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A muscle-based articulatory and OT account of Japanese /t/-alternations

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Jang, Hayeun. 2026. A muscle-based articulatory and OT account of Japanese /t/-alternations. *Linguistic Research* 43(1): 227-256. This study demonstrates that a muscle-based approach provides an explanatory account of the affrication and palatalization of Japanese /t/ that are difficult to explain using conventional phonological approaches. The central asymmetry is that /t/ becomes [tɕ] with a posterior place before front high /i/, whereas it becomes [ts] without change in place of articulation before non-front high /ɯ/. The results of the simulations using the 3D tongue model of ArtiSynth show that the shape of the tongue for the letter /t/ varies depending on the coarticulated tautosyllabic vowels. This is because the activated muscle bundle of the tongue differs based on the vowels. In the context of /i/, a muscle activation lowering the tip of the tongue is essential to keep the tip of the tongue from going out of the mouth. The palatalization of /t/ is characterized by a lowered tongue tip and an elevated tongue body. In the coarticulation of tautosyllabic /t/ and /ɯ/, the activated tongue muscle raised the entire tongue without significantly lowering the tongue tip, causing affrication of /t/. The affrication and palatalization of Japanese /t/ are formally captured in an Optimality-Theoretic (OT) analysis as assimilations of constriction orientation (CO) between the tongue tip and body in tautosyllabic onset–vowel sequences, grounded in a muscle-based account and gestural representations. The proposed OT grammar that uses AGREE(CO) and IDENT(CO) can derive the Japanese /t/ alternation patterns. **(Sungkyunkwan University)**

Keywords Japanese /t/ alternations, palatalization, affrication, muscular understanding, articulatory simulation, constriction orientation, OT analysis

1. Introduction

Japanese /t/-alternations have been a central topic in phonological and phonetic research, particularly regarding palatalization before the front high vowel /i/ and

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affrication before the non-front high vowel /ɯ/ (Itô and Mester 2003, 2015; Labrune 2012). While both environments trigger affrication—yielding [tɕi] and [tsɯ], the place of articulation shifts posteriorly only before /i/, whereas it remains anterior (alveolar) before /ɯ/. Early generative accounts often characterized this pattern as a 'Crazy Rule' (Bach and Harms 1972)—a rule viewed as a historical residue of sound changes.

Current theoretical frameworks do not fully capture the underlying mechanisms behind this asymmetry. Aerodynamic approaches have attributed the affrication of /t/ before high vowels to aerodynamic conditions created by a narrow constriction following stop release, which generates turbulent noise and yields a [+strident] outcome (Kim, H. 2001; Kim, Y. 2019). While such explanations successfully account for the emergence of affrication before both /i/ and /ɯ/, they do not explain why a posterior shift in constriction location occurs only before the front vowel /i/ and not before the non-front vowel /ɯ/. Optimality-Theoretic (OT) analyses often rely on descriptive constraints (e.g. PAL, *ti, *tɯ) to capture the data (Ito and Mester 1995, 2003). However, these constraints lack independent physiological grounding, often serving as formal labels for the observed phenomena rather than offering explanatory depth into the underlying motor system. Within Articulatory Phonology based on Task Dynamics (Browman and Goldstein 1986, 1989, 2000), coarticulation is modeled through the temporal overlap of gestures defined over tract variables. At the level of constriction location, a more posterior tongue body target (as for /ɯ/) might be expected to exert a greater posterior pull on the tongue tip than a more anterior target (as for /i/). However, tongue body and tongue tip gestures are defined as distinct tract variables with partially overlapping articulatory resources: they share jaw and tongue body parameters, while the tongue tip additionally recruits its own length and angle parameters. These additional degrees of freedom may allow the tongue tip to maintain some independence from tongue body position, and the degree of this independence may vary depending on the spatial proximity between tongue body and tongue tip targets. Yet the shared articulatory parameters also provide a pathway through which a posterior tongue body position could indirectly pull the tongue tip backward. Whether the tongue tip's own degrees of freedom fully compensate for this pull, or whether spatial proximity between targets is the determining factor, cannot be resolved through qualitative reasoning within the gestural framework alone.

