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原　著

Typical Adult Speakers' Tongue-Palate Contact Patterns for Japanese Alveolar and Post-Alveolar Sounds

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Abstract: OBJECTIVE: More than 160 clients with articulation disorder have undergone visual feedback training using electropalatography (EPG). However, EPG data regarding typical tongue-palate contact patterns for Japanese speakers are limited. The purpose of this study was to generate EPG target patterns for the Japanese alveolar and post-alveolar consonants which were most often practised during EPG therapy.

METHODS: The participants were 15 Japanese-speaking adults without present or past speech, language, or hearing problems. EPG data were recorded for [t, d, n, s, ɕ, t͡s, d͡z, t͡ɕ, d͡ʑ] in vowel-consonant-vowel syllables, such as [ata]. Cumulative templates were generated from the maximum contact frame for each sound; a quantitative analysis, such as alveolar total, centre of gravity and variability index, was performed to examine the difference of each sound.

RESULTS: Although tongue-palate contact proportion varied for each person, basic configurations for each sound were similar. A cumulative template, inclusive of all participants, represented target patterns that are specific for each sound. Quantitative analysis revealed distinctive characteristics of each sound.

CONCLUSION: The cumulative templates and quantitative characteristics for each Japanese consonant provided valuable information for visual feedback training as well as EPG assessment.

Key words: electropalatography, Japanese consonants, typical contact pattern, visual feedback training

成人の日本語話者における歯茎音・後部歯茎音の舌と口蓋の典型的接触パターン

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要　約：目的：構音障害のある人を対象としてエレクトロパラトグラフィ（EPG）を用いた視覚的フィードバック訓練を実施しているが，典型的な日本語音の舌と口蓋の接触パターンに関するEPGデータは限られている．今回は最も高頻度に練習される歯茎音，歯茎硬口蓋音について目標パターンを作成することを目的とした．

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方法：対象は発声発語器官や聴力に問題のない15名の日本語話者の成人である．子音[t, d, n, s, ɕ, t͡s, d͡z, t͡ɕ, d͡ʑ]を含む「あた」など母音・子音・母音の音節をEPGで記録し，子音産生時の最大接触フレームおよび開放フレームを抽出し累積した．また，各子音の特徴を示す量的分析を行った．

結果：子音産生時の舌と口蓋の接触状態は個々人によって差はあるが基本的な接触パターンは一致していた．15名のデータを累積することにより各音の特徴が明らかとなった．

結論：EPGを用いた評価や視覚的フィードバック訓練に役立つ日本語子音の有用なデータが得られた．

索引用語：エレクトロパラトグラフィ，日本語子音，典型的な接触パターン，視覚的フィードバック訓練

Introduction

Electropalatography (EPG) is a tool that provides information regarding the location and timing of the tongue's contact with the hard palate during speech[1]. It has been used in clinical practice for diagnosis[2] and treatment[3]. During visual feedback therapy using EPG, clients' abnormal articulation patterns are displayed on a computer screen; they can use this dynamic visual feedback to help them produce normal articulation. For this procedure, it is indispensable to display the normal contact pattern as a target model.

Michi et al.[3] reported that visual feedback treatment was more efficient than conventional articulation therapy for changing abnormal articulatory behaviour in clients with cleft palate. The effect of visual feedback therapy using EPG has been reported in several other studies[4,5].

In December 2004, we introduced visual feedback training for clients with cleft palate who had residual articulation disorders which persisted even after longstanding conventional articulation therapy. Fujiwara[6] reported the course of five participants whose residual articulation disorders associated with cleft palate were improved by visual feedback therapy using EPG. At first, the WinEPG system and Portable Training Unit (PTU) (Articulate Instruments Ltd., Edinburgh, UK) were obtained and EPG artificial plates were ordered from dental laboratories in the UK, a procedure which was time-consuming and very expensive. To facilitate the clinical use of EPG, continued experiments have been performed to generate a more convenient and economical EPG plate[7]. Our modified Reading type artificial plate has 62 electrodes which are placed according to identifiable anatomical landmarks[8]. This configuration makes it possible to compare tongue-palate contact pattern on an interpersonal basis. Thus, the cumulative EPG patterns of normal speakers can be used as a target for visual feedback training.

