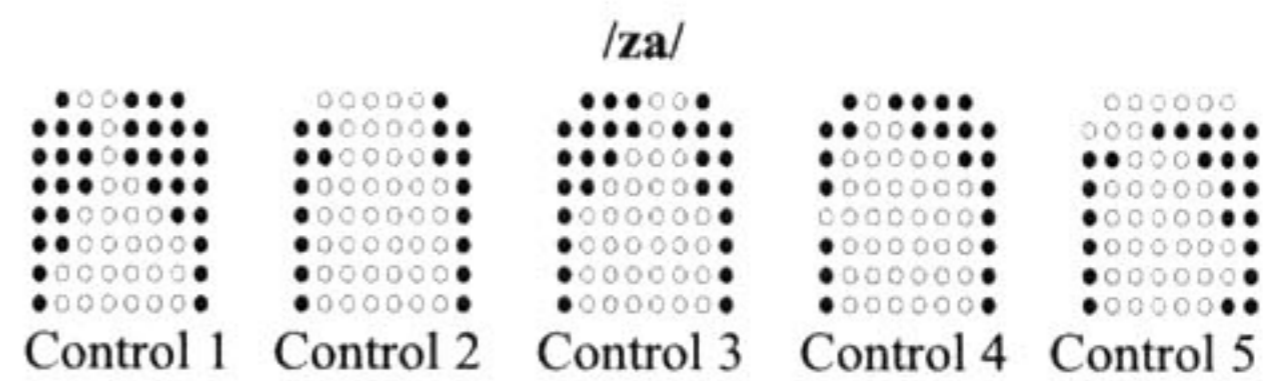
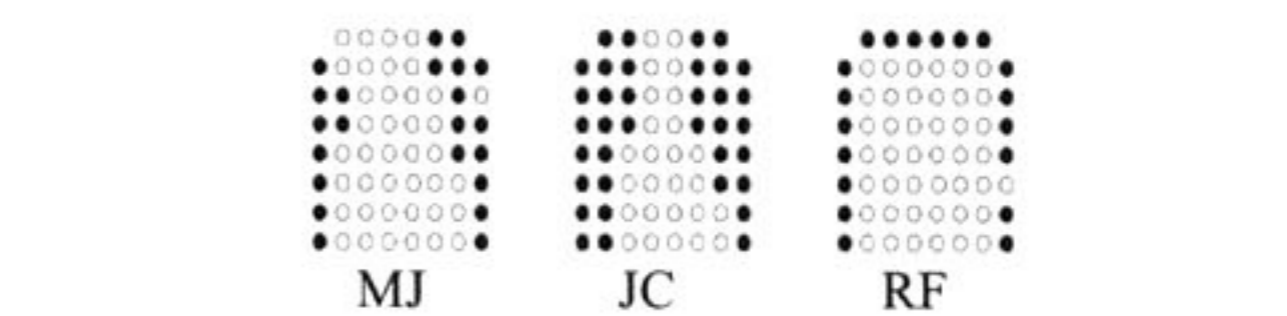
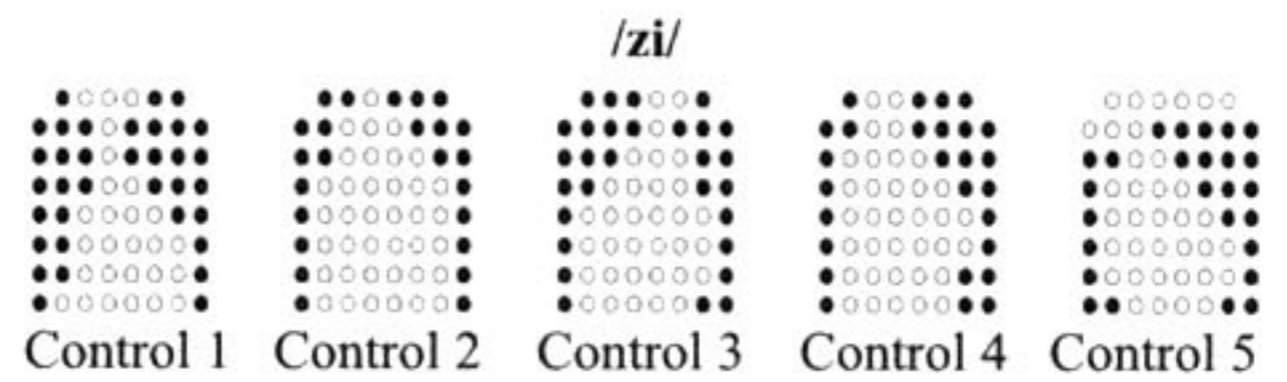
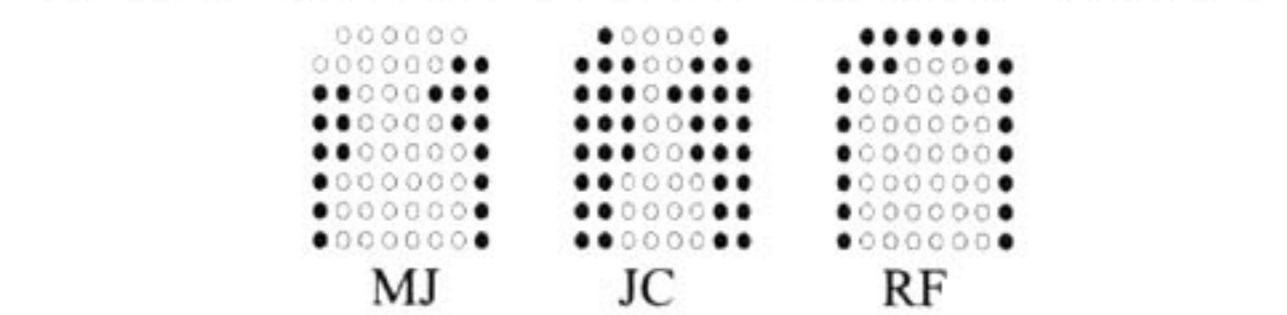
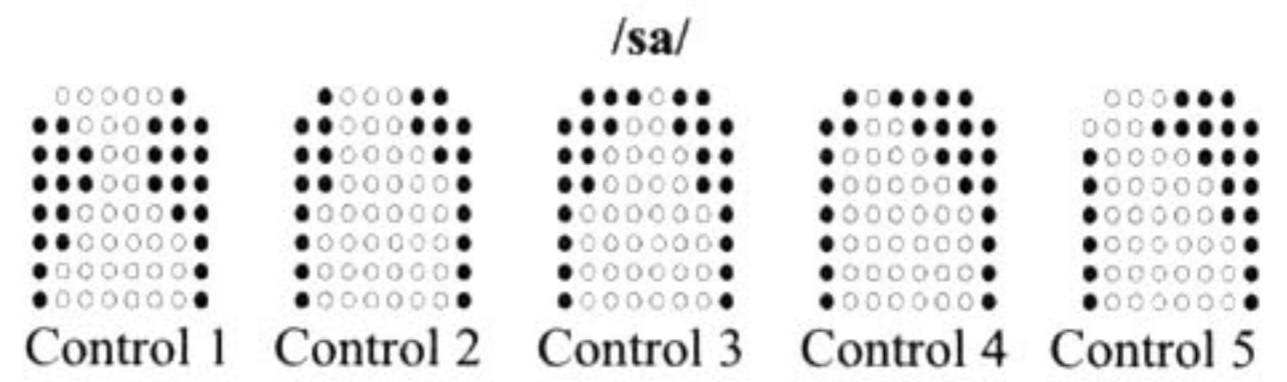
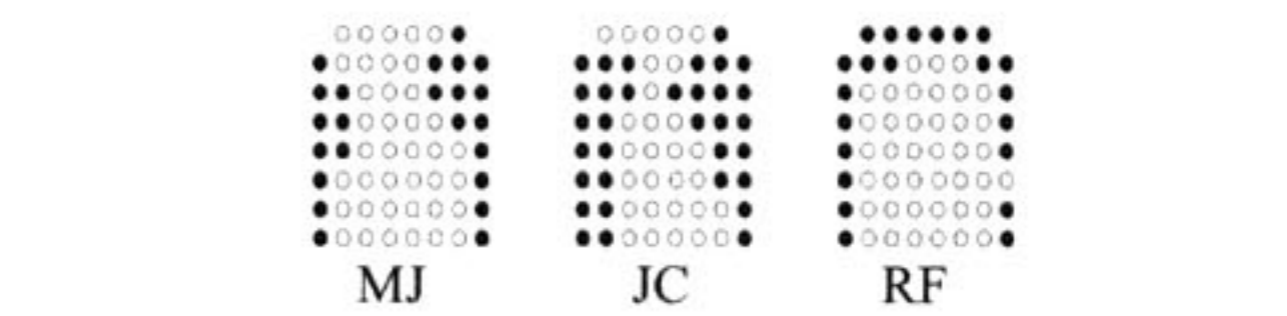
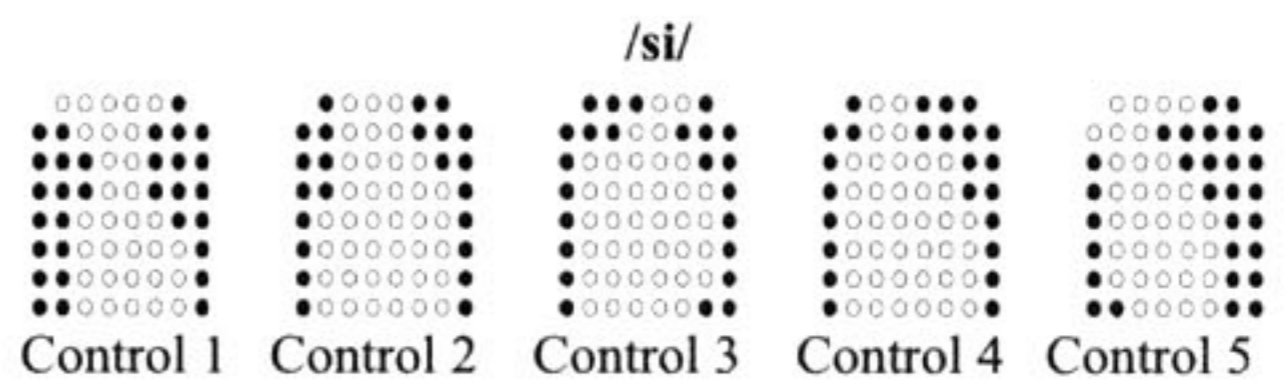
The words read aloud by each of the control subjects during the EPG assessment were judged to be perceptually acceptable by the two speech-language pathologists who phonetically transcribed the productions.