This study proposes that the apparent asymmetry in Japanese /t/-alternations can be explained by examining the physical mechanisms underlying tongue movement, rather than by appealing solely to surface articulatory configurations or phonological features. In traditional feature-based approaches, the tongue has been characterized in terms of a small set of discrete articulatory components (e.g. tip, body, and root), each associated with distinct phonological features. Articulatory Phonology advances beyond this by introducing tract variables with richer degrees of freedom. Nevertheless, even within this framework, tongue-tip and tongue-body gestures are modeled as separate task-dynamic units, and the biomechanical coupling between them, arising from their shared muscular substrate, is not directly represented at the level of gestural specification. The present study reconceptualizes the tongue as a system composed of multiple interacting muscles. The movement of the tongue emerges from complex patterns of muscular synergy and antagonism among intrinsic and extrinsic tongue muscles. The central hypothesis of this study is that the muscle bundles recruited for producing /i/ differ systematically from those activated for /ɯ/. These distinct activation patterns apply different mechanical forces to the tongue tip. Without muscular-level analysis, the causal basis of context-specific articulatory displacement remains inaccessible; muscle-based simulation is thus essential for revealing the physiological origins of these asymmetries.

We adopt a muscle-based 3D articulatory simulation to investigate how different patterns of tongue muscle activation associated with the vowels /i, ɯ, a/ interact with the articulation of a tautosyllabic onset /t/. By selectively modeling the contributions of key intrinsic and extrinsic tongue muscles in shaping segment-specific tongue configurations, this approach captures differences in the relative movement orientation of the tongue tip and tongue body that are not directly observable in traditional articulatory descriptions.

Crucially, we argue that these articulatory patterns can be formally captured within an Optimality-Theoretic (OT) framework by modeling consonant–vowel interaction as assimilation in constriction orientation (CO) between the tongue tip and tongue body. By translating simulation-derived forces into OT constraints, the present study constructs a phonological model with explicit physiological grounding. It provides a unified account of Japanese /t/ palatalization and affrication by integrating muscle-based articulatory simulation with gestural representations and OT constraint interaction, thereby linking biomechanical plausibility with phonological computation.

The remainder of this paper is organized as follows. Section 2 reviews the placement and function of the tongue muscles incorporated into the simulation model and introduces the articulatory simulations used in this study. Section 3 proposes gestural representations for these patterns and develops an OT analysis based on constriction-orientation assimilation. Section 4 concludes.

2. Tongue tip movement in production of vowels

The interplay between tongue tip and tongue body movement is central to the Japanese /t/ alternation. While the tip (and blade) of the tongue articulates alveolar sounds and vowel articulation has traditionally been attributed to the tongue body, the tongue is a hydrostatic muscular system whose parts cannot move independently: movement of the tongue body necessarily affects the tongue tip. This interdependence motivates the need for a systematic characterization of tongue tip–body coordination, which the present study argues is best captured at the level of tongue musculature. This section selectively reviews the tongue muscles most relevant to these patterns and examines their roles in vowel and /t/ articulation using 3D simulations.

2.1. Tongue muscles in speech production

The shape and location of the tongue in the mouth are controlled by the extrinsic tongue muscles, which enter the tongue from the outside. Extrinsic tongue muscles are mostly responsible for changing the position of the tongue (Hardcastle 1976; Gick et al. 2013; Jang 2022). Figure 1 shows the placement of extrinsic muscles.