In Japan, several types of EPG equipment have been used to study tongue-palate contact patterns for Japanese consonants. Imai, Wakumoto and Niu[9] reported the EPG patterns of [ta], [sa], and [ɾa], using Dynamic Palatograph (DP-20, Rion Co., Ltd., Tokyo, Japan). The results were presented as four types of schema: T type for [ata], S type for [asa], L & R types for [aɾa]. It was difficult to quantify the tongue-palate contact area, because the artificial plate for the Japanese EPG system (Rion Co., Ltd.) was made from a set of standard templates to fit the individual's palate. Therefore, the number of electrodes varied with each subject; furthermore, each electrode was placed at a different point within the hard palate[10]. This made it difficult to compare lingual contact patterns among subjects, and is probably a reason why there are limited EPG data regarding typical tongue/palate contact for Japanese sounds. Mochizuki, Yamagata and Tokutomi[11] used the thin film type of palatography sensor, which has 96 electrode arrays covering the palate and maxillary teeth. Japanese consonants [s, t, n, ɾ, ʃ, k] in a short sentence were analysed. The contact pattern of each sound was shown as the common contact area for 18 subjects. However, it was inadequate to use their patterns as the reference patterns for our clinical application, as the number and placement of electrodes were different from our Reading type EPG plate.

At the time of starting EPG visual feedback training in 2004, no previous study was available in which the Reading type EPG plate was used to analyse Japanese sounds. It was urgent to make a target pattern for Japanese sounds. Initially, a speech therapist showed a model to the client during therapy. Then, a cumulative pattern was generated from EPG recordings of five typical-speaking adults[12]. The speech materials comprised five vowels and 14 consonants including alveolars, post-alveolars, palatals, and velars. As the generated EPG pattern displayed common interpersonal contact patterns, it was useful as a target pattern at the beginning.

This time, 15 typical-speaking adults participated in the study. The purpose of this study was to generate cumulative EPG templates for Japanese sounds which are more accurate as target patterns during visual feedback therapy. Quantitative analysis was also performed to gain objective analysis values for each sound.

Method

1. Participants

The participants were 15 Japanese adults (eleven females and four males) without present or past speech, language, or hearing problems. Age range was 21–58 years, with an average of 31.4 years. They were EPG researchers, including speech therapists and dentists, and students in the department of speech therapy. All of them possessed an EPG artificial plate prior to this study. From the upper and lower impression of each participant, it was confirmed that the occlusion and dental arch were within normal limits. This study followed the principles of the Declaration of Helsinki and informed consent was obtained from all participants.

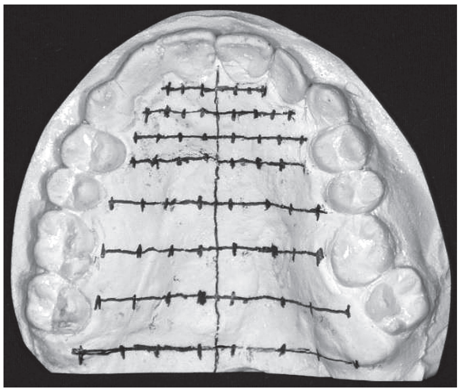
2. Materials

1) Instrumentation

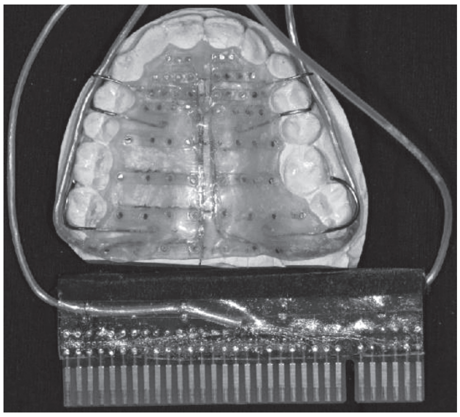
In this study, WinSTARS for EPG (EPG Research Centre, Nishinomiya, Japan) was used with an EPG sampling rate of 100 Hz, simultaneously with the acoustic signal. To record the dynamic tongue-palate contact patterns, each participant wore an artificial EPG plate that was individually constructed to fit against the hard palate. A modified Reading type plate contained 62 electrodes, embedded in accordance with anatomical landmarks. The tongue-palate contact signal was sent to the EPG system by Bluetooth and the recorded data were analysed using Articulate Assistant Software (Articulate Instruments Ltd.).

