Evaluation of Tongue Position during Speech Production in Various Anatomic Form of the Hard Palates

By

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Dedication

To my parents for their unconditional love and great support and for making me who I am today.

To my sister and brothers who always be there for me. I am lucky to have all of you in my life.

To my family, my aunts and uncles for their loves, their support and for giving me the opportunity to explore this wonderful world.

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Abstract

Introduction: Our objective is to determine if there is any covary of the lingual configuration during the /r/ production and the palatal morphology in adults with typical speech and morphology.

Methods: Dental impressions and data on tongue positions were obtained from 20 consenting participants. Palatal measures were analyzed using MatLab. Five small (2.5mm x 2.5mm) sensors were placed on the landmarks. Wave Electromagnetic Speech Measurement System was used to measure articulatory kinematics, movement of the lower lip, tongue tip, and tongue middle. The height differences between sensors on the tongues during the /r/ sound production that represented the /r/ in all positions in the phrases were measured. Covariation between the tongue configurations and the palatal structural measures were analyzed.

Results: The palatal morphologies were observed to have anatomical difference among individuals. Variability in tongue positions across participants suggested that there are many different ways to shape the tongue to produce the /r/ sound. Key results from the covariation analysis indicate a covariation between the tongue configuration during /r/ and the morphology of the hard palate.

Conclusions: Different strategies to achieve the /r/ sound production may be needed and palatal morphology should be taken into account when training different individuals to produce the /r/ sound. Moreover, dental practices such as removable dentures, orthodontic treatment, or orthognathic surgery, which could change the environment of the tongue, might affect the tongue configuration while producing speech.

Keywords: tongue position, lingual configuration, speech, /r/ sound production, palate, palatal morphology, Wave Electromagnetic Speech Measurement System,

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Background

Speech Production

Speech production starts in the brain. After the creation of the message and the lexico-grammatical structure in our mind, we come to the physical production of sounds. Speech is then achieved by compression of the lung volume causing airflow, which goes through the trachea, larynx, where the voice is produced, and then to the oral and nasal cavities. Articulators, which could be active or passive include the upper and lower lips, upper and lower teeth, tongue (tip, blade, front, back), and roof of the mouth (alveolar ridge, palate and velum). These structures transform the sound into intelligible speech (1). Speech sounds are distinguished from one another in terms of the place and the manner with which they are articulated (**Figure** 1 and **Figure** 2)

Speech sounds are generally divided into 2 categories: *consonant sounds* and *vowel sounds* (3).

Vowel sounds- the production is generally by the position of the tongue and lips without airstream obstruction and with the upper and lower teeth more widely separated. All vowel sounds are voiced, and it is for this reason that vowel sounds are generally less affected by the malpositioning of the teeth or jaws than consonant sounds are.

Consonant sounds- the production requires the obstruction or partial closure (i.e., sphinctering) of the airstream at specific sites along the vocal tract (See Figure 2). The classifications of consonant sounds are based on the extent of airstream obstruction, the site of airstream obstruction, and whether the vocal cords vibrate. With regard to the consonant sounds, the different extents of airstream obstruction are generally considered to fall into the following categories.

- *Plosive/stop:* Air pressure is stopped within the oral cavity at a specific location, and it is then suddenly released. Examples are: /p/, /b/, /t/, /d/, /k/, and /g/.
- *Fricative*: Air pressure is partially blocked or obstructed within the vocal tract, thereby causing turbulent airflow. Examples are: /f/, /v/, /s/, and /z/.
- *Affricative*: There is a sequencing of the airstream initially with complete obstruction (i.e., plosive/ stop) followed by fricative (i.e., partial vocal tract obstruction) at the same location. Examples are: /ch/, and /j/.
- *Nasal*: Air is allowed to pass freely through the nasal cavity. Examples are: /m/, /n/, and /ng/
- *Liquid/ Glide:* The tongue approaches a point of articulation within the mouth but does not come close enough to obstruct or constrict the flow of air to create turbulence (as with fricatives). Examples are: /j/, /w/, /r/, /l/

The anatomic locations of the vocal organs that block or partially block the airflow (i.e., places of articulation) include the following: bilabial (upper and lower lips); labiodental (lower lip to upper teeth); interdental (tongue between the upper and lower teeth); lingual to palate alveolar (tongue to alveolar process of the upper jaw); lingual to palate (tongue to hard palate); and glottal (vocal cords to each other) (**Table 1**) (3).

In comparison to the nasals, the rest of the sounds that comprise the semivowels are not as easy to classify or describe. Phoneticians generally agree on /j/ and /w/ as glides, but the /l/ and, in particular, the /r/, present a different story. Most phoneticians treat the /r/ sound as a glide. It could release a vowel in the words *run* and *reed*, or it could terminate a vowel as in *car* and *care*. In this sense, it may function as either an onglide or an offglide. Additionally, the /r/ and /l/ sounds

are frequently grouped by phoneticians as liquids. However, this term is difficult to define and often confused.

The /r/ Sound

An /r/ sound such as that found in American English is rarely possessed in other languages. The American English /r/ is probably the most variable of the speech sounds, based on the way it functions in the various dialects. The /r/ is a member of a class of phonemes in English that includes the /r/- colored vowels. It does not have a precise description of its articulation, but it is often described, as in Table 1, as "lingual-palatal," involving the tongue blade and hard palate. In fact, several rather distinct articulations will produce sounds that native speakers of the language will perceive as /r/. Serving as both onglide and an offglide, it could occur in every word position and in union with other speech sounds. Mastery of the /r/ series by children typically requires six years, and some non- native speakers might require even more time. The International Phonetic Alphabet (IPA) suggests the /ɹ/ symbol for the American English /r/- sound, American phoneticians have adopted the standard alphabet form as the symbol of choice. In the IPA alphabet, the /r/ symbol actually represents a rolled or thrilled 'r' as found in the Spanish word for dog – perro. [1]

The /r/ sound distribution could be in the initial position as in "rabbit", or "wrench," in the middle position as in "carrot," or" barrel," and in the final position as in "car," or "star." It is a late speech sound development when compared to other speech sounds that have certain areas of articulation and also the most common sound to be produced with error.

[1] In this study, we used /r/ to refer to all variations of the sound, unless noted otherwise.

Nearly half of the children at age 3 have mastery in at least two positions. And the relative age when almost all the children have mastery in at least two positions is not until 6 years of age. The relative age for at least 75% mastery in each position is 4 years- old for the initial and middle and 3 and a half years- old for the final position (4)

The physiological description of the /r/ sound is as follow.

1.The lips are typically rounded.

2.The tongue is raised toward the hard palate, the front usually in close approximation to the alveolar ridge; the back of the tongue may be raised slightly; the root may retract into the pharynx; it is possible for the tongue from to be retroflexed in some productions.

3.The velopharyngeal port is closed.

4.The vocal folds are adducted

5.Air flow is through the oral cavity as the tongue moves toward the next position.

The American English /r/ poses genuine difficulties for the non- native speaker, almost without exception. The production of /r/ could be improved by rounding and slightly pursing the lips. Conversely, spreading the lips usually results in a tendency to flap or trill the sound (4).

Hard Palate

The palate consists of 2 parts: the hard palate as the anterior 2/3 of the palate and the soft palate as the posterior 1/3. The hard palate is a bony structure formed by 2 bones: the palatine process of the maxilla and the horizontal plates of the palatine bone. It forms the roof of the mouth and separates nasal cavity from oral cavity (**Figure**).

The nasal side of the bony palate is covered by the ciliated columnar epithelium of the nasal cavity. The oral side of the palate is lined with the keratinized stratified squamous epithelium and is provided with numerous mucus-secreting palatine glands in the posterior half.

Hard Palate Development

The development of the hard palate consists of a major contribution from neural crest and a number of molecular, mechanical and morphological steps involving the fusion of contributing structures. The development begins during week 5 of embryonic period, but fusion of its component parts is not complete until week 12 (5).

The palate forms from 2 major parts: the primary and secondary palates (5, 6).

The primary palate or median palatine bone

The primary palate develops from the innermost or ventral portion of the intermaxillary segment at the end of week 5. It is formed by merging of the medial nasal prominences, of the upper jaw. The segment forms a wedge-shaped mesodermal mass between the maxillary prominences of the developing upper jaw.

Membrane bone develops in the primary palate, forming the premaxillary part of the upper jaw and carrying the incisor teeth. The bone then extends into the lateral palatine processes to form the hard palate. The palatine raphe indicates the line of fusion of the lateral palatine processes. The nasopalatine canal persists in the palatine midline between the premaxillary portion of the maxilla and the palatine processes of the maxilla. The canal eventually obliterates except for the incisive foramen. The posterior portions of the lateral palatine processes do not become ossified, but extend past the nasal septum and fuse to form the soft palate and uvula and it is, the last portion of the palate to form.

The secondary palate

The secondary palate develops from 2 horizontal mesodermal projections called the lateral palatine processes or palatine shelves that formed on the inner surfaces of the maxillary prominences, which appear in week 6. The projections project obliquely downward on each side of the tongue. As the jaw develops, the tongue moves down and the lateral palatine processes grow toward each other and fuse. They also fuse with the primary palate and the nasal septum, the latter developing as a downward growth from the merged medial nasal prominences. Fusion begins anteriorly in week 9 and is completed posteriorly by week 12

Tongue

Doran and Baggett (7) identified 2 types of mammalian tongues:

Type l is the spatulate fleshy tongue found in almost all mammals. It could protrude up to 50% over its resting length and is capable of fairly complex movements.

Type ll tongues are the highly flexible whip-like organs found in anteaters and other myrmecophagous mammals.

The tongue is an extra-ordinary organ. It is a boneless mass composed of intrinsic and extrinsic muscles (**Figure 1**).

Intrinsic muscles

They only attach to other structures in the tongue and are named by the direction in which they travel: **superior longitudinal, inferior longitudinal, transverse and vertical** muscles of the tongue. These muscles alter the shape of the tongue by: lengthening and shortening it, curling and uncurling its apex and edges as in tongue rolling, and flattening and rounding its surface. This provides shape, and helps facilitate speech, swallowing, and eating (8).

Extrinsic muscles

Their main functions are altering the tongue's position allowing for protrusion, retraction, and side-to-side movement (8). They are as follows:

Genioglossus

Attachments: Arises from the mental symphysis and inserts into the dorsum of the tongue

Function: Inferior fibres protrude the tongue, middle fibres depress the tongue, and superior fibres draw the tip back and down

Hyoglossus

Attachments: Arises from the hyoid bone and inserts into the side of the tongue

Function: Depresses and retracts the tongue

Styloglossus

Attachments: Originates at the styloid process of the temporal bone and inserts into the side of the tongue

Function: Retracts and elevates the tongue

Palatoglossus

Attachments: Arises from the palatine aponeurosis and inserts broadly across the tongue

Function: Elevates the posterior aspect of the tongue

All of the intrinsic and extrinsic muscles are innervated by the hypoglossal nerve (CN XII), except palatoglossus, which has vagal innervation (CN X).

The tongue size, strength, state of health, movement patterns and resting position are the characteristics that could be used to indicate its functional performance.

The methods available for studying tongue movement have occurred in the last 30 years (10).

Electropalatography (EPG)

With this technology, intra-oral sensors are embedded in a plastic base plate (5 mm thick) that covers the hard palate and is anchored to the maxillary teeth. The pressure sensors respond to the points of contact between the tongue surface and the device. It cannot measure the actual tongue movement. However, this method when used in conjunction with other methods such as ultrasound, could add a greater value in speech research (11).

Applied Diagnostic Cineradiography (CFG) and Videofluorography (VFG)

CFG became available in 1950s and was used to study human swallowing pattern (12). The first clinical cameras were slow (25-30 frames per sec), and used 35-mm film. During late 1980s, VFG, which requires much lower radiation levels, became a standard radiological diagnostic tool. The first markers for the measurement of jaw movement were simple amalgam fillings on the buccal surface of canines or molars, which appeared as, black dots on the films. The recent study in human (13) used small lead discs (4x0.4 mm.) cemented to upper and lower teeth, and to the tongue. However, radiation exposure for human subjects was a main concern with this technique.

X-ray Microbeam (XRMB)

This technique was invented in the early 1970s and required much lower levels of radiation than VFG. The limitation was that it images only the position of the gold pellets glued to the tongue and teeth. Therefore, additional instrumentation was needed to capture tongue surface information- for example, a sagittal ultrasound recording of the same utterance was recorded for each subject immediately after the microbeam record was obtained and matched to the pellet positions (14).

Ultrasonography (US)

Ultrasound images soft tissue in real time and has several advantages over VFG: no ionizing radiation and midline submental transducer placement minimizes masking of the tongue by the hard tissues (mandible and teeth). A major disadvantage of US is the absence of spatial information on the relationship between the visualized tongue surface and the rest of the vocal tract. This technique was combined with EPG and jaw motion recording to study the interactions of the tongue, palate and mandible (15). However, it is clear that new and very sophisticated ultrasound technology could generate the data to produce 3D models of the tongue surface. If the research objective is to understand tongue behavior in feeding and speech as a basis for developing either better clinical diagnostic test of treatment approaches, this technique needs simplification. (10).