The representative tongue-to-palate contact diagrams generated for each control subject's productions of the oral alveolar stops /t, d/, alveolar fricatives /s, z/, and velar stops /k, g/ in the /i/ and /a/ vowel environments are presented in Figures 3–5. The alveolar stops were formed with full anterior closure (i.e., complete contact across the anterior rows of the palate) in the alveolar and postalveolar zones and complete lateral seal (Figure 3). This pattern of contact formed a horseshoe-shaped configuration, which is reportedly characteristic of alveolar stops (Gibbon & Nicolaidis, 1999).

The control subjects' alveolar fricatives were produced with complete contact along the lateral margins of the palate (control subject 4's /za/ excepted) and a characteristic channel or groove of noncontacted electrodes in the anterior region of the palate (Figure 4). Maximum constriction was located primarily in the alveolar zone. For productions of /si/ (two subjects), /sa/ (one subject), /zi/ (two subjects), and /za/ (three subjects) maximum constriction extended into, or occurred within, the postalveolar zone. Visual inspection of the grooves revealed their configurations to be variable among subjects. On an individual subject basis, however,



**Figure 3.** Representative frames of maximum contact generated from the control subjects' and TBI subjects' productions of the oral alveolar stops /ti/, /ta/, /di/, /da/. *Note:* Contacts displayed on the left-hand side of the tongue-to-palate contact diagrams above were made on the right-hand side of the EPG palate, and vice versa.



**Figure 4.** Representative frames of maximum contact generated from the control subjects' and TBI subjects' productions of the alveolar fricatives /si/, /sa/, /zi/, /za/.

each subject's groove configurations appeared to be consistent, in terms of width and location of constriction, across vowel environments and voicing contrasts. Control subject 2 formed an exception, demonstrating wide grooves for /si/, /sa/, and /za/, but a narrow groove for /zi/ (see Figure 4).