2) Speech material

Vowel-consonant-vowel nonsense syllables,



Maxillary impression and design of electrode configuration



EPG artificial plate and multiplexer

Figure 1 The electrodes are arranged in eight horizontal rows, with eight electrodes in every row except the most anterior, which has six. The most posterior row of electrodes is located on the junction between the hard and soft palates. The anterior four rows are spaced at half intervals compared to the posterior four rows.

including plosive and nasal consonants [t, d, n], fricatives [s, ɕ], and affricates [t͡s, d͡z, t͡ɕ, d͡ʑ], were used as speech material. These alveolar and post-alveolar consonants were selected because they were most often practised during EPG therapy[13]. Each consonant was preceded by the Japanese vowel [a] to clearly communicate the onset of tongue-palate contact for each consonant. The following vowel was [a] for the consonants [t, d, n, s], [i] for the consonants [ɕ, t͡ɕ, d͡ʑ], and [ɯ] for the consonants [t͡s, d͡z], according to the Japanese sound system. As the dominant syllables are vowel and consonant-vowel in Japanese, no vowel-consonant context was selected.

3. Recording procedure

All participants were required to wear the EPG plate for approximately 2 hours before EPG recording for adaptation to an EPG plate, based on the study by McLeod and Searl[14]. The participants were asked to repeat each nonsense syllable four times in succession at a natural speed.

4. Maximum contact frame and cumulative frame

To generate cumulative frames for each consonant, the following steps were taken in accordance with McLeod's study[15].

1) Annotation of the frame with maximum contact and with release for each consonant produced by each participant:

Each sound was identified from the sound, sound waveform, and wide-band spectrogram, and a frame with the highest number of contacts was selected as the maximum contact frame. The releasing frame (i.e., the first frame when the alveolar closure was opened) was also annotated for plosives and affricates.

2) A cumulative frame generation for each consonant, inclusive of all participants:

The maximum contact frames and the releasing frames for the target phoneme for all participants were accumulated, using the filter function of the Articulate Assistant Software. A darker frame