Magnetic Resonance Imaging (MRI), MRI movie or real- time MRI

It is a newer method for examining soft tissues. This technique is non-invasive with no radiation exposure, and capable of imaging speech production processes. However, MRI has serious limitations as a research tool for studies of speech or deglutition because the subject is supine and the data acquisition is slow when compared with the duration of normal feeding and speaking events (16).

NDI Wave Speech Research System (Northern Digital, Inc, Waterloo, ON)

Wave speech research system is an electromagnetic articulography (EMA) system that supports three dimensional (3D) tracking of 5 or 6 degree-of-freedom (5-DOF, 6-DOF) sensors affixed to the tongue in one of two electromagnetic field volume settings (300 mm^2 or 500 mm^2). 5-DOF sensors allow tracking of x, y, and z spatial coordinates as the tongue moves, as well as angular coordinates characterizing rotation about the transverse axis (pitch) and anterior–posterior

axis (roll). 6-DOF sensors have the added capacity for tracking angular coordinates characterizing rotation about the inferior–superior axis (yaw).

The NDI Wave follows the basic operating principles of two-dimensional magnetometer systems. In short, a signal of varying strength is induced in a receiver (sensor) via an alternating electromagnetic field, generated by a transmitter. The strength of the induced signal varies with the distance and relative orientation between the receiver and the transmitter. Thus, sensor location could be derived from signal strength, but changes in sensor orientation confound the relationship. In the simplest case, when the long axes of the receiver and transmitter coils maintain a parallel relationship, sensor position registration is straightforward. However, changes in sensor orientation result in potential increases in tracking error.

In practical application, rotational misalignment is particularly likely for tongue and jaw sensors as a result of variations in pitch. In principle, the hardware and software design of 3D magnetometer systems could eliminate the problem of rotational misalignment (17). However, for the 3D NDI Aurora system, a predecessor to the NDI Wave with a 40-Hz sampling rate, both sensor orientation and distance affect tracking accuracy (18). Adapted from the Aurora system (18) (19) the NDI Wave has design features, such as real-time movement data display and automated head-movement compensation, that may bolster the development of clinical applications (20).

In a performance study by Jeff Berry, three experiments were used to assess the NDI Wave: tracking sensors affixed to a static rigid body positioned systematically at different locations within the electromagnetic field volume, tracking sensors affixed to a dynamic rigid body (a four-bar-linkage) following a repetitive path of motion and supported by a static framework positioned systematically at different locations within the electromagnetic field volume, and tracking human

jaw movements during speech. The data sets were used to estimate positioned tracking error and variability of the NDI Wave system using known distance comparisons. In summary, dynamic tracking accuracy was superior for the 300-mm^3 field (compared with the 500-mm^3 field) of the NDI Wave system. Tracking accuracy did not vary significantly along the anterior–posterior and inferior–superior dimensions of the field and did not appear to be influenced by use of the automatic head movement correction settings. Although extreme tracking errors (> 2 mm) did occur within the near field of the 300-mm^3 volume, these errors occurred in < 1% of samples. Within the near field of the 300-mm^3 volume, 88% of dynamic positional errors were < 0.5 mm and 98% were < 1.0 mm. Human jaw tracking for 10 subjects during paragraph reading revealed tracking errors that were typically < 0.5 mm. Taken together, these results suggest that tracking accuracy for the NDI Wave system may be bolstered by using the 300-mm^3 volume setting and positioning subjects so that sensors stay within 200 mm of the field generator surface (21).

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Literature Review

The position of the tongue during various activities has been of interest across a variety of disciplines for the better part of a century. Baker in 1954 explained that in normal breathing using the nasal air passages, the tongue is found to be in a rest position; the anterior part of the tongue, including the tip, is lowered to contact the lingual surfaces of the mandibular or maxillary anterior teeth.

In forced breathing through the mouth, the mandible is depressed, the lips are opened, and the tongue laterally remains in contact with the lingual surfaces of the mandibular teeth dropping away from the maxilla (1).

The tongue contributes to deglutition, growth and development of the jaws, and also alignment of teeth in occlusion (2). The tongue has also been found to play an important role in speech as many researchers have found changes in tongue shape between classes of vowels and consonants. For example, tongue movement in the anterior-posterior plane, such as tongue retraction and advancement, was found to be crucial for the production of /w/ in typical male speakers (3). During speech production, the tongue moves and contacts different points and positions of the palate in the pronunciation of speech, including consonants, vowels, words, and connected language.

It has been known that any dental malposition or abnormal size of the jaw could create a significant impact on speech (4). A study using auditory and visual descriptions found relationships between various occlusal anomalies and sound production. The more severe the malocclusion, the more likely a speech sound error would occur (5). Class II morphology with nasal obstruction and inferior tongue posture are related to a relatively narrow maxilla dentition.

Class III malocclusion with enlarged tonsils with an anterior tongue posture might induce protrusion of the mandible (6).

The vowel context was found to significantly affect the amount of tongue- palate contact present, with /i/ having the most and /a/ having the least amount of contact (7). A study has found that the speakers with partial glossectomy had a significantly lower mean of second formant frequency (F2) during the vowel /i/ than the control group due to a restricted range of tongue movement in the anterior-posterior dimension during vowel production (8).

The tongue is a highly complex organ, which makes it difficult to be examined. New technology including many imaging techniques (cinefluorography, ultrasound, electro-palatography, NMRI, and others), have examined the spatial and temporal relationships of the tongue surface in sound production (9).

Another new invention includes NDI Wave Speech Research System, which is an electromagnetic articulography (EMA) system that supports three dimensional (3D) tracking of 5 or 6 degree-of-freedom (5-DOF, 6-DOF) sensors in one of two electromagnetic field volume settings (300 mm3 or 500 mm3) (10). With this new technology, researchers have been able to track the moment- to –moment position of the tongue during speech production.

A study on tongue position using 3D electromagnetic tracking system found that positional variability of the tongue differed between the front (e.g., alveolar and post- alveolar) and back (velar) consonant groups. By using two 5-DOF sensors, they were able to show that tongue position variability of the front consonants was explained, to a degree, by palate curvature and palate length. However, the variability of the back consonants was not explained (11).

Many studies have shown that the size and form of the palate varies among individuals. Palatal shapes of healthy children between 3 and 6 years of age were found to change and became

proportionally higher in both frontal and sagittal planes (12). While in adolescent female, palatal form appeared to have already attained adult characteristics, the change was found to continue until young adulthood in male. (13). A significant difference with arch and palatal form was found among males and females with the predominant palatal form are both U and V shaped in males and U-shaped in females (14). A study found the effect of tooth loss in the horizontal regression of the maxilla which may enhance the bone resorption that could ultimately result in the marked reduction of the width and depth of the alveolar arch concomitant with the alteration of the hard palate (15).

The palatal morphology could vary due to the pattern of craniofacial growth, which is under the influence of several genetic and environmental factors. Heredity has been suggested as a strong etiological factor in malocclusions, which also involved palatal dimensions. A study in 1970 (16) analyzed data from 32 pairs of same-sexed twins (14 monozygotic (MZ) and 18 dizygotic (DZ)) aged between 10-12 years old to evaluate the relative influence of genetics and environment on the palatal dimensions. The assumption was made that any observable difference between the two members of MZ twin pair results from environmental influences alone, while the differences between the two members of DZ twin pair will result also from differences in their genetic constitutions. The palatal width, height and length data measured on stone casts of maxillary arch showed no significant differences between the mean intrapair variances for any of the palatal dimensions. However, statistically significant difference was found in all dimensions when they compared the mean intrapair variances of MZ twin and DZ twins, revealing a significant component of hereditary variability.

However, an environmental factor such as breathing pattern was found to have an effect of the morphology of the hard palate. A cross-sectional study was done to determine the relationship

between airway obstruction, palatal vault formation and malocclusion. From the 1065 examined children in this study, 20% presented known allergies. Eighty percent of the allergic children had high palatal vaults. High palatal vaults were also observed in children with enlarged tonsils, lip incompetency (85.8%), and children with Class II (73.6%) and Class III (65.3%) (17).

Subjects with prolonged mouth breathing showed a significant reduction of the palatal surface area and volume, leading to a different development of the palatal morphology when compared with subjects with normal breathing pattern. In particular, the palatal surface area and palatal volume were, respectively, 13.5 and 27.1 per cent smaller in the subject group when compared to the control group (18).

Moreover, a recent study found that patients with obstructive sleep apnea (OSA) had significantly smaller palatal area measurements when compared with those without OSA ($P < .00$). OSA patients had significantly narrower maxilla with smaller intermolar and intercanine widths ($P < .001$). A positive correlation was found between the palatal morphology and pharyngeal dimensions (19).

A study in 2013 found that palatal morphology varies widely in its degree of concavity and in anteriority and sharpness. They then proposed the three prominent ways to identify hard palate shape, as shown in **Figure 2**. Midsagittal images were collected from a group of 36 healthy adult subjects using real-time magnetic resonance imaging (rtMRI) (20).

Several studies have shown that the morphology of the palate has a substantial impact on articulatory strategies. Speakers with flatter palates reduced their tongue variability in tongue height, when compared to those with dome shaped, in order to keep the acoustic output constant (21).

Apart from the variation of the form of the hard palate among individuals, there are many factors that could alter the form of the hard palate within individuals. Palatal expander, complete denture, palatal coverage-typed retainers, and surgically assisted rapid palatal expansion procedure are good examples of common dental treatments that may affect the shape of the palate, thus may alter tongue position and speech production.

A study found changes in speech after palatal alteration. A mechanical device was used to dynamically change the thickness of an artificial palate. Acoustic, perceptual, and speech movement changes were examined in response to the experimental conditions. The study used an electro- magnetic articulography (EMA) system to look for evidence of compensatory articulation. There was frequent overshoot of the tongue in forming the constriction, causing speech errors in the first syllable with the fricative. However, compensation by the tongue for the unexpected palatal inflation became evident around the second syllable and the speech error disappeared in the successive syllables (22).

Artificially flattening palate shape also forces corresponding changes in jaw height and the positioning of the tongue. A study used EMA and simultaneous acoustic recordings to estimate tongue configurations during production of [s š t k] in the presence of a thin and a thick palate. The thick palate lowered the center of gravity and the jaw was lower and the tongue moved further backwards and downwards (23).

In American English, the phoneme /r/ has been found to have the most variable of the speech sounds (24) and relatively large amounts of articulatory variability (25, 26). In individuals with residual speech errors, the most common errors are variations of /ɹ/ (e.g., initial /ɹ/, /ɹ/-controlled vowels such as /iɹ/, and blends such as /tɹ/). This is a particularly challenging sound, as it requires two lingual constrictions, while the majority of English sounds require only one place

of constriction. To produce a perceptually accurate /r/, there must be a retraction of the tongue into pharyngeal cavity along with an approximation of a point on the surface of the tongue near the hard palate. Many individuals also use lateral bracing of the tongue against the upper molars, along with lip rounding, both of which create additional complexity in the production (27). To add to these challenges, there are multiple ways to produce a perceptually accurate /r/. Two articulatory variants of /r/ are commonly mentioned: "retroflex" /r/ (produced with a raised tongue tip and a lowered tongue body) and "bunched" /r/ (produced with a lowered tongue tip and a raised tongue body towards the hard palate; (28, 29) (

Figure 6). However, "retroflexed" and "bunched" are broad categories. The way an individual produces /r/ seems to be completely individualized; the tongue shape for /r/ does not even seem to show any patterns by geographical region based on x-ray, ultrasound and MRI studies (30).

With regard to /r/, clinicians are taught to focus on a single "place of articulation" (in the alveolar/ postalveolar region) (29). In order to achieve the same acoustic output, it is possible that there is an articulatory difference in compensation for the morphological variation in palatal shelves among individuals. One study found a difference in tongue patterns between subjects with retroflex and bunched vocal tract configurations. The results also suggested that the differences could be largely explained by differences in whether the long cavity behind the palatal constriction acted as a half- or a quarter-wavelength resonator (31).

A review study used findings from a number of published x-ray and MRI studies of tongue shapes for /r/ using speakers from various dialect regions. They also characterized the variability of tongue shapes used for /r/ in a cineradiographic database of elderly men with normal speech from the area of Cincinnati, OH. Results show that variability in tongue shape prevalence is

common across different regional populations and concluded that tongue configuration is likely a matter of individual variation (30).