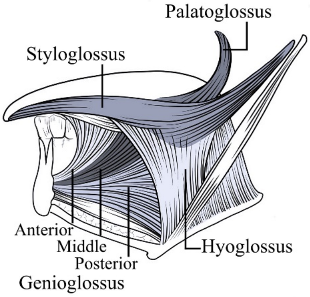


Figure 1. Placement of extrinsic muscles of the tongue

The majority of the inferior region of the tongue is made up of the genioglossus, which begins in the mandible. On contraction, the posterior part of the genioglossus pulls the tongue's root forward. The tongue is dragged forward in the mouth while the jaw stays still. It is known that the tongue root's location and the tongue body's height interact in a particular manner (Hall and Hall 1980; Archangeli and Pulleyblank 1994): when the tongue root advances, the tongue body compresses and rises, and when the tongue root retracts, the tongue body lowers. It has been argued that front and/or high vowels, as well as (alveo-)palatal consonants, are articulated by the genioglossus posterior (MacNeilage and Sholes 1964; Fujimura and Kakita 1979; Honda 1983; Gick et al. 2013; Recasens 2016). However, Hardcastle (1976) argues that additional tongue muscles must engage in addition to the genioglossus posterior in order for the tongue to be raised. The function of the genioglossus posterior is examined in the following section through simulations of the front high vowel /i/.

From the styloid process of the skull near the ear, the styloglossus enters the tongue, runs along the lateral side of the tongue, and exits at the tip of the tongue. It has been explained that the styloglossus is active in articulating non-low back vowels because it raises and retracts the tongue (Zemlin 1968; Hardcastle 1976; Bear et al. 1988; Epstein et al. 2002). By simulating the articulation of the non-front high vowel /ɯ/, the styloglossus's contribution will be investigated in the next section.

The intrinsic tongue muscles, which are fully located inside the tongue, only have an impact on the shape of the tongue (Hardcastle 1976; Gick et al. 2013; Jang 2022). Figure 2 shows the placement of intrinsic muscles.

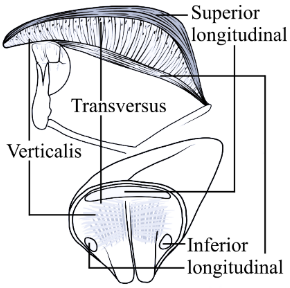


Figure 2. Placement of intrinsic muscles of the tongue

The superior longitudinal and the verticalis have been proposed as the intrinsic muscles involved in the articulation (closure phase) of coronal stops. The superior longitudinal runs longitudinally down the tongue from front to back. The tongue is shortened, raised, and somewhat curled backward when the superior longitudinal is contracted (Hardcastle 1976; Stevens 2000; Epstein et al. 2002; Gick et al. 2013). The articulation of coronal consonants is accomplished by these functions of the superior longitudinal (Hardcastle 1976; Epstein et al. 2002; Stone et al. 2004). According to Epstein et al. (2002), the superior longitudinal lateral fibers may assist maintain the sides of the tongue up.

To establish contact with the mouth's roof during palatal and alveolar stops, the tongue flattens and extends laterally during contraction of the verticalis, which places up-down within the tongue (MacNeilage and Sholes 1964; Hardcastle 1976; Epstein et al. 2002; Gick et al. 2013). This tongue position can also be used for the fricative /s/ and high front vowels (Hardcastle 1976; Epstein et al. 2002). In the following section, the role of the superior longitudinal and the verticalis will be examined by simulating the articulation of the (denti-)alveolar consonant /t/.

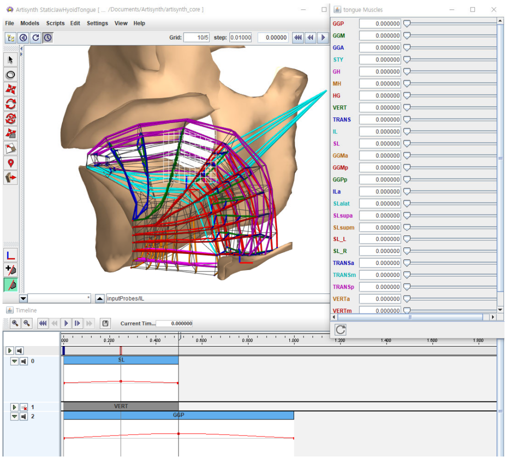
2.2. 3D tongue simulation

A central methodological challenge is how to examine tongue muscle activity during speech production. Electromyography (EMG) experiments were carried out in the past. The muscle being investigated is punctured with tiny hooked wire electrodes. The electrodes track the electrical activity of the muscles directly. However, EMG data are difficult to interpret due to limitations in electrode placement and muscle-specific resolution. Due to this, only the electrical activity of the extrinsic tongue muscles has been recorded in the majority of EMG research. Additionally, the EMG data gathering technique is invasive. Moreover, the invasive nature of EMG restricts its applicability in large-scale linguistic research. For this reason, EMG is not widely employed in contemporary linguistic research.