In the production of velar stops, closure is expected to be formed in the posterior region of the palate by the action of the tongue body. The representative frames of maximum contact for the velar stops produced by the control subjects in the present study were characterized by posterior contact with, for the majority of productions, closure along the posterior row of the palate (row 8) at the junction of the hard and soft palates. Closure was not detected, however, for one subject's production of /ki/, two subjects' production of /ga/, and four subjects' production of /ka/ (Figure 5). Other EPG studies have reported similar results for normal speakers (Dagenais et al., 1994; Hardcastle, Morgan Barry, & Clark, 1987). Both Hardcastle et al. (1987) and Dagenais et al. (1994) suggested that contact may have occurred on the soft palate (i.e., posterior to the artificial palate) in the cases of no EPG closure. This is likely to be the case in the present study, as each control subject's velar stops were phonetically transcribed as acceptable productions. Friction would have been expected to be heard had closure not occurred.

Further examination of the control subjects' velar stop productions revealed coarticulatory effects to be operating. The coarticulation effects were associated with vowel environment, with greater lengths of lateral contact (i.e., more anterior contact) observed for the velar stops that were produced in the high, front /i/ vowel environment compared to the low /a/ vowel environment. Again, the EPG studies conducted by Hardcastle et al. (1987) and Dagenais et al. (1994) found similar coarticulatory effects to be exhibited by their normal speakers.

Inspection of the quantitative contact area data collected for the control subjects' velar stop productions revealed further evidence of coarticulatory effects related to vowel environment. The contact area data, recorded as the mean number of electrodes contacted at the frame of maximum contact, are presented in Table 1 for the control subjects combined. For the control subjects' /k/ and /g/ productions in the /i/ vowel environment, greater numbers of electrodes were contacted compared to the same consonant productions in the /a/ vowel environment.

The mean COG values calculated for the control subjects' consonant productions are presented in

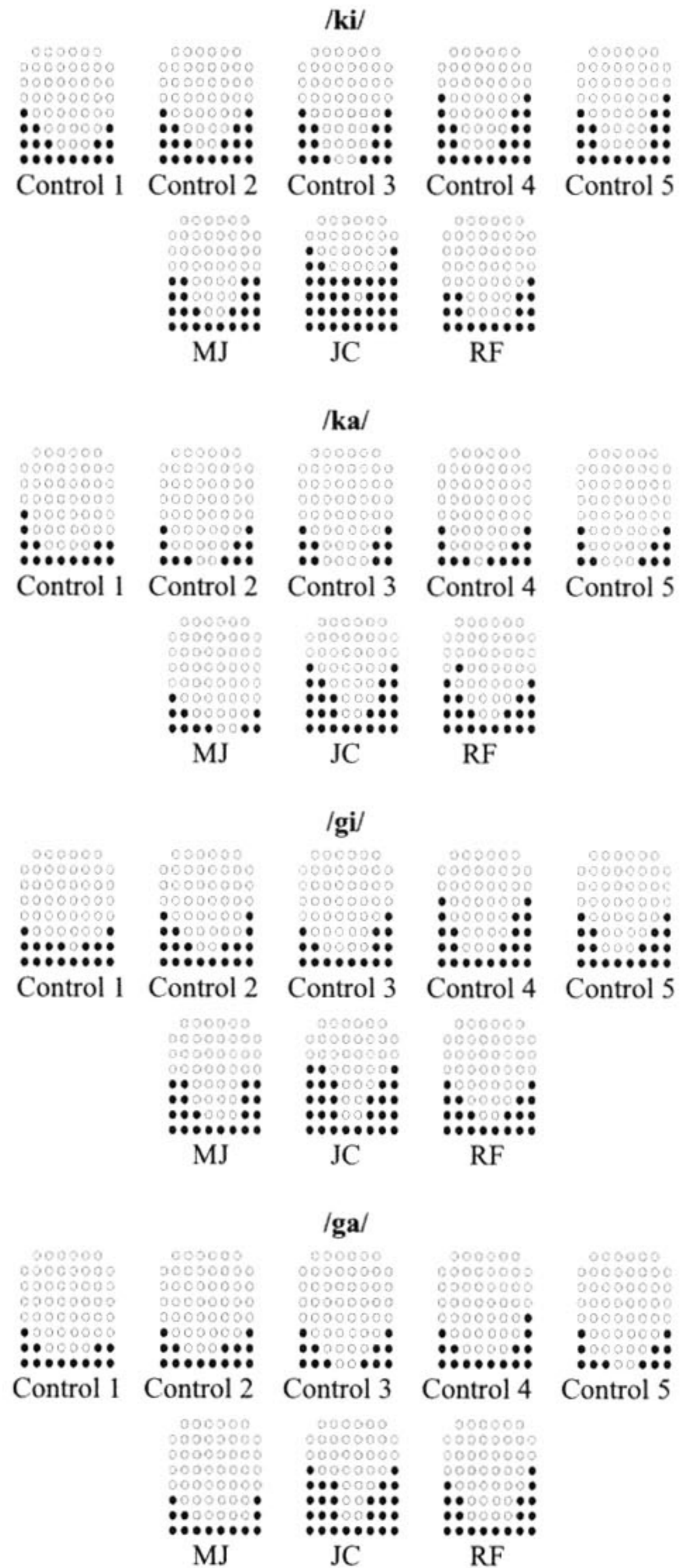


Figure 5. Representative frames of maximum contact generated from the control subjects' and TBI subjects' productions of the velar stops /ki/, /ka/, /gi/, /ga/.

Table 2. The mean COG values revealed an anterior concentration of electrode contacts for the alveolar stops (range 5.30–5.44) and the alveolar fricatives

**TABLE 1.** Mean number of contacts at frame of maximum contact calculated for the three individual TBI subjects and the control subjects combined.