Strong evidences that vowel articulation is influenced by palate shape (32) and by pharyngeal space (33) were found. Although these apply to vowels rather than /r/, it would be interesting to see if the /r/ configuration could also be influenced or not. Moreover, one interesting question that was raised is whether the most appropriate /r/ tongue shape for a particular individual could be predicted from anatomy (29). However, currently, there is little information about the relationship between the tongue position and the hard palate during /r/ production. Therefore, it would be of value to identify if there are differences in tongue position/ configuration during speech production, particularly in the /r/ sound, among individuals with various forms of the hard palate.

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Statement of the Thesis

To measure any covariation of palatal morphology and lingual configuration during the production of the /r/ sound. The current investigation characterized palatal morphology with a series of algorithmically derived measures acquired from 3D scans of maxillary casts. Lingual configuration during /r/ production was acquired by capturing motion of four sensors on the tongue using the NDI Wave EMA system during speech production. The research question was, "In adults with typical speech and morphology, does the lingual configuration during the /r/ production covary with the palatal morphology?"

Null hypothesis = There is no covariation of tongue position during /r/ production and parameter measures of the hard palate.

Alternative hypothesis = There is covariation of tongue position during /r/ production and parameter measures of the hard palate.

Evaluation of Tongue Position during Speech Production in Various Anatomic Form of the Hard Palates

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Abstract

Introduction: Our objective is to determine if there is any covary of the lingual configuration during the /r/ production and the palatal morphology in adults with typical speech and morphology.

Methods: Dental impressions and data on tongue positions were obtained from 20 consenting participants. Palatal measures were analyzed using MatLab. Five small (2.5mm x 2.5mm) sensors were placed on the landmarks. Wave Electromagnetic Speech Measurement System was used to measure articulatory kinematics, movement of the lower lip, tongue tip, and tongue middle. The height differences between sensors on the tongues during the /r/ sound production that represented the /r/ in all positions in the phrases were measured. Covariation between the tongue configurations and the palatal structural measures were analyzed.

Results: The palatal morphologies were observed to have anatomical difference among individuals. Variability in tongue positions across participants suggested that there are many different ways to shape the tongue to produce the /r/ sound. Key results from the covariation analysis indicate a covariation between the tongue configuration during /r/ and the morphology of the hard palate.

Conclusions: Different strategies to achieve the /r/ sound production may be needed and palatal morphology should be taken into account when training different individuals to produce the /r/ sound. Moreover, dental practices such as removable dentures, orthodontic treatment, or orthognathic surgery, which could change the environment of the tongue, might affect the tongue configuration while producing speech.

Keywords: tongue position, lingual configuration, speech, /r/ sound production, palate, palatal morphology, Wave Electromagnetic Speech Measurement System,

Introduction

Speech is a vocalized form of communication used exclusively by humans to communicate in a more complex and complicated form than other animals. Each spoken word is created out of the phonetic combination of a limited set of vowel and consonant speech sound units. The various vocabularies and their sets of speech sound units differ around the world, creating thousands of different and mutually unintelligible languages.

Speech sound production involves shaping the voice using the movement of soft tissue organs in the craniofacial region, such as the lips and tongue, while articulating these structures against the hard tissue organs such as teeth and hard palate. The hard palate is crucial to the acquisition and production of any spoken language, as children with cleft palate demonstrate a marked improvement in the intelligibility of speech following primary palate repair (Dorf & Curtin, 1982; Murthy, Sendhilnathan, & Hussain, 2010).

Interestingly, speech is described as having a "many-to-one" problem (Atal, Chang, Mathews, & Tukey, 1978) that is, there are many articulator configurations that could achieve the same acoustic or perceptual outcome. The soft tissue structures could compensate for changes in the hard structures or trade roles. For instance, the lips could be rounded to accommodate less motion in the tongue during a speech sound like "r" to achieve a similar sound. The tongue is required to adapt its shape to achieve the same acoustic output if there is any change in the environment around the tongue such as variations in palatal morphology or presence of an appliance. Orthodontic treatments involving lingual braces, maxillary expanders, retainers, orthognathic surgery or other dental treatments such as placement of removable dentures alter the hard surfaces against which the tongue articulates, which could affect both how speech is produced

and how it sounds. Therefore, speech production should be taken into account when planning various treatments that involve the shape or function of these structures.

In the past, studies about tongue position during speech production were completed using technology such as electropalatography (EPG) (Stone & Lundberg, 1996), cineradiography (CFG) (Palmer, Hiiemae, & Liu, 1997), and x-ray microbeam (XRMB) (Stone, 1991). However, the information was limited by the technology available and the limited number of participants because of the exposure to radiation. Hence, the data presented about the configuration of the tongue during speech sounds showed a static position of the tongue in a single plane of reference for a single talker or subjective report of the speech, which did not really represent the realistic situation. With improved technology we have today, we are able to track the moment-to–moment position of the tongue during speech production in three dimensions across many talkers, providing us with greater information about the kinematics and position of the tongue during the production of particular speech sounds. Such rich, dynamic data provide the opportunity to evaluate the interaction between tongue position and the morphology of the hard structures, such as the maxillary palate. This study was conducted in adult individuals to monitor the tongue position during speech production and the relationship between the configuration of the tongue and the shape of the hard palate.

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Materials and Methods

Twenty consenting healthy native American English speakers, aged between 20 and 50 years old participated in the study.

Inclusion Criteria

- Full permanent dentition (except for third molars) with no dental prosthesis or any type of devices that covered the palate

- Reasonably aligned upper and lower dentitions (no more than 2 mm of crowding attributed purely to the slippage of the contact points)

- Normal vision (corrected)- self-report

- Normal hearing confirmed by pure tone hearing screening (500, 1k, 2k, 4k, Hz threshold less than 20 dB)

- No history of speech and/or language disorder and/or have and/or received speech or language treatment

- No history of neurological disorders

- No history of enrollment in special education services

Exclusion Criteria

- Incomplete speech data obtained

- Non- native American English speaker

- Tongue lesion or piercing presented

The assessments of speech and tongue positions were conducted at the Cleveland Hearing and Speech Center. Dental impressions for study models were obtained at the Department of Orthodontics, School of Dental Medicine, Case Western Reserve University.

Speech Sampling and Recording Procedures

All samples were recorded using a video- recorder and a head-mounted microphone. Participants were seated in an adjustable dental chair with a headrest in a sound- treated room. A head- mounted microphone was used to record the acoustic signal, which would digitize direct-to-disk, after passing through a hardware pre- amplifier and low- pass filter.

To measure articulatory kinematics, movement of the lower lip, tongue tip, and tongue body were measured using 5 small (2.5mm x 2.5mm) sensors placed midsaggitally, and laterally. Specifically, tongue sensors were placed (Figure 7): Tongue tip (TT) sensor = mid-sagittally, 1 cm from the tongue tip, Tongue right (TR) and Tongue left (TL)= 1 cm from the tongue tip and 1 cm from the lateral edge of the tongue, on the right and left sides respectively, Tongue body (TB) sensor= 2 cm from the tongue tip on the midline of the tongue, and Tongue dorsum (TD) sensor= 1 cm from the tongue body on the midline of the tongue. Sensors moment- to- moment positions were tracked at 400 Hz using the Wave Electromagnetic Speech Measurement System (Northern Digital Inc., 2010). The sensors were adhered to the tongues using physiological glue (PeriAcryl 90, Gluestitch Inc, Canada).

Positional measures included:

x range(mm)= the movement in the lateral dimension

y range(mm)= the movement in the anteroposterior dimension

z range(mm)= the movement in the vertical dimension

Elicitation Set

Participants read the speech stimuli aloud from a 50- inch plasma screen mounted within their visual field. Twenty repetitions of each of the stimuli in a carrier phrase were presented and produced in a random order. Participants were instructed to read the stimuli at a normal rate and loudness. The elicitation was self- paced. The productions were similar to, "Say CVC again" where C was one of the 13 consonants: /b, p, t, d, k, g, f, v, s, z, sh, ch, j/ and V was one of the vowels (i.e. "bob," "pop," "tot," "dod," "gog"). The primary word stress was on the CVC syllable. There were a total of 300 productions per participant and it was anticipated that elicitation would take approximately 30 minutes. Other real- word phrases were elicited, including "Take a duck," "Cat is out," "See nice boys," "Red ball," "No you share," "Load a rug," "Show late," "Zoo good," "Go sit fish," "Yellow shoe on," "Dock a pass," and "Day you race." Each speaker's production sounds were perceptually checked as "correct" when determined by trained listeners.

Tongue position measures were made at the moment that the "r" sound was produced using landmarks in the position record for the TB sensor. Research assistants marked the moment of the "r" sound by viewing at the microphone signal time-aligned with the position record. Using vertical displacement and minima of the speed of the sensor as a guide, the moment of "r" could be identified (Figure). The 3D position of the TT, TB, TR, and TL sensors were recorded for that moment across all 20 productions of the phrase where the "r" sound occurred in the initial, medial, or final phrase position. To quantify the position of the tongue for the purpose of correlation with the palatal morphology measures, differences in vertical position were calculated at the moment of the /r/ production as a mean to characterize tongue configuration (Table 2)

Palatal Size and Shape

Palatal Data Processing

Dental impressions of upper and lower arches were made using alginate impression material. The impressions were poured with white stone and then optically scanned into a common 3D mesh file format using a 3D Scanner (Ortho Insight 3D, Motion View Software, LLC, Hixson, TN) and saved in STL files. The meshes were imported to MATLAB (MathWorks, Natick, MA). Palatal size and shape were manually marked using a custom tool (See **Figure**). The data then were measured and analyzed using MATLAB.

Reference Frame

The local reference frame of the palates was generated based on five landmarks. Landmarks were chosen for their ease in identification, property that researchers could mark them within a few millimeters, and the expectation of little drift over time and across multiple impressions essentially, the reliability of the landmarks. The origin of the palate was defined as being the labial gingival margin between the maxillary central incisors (Figure 11).

The constructed transverse plane was defined by three points. The first point was the palatal gingival margin between the upper central incisors. The remaining two points that define the transverse plane were the left and right buccal gingival margin between the premolars and the first molars and center of the tooth or in line with any visible central fossa on the interior vertical plane of the tooth. These three points defined the constructed transverse plane. See Figure 12.

The first point of the constructed transverse plane definition set of points was reused as part of the definition of the sagittal plane. The second point used to define this plane was a point lined on the posterior aspect of the midpalatal suture. These two points indicated the direction,

but the points were not guaranteed to be on the sagittal plane. The sagittal plane was defined by the cross product of the vector orthogonal to the transverse plane and the line defined by the two points. See Figure 13.

The origin point, occlusal and sagittal planes completely defined the reference frame of the palate with the coronal plane being defined implicitly as orthogonal to the constructed occlusal and sagittal planes, which were all shifted to the origin point. See **Figure** .

The vector orthogonal to the sagittal plane pointing to the right was defined as the X-direction, the vector orthogonal to the coronal plane point forward was defined as the Y-direction, and the vector orthogonal to the constructed transverse plane pointing up was defined as the Z-direction.

Landmark Locations (Figure 14)

Incisive papilla (IP) = the point between upper central incisors.

Midpalate (MP) = the point on the palatal suture at the upper first molar area (if the premolars were missing, second molar area was used)

Upper right molar (MR) = the point at the lowest part of the palatal gingival margin (Ciusa, Dimaggio, Sforza, & Ferrario, 2007) of the upper right first molar (if the premolars were missing, second molar gingival margin was used)

Upper left molar (ML) = the point at the lowest part of the palatal gingival margin of the upper left first molar (if the premolars were missing, second molar gingival margin was used)

Line Fit

A line was fit to the palate in the coronal plane between the left and right maxillary first molars. Points were selected at the deepest part of the palatal gingival margin of left and right

maxillary first molars. Figure 15 shows the line between the mean positions of the molar points in the coronal plane.

A line was generated at the mean depth orthogonal of the coronal plane. The palate mesh was composed of many thousands of nearly half a million vertices at arbitrary locations, which were connected together to form faces. The point on every line that connects vertices on either side of the palate line was calculated. A least squares regression was used to determine the fit of a line to the data. The goodness of that fit was the coefficient of a polynomial.

The line was fit using a sixth order polynomial. The polynomial was used to characterize the shape of the palate. The number of roots (between the beginning and the end marker) indicates the palate shape. A palate with three roots indicates an "M" shape as illustrated by the palate in Figure 9a. The location of the roots of the derivative of the polynomial classified the shape, depth or breadth of the palate.

Two measures were used to evaluate the quality of the fit. The first was the coefficient of determination (R^2). The coefficient of determination quantifies how well the line fits the given data. The palate line in Figure 9a has an $R^2 > 0.99$. The Root Mean Square Error (RMSE) provides a physical measure of how closely the line fit matches the physiology. The line on the palate in Figure 9a has an RMSE value of less than 0.2 mm.

Structural Measures (Figure 16 and Figure 17)

Palatal width (PW): the distance between MR and ML

Palatal height (PH): the largest perpendicular distance from the point on the palate to the line drawn between MR and ML

Palatal Shape (PS): the palatal height over the palatal width indicating whether the palate is wide (less than 1) or narrow (greater than 1)

Palatal depth (PD): the anteroposterior distance from IP to the line drawn from MR to ML.