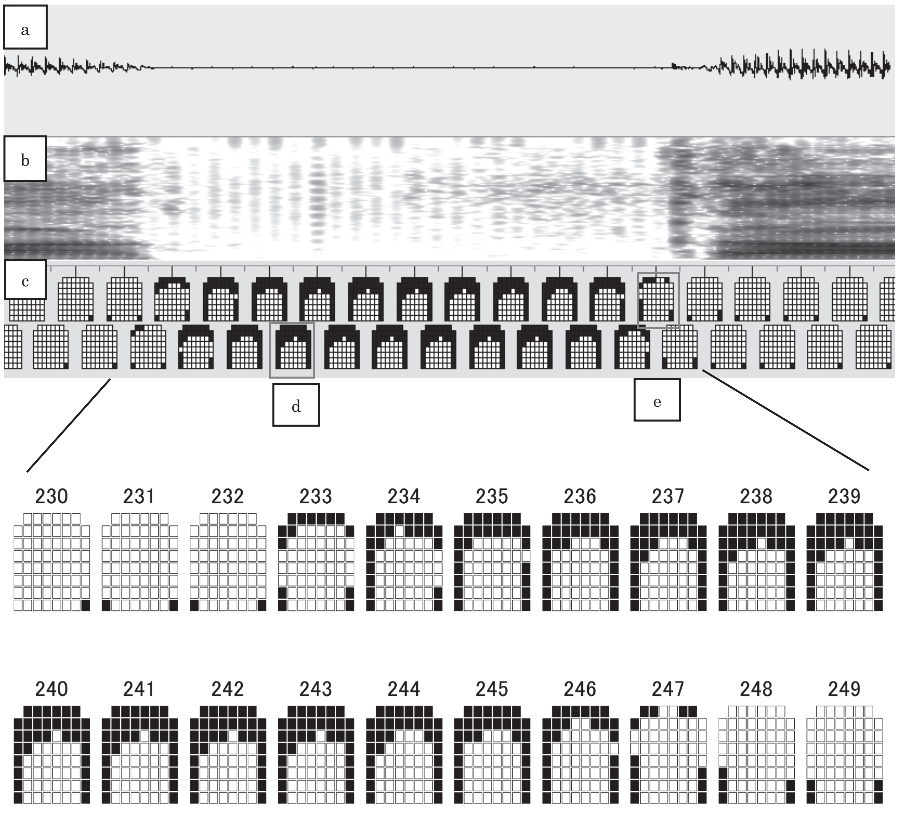


Figure 2 Analysis screen of normal [ata] and enlarged EPG consecutive pattern
a: sound wave, b: sound spectrogram, c: EPG consecutive pattern, d: maximum contact frame (238), e: releasing frame (247)

indicated more frequent electrode contact. The number on each electrode showed the percentage of tongue contact to that particular electrode. One hundred percent indicated that the electrode was contacted by every participant; conversely, 0 percent indicated that the electrode was never contacted by any participant.

5. Analysis values

1) Alveolar total

Alveolar total represented the contact ratio in the frontal three rows, a total of 22 electrodes. It is suited to analysing the alveolar and post-alveolar consonants.

2) Centre of Gravity (CoG) value

Centre of gravity expressed the location of the main concentration of activated electrodes across the palate. The calculation assigned progressively higher values towards the more anterior row[16].

$$CoG = \frac{\begin{pmatrix} 7.5R_1 + 6.5R_2 + 5.5R_3 + 4.5R_4 + \\ 3.5R_5 + 2.5R_6 + 1.5R_7 + 0.5R_8 \end{pmatrix}}{\text{Total number of contacts}}$$

3) Variability index value

Variability index was defined as a value to indicate the stability/variability of articulatory gestures. To calculate the index, the percent frequency of activation of each contact was measured across repetitions. For each contact, 100% and 0% activation frequency represented invariance and were assigned a variance index of 0. The variability index increased as contact frequency approached 50%, which was assigned a variance index of 50. The overall variability index was calculated by summing the index values for all contacts and dividing by 62[17].

6. Statistical analysis

Statistical analyses for the alveolar total, the CoG, and the variability index were conducted using an