Subjects	Alveolar Stops				Alveolar Fricatives				Velar Stops			
	ti	ta	di	da	si	sa	zi	za	ki	ka	gi	ga
Controls	24.07 (3.75)	23.60 (3.33)	24.00 (2.85)	24.20 (2.54)	16.27 (2.91)	16.21 (3.12)	17.53 (3.20)	16.73 (4.71)	18.50 (2.24)	11.47 (3.09)	17.87 (2.07)	13.27 (2.40)
MJ	26.00 ↑0.51	24.00 ↑0.12	22.67 ↓0.47	23.67 ↓0.21	14.33 ↓0.67	12.67 ↓1.13	16.00 ↓0.48	16.00 ↓0.15	21.33 ↑1.26	10.00 ↓0.48	20.33 ↑1.19	12.33 ↓0.39
JC	28.67 ↑1.23	26.00 ↑0.72	28.33 ↑1.52	28.00 ↑1.50	19.67 ↑1.17	18.67 ↑0.79	21.33 ↑1.19	21.00 ↑0.91	30.00 ↑5.13	23.33 ↑3.84	25.33 ↑3.60	25.67 ↑5.17
RF	28.00 ↑1.05	28.33 ↑1.42	29.67 ↑1.99	29.00 ↑1.89	NG	NG	NG	NG	17.33 ↓0.52	20.33 ↑2.87	21.00 ↑1.51	17.67 ↑1.83

Note: Data for alveolar consonants represent number of electrodes contacted within anterior region (anterior four rows) of palate; posterior region (posterior four rows) for velar consonants. NG = No groove exhibited. Numbers in parentheses represent standard deviations. ↑ or ↓ = Number of standard deviations above or below the control group mean.

**TABLE 2.** Mean COG index values at frame of maximum contact calculated for the three individual TBI subjects and the control subjects combined.

Subjects	Alveolar Stops				Alveolar Fricatives				Velar Stops			
	ti	ta	di	da	si	sa	zi	za	ki	ka	gi	ga
Controls	5.34 (0.25)	5.31 (0.27)	5.30 (0.27)	5.44 (0.26)	4.97 (0.36)	5.07 (0.28)	5.04 (0.34)	5.03 (0.31)	2.09 (0.26)	1.63 (0.14)	1.96 (0.26)	1.63 (0.22)
MJ	5.29 ↓0.2	5.34 ↑0.11	5.38 ↑0.30	5.37 ↓0.27	4.68 ↓0.81	4.52 ↓1.96	4.76 ↓0.82	4.96 ↓0.23	2.24 ↑0.58	1.48 ↓1.07	2.15 ↑0.73	1.48 ↓0.68
JC	4.91 ↓1.72	5.10 ↓0.78	5.03 ↓1.00	5.15 ↓1.12	4.7 ↓0.75	4.33 ↓2.64	4.86 ↓0.53	4.96 ↓0.23	2.92 ↑3.19	2.41 ↑5.57	2.63 ↑2.58	2.61 ↑4.45
RF	5.38 ↑0.16	5.18 ↓0.48	5.16 ↓0.52	5.34 ↓0.38	NG	NG	NG	NG	2.00 ↓0.35	2.20 ↑4.07	2.15 ↑0.73	2.37 ↑3.36

Note: COG = Center of gravity. NG = No groove exhibited. Numbers in parentheses represent standard deviations. ↑ or ↓ = Number of standard deviations above or below the control group mean.

(range 4.97–5.07), and a posterior concentration for the velar stop productions (range 1.63–2.09).

Hardcastle, Gibbon, and Nicolaidis (1991) noted that tongue-to-palate contact asymmetry is a frequently observed phenomenon demonstrated by both normal and pathological speakers. In the present study, asymmetry was evidenced in the mean lateral asymmetry values calculated for the control subjects' consonant productions (Table 3). Two of the five control subjects (control subjects 4 and 5) demonstrated a greater degree of asymmetry compared to the other three subjects, with a right-sided emphasis for electrode contacts. As a group, the control subjects' lateral asymmetry values also in-

dicated a right-sided contact emphasis for all consonant productions (Table 3).

## Case Reports

### Case 1

MJ, a 29-year-old male, sustained a severe TBI in a motor vehicle accident 25 months prior to the EPG assessment. He had a Glasgow Coma Score (GCS) of 3 at the scene of the accident, and a computed tomography (CT) scan revealed generalized cerebral edema consistent with diffuse axonal injury.

At the time of the EPG recording, MJ reportedly exhibited mild high-level cognitive language defi-



**TABLE 3.** Mean lateral asymmetry values at frame of maximum contact calculated for the three individual TBI subjects and the control subjects combined.

Subjects	Alveolar Stops				Alveolar Fricatives				Velar Stops			
	ti	ta	di	da	si	sa	zi	za	ki	ka	gi	ga
Controls	-0.07 (0.08)	-0.03 (0.06)	-0.05 (0.09)	-0.03 (0.07)	-0.15 (0.18)	-0.14 (0.18)	-0.15 (0.18)	-0.12 (0.15)	-0.10 (0.11)	-0.08 (0.14)	-0.14 (0.05)	-0.08 (0.09)
MJ	-0.02 ↑0.63	+0.03 ↑1.00	-0.04 ↑0.11	0 ↑0.43	-0.16 ↓0.06	-0.12 ↑0.11	-0.26 ↓0.61	-0.20 ↓0.53	-0.09 ↑0.09	+0.07 ↑1.07	-0.06 ↑1.60	-0.08 0
JC	-0.02 ↑0.63	+0.04 ↑1.17	+0.02 ↑0.78	+0.06 ↑1.29	-0.01 ↑0.78	-0.05 ↑0.50	+0.05 ↑1.11	-0.01 ↑0.73	+0.02 ↑1.09	-0.04 ↑0.29	-0.03 ↑2.20	-0.01 ↑0.78
RF	+0.03 ↑1.25	+0.03 ↑1.00	+0.02 ↑0.78	+0.03 ↑0.86	NG	NG	NG	NG	-0.20 ↓0.91	-0.10 ↓0.14	-0.12 ↑0.40	-0.18 ↓1.11

Note: NG = No groove exhibited. Positive value indicates greater number of contacts on left side of tongue-to-palate diagram or EPG frame. Negative value indicates greater number of contacts on right side of EPG frame. Numbers in parentheses represent standard deviations. ↑ or ↓ = Number of standard deviations above or below the control group mean.

cits and memory deficits, along with ataxia in both upper limbs and a right spastic hemiparesis. In regard to motor speech function, he presented with mild spastic dysarthria, with mild consonant imprecision identified as a feature of his speech. Single-word and sentence productions were calculated using the Assessment of Intelligibility of Dysarthric Speech as being 82% and 96.05% intelligible, respectively. The phonetic transcriptions of the words read aloud by MJ during the EPG assessment revealed each target word-initial consonant to be perceptually acceptable.