PW, PH and PD are the common palate measures used in dentistry (Riquelme & Green, 1970) (Suresh, Sumathy, Banu, Kamakshi, & Prakash, 2012). (Ciusa et al., 2007). (Ferrario, Sforza, Colombo, Dellavia, & Dimaggio, 2001). However, the limitation of the three measures are that they are not able to differentiate the palates that have the same measurement for PW and PH but different in shape.

Palate area (PA): the area of the coronal section of the palate at the MR-ML line, bound by the MR-ML line and the palate.

Rectangular area (RA): the area of PW x PH

The **palatal measure (PM)** is the percentage of the possible rectangular area filled by the palate area.

This measure allows us to tell the difference between the palates that may have the same measurement for PW and PH. The palate that has the lower number in PM means it has less PA filled in RA. It is likely that that palate has narrower palatal arch shape than the one with the higher PM.

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Statistical Analysis

Descriptive statistics (Mean, Standard deviation (SD), Maximum (Max) and Minimum (Min)) were calculated for each variable.

The distribution of each variable was tested for normality distribution using the Shapiro-Wilks test for normality.

Coefficient of variation was run to see the variability in the tongue position within and across the participants.

Because the majority of the variables were continuous data, Pearson correlation coefficients ($p < 0.10$) were used to compute the association within and between variables.

Results

Dental impressions were obtained from 20 participants. Palatal measures were analyzed using MatLab. Data on tongue positions were also obtained from the participants. Ten incomplete speech data sets were not included in the analysis. Data were incomplete because of the tendency of the affixed sensors to fall off of the tongue. The data from the remaining ten participants (6 females and 4 males, average age= 23 years (20-35) were analyzed for covariation.

Palatal Size and Shape

Table 3 shows summary statistics for palate measures (Palatal width (PW), Palatal height (PH), Palatal depth (PD), Rectangular area (RA), Palatal area (PA), Palatal measure (PM)) from all participants. **Table 4** shows summary statistics for palate measures of participants after exclusion. Note that the average measures are very similar.

Tongue Position Measures

The height differences between sensors on the tongues during the /r/ sound production that represented the /r/ in all positions in the phrases (initial= “red ball”, median= “load a rug”, and final= “no you share”) were measured and are presented in **Table 5**. Data from the tongue dorsal sensor were removed from the analysis as the sensors failed to give adequate information.

Descriptive data of the height differences between sensors showed the TB sensors were higher than the TT sensors in all phrase positions. The outlier data (showed more than 2 standard deviations) were removed from the set. The TR sensors were higher than the TL sensors in all phrase positions. The TR sensors were also higher than the TT sensors but lower than the TB sensors in all phrase positions. A similar pattern was found in the TL sensors.

The coefficient of variation (Table 6) showed that the variability within each participant, across repetitions of the /r/ in a given phrase position, was less than the variability across participants. While there was a lot of individual variability in how /r/ was produced, it was much less than the variability between participants. It is interesting to see that there was so much variability, between-subjects, in the measures for the initial /r/ productions.

The data of the tongue positions during the /r/ sound production in each position in the phrases were analyzed to see if there were any associations between positional measures and structural measures.

Correlations between Tongue Configurations and Structural Measures

Pearson correlation coefficients ($\alpha < 0.1$, degree of freedom (*df*)= 2) were computed between the tongue configurations and the palatal structural measures (Table 7). The position between each sensor (TB-TT, TL-TR, TR-TT, TR-TB, TL-TT, TL-TB) in the z range (height) was calculated when /r/ sound was produced in each position: initial, medial, and final.

The results showed positive correlations between palatal height and the TB-TT height differences but only the final phrase TB-TT showed a significant correlation (r= 0.77, p= 0.043, *df*= 2).

Palatal height also had significant positive correlations with the TR-TT height differences in all /r/ phrase positions (initial: r= 0.87, p= 0.01, *df*= 2, medial: r= 0.79, p= 0.03, *df*= 2, final: r= 0.71, p= 0.07, *df*= 2) but had negative correlations with the TL-TB height differences with a significant correlation found in the final phrase TL-TB (r= -0.76, p= 0.05, *df*= 2.)

Interestingly, significant positive correlations were noted in the TR-TB height differences in all /r/ phrase positions and both palatal width (initial: r= 0.68, p= 0.09, *df*= 2, medial: r= 0.79,

p= 0.04, *df*= 2, final: *r*= 0.82, *p*= 0.02, *df*= 2) and palatal depth (initial: *r*= 0.73, *p*= 0.06, *df*= 2, medial: *r*= 0.81, *p*= 0.03, *df*= 2, final: *r*= 0.73, *p*= 0.06, *df*= 2.)

Negative correlations were noted in the TB-TT and palatal width with a significant correlation found in the medial phrase position (*r*= 0.72, *p*= 0.07, *df*= 2.)

Both palatal area and rectangular area showed positive correlations with the TR-TB height differences but significant correlations were found in the initial (*r*= 0.75, *p*= 0.05, *df*= 2 and *r*= 0.82, *p*= 0.02, *df*= 2 for palatal area and rectangular area respectively) and medial /r/ phrase positions (*r*= 0.74, *p*= 0.06, *df*= 2 and *r*= 0.83, *p*= 0.02, *df*= 2 for palatal area and rectangular area respectively.)

Palatal area and rectangular area showed negative correlations with the TL-TR height differences in all phrase positions except PA to the initial TL-TR. However, only the medial phrase position showed significant correlations (*r*= -0.92, *p*= 0.00, *df*= 2 and *r*= -0.7, *p*= 0.07, *df*= 2 for PA and RA respectively.)

A significant positive correlation was noted in the TL-TR height difference in the initial phrase and palatal area (*r*= 0.69, *p*= 0.09, *df*= 2.)

Palatal measure was found to have negative correlation with the TL-TB height differences in all /r/ phrase positions but a significant correlation was found only in the medial phrase (*r*= -0.76, *p*= 0.05, *df*= 2.)

Discussion

The results of the current research indicate a covariation between the tongue configuration during /r/ and the morphology of the hard palate. Unlike previous studies, this investigation included data from the lateral edges of the tongue during speech articulation. Using measures of vertical difference between the landmarks of the tongue during the production of /r/ in different phrase positions, the correlation coefficients indicate a relationship to the shape of the hard palate, as measured.

The palatal morphologies were found to have anatomical difference among individuals. The palatal structural measures showed slightly lower number in the palatal width, palatal height, and palatal depth when compared to the study done in Yemeni population (Al-Zubair N. M., Al-Labani M. A., Al-Motareb F.L., 2015).

Most of the studies done on the palatal measures in the past discussed the palatal width, height, and depth (Al-Zubair N. M., 2015; Ciusa, Dimaggio, Sforza, & Ferrario, 2007). In the current study, we proposed an additional measurement (PM): palatal measure, which is the percentage of the rectangular area (palatal width x palatal height measured from the highest point of the palate to the line drawn between molar right and left) filled by the palatal area (the area of the coronal section of the palate at the MR-ML line, bound by the MR-ML line and the palate). This PM allows us a better understanding when the 2 palates share the same height and width but have different anatomical morphologies: the palatal vault curvature, lateral palatal slope, presence of a tori, etc.

Although the palatal measurement was calculated from the palatal width and palatal height, the results in this study showed no significant correlation between the palatal measure and palatal width nor the palatal measure and palatal height.

Placing tongue sensors in the specific positions on the tongue, which is a mobile, difficult to control organ has been reported to be a challenge could be challenge. The positions of each sensor, in relation to each other, may have changed as the tongue tended to change its form as it moved. A similar situation was discussed in a study done in 2013. In that study only 2 sensors were used along the midline and they mentioned that placement of the sensors varies between individuals. That was considered a limitation of this technique (Rudy, Yunusova, 2013). The physiological glue (PeriAcryl®) used in this study was indicated for use in the oral cavity as a securing agent for free gingival grafts and as a liquid dressing for donor sites, biopsy sites and securing other types of dental dressings. However, tongue sensors were found to fall off in some participants. The tongue position study was therefore called off after 2 attempts of replacing sensors on the tongue.

Non- native American English speakers were excluded from the study as the American English /r/ poses genuine difficulties for the non-native speaker, almost without exception (Edwards, 1992). The study also showed that production of /r/ rounding and slightly pursing the lips to improve /r/. Conversely, spreading the lips usually results in a tendency to flap or trill the sound. Another study used MRI to compare misagittal tongue shapes for sustained English /r/ sounds found differences between the native speakers of American English and non- native speakers (Masaki, Akahane-Yamada, Tiede, Shimada & Fujimoto, 1996).

The results in this study showed variability across participants and suggested that there are many different ways to shape the tongue to produce the /r/ sound. The data from the participants showed that, on an average, the position of the tongue body (TB) sensors were higher than the position of the tongue tip (TT) sensors in all phrase positions. This could indicate that in average, the participants in this study used the “bunched” configuration to achieve the /r/ sound productions.

The endpoints of the articulatory for /r/ have been characterized in many studies as a "bunched" configuration with the tongue dorsum raised toward the middle portion of the palate and the tongue tip lower than the dorsum, and a "retroflex" configuration with the tongue tip raised toward the front portion of the palate and the dorsum lower than the tongue tip (Bacsfalvi, 2008; Boyce, 2015). The findings from the present study are in agreement with an ultrasound study done in 2010. In their study, they reported that, out of 27 American English speakers, only 2 produced only the retroflex variant, 11 produced only the bunched variant, and 14 used varying tongue shapes (Mielke, Baker, Archangeli, 2010).

Our results show that participants with higher palatal vault seem to raise their tongue body up higher when compared to the tongue tip (more "bunched" configuration) than those with lower palatal vault as the TB-TT sensors height difference showed positive correlations with the palatal height in all phrase positions. Interestingly, tongue body was found to be higher when compared to the tongue tip (more "bunched" configuration) in those with narrower palate (the TB-TT sensors height difference showed negative correlations with the palatal width in all phrase positions). On the other hand, a study done in 1998 concluded that tongue shape for American English /r/ do not seem to be reliably linked to gender, measured of oral cavity size, or formant frequencies measured for two of the test words (Westbury, Hashi, Lindstrom, 1998). However, that study was done using materials from X-ray Microbeam Speech Production Database (XRMB- SPD) and the oral cavity size measurements were done differently.

It is well known that during /r/ sound production, the coronal section of the front part of the tongue is either relatively flat or shows a mild mid-sagittal groove (Secord, 2007). Less known among clinicians is that during the /r/ sound production, there is an asymmetry present in the height position between the right and the left sides on the tongue.

Our results showed the right sensor on the tongue was slightly higher than the left sensor during all /r/ sound production, in all phrase position on average. Similar findings were observed in MRI slides from a study done by Boyce in 2015 (Boyce, 2015). The result from this current study might be partially attributed to the sensor positioning error. Further studies may be warranted to investigate this observation. It would be interesting to study if the asymmetry found between the right and the left sides of the tongue during speech sound production has any correlation with the right- or left- handedness.

The right side of the tongue was found to be about 2 mm lower position when compared to the tongue body during /r/ sound production in all phrase positions. The height difference between the tongue right (TR) and tongue body (TB) sensors were found to have strong positive correlations with all palatal structural measures except for palatal height and palatal measure.

Interestingly, the left side of the tongue was also found to be lower (4 mm) than the tongue body during /r/ sound production in all phrase positions.

However, no correlations between the palatal structural measures and the height difference between the tongue left (TL) and TB sensors were found.

The data showed variation in palatal structural measure among individuals and different position of the tongue while producing the same sound. The results note the correlations between the palatal structural measures and the tongue configurations. These observations suggested that teaching the same single tongue configuration for /r/ sound production may not work for everybody. Different strategies to achieve the /r/ sound production may be needed and palatal morphology should be taken into account when training different individuals to produce the /r/ sound.

Studies showed that artificial palatal alterations affected the positioning of the tongue (Honda, Fujino, & Kaburagi, 2002; Thibeault, Menard, Baum, Richard, & McFarland, 2011). In dentistry, common practices such as placement of a maxillary removable denture could also change the environment of the tongue, and thus alter the speech production. Moreover, orthodontic treatment may lead to temporary (such as from the palatal expander, lingual braces, maxillary retainers treatment) or permanent (such as in orthognathic surgery, anterior retraction in extraction cases) alterations in the palatal morphology, thus could also affect the tongue configuration while producing speech.

In general, tongue is assumed to adapt to a new environment (De Felippe, Da Silveira, Viana, & Smith, 2010; Honda et al., 2002; Thibeault et al., 2011) but there are cases, especially in the elderlies, where this might not hold true (Tanaka, 1973). Therefore, palatal shape, thickness of the material or the patient's speech articulations should be taken into account when providing treatment.