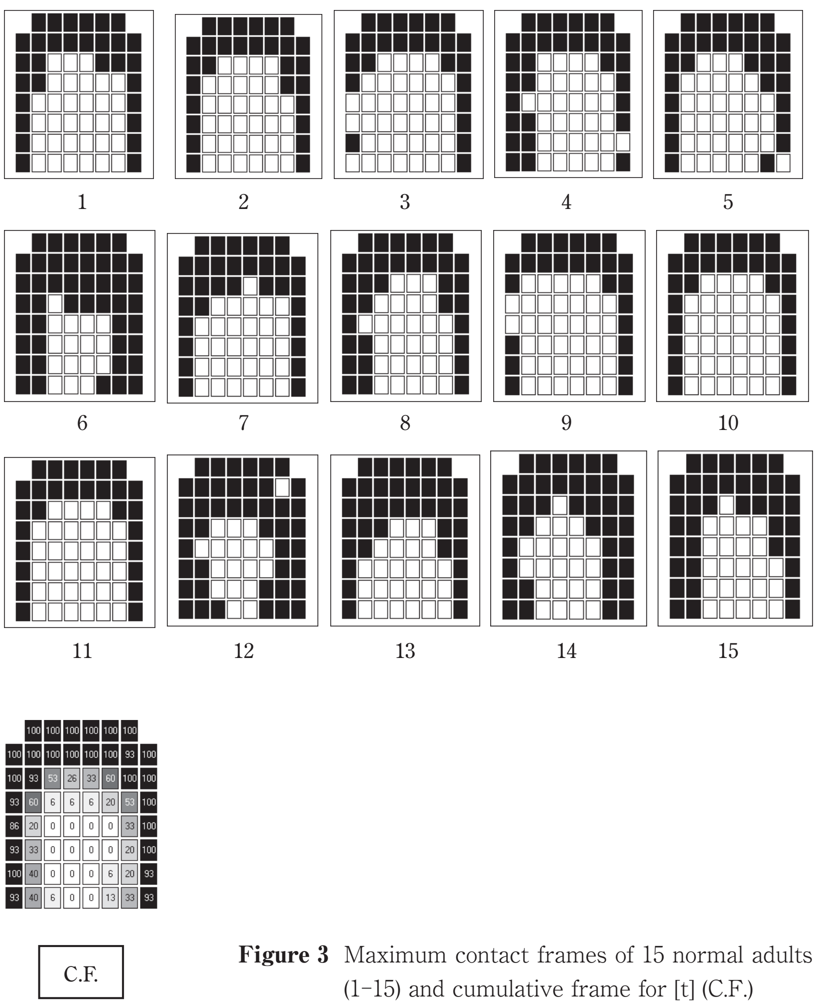


Figure 3 Maximum contact frames of 15 normal adults (1–15) and cumulative frame for [t] (C.F.)

analysis of variance and the Tukey HSD test. P-value <0.05 was considered to be significant.

Results

1. Cumulative frames

Figure 4 provides cumulative EPG images for [t, d, n, s, t͡s, d͡z, ɕ, t͡ɕ, d͡ʑ], created from the data of the 15 participants. The left side is the maximum contact frame and the right side is the releasing frame.

The cumulative patterns for alveolar stop [t, d] and alveolar nasal [n] sounds exhibit an identical horseshoe pattern, in which the anterior two rows and bilateral sides of electrodes are contacted. As for the releasing frames, the percentage at the midst of the front row is the lowest, which indicates a horseshoe-shaped constriction begins releasing at the alveolar portion in most cases.

In the fricative [s] sound, the bilateral sides of electrodes are also contacted; however, there is an anterior groove at the alveolar portion, where the air turbulence causes the creation of fricative sound. Although the maximum contact frames for alveolar affricatives [t͡s, d͡z] are very similar to those for alveolar stops, the releasing frames for these affricatives differ from those for alveolar stops (i.e., the lateral bracing is much tighter for affricatives). The contact percentage at the alveolar portion for [d͡z] is lower than that for [t͡s], which indicates that not every participant made a complete horizontal closure for [d͡z].

As for the cumulative patterns of post-alveolar fricative [ɕ] and affricatives [t͡ɕ] and [d͡ʑ], the tongue-palate contact area is wider than those for alveolar stops, fricatives, and affricatives. Bilateral constriction increasingly becomes wider toward the front row, which indicates that the middle to front portion of the tongue is raised toward the palate. The location of the narrowest central groove for these post-alveolar sounds is at the second row, which is posterior to the grooving position for the alveolar fricatives and affricatives.