EPG analysis of the tongue-to-palate contacts produced by MJ for the alveolar stops revealed his spatial configurations to be similar to the control subjects' in that he exhibited complete contact along the lateral margins of the palate and full anterior closure at the frame of maximum contact. The anterior-to-posterior midline locations and lengths of contact were also consistent with the control subjects' contacts. Supporting these findings, the mean number of contacts and mean COG values calculated for MJ's alveolar stop productions at the frame of maximum contact were found to be within one standard deviation of the mean values obtained by the group of control subjects (see Tables 1 and 2).

Visual inspection of MJ's representative frames of maximum contact for alveolar fricatives revealed his tongue-to-palate contacts to be characterized by a central groove. Complete lateral contact was also exhibited, as per the control subjects. The locations and widths of maximum constriction were consis-

tent with (at least one of) the control subjects, except the groove width for /zi/, which was greater than the widths observed for the control subjects. The quantitative calculations of mean number of contacts and mean COG indicated that only MJ's production of /s/ in the /a/ vowel environment differed by more than one standard deviation from the control group's mean values. The mean number of contacts was lower and the main concentration of electrodes was located further back along the palate compared to the control subjects.

Visual inspection of MJ's representative frames of maximum contact for velar stops revealed complete closure across row 8 of the palate for /g/ productions in both the /i/ and /a/ vowel environments and for /k/ in the /i/ vowel environment. Closure was not detected for /k/ in the /a/ vowel environment, as per four of the five control subjects. Normal coarticulatory effects appeared to be operating, with longer lengths of contact being noted along the lateral margins of the palate for /k/ and /g/ when in the high, front /i/ vowel environment compared to when in the low /a/ vowel environment. The finding was further supported by the mean number of contacts and mean COG values calculated at the frames of maximum contact (see Tables 1 and 2). The mean number of electrodes contacted for /k/ and /g/ in the /i/ vowel environment was approximately double the mean number of electrodes contacted in the /a/ vowel environment. In fact, MJ's mean numbers of contacts for velar stops in the /i/ vowel environment were more than one standard deviation greater than the mean numbers of

contacts calculated for the control subjects' productions of /k/ and /g/ in the /i/ vowel environment. In regard to the mean COG values, higher values were obtained for MJ's velar stops produced in the /i/ vowel environment compared to the velar stops in the /a/ vowel environment, indicating that the main concentration of contacted electrodes was more anterior for the velar stops in the /i/ vowel environment. This again demonstrates coarticulatory effects related to the vowel environment. MJ's mean COG values were consistent with the control group's values, except for /ka/, which was 1.07 standard deviations below the control group mean (see Table 2).

In regard to lateral asymmetry, MJ exhibited a right-sided contact emphasis (i.e., negative value) as per the control group for all consonant productions except for /ta/ and /ka/, for which a left-sided contact emphasis (i.e., positive value) was demonstrated, and for /da/ for which the mean value was calculated as zero. The mean lateral asymmetry values for /ta/ and /ka/ differed from the control group's mean values by 1 and 1.07 standard deviations, respectively. For the other productions that had a right-sided contact emphasis, the degree of asymmetry was within 1 standard deviation of the control group means, with one exception that was /gi/ (see Table 3).

In summary, the spatial characteristics of MJ's tongue-to-palate contacts exhibited during production of the alveolar stops /t, d/, the alveolar fricatives /s, z/, and the velar stops /k, g/ appeared to be consistent with the control subjects' contact features. A few discrepancies were noted, however, which related to the number of electrodes contacted. For the production of /sa/, a smaller contact area was recorded compared to the control group, whereas for the velar stop productions in the /i/ vowel environment, greater numbers of contacts were demonstrated. These discrepancies in contact area may be suggestive of mild impairments in lingual motor control; however, they were not evidenced as perceptually, as indicated by the phonetic transcriptions. It has been proposed though, that the identification of consonants produced in word-initial positions, like those in the present study, are crucial to speech perception (Marslen-Wilson, 1980, cited in Adams, Weismer, & Kent, 1993) and that "speech motor control may be structured, at least in part, to produce good word onsets" (Weismer & Liss, 1991, cited in Adams et al., 1993, p. 48). It is possible then that the underlying spatial discrepancies identified in MJ's productions may become

more apparent for consonants produced in the word-final position, where less effort is perhaps utilized, or for consonant clusters, which pose complex articulatory challenges. Importantly, MJ's tongue-to-palate timing characteristics should also be considered. As reported in the previous study by Goozée et al. (1999), timing disturbances were identified in MJ's productions of word-initial consonants and are, therefore, likely to be related, perhaps even more so than spatial disturbances, to the mild consonant imprecision perceived in MJ's speech.

### Case 2

JC, a 23-year-old male, sustained a severe TBI (GCS = 3) in a motor vehicle accident 20 months prior to the EPG assessment. A CT scan revealed severe axonal injury, with no mass lesions. JC reportedly exhibited high-level cognitive language deficits and memory deficits and presented with a right spastic hemiparesis.

In regard to motor speech function, JC's speech was diagnosed as mild spastic dysarthria, with mild consonant imprecision identified in relation to articulatory functioning. Quantitative analysis of JC's level of intelligibility using the Assessment of Intelligibility of Dysarthric Speech indicated that his single word and sentence productions were 81% and 94.98% intelligible, respectively.

The spatial configurations of JC's alveolar stops were similar to the control subjects' stops in that he consistently demonstrated full anterior closure, with most anterior contact at row 1, and complete lateral seals. Quantitative analysis of the mean number of electrodes contacted, however, revealed that JC exhibited greater amounts of contact compared to the control subjects for /t/ and /d/ in both the /i/ and /a/ vowel environments, with the mean number of contacts for /ti/, /di/ and /da/ greater than 1 standard deviation above the control group's means (see Table 1). The COG values calculated for the same productions (/ti/, /di/, /da/) were greater than, or equal to, 1 standard below the control group's means (see Table 2), most likely reflecting, in this case, the increased amount of contact on the palate. Despite the finding of increased contact areas and differences in COG values, each of JC's alveolar stop productions were judged to be perceptually acceptable by the two speech-language pathologists who transcribed the productions.