The WAVE technology allowed us to track the movement of the tongue during the /r/ sound production and detect the position of the tongue when certain /r/ phrase positions were produced. The results presented in this study provide one of the answers to how the /r/ sound production could be influenced. The findings indicate correlation of the differences in palatal morphological among individuals and the different tongue configurations. For future similar palatal studies, additional measures of the palate besides palatal width, palatal height and palatal depth may be included to represent the actual palatal anatomic morphology. Similarly, gender differences could be investigated.

Lastly, further studies are needed to observe the tongue configurations during the production of speech sounds that are closely related to the dental structures especially those in the linguopalatal articulatory group such as, /ch/, /j/, sh/, /zh/ in different shape of palatal morphology.

In conclusion, different strategies to achieve the /r/ sound production is suggested and palatal morphology should be taken into account when training different individuals to produce the /r/ sound. Moreover, dental practices such as removable dentures, orthodontic treatment, or orthognathic surgery, which could change the environment of the tongue, might affect the tongue configuration while producing speech.

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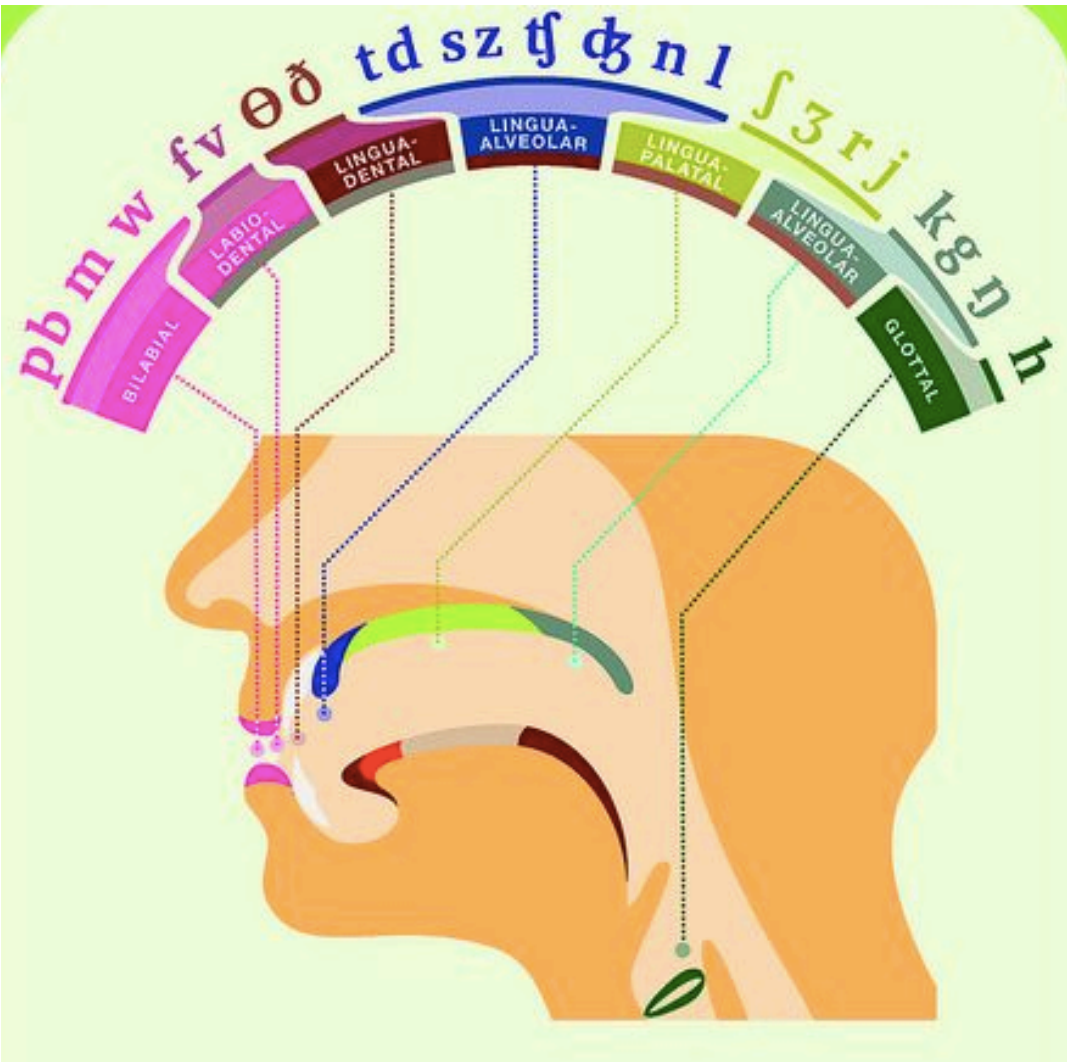


Figure 1: Places of articulation (2)

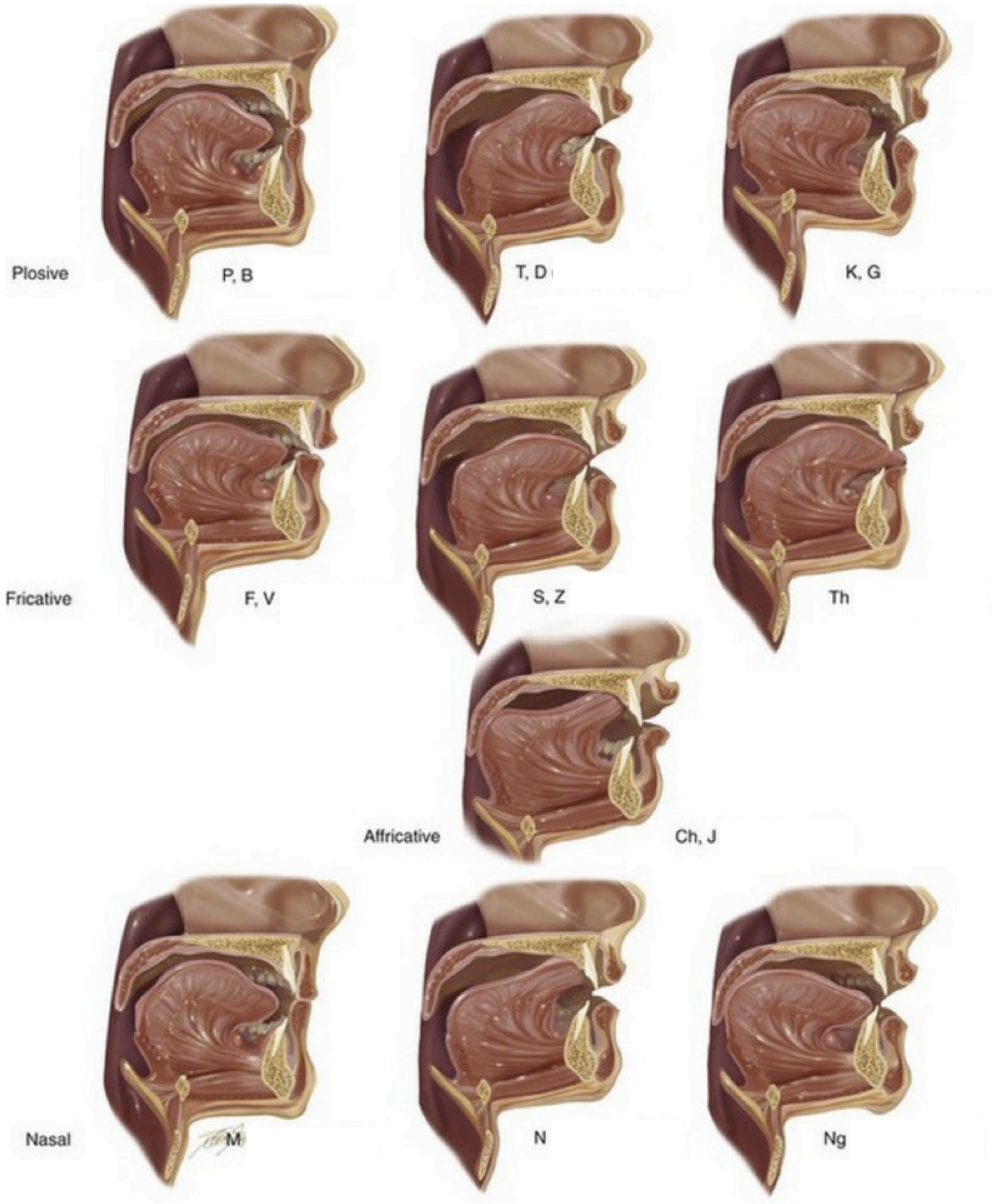


Figure 2: Demonstrates the articulation of sounds created by specific positions of the lips, tongue, and teeth in the presence of harmonious jaws and occlusion (3)

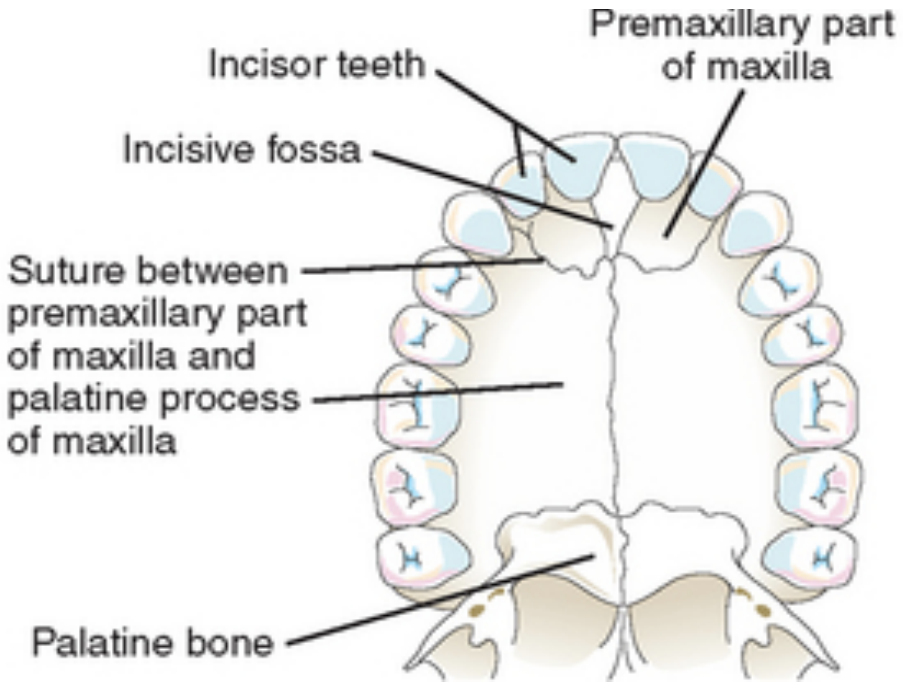


Figure 3: Components of the hard palate (5)

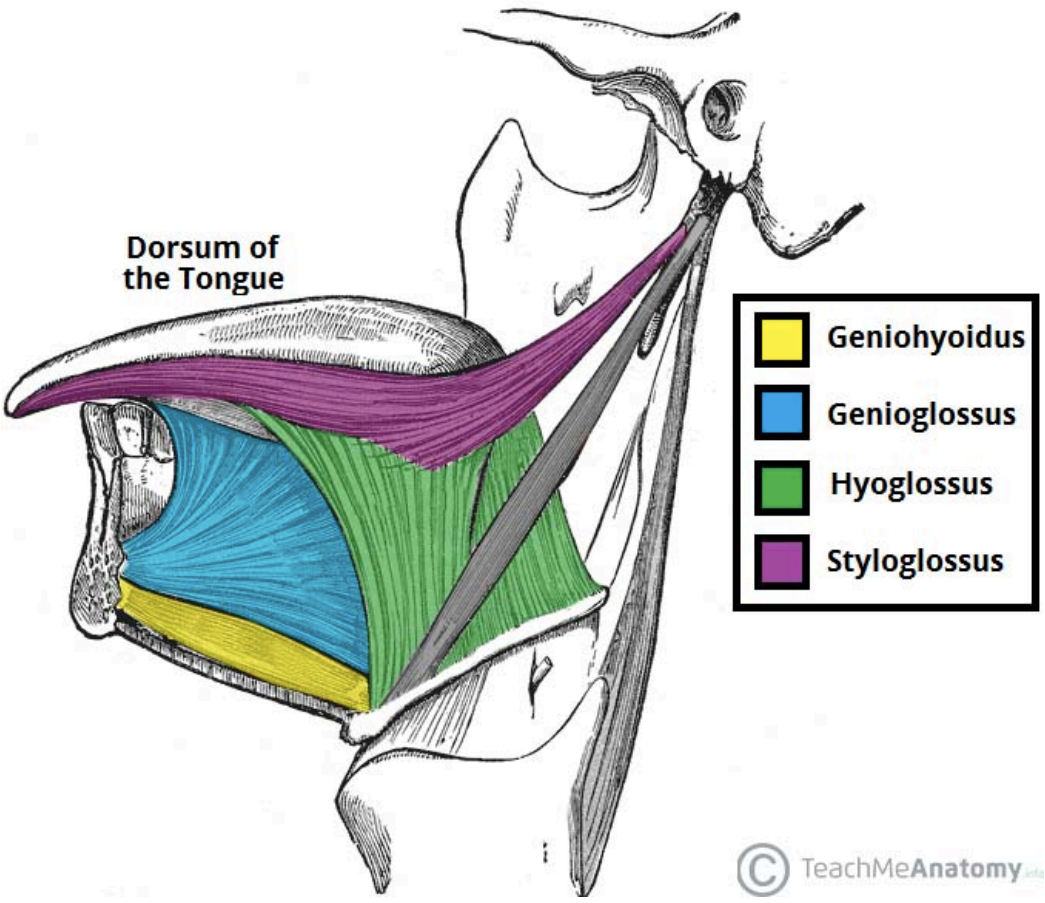


Figure 1: Extrinsic muscles of the tongue (9)