2. Analysis values

1) Alveolar total

Figure 5 shows the mean alveolar total, the contact

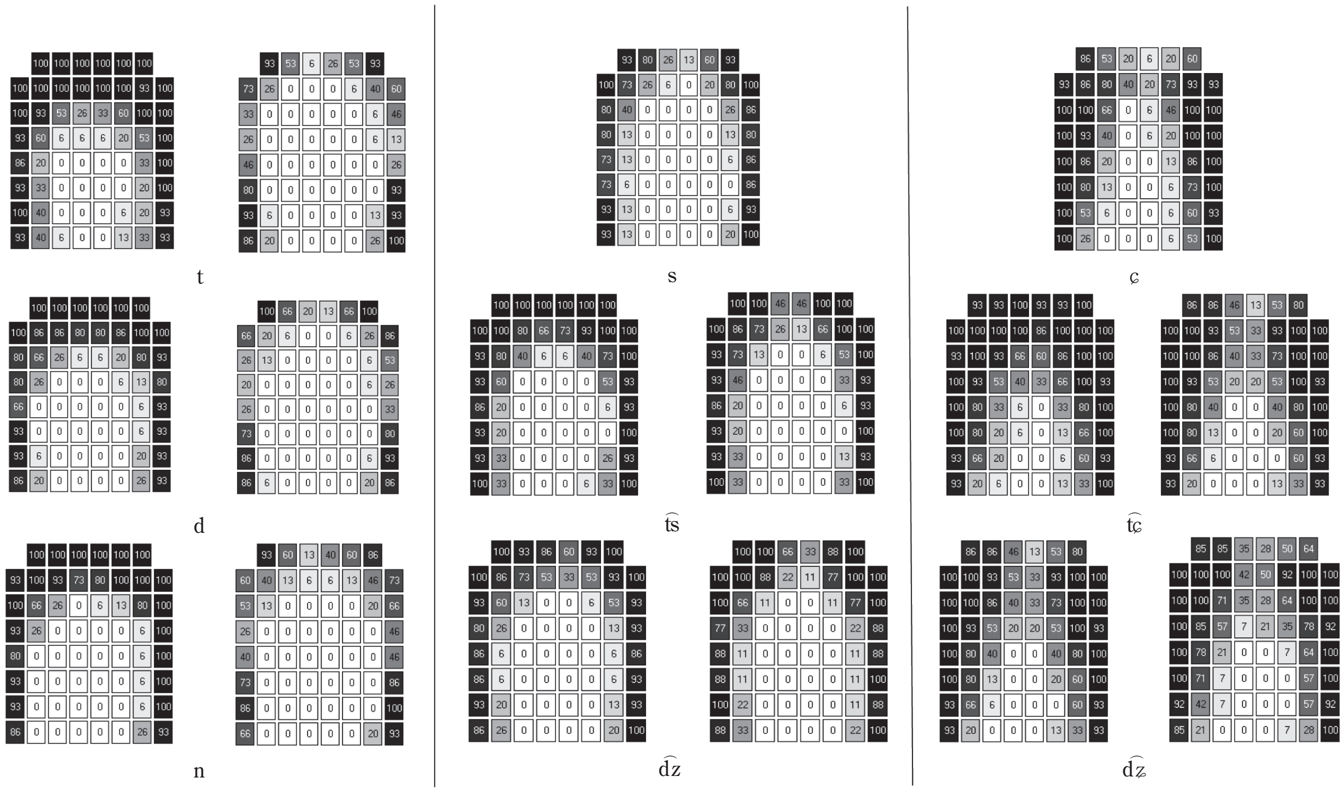


Figure 4 Cumulative patterns for consonants [t, d, n, s, t͡s, d͡z, ɕ, t͡ɕ, d͡ʑ], maximum contact frame on the left and releasing frame on the right

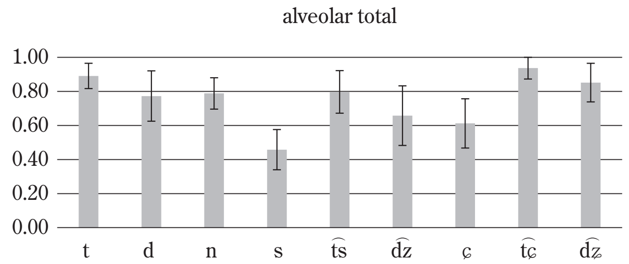


Figure 5 Mean alveolar total and contact ratio in frontal 3 rows, for each consonant

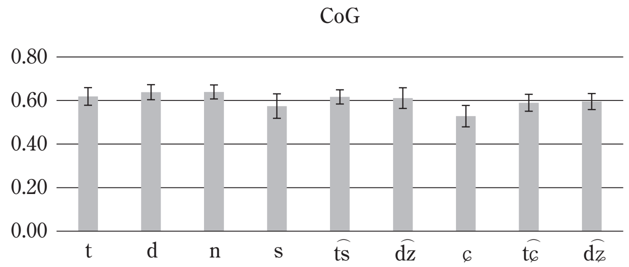


Figure 6 Mean Center of Gravity (CoG) value for each consonant

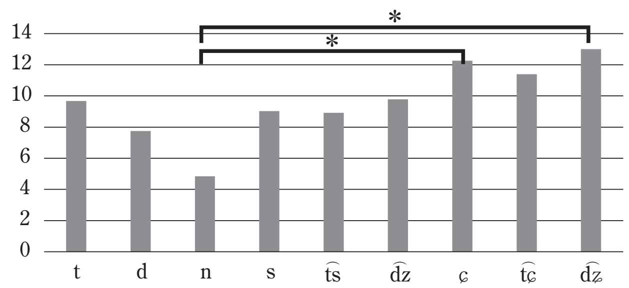


Figure 7 Mean variability index for each consonant

ratio in the frontal three rows, for each sound. The highest value was 0.94 for [t͡ɕ], followed by 0.89 for [t], 0.85 for [d͡ʑ], 0.8 for [t͡s], 0.79 for [n], 0.77 for [d], 0.66 for [d͡z], 0.61 for [ɕ], and 0.46 for [s] sound. The alveolar total of [s] was significantly lower than those of all the other sounds, and the alveolar total of [ɕ] was also significantly lower than those of the other sounds except [s]. Although the difference was not statistically significant, the alveolar totals of voiceless [t, t͡s, t͡ɕ] sounds were higher than those of voiced [d, d͡z, d͡ʑ] sounds.