The phonetic transcriptions of JC's alveolar fricatives revealed that one transcriber identified one production of both /s/ and /z/ to be backed and the

duration of all three productions of /z/ and one production of /s/ to be lengthened. The other transcriber perceived lateral release in one production of /s/. Visual inspection of JC's representative frames of maximum contact revealed his alveolar fricative productions to be characterized by a groove configuration and complete lateral contact, as per the control subjects. In regard to the location of maximum constriction, JC's /s/ constrictions at row 3 were backed compared to the control subjects, the majority of whom produced maximum constrictions in the alveolar zone (rows 1–2) of the palate. This finding could be considered consistent with the phonetic transcriptions made by one of the speech-language pathologists. Inspection of JC's mean COG values indicated that the concentration of contacted electrodes was also backed compared to the control group (i.e., lower mean COG values). However, only for /sa/ was the difference greater than 1 standard deviation (see Table 2). The widths of JC's grooves at maximum constriction for /s/ was one electrode. For /s/ in the /a/ vowel environment, this width was consistent with the control subjects. For /si/, however, it was smaller than the control subjects' range of widths, suggesting an increased number of contacts. Inspection of the mean number of contacts supported this conjecture (see Table 1).

The groove configurations for JC's /s/ productions across the /i/ and /a/ vowel environments were similar; so too were the groove configurations for /z/. However, comparison between the groove configurations for /s/ and /z/ revealed a marked difference. For /z/, JC demonstrated a long central groove, which was two electrodes wide and extended from rows 1 to 4. Although the width of the groove at maximum constriction was consistent with the control subjects' widths, the length was longer. The mean numbers of contacts exhibited by JC for his /z/ productions were greater in comparison to the control subjects. Only for /zi/, however, was the difference greater than 1 standard deviation above the control group's mean (see Table 1). Mean COG values calculated for JC's productions of /z/ in both vowel environments were within 1 standard deviation of the control subjects' mean values (see Table 2).

JC exhibited complete closure for productions of /k/ and /g/ in both /i/ and /a/ vowel environments. For /ka/, /ga/, and /gi/ closure was observed along row 8 only. Closure was more expansive for /ki/, extending across rows 5 to 8 (exception row 6). In addition, compared to the control subjects, increased anterior-to-posterior lateral lengths of contact were

noted for JC's /ki/, /ka/, and /ga/ productions. For /k/ and /g/ in both vowel environments, the mean numbers of electrodes contacted by JC were markedly greater than the mean values calculated for the control group, with JC's mean values ranging from 3.60 to 5.17 standard deviations above the control group's means (see Table 1). In accordance, the COG values indicated that JC's concentration of electrode contacts, although still within the posterior region of the palate, was more anterior than the control subjects' concentrations.

As with JC's alveolar stops, the increased contact areas and differences in COG values observed for JC's velar stops did not appear to appreciably affect the perceptual acceptability of the productions as judged by the two speech-language pathologists who transcribed the samples.

Coarticulatory effects related to vowel environment appeared to be operating for JC's /k/ productions, with longer lengths of lateral contact and a higher number of contacts recorded for /ki/ in comparison to /ka/. Similar coarticulatory effects were not apparent, however, for JC's /g/ productions.

In regard to lateral asymmetry, JC demonstrated a left-sided contact emphasis (i.e., positive value) in contrast to the control subjects for the alveolar stops /ta/, /di/, and /da/, with the mean lateral asymmetry values for /ta/ and /da/ differing from the control group's means by 1.17 and 1.29 standard deviations, respectively (see Table 3). For the majority of the alveolar fricatives and velar stops, a right-sided contact emphasis was noted as per the control group, except for /zi/ and /ki/. The mean lateral asymmetry values of these productions revealed a left-sided contact emphasis and differed from the control group's means by more than 1 standard deviation. Finally, although the mean lateral asymmetry value for /gi/ revealed a right-sided contact emphasis like the control group, the degree of asymmetry was smaller compared to the control group by 2.20 standard deviations (see Table 3).

In summary, a consistent discrepancy between the number of tongue-to-palate contacts exhibited by JC and the control subjects was observed, with JC demonstrating increased number of contacts for word-initial consonant productions. This finding is perhaps indicative of subtle lingual motor control disturbances or, given that JC presented with spastic dysarthria, may be the result of rigid, less flexible tongue movements up to the palate. A structural basis for the spatial differences was excluded, as visual inspection of JC's palate revealed no apparent morphological irregularities (e.g., an exception-

ally flat palate) that would be likely to result in increased tongue-to-palate contacts.

Finally, the finding of increased tongue-to-palate contacts suggests that the tongue may have been in contact with the palate for longer than normal. This was indeed the case for JC, as reported in Goozée et al. (1999). Disturbances in the spatial and timing characteristics of tongue-to-palate contacts would be expected to result in consonant imprecision; however, as with MJ, the majority of JC's consonant productions were judged to be perceptually acceptable. Again, it is likely that the disturbances that were observed may become more evident for consonants in the word-final position and in consonant clusters.

### Case 3

RF, a 27-year-old male, sustained a severe TBI (GCS = 4) in an assault 63 months prior to the EPG assessment. A CT scan revealed a focal hemorrhage in the anterior corpus callosum and left frontal region with intracerebral and intraventricular blood, a depressed compound fracture of the fronto-parietal bones with subarachnoid blood, and diffuse brain injury. RF was reported to exhibit high-level cognitive language deficits, memory deficits, slowed cognitive processes, and limited insight. He presented with spastic quadriplegia and gross and fine ataxia and required a wheelchair for mobilization. When seated in his wheelchair, RF typically exhibited a flexed posture.

In regard to motor speech function, RF's speech was diagnosed as moderate spastic-ataxic dysarthria. He was perceived to exhibit a number of deviant articulatory-related speech features, including moderate consonant imprecision and prolongation of phonemes. Overall intelligibility was perceived to be reduced. This was supported by the quantitative results obtained using the Assessment of Intelligibility of Dysarthric Speech, which indicated that RF's single word and sentence productions were 39% and 69.09% intelligible, respectively.