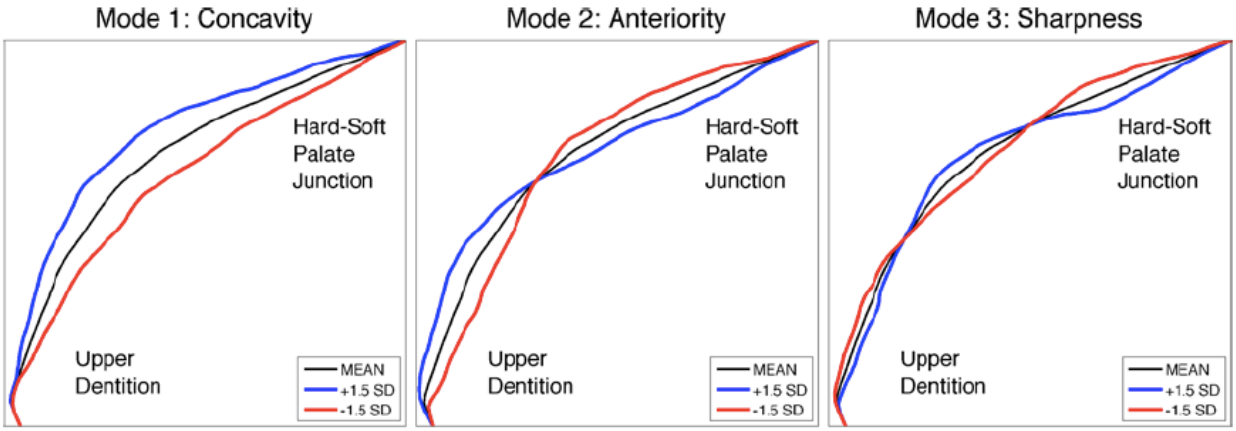


Figure 2: The three largest modes of variation in hard palate shape, determined in completely data driven fashion, without imposing any prior notions about expected shape variations, by applying Principal Component Analysis (PCA) to the observed hard palate shape. (a) the height or degree of concavity of the palatal dome, (b) the position of the dome in relation to the anteriority of the palate, and (c) the angularity (sharpness/ flatness) of the dome around the apex (20)

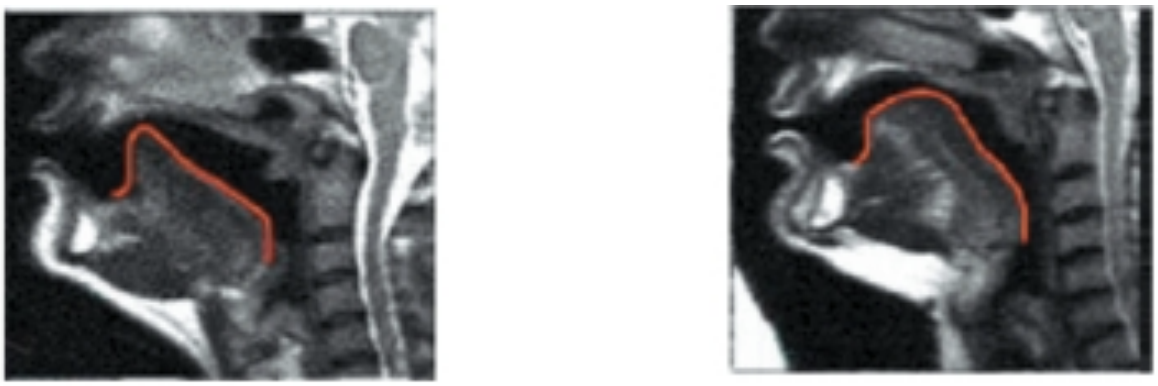


Figure 6: Midsagittal MR images of two tongue configurations for American English /r/ (31)

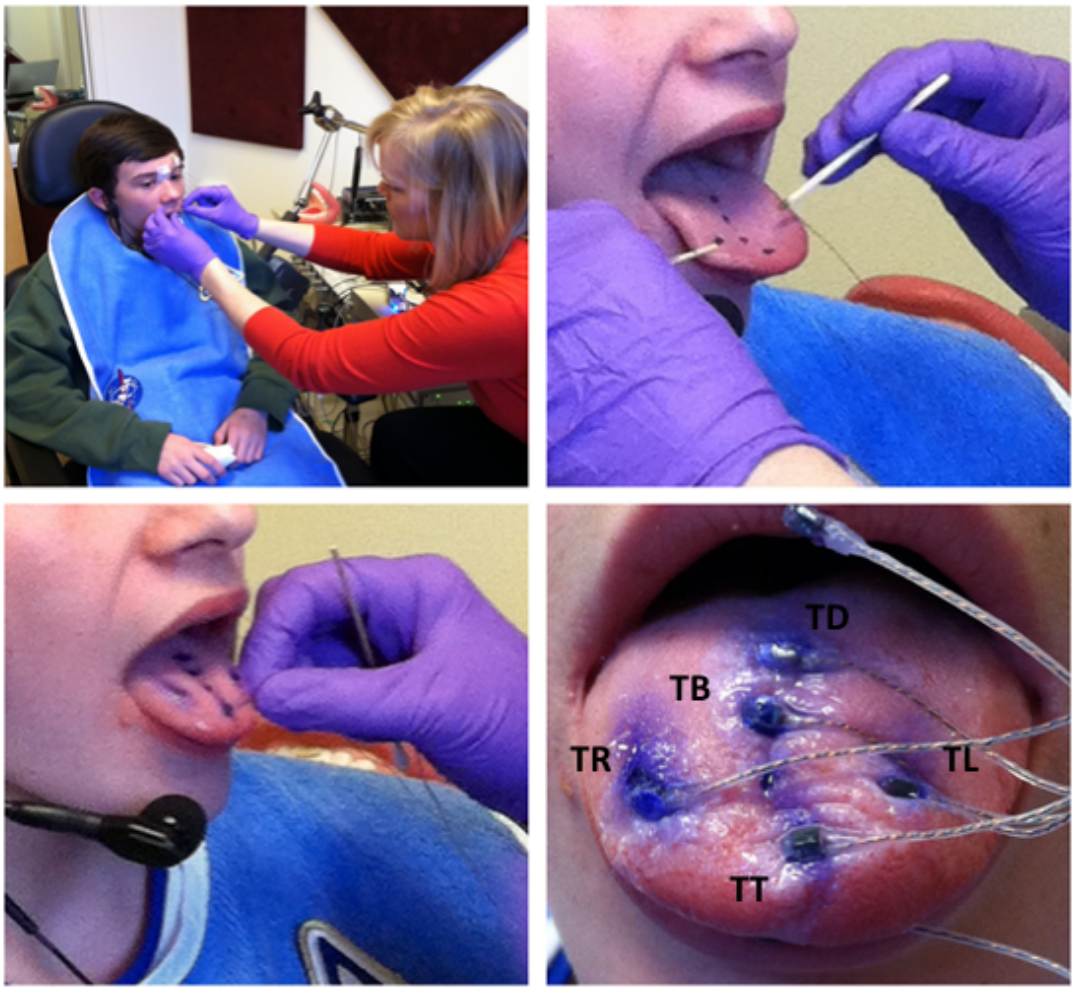


Figure 7: Tongue sensors positions and placements. Fig. 1a.) shows, Fig. 1b.) shows tongue sensors landmarks marked, Fig. 1c.) shows placement of tongue tip sensor, Fig. 1d.) shows sensors placed on the landmarks on the tongue: TT= tongue tip, TR= tongue right, TL= tongue left, TB= tongue body and TD= tongue dorsal.

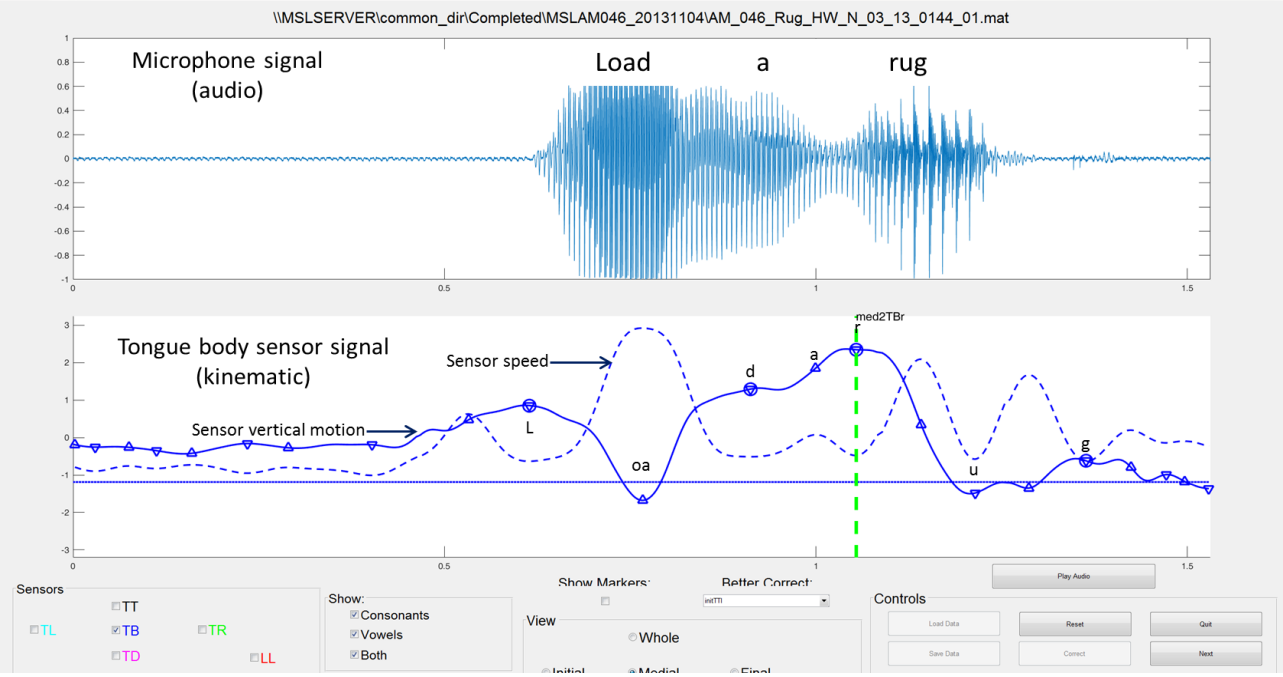


Figure 8: Screen showed the microphone signal time-aligned with the position record. The vertical displacement and minima of the speed of the sensor was used as a guide to identify the moment of "r".

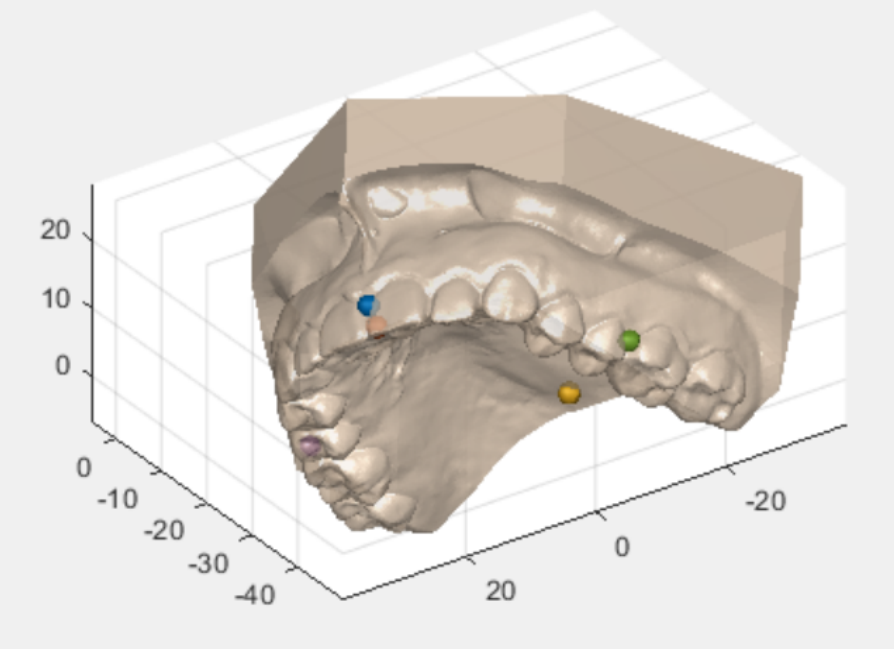


Figure 9: MATLAB tool for selecting landmark on a palatal mesh. The colored spheres are the landmarks used to determine a reference frame for the palate.