2) Centre of gravity

Figure 6 shows the mean CoG value for each sound. The lowest CoG value was 0.53 in [ɕ] sound, which was significantly lower than those of all the other sounds. The CoG value tended to increase consecutively from [ɕ], [s], [t͡ɕ, d͡ʑ], [t͡s, d͡z] to [t, d, n].

3) Variability

Figure 7 shows the mean variability index for each sound. The lowest variability index was 4.839 in [n] sound, the highest variability was 13.011 in [d͡ʑ] sound, and the second-highest was 12.258 in [ɕ] sound. A significant difference was found between [n] and [d͡ʑ, ɕ].

Discussion

The aim of this study was to generate typical tongue-palate contact patterns during production of Japanese consonants which would serve as a target of visual feedback training using EPG. EPG recordings of 15 typical-speaking adults were obtained to analyse tongue-palate contact patterns for nine Japanese consonants, including stop consonants [t, d, n], fricatives [s, ɕ], and affricates [t͡s, d͡z, t͡ɕ, d͡ʑ], which were most often practised during EPG therapy. For each consonant, the maximum contact frame and the releasing frame were annotated, and cumulative patterns were generated by accumulating 15 frames extracted from 15 participants.

The maximum contact frames of [t, d, n, t͡s, d͡z] are an almost identical horseshoe pattern; the frontal two rows and bilateral side of the palate are closed. This is a pattern of typical alveolar stop consonants. The [s] sound may be an alveolar consonant, but there exists a central groove at the frontal two rows, which is essential for fricative sound. As for [ɕ, t͡ɕ, d͡ʑ] sounds, the frontal and bilateral contact is much tighter than for [t, d, n, t͡s, d͡z] sounds. This is caused by the difference of the following vowel for each consonant, i.e. [i] for [ɕ, t͡ɕ, d͡ʑ], [a] for [t, d], and [u] for [t͡s, d͡z]. During production of high front vowel [i], the sides of the back of the tongue are closed against the upper molars, while the middle to front portion of the tongue is raised high, nearly touching the palate and alveolar ridge. Coarticulation with a high vowel has made the EPG patterns for [ɕ, t͡ɕ, d͡ʑ] different from those for [s, t͡s, d͡z].

Comparing the releasing frames of plosives [t, d] and affricatives [t͡s, d͡z], the frontal two rows' constriction and the bilateral constriction are much tighter in affricatives; the releasing frames of [t͡s, d͡z] are similar to the maximum contact frame of [s]. The frontal constriction in the releasing frame is indispensable to distinguish affricatives from plosives. The releasing frames for [t͡ɕ, d͡ʑ] are similar to the maximum contact frame of [ɕ], in which the bilateral constriction is much tighter than that of [s]. This is also derived from the difference of the following vowels, i.e. [a] for [s] and [i] for [ɕ, t͡ɕ, d͡ʑ]. Thus, it is very important to pay attention to the releasing frames during the practise of affricative sounds.

The generated EPG patterns were similar to those of a previous Japanese study[9,11]; however, it is difficult to compare closely because of the difference of EPG plate in which the number and the placement of electrodes each differ.

The Reading type EPG plate has been widely used to analyse various languages. McLeod and Roberts[15] reported the templates of tongue-palate contact for the sounds /t, d, s, z, n, l, r, j, ʃ, ʒ, k, g, ŋ/, using EPG recordings of eight Australian adults. The EPG plate configuration and method of generating cumulative frames are the same as in our study. The resulting templates for [t, d, n, s] are consistent with the maximum contact frame of the present study. The template for [ʃ] in McLeod's study is different from the cumulative frame for Japanese [ɕ] in bilateral constriction at the frontal two rows. This difference represents the place of articulation of Japanese [ɕ] (alveolo-palatal fricative) and Australian English [ʃ] (postalveolo-palatal fricative). Gibbon, Yuen, Lee and Adams[18] analysed tongue-palate contact patterns for /t/, /d/, and /n/ from EPG recordings of 15 English-speaking adults. Spatial characteristics of these sounds were classified according to three criteria: (1) anterior constriction, (2) bilateral constriction, and (3) zero posterior central contact. These criteria result in a so-called horseshoe pattern which is common among alveolar stops and nasals. Our investigation demonstrated the same horseshoe pattern for [t, d, n], which revealed that the tongue-palate contact pattern for the same phonetic inventory is identical, regardless of differences in language.