As with the other two subjects with dysarthria following TBI presented previously, the spatial configurations of RF's alveolar stops were similar to the control subjects' stops in that the features, full anterior closure and complete lateral seal, were demonstrated. The anterior-to-posterior midline location and length of contact for RF's /t/ productions in both the /i/ and /a/ vowel environments were consistent with the control subjects', whereas longer midline lengths of contact were observed for /d/,

with midline contact extending over 4 rows. Analysis of the mean number of contacts, however, revealed that RF demonstrated greater amounts of contact compared to the control group (i.e., greater than 1 standard deviation) not only for /d/, but also for /t/ in both vowel environments (see Table 1). His mean COG values, though, were within 1 standard deviation of the control group's means (see Table 2). Phonetic transcription of RF's alveolar stops indicated that two of his productions of /t/ and /d/ were perceived differently by the speech-language pathologists who transcribed the samples. One transcriber described the /t/ and /d/ productions as being voiced and dental, respectively; the other transcriber regarded the articulatory placements for the productions of /t/ and /d/ to be backed. The latter transcriber's description may reflect the increased contact areas identified using EPG.

Phonetic transcription of RF's alveolar fricatives indicated that his productions of /z/ were recognizable, although one production was transcribed as dental. The three productions of /s/ were not readily recognizable, however, being transcribed as distorted voiceless interdental fricatives. EPG analysis revealed that in the production of the alveolar fricatives /s, z/, RF demonstrated complete closure along the anterior row (row 1) of the palate rather than a characteristic groove pattern. This finding is likely to account for the way in which RF's /s/ productions were perceived. In addition, lateral contact was incomplete on the right-hand side of the representative frames of maximum contact for /si/, /za/, and /zi/ (see Figure 4). It should be noted, however, that RF was missing a tooth (first molar) near the lateral electrode that showed no contact. Because the expected groove pattern was not exhibited, the mean number of contacts, COG, and lateral asymmetry values were not calculated for RF's alveolar fricative productions.

In contrast to the deviant spatial configurations observed for the alveolar fricatives, RF demonstrated configurations for velar stops that were consistent with the control subjects, with full closure detected along the posterior row of the palate (row 8). Differences among RF's and the control subjects' productions were noted, however, in regard to the mean number of contacts, with greater mean values (i.e., greater than 1 standard deviation) recorded for RF's productions of /ka/, /gi/, and /ga/ (see Table 1).

Examination of the features, lateral length of contact, COG, and mean number of contacts revealed that RF may not have been exhibiting nor-

mal coarticulatory effects in his velar stop productions. First, the length of lateral contact was longer for velar stop productions in the /a/ vowel environment compared to the /i/ vowel environment. Also, in the production of /ka/, a greater number of electrodes were contacted compared to /ki/. These findings would not normally be expected given that the influence of the /i/ vowel, which involves a high front tongue posture, would be expected to produce a greater number of contacts compared to the low /a/ vowel, as found by Dagenais et al. (1994) for a group of normal speakers. In addition, RF's mean COG values for /k/ and /g/ in the /a/ vowel environment were 4.07 and 3.36 standard deviations greater, respectively, than the mean COG values calculated for the control group. These values were also greater than the mean COG values recorded for the same velar stops in the /i/ vowel environment, indicating that the main concentration of electrodes was located more anteriorly when followed by /a/ in comparison to /i/ (see Table 2). This clearly is not in accordance with the control group's values and differs to reports in the literature regarding normal coarticulatory effects.

RF's velar stops were judged as perceptually acceptable by one of the speech-language pathologists who phonetically transcribed the productions. The other transcriber identified possible voicing distinction problems, with two of the productions of /g/ being perceived as voiceless.

RF's mean lateral asymmetry values for alveolar stops indicated a left-sided contact emphasis (i.e., positive values), which was opposite to the control group, with /ta/ and /ti/, 1 and 1.25 standard deviations away from control group's means, respectively. For the velar stops, RF demonstrated a right-sided contact emphasis, with the degree of asymmetry for /ga/, 1.11 standard deviations greater than the control group mean (see Table 3).

To summarize, the most notable spatial distortion noted in RF's consonant productions was the complete closure exhibited across the palate for the fricatives. Hardcastle and Gibbon (1997) referred to this type of spatial distortion, stating it was an example of articulatory overshoot. Overshooting could be considered, particularly in this case, to indicate an impairment in motor control and is likely to have as its basis, incoordination in the force, accuracy, speed, and range of tongue movements. This would certainly be consistent with RF's diagnosis of spastic-ataxic dysarthria. A greater amount of contact was also observed for RF's alveolar and velar stops in comparison to the control

subjects' productions and again, overshooting could be regarded as being responsible. A structural cause for the increased tongue-to-palate contacts was ruled out as visual inspection of RF's palate revealed no apparent structural anomalies.

Finally, the finding of increased contacts suggests that the duration of time the tongue spent in contact with the palate would have been longer than normal. As with JC, this was indeed the case for RF (see Goozée et al., 1999). Together, the spatial and timing disturbances exhibited by RF would have contributed to his moderate consonant imprecision.

### CONCLUSION

The present study demonstrated that EPG provides a means of directly and objectively identifying the nature and severity of aberrant tongue-to-palate placements exhibited in the speech of individuals with dysarthria following TBI. The patterns and locations of the tongue-to-palate contacts generated for the majority of the alveolar and velar stop consonants by the three TBI subjects in the present study were consistent with the contacts produced by the group of five control subjects. Differences were noted, however, in terms of the amount of tongue-to-palate contact, with two of the TBI subjects consistently demonstrating increased contacts. This type of spatial discrepancy reflects reduced precision and accuracy of tongue contact and is suggestive of impaired lingual motor control. The subject with moderate spastic-ataxic dysarthria also notably exhibited complete closure across the palate during fricative production. Hardcastle (1976) reported that the fricatives are complex articulations, requiring maximal precision in both muscular control and sensory feedback. The level of neuromuscular control exhibited by the subject with moderate dysarthria, therefore, was clearly inadequate for the groove configuration to be formed effectively.