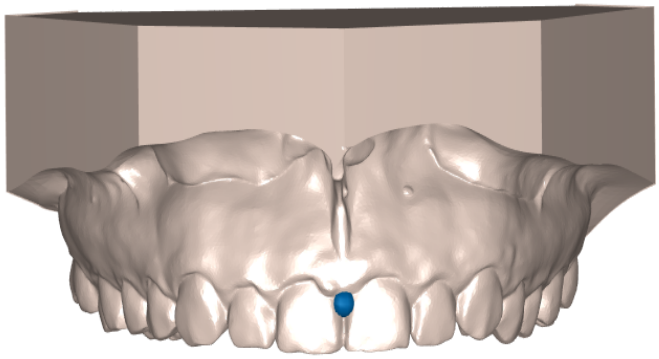


Figure 10: The origin of the palate reference frame is the labial gingival margin between the maxillary central incisors, shown in blue.

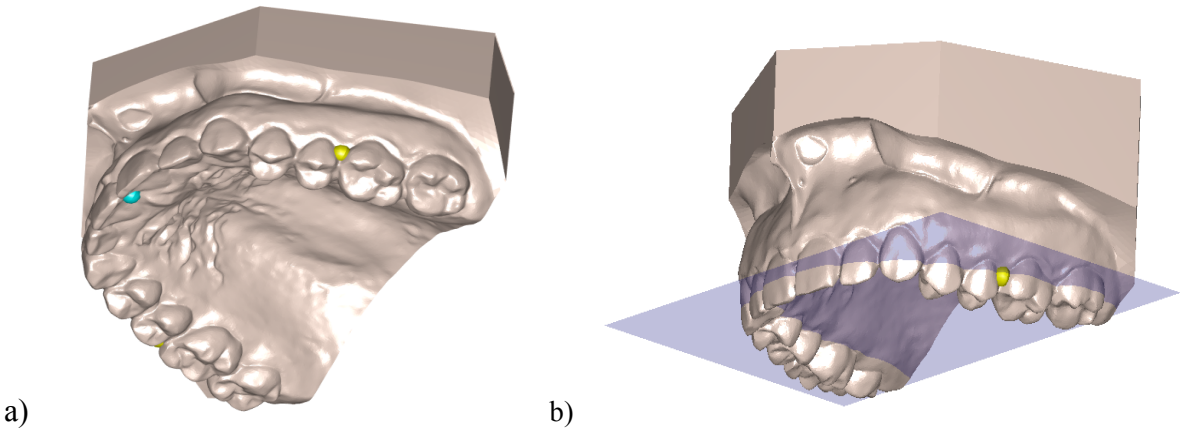


Figure 3: The transverse plane was defined by three landmarks. a) The palatal gingival margin between the upper central incisors (shown in cyan) and the buccal gingival margin between the left second premolar and the first molar (shown in yellow). (The right buccal gingival margin was obscured.) b) The constructed transverse plane is shown in transparent blue.

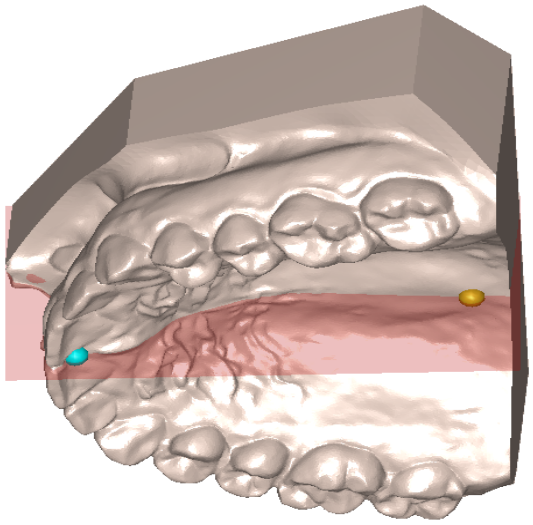


Figure 12: The sagittal plane was shown in transparent red. It was defined by the plane through the lingual gingival margin between the maxillary central incisors and a point on the palatal suture that was also orthogonal to the occlusal plane.

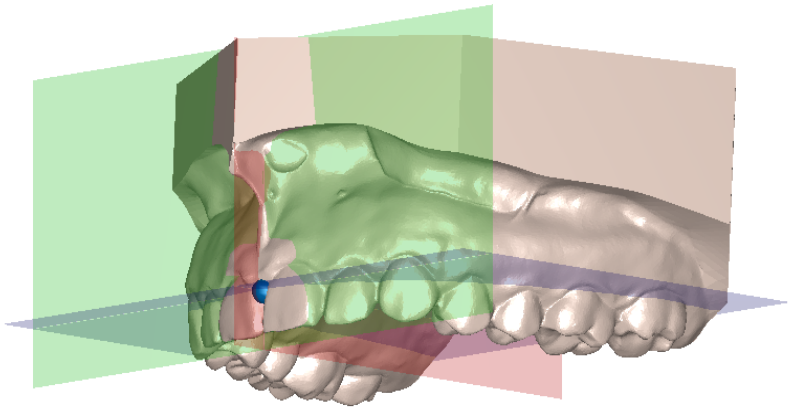


Figure 13: Anatomical planes of the palate intersecting the origin (defined as the labial gingival margin between the maxillary central incisors). The red plane = the sagittal plane, the green plane = the coronal plane, and blue plane = the constructed occlusal plane.

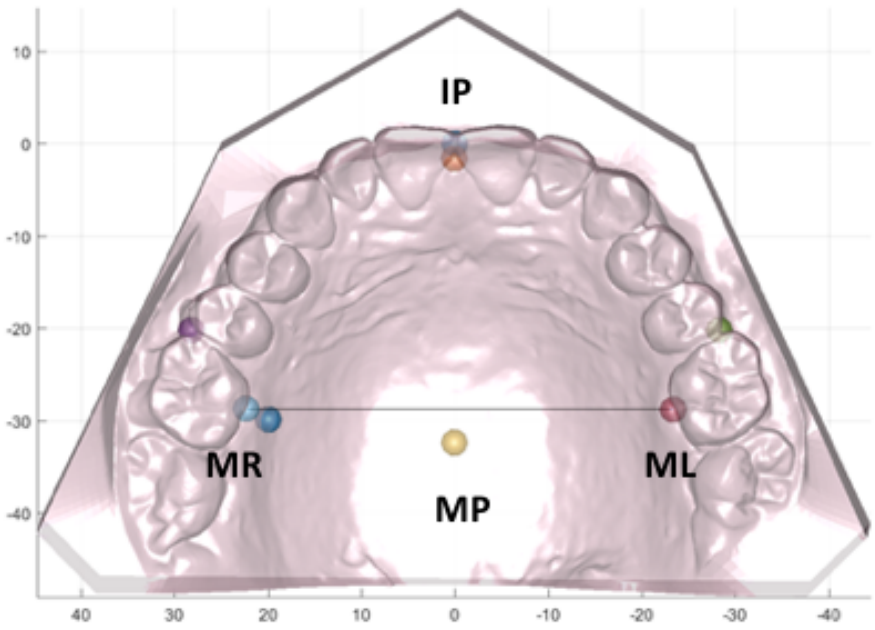
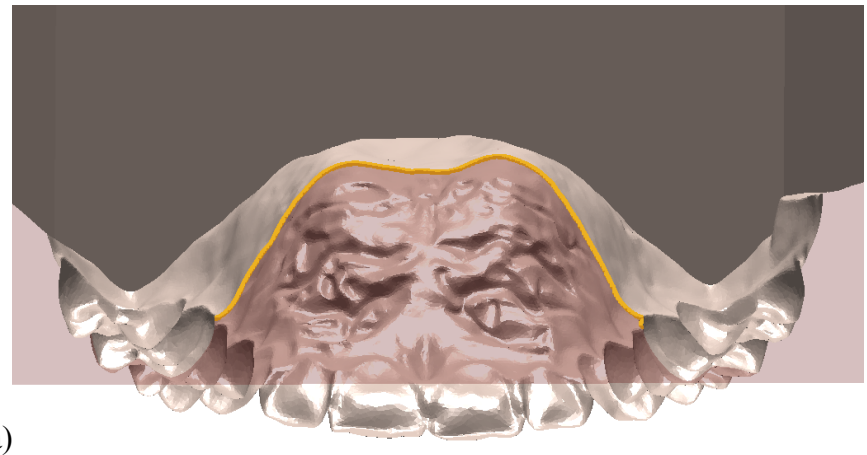


Figure 14: Landmark locations: picture shows incisive papilla (IP)(orange dot), midpalate (MP)(yellow dot), upper right molar (MR)(light blue dot), and upper left molar (ML)(red dot).

a)



b)

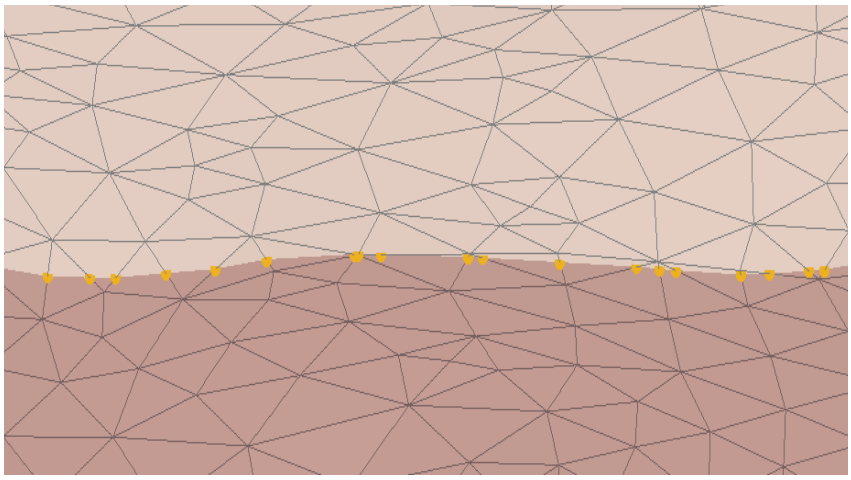


Figure 15: a) A line fit to the palate is shown in yellow. The coronal plane at the mean depth of palate profile is transparent red. The points where the plane intersects the lines connecting the vertices of the digital scan (darker gray) are shown close-up (b)

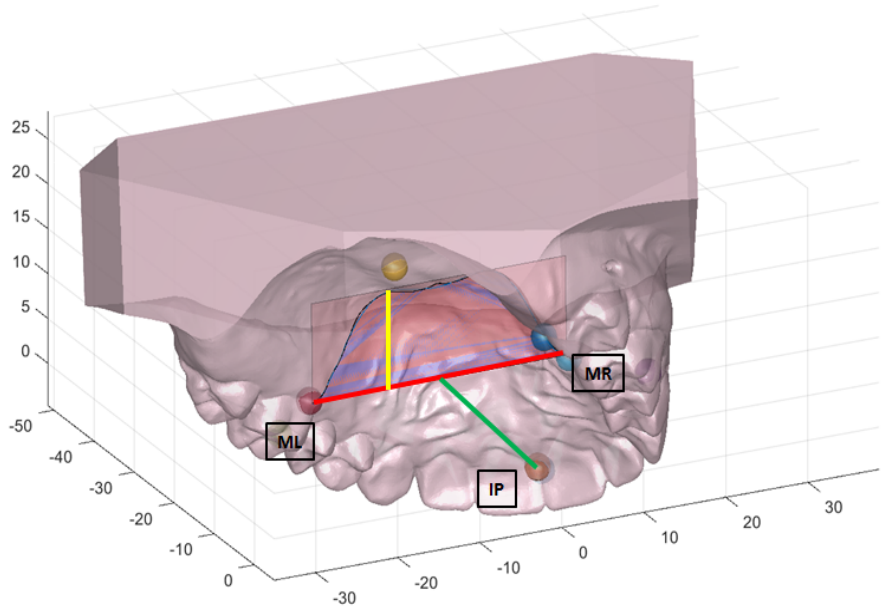


Figure 16: Picture shows palatal width (PD)(red line), palatal height (PH)(yellow line), palatal depth (PD)(green line)