Quantitative analysis

Alveolar total value shows the contact ratio (% contact) in the frontal three rows. Our result shows a high ratio (77-94%) in alveolar stops and affricatives. Gibbon et al.[18] also analysed the anterior constriction and reported 99% of /t, d, n/ showed complete anterior constriction. Gibbon et al.[18] set the anterior constriction criteria as 100% contact at either Row 1 or Row 2, or both; their resulting value was higher than the value in our study. Both studies revealed that it is essential to have anterior constriction to produce alveolar stops and affricatives. In Japanese affricatives, the alveolar total value for [d͡z] was 66%, the lowest value among Japanese affricatives; this is likely because some participants produced [z] instead of [d͡z], which is a common phonetic realization that is well known as the neutralization between /d/ and /z/ in Japanese linguistics[19].

CoG value shows the location of the main concentration of the contacted electrodes. Higher CoG value was associated with more anterior tongue placement. As alveolar and alveolo-palatal sounds were used as speech stimuli in this study, the CoG values for these sounds are generally high, compared with the CoG value in palatals and velars[12]. These values have clinical implications in speech therapy, because the most common articulation disorder among clients with cleft palate is so-called "palatalised misarticulation," in which the place of articulation of alveolar sound is retracted to the hard palate or velar[20,21]. Improvement by speech therapy can be objectively shown in terms of CoG value change[6].

The variability index provides a value for the stability/variability of articulatory gestures (i.e., a lower variability index is related to more stable articulatory gestures or vice versa). In this study, the variability index was the lowest in [n] sound and gradually increased to [d] and [t]. Comparing the cumulative frames of these three sounds, [n] was less likely to have bilateral constriction than the other two sounds; the value increased gradually with increases in bilateral constriction. This indicates that more bilateral constriction is required for production of alveolar plosives than for production of alveolar nasals. Gibbon et al.[18] reported the frequency of bilateral constriction in 15 normal speakers' productions of /t/, /d/ and /n/; the rate of bilateral constriction was higher for /t/ and /d/, compared with /n/ (87% of /t/, 83% of /d/, and 49% of /n/). Our study revealed the same tendency in bilateral constriction. This reflects a difference of intraoral pressure, which is necessary to produce plosive sounds and nasals. Fujiwara, Hiramoto and Kawano[22] studied intraoral pressure of /p, b, m/, using pneumotachography. The mean pressure was much higher for /p/ and /b/, compared with /m/ (6.2 cmH_2O for /p/, 4.4 cmH_2O for /b/, 0.6 cmH_2O for /m/). Although velopharyngeal closure plays an important role in increasing intraoral pressure, a firm seal of the oral cavity is also required (i.e. bilabial closure for bilabial sounds and tongue-palate contact for alveolar sounds, in both alveolar region and in bilateral constriction). A significant difference in variability index was found between [n] and [d͡ʑ, ɕ]. This is thought to depend on the differences of the following vowels; [na] vs. [d͡ʑi, ɕi]. The preceding consonants before high front vowel /i/ tend to increase contact to the palate, thus causing the rise of the variability index.

Conclusion

Although tongue-palate contact patterns vary from person to person, there exist typical patterns to produce Japanese consonants. The generated EPG patterns show the integral part of contact and noncontact. They are highly accurate as target models for visual feedback training. Their spatial and quantitative analysis characteristics have implications in articulation therapy as well as assessment of Japanese consonants.

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Declaration of interest: The authors report no declarations of interest.

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The recorded sounds using EPG are basically enclosed with parenthesis as [t]. In some quotation of references, slash enclosed expression as /t/ is used, faithful to the original text.

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