Although the underlying spatial disturbances identified in the TBI subjects' word-initial consonant productions did not necessarily manifest perceptually, it was noted in the case discussions that the spatial disturbances may become more evident for consonants produced in other word-positions, particularly the word-final position, and in consonant clusters. This conjecture should form an important consideration in future studies that aim to investigate the tongue-to-palate contacts produced by individuals with dysarthria following TBI. In

addition, future studies following this line of research should consider incorporating alternative analysis strategies. One strategy could involve visual scanning of the series of EPG frames recorded during the production of consonants. In the present study, perceptual features such as lateral release in /s/ production (case 2, JC) and interdental fricative production (case 3, RF) were identified, but could not be adequately explained through an analysis of one frame (i.e., the first frame of maximum contact) only. By scanning through the series of EPG frames generated by JC and RF during fricative production, other contact patterns likely to have been responsible for the deviant perceptual features may have been identified. Finally, the present study focused on the spatial characteristics of tongue-to-palate contacts; however, the importance of interpreting this data in the light of timing characteristics for the purposes of planning therapy is recognized.

In regard to therapy, the EPG system itself could be used to provide visual feedback of tongue-to-palate contacts, which in turn could be used to redirect and improve the accuracy of tongue placements during speech production (Hardcastle et al., 1985). This form of therapy would be best directed at obviously deviant spatial patterns that affect consonant precision, such as the deviant pattern of complete anterior closure exhibited by RF for fricatives. Gauging a TBI subject's visual, comprehension, and cognitive skills would be an important first step in planning EPG therapy to ensure that the individual can, for example, understand the relationship between the visual feedback display and his or her own tongue-to-palate contacts. Provided these skills are adequate, EPG therapy could proceed with guarded optimism.

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## REFERENCES

- Adams, S. G., Weismer, G., & Kent, R. D. (1993). Speaking rate and speech movement velocity profiles. *Journal of Speech and Hearing Research*, 36, 41–54.
- Byrd, D., Flemming, E., Mueller, C. A., & Tan, C. C. (1995). Using regions and indices in EPG data reduction. *Journal of Speech and Hearing Research*, 38, 821–827.
- Dagenais, P. A., Lorendo, L. C., & McCutcheon, M. J. (1994). A study of voicing and context effects upon consonant linguapalatal contact patterns. *Journal of Phonetics*, 22, 225–238.
- Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders*. Philadelphia: W. B. Saunders.
- FitzGerald, F. J., Murdoch, B. E., & Chenery, H. J. (1987). Multiple sclerosis: Associated speech and language disorders. *Australian Journal of Human Communication Disorders*, 15, 15–33.
- Gibbon, F. (1990). Lingual activity in two speech-disordered children's attempts to produce velar and alveolar stop consonants: Evidence from electropalatographic (EPG) data. *British Journal of Disorders of Communication*, 25, 329–340.
- Gibbon, F., & Nicolaidis, K. (1999). Palatography. In W. J. Hardcastle & N. Hewlett (Eds.), *Coarticulation in speech production: Theory, data and technique* (pp. 229–245). Cambridge, UK: Cambridge University Press.
- Goozée, J. V., Murdoch, B. E., & Theodoros, D. G. (1999). Electropalatographic assessment of articulatory timing characteristics in dysarthria following traumatic brain injury. *Journal of Medical Speech-Language Pathology*, 7(3), 209–222.
- Hardcastle, W. J. (1976). *Physiology of speech production: An introduction for speech scientists*. London: Academic Press.
- Hardcastle, W. J. (1984). New methods of profiling lingual-palatal contact patterns with electropalatography. *Phonetics Laboratory Work in Progress, University of Reading*, 4, 1–40.
- Hardcastle, W. J., & Gibbon, F. (1997). Electropalatography and its clinical applications. In M. J. Ball & C. Code (Eds.), *Instrumental clinical phonetics* (pp. 149–193). London: Whurr Publishers.
- Hardcastle, W. J., Gibbon, F. E., & Jones, W. (1991). Visual display of tongue-palate contact: Electropalatography in the assessment and remediation of speech disorders. *British Journal of Disorders of Communication*, 26, 41–74.
- Hardcastle, W. J., Gibbon, F., & Nicolaidis, K. (1991). EPG data reduction methods and their implications for studies of lingual coarticulation. *Journal of Phonetics*, 19, 251–266.
- Hardcastle, W., Jones, W., Knight, C., Trudgeon, A., & Calder, G. (1989). New developments in electropalato-

- raphy: A state-of-the-art report. *Clinical Linguistics & Phonetics*, 3(1), 1–38.
- Hardcastle, W. J., Morgan Barry, R. A., & Clark, C. J. (1985). Articulatory and voicing characteristics of adult dysarthric and verbal dyspraxic speakers: An instrumental study. *British Journal of Disorders of Communication*, 20, 249–270.
- Hardcastle, W. J., Morgan Barry, R. A., & Clark, C. J. (1987). An instrumental phonetic study of lingual activity in articulation-disordered children. *Journal of Speech and Hearing Research*, 30, 171–184.
- Jones, W., & Hardcastle, W. J. (1995). New developments in EPG3 software. *European Journal of Disorders of Communication*, 30, 183–192.
- Morgan Barry, R. (1995). Acquired dysarthria: A segmental phonological, prosodic and electropalatographic investigation of intelligibility. In S. Howard & M. Perkins (Eds.), *Case Studies in Clinical Linguistics* (pp. 181–211). London: Whurr Publishers.
- Nguyen, N. (1996). A Matlab package for the analysis of EMA/EPG data. *QMC Working Papers in Speech and Language Sciences*, 1, 5–12.
- Theodoros, D. G., Murdoch, B. E., & Chenery, H. J. (1994). Perceptual speech characteristics of dysarthric speakers following severe closed head injury. *Brain Injury*, 8(2), 101–124.
- Yorkston, K. M., & Beukelman, D. R. (1981). *Assessment of intelligibility of dysarthric speech*. Austin, TX: Pro-Ed.

## APPENDIX

### Word List

a tar	a Sarge	a cart
a tease	a seal	a quiche
a darn	a tsar	a guard
a dean	a zeal	a geek