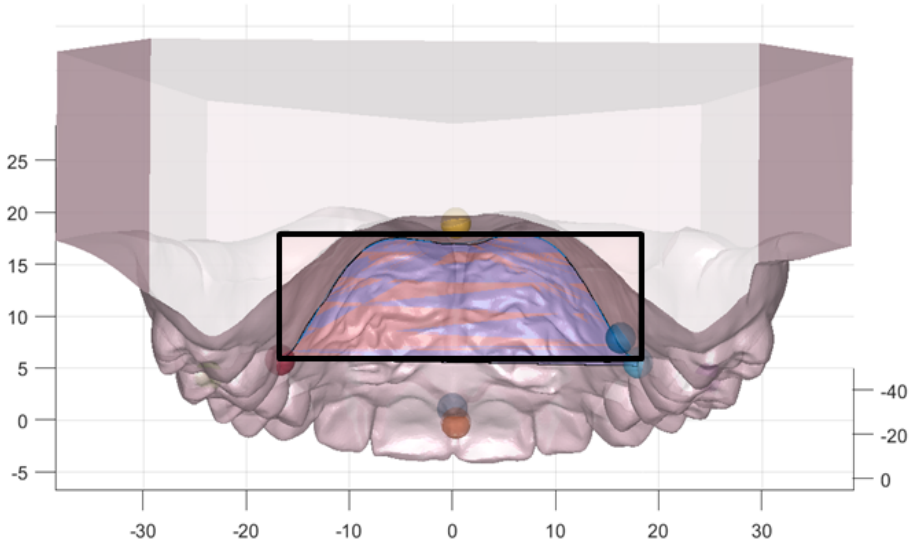


Figure 17: Picture shows palatal area (PA)(area in pink/purple) and rectangular area (area in black rectangle)

Table 1: Kinesiologic Positions for the Oral and Pharyngeal Musculature during the Articulation of Speech Sounds (3)

Structural Components of the Articulatory valve	Closed valve voiceless	Closed valve voiced	constricted valve voiceless	constricted valve voiced	Voiced nasals
Labiodental (upper teeth and lower lip)			“f” /f/	“v” /v/	
Bilabial (lips)	“p" /p/	“b” /b/		“w" /w/	“m" /m/
Linguodental (tougue tip and upper teeth)			“th" /θ/	“th” /δ/	
Linguoalveolar (tongue tip and alveolar)	“t" /t/	“d" /d3/	“s” /s/	“z” /z/ “l” /l/	“n" /n/
Linguopalatal (tongue blade and hard palate)	“ch"	“j" /dʒ/	“sh"	“zh” /ʒ/ “r” /r/ “y” /j/	
Linguovelor (tongue back and velum)					“ng" /r/
Linguo-velor-pharyngeal (tongue back, velum, and pharyngeal wall)	“k" /k/	“g" /g/			
Glottal (glottis)			“h" /h/		

Table 2: Abbreviations and definition of the sensors height differences measures

Measure	Definition
TB-TT (mm)	Difference in height between TB and TT sensors
TL-TR (mm)	Difference in height between TL and TR sensors
TR-TT (mm)	Difference in height between TR and TT sensors
TR-TB (mm)	Difference in height between TR and TB sensors
TL-TT (mm)	Difference in height between TL and TT sensors
TL-TB (mm)	Difference in height between TL and TB sensors

Table 3: Summary statistics (Mean, SD, Max and Min in mm) of palate measures (PW= palatal width, PH= palatal height, PD= palatal depth, RA= rectangular area, PA= palatal area, PM= palatal measure) of all participants.

n=20	Mean(mm)	SD	Max(mm)	Min(mm)
PW	35.85	4.2	45.66	30.6
PH	14.17	1.98	17.28	11
PD	30.1	3	35.77	26.45
RA	509.43	102.29	740.62	334.85
PA	350	64.56	481	240
PM	0.7	0.04	0.76	0.61

Table 4: Summary statistics (Mean, SD, Max and Min in mm) of palate measures (PW= palatal width, PH= palatal height, PD= palatal depth, RA= rectangular area, PA= palatal area, PM= palatal measure) of the included participants.

n=10	Mean (mm)	SD	Max (mm)	Min (mm)
PW	37.07	4.27	45.64	33.02
PH	13.87	1.61	17.02	12.2
PD	30.64	2.85	35.72	27.17
RA	516	96.33	740.62	429.29
PA	357.33	56.55	479.64	311.62
PM	0.7	0.04	0.76	0.61

Table 5: Descriptive statistics of the height differences between sensors (TB= tongue body, TT= tongue tip, TR= tongue right, TL= tongue left) during the /r/ sound production that represented the /r/ in all positions in the phrases

		Mean(mm)	SD	Max(mm)	Min(mm)
Initial /r/	**TB-TT**	5.56	4.89	14.1	-2.68
	TL-TR	-2.77	4.13	3.81	-8.2
	TR-TT	3.44	3.67	6.81	-4.22
	TR-TB	-2.72	2.8	2.38	-8.37
	TL-TT	0.2	2.2	3.63	-2.54
	TL-TB	-4.96	3.85	3.53	-9.63
Medial /r/	**TB-TT**	6.69	4.64	13.19	-0.88
	TL-TR	-3.15	4.17	2.53	-9.47
	TR-TT	4.13	2.87	7	-1.95
	TR-TB	-1.52	3.59	3.88	-7.61
	TL-TT	1.16	3.32	7.6	-2.6
	TL-TB	-4.45	4.48	3.88	-11.03
Final /r/	**TB-TT**	6.99	4.45	12.94	-5.67
	TL-TR	-3.05	4.71	5.94	-7.88
	TR-TT	4.56	2.07	1.2	7.18
	TR-TB	-2.08	3.17	3.68	-5.91
	TL-TT	0.85	3.85	7.07	-4.2
	TL-TB	-4.86	4.33	3.68	-9.73

Table 6. Coefficient of Variation shows the variability within each participant, across repetitions of the /r/ in a given phrase position, and the variability across participants.

	Within-subjects	Between-Subjects
Initial	60%	238%
Medial	50%	147%
Final	56%	132%

Table 7: Pearson correlation coefficients ($\alpha < 0.1$) for tongue configurations (TB= tongue body, TT= tongue tip, TR= tongue right, TL= tongue left) and palatal structural measures (PW= palatal width, PH= palatal height, PD= palatal depth, RA= rectangular area, PA= palatal area, PM= palatal measure). Significant results are in red with asterisk.

		PW	PH	PD	RA	PA	PM
Initial /r/	**TB-TT**	-0.64	0.59	-0.52	-0.18	-0.09	0.11
	TL-TR	-0.19	-0.43	-0.21	-0.49	0.67	-0.4
	TR-TT	0.1	**0.87***	0.23	0.67	0.58	-0.07
	TR-TB	**0.68***	0.31	**0.73***	**0.82***	**0.75***	-0.01
	TL-TT	-0.34	0.32	-0.15	-0.14	-0.46	-0.6
	TL-TB	0.35	-0.3	0.4	0.08	-0.28	-0.6
Medial /r/	**TB-TT**	**-0.72***	0.45	-0.58	-0.34	-0.27	0.05
	TL-TR	-0.47	-0.39	-0.46	**-0.71***	**-0.92***	-0.49
	TR-TT	-0.06	**0.79***	0.14	0.48	0.56	0.19
	TR-TB	**0.79***	0.18	**0.81***	**0.83***	**0.74***	-0.02
	TL-TT	-0.6	0.18	-0.41	-0.43	-0.61	-0.41
	TL-TB	0.33	-0.34	0.38	0.03	-0.4	**-0.76***
Final /r/	**TB-TT**	-0.57	**0.77***	-0.36	0.01	0.04	0.04
	TL-TR	-0.27	-0.49	-0.26	-0.57	-0.62	-0.18
	TR-TT	-0.44	**0.71***	-0.31	0.07	-0.01	-0.14
	TR-TB	**0.82***	-0.17	**0.73***	0.63	0.55	-0.03
	TL-TT	-0.56	-0.04	-0.47	-0.54	-0.63	-0.25
	TL-TB	0.39	**-0.76***	0.32	-0.18	-0.31	-0.24

Appendix

Sub	sex	init of TR-TT	init of TR-TB	init of TL-TT	init of TL-TB	init of TL-TR
'MSLAF048'	f	5.45	-3.23	2.56	-6.12	-2.89
'MSLAF052'	f	5.66	-1.43	-2.54	-9.63	-8.20
'MSLAF057'	f	6.38	-1.16	-0.90	-8.44	-7.28
'MSLAF061'	f	3.74	-1.07	-0.10	-4.91	-2.48
'MSLAF070'	f	6.81	2.38	-1.28	-5.70	-8.08
'MSLAF078'	f	2.68	-4.71	2.02	-5.37	-0.66
'MSLAM043'	m	1.05	-2.47	-2.41	-5.94	-3.46
'MSLAM046'	m	-4.22	-3.19	3.63	3.53	-0.10
'MSLAM049'	m	5.44	-3.91	0.81	-0.31	3.81
'MSLAM052'	m	5.46	-8.37	0.20	-6.68	1.69

Sub	sex	med of TR-TT	med of TR-TB	med of TL-TT	med of TL-TB	med of TL-TR
'MSLAF048'	f	6.04	-4.36	3.37	-7.02	-2.67
'MSLAF052'	f	6.87	-1.56	-2.60	-11.03	-9.47
'MSLAF057'	f	5.41	-1.37	0.56	-6.22	-4.85
'MSLAF061'	f	2.98	-0.31	-1.45	-4.74	-4.43
'MSLAF070'	f	7.00	3.36	-1.65	-5.28	-8.64
'MSLAF078'	f	5.45	-4.96	4.53	-5.88	-0.87
'MSLAM043'	m	1.09	-2.54	-1.77	-5.40	-2.86
'MSLAM046'	m	2.85	3.88	2.85	3.88	-3.15
'MSLAM049'	m	-1.95	0.31	0.19	2.84	2.53
'MSLAM052'	m	5.58	-7.61	7.60	-5.59	2.02

Sub	sex	fin of TR-TT	fin of TR-TB	fin of TL-TT	fin of TL-TB	fin of TL-TR
'MSLAF048'	f	6.42	-5.13	2.45	-9.10	-3.97
'MSLAF052'	f	5.68	-1.85	-2.20	-9.73	-7.88
'MSLAF057'	f	7.18	-1.36	-0.22	-8.76	-7.40
'MSLAF061'	f	3.83	0.61	-1.36	-4.57	-4.90
'MSLAF070'	f	3.13	0.67	-4.20	-6.66	-7.33
'MSLAF078'	f	3.93	-5.00	5.53	-3.39	1.60
'MSLAM043'	m	1.20	-1.45	-2.35	-5.00	-3.55
'MSLAM046'	m	2.97	3.68	2.97	3.68	-3.05
'MSLAM049'	m	4.56	-5.10	0.85	0.83	5.94
'MSLAM052'	m	7.03	-5.91	7.07	-5.87	0.04

Sub	sex	fin TB-TT	init TB-TT	med TB-TT
'MSLAF048'	f	11.54	8.68	10.40
'MSLAF052'	f	8.85	8.34	8.43
'MSLAF057'	f	8.54	7.93	9.03
'MSLAF061'	f	3.22	4.81	3.29
'MSLAF070'	f	7.07	4.42	3.64
'MSLAF078'	f	8.93	7.38	10.41
'MSLAM043'	m	2.38	3.53	2.73
'MSLAM046'	m	-0.57	-0.93	-0.88
'MSLAM049'	m	6.99	-2.68	6.69
'MSLAM052'	m	12.94	14.10	13.19

Sub	sex	concave	mshape	rect_rea	palate_area	palate_wid	palate_wid	palate_hei	palate_dep	palate_hei	palate_mea
'MSLAF048'	f	3.00	1.00	459.70	317.69	33.02	33.02	13.98	28.00	13.92	0.69
'MSLAF052'	f	3.00	1.00	472.39	359.86	35.34	35.34	13.31	29.90	13.37	0.76
'MSLAF057'	f	1.00	0.00	454.26	317.48	34.26	34.26	13.29	29.07	13.26	0.70
'MSLAF061'	f	1.00	0.00	488.82	335.25	38.19	38.18	12.79	34.69	12.80	0.69
'MSLAF070'	f	3.00	1.00	510.33	362.96	37.86	37.86	13.54	35.72	13.48	0.71
'MSLAF078'	f	3.00	1.00	440.58	315.40	34.80	34.80	12.65	30.01	12.66	0.72
'MSLAM043'	m	3.00	1.00	429.29	311.62	34.76	34.75	12.20	28.40	12.35	0.73
'MSLAM046'	m	1.00	0.00	609.08	434.44	45.64	45.64	13.41	27.17	13.35	0.71
'MSLAM049'	m	1.00	0.00	555.24	338.95	33.62	33.61	16.52	30.90	16.51	0.61
'MSLAM052'	m	1.00	0.00	740.62	479.64	43.35	43.29	17.02	32.51	17.08	0.65