For the purpose of modeling the articulations, this study uses the biomechanical 3D tongue model from The affrication and palatalization of Japanese /t/ are formally captured in an Optimality-Theoretic (OT) analysis as assimilations of constriction orientation (CO) between the tongue tip and body in tautosyllabic onset–vowel sequences, grounded in a muscle-based account and gestural representations. version

3.4 (https://www.artisynth.org). An open-source Java framework called ArtiSynth allows for the coupled simulation of three-dimensional models of rigid and deformable bodies (Lloyd et al. 2012). Based on precise anatomical information, the model incorporates tongue muscles in a mesh framework. The ArtiSynth 3D tongue model has been used to study the physiologic functions of the tongue in speech production and the articulatory motivation of phonological patterns (Gick et al. 2014; Dabbaghchian et al. 2017; Mayer et al. 2017; Jang 2020).

The simulations employ a static jaw–hyoid–tongue model in which the jaw–hyoid model (Hannam et al. 2008) is dynamically coupled with a three-dimensional finite-element tongue model (Vogt et al. 2006). The control windows in Figure 3 can be used to individually regulate the level and duration of activity for each intrinsic and extrinsic tongue muscle. The display settings for the model viewer window were adjusted in Figure 3 to more clearly show the tongue model's muscular structure.



Grid: 10/5
step: 0.01000
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Current Tim... 0.000000

GGP 0.000000
GGM 0.000000
GGA 0.000000
STY 0.000000
GH 0.000000
MH 0.000000
HG 0.000000
VERT 0.000000
TRANS 0.000000
IL 0.000000
SL 0.000000
GGMa 0.000000
GGMp 0.000000
GGPp 0.000000
ILa 0.000000
SLalat 0.000000
SLsupa 0.000000
SLsupm 0.000000
SL_L 0.000000
SL_R 0.000000
TRANSa 0.000000
TRANSm 0.000000
TRANSp 0.000000
VERTa 0.000000
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Figure 3. Graphical User Interface of ArtiSynth's Static Jaw-Hyoid-Tongue model

The present simulations are not intended to predict speaker-specific articulatory trajectories. Rather, they serve as a proof of concept that the observed asymmetry can arise from general biomechanical interactions under minimal assumptions. The goal of the present simulations is not to achieve quantitative anatomical matching with individual speakers, but to test whether a minimal muscle-based system can generate coarticulatory asymmetries of the relevant structural type. The model is therefore intentionally simplified and designed to demonstrate mechanistic plausibility rather than empirical exhaustiveness.

The muscle activation levels used in the simulations (0.1, 0.2, 0.3 on a normalized scale from 0 to 1) are intended to represent relative degrees of muscle excitation rather than fixed physiological magnitudes. These values follow conventions adopted in previous ArtiSynth-based tongue modeling studies (e.g., Jang 2020), where low-to-moderate activation ranges are used to explore articulatory behavior while avoiding biomechanical saturation. In the model, an activation value of 1 corresponds to full recruitment of a muscle. Prior to the reported analyses, we therefore conducted exploratory testing and parameter tuning over a broader portion of this normalized range. The interval selected for the present study (0.1–0.3) falls within the low-to-moderate activation regime, where systematic and stable changes in tongue configuration emerge while avoiding biomechanical saturation, non-physiological deformation, or numerical instability. Importantly, the observed articulatory patterns do not depend on any single activation value: the relative orientation between the tongue tip and tongue body remains stable across this range, indicating that the results are robust to moderate parameter variation.

2.2.1. Simulation of vowels

In simulating the high front vowel /i/, the genioglossus posterior was activated. Figure 4 shows a screenshot of the tongue shape that is produced when the genioglossus posterior (GGP) is activated to 0.3 on a scale of 0 to 1. The model viewer's "enable slicing" option was used in order to effectively show the tongue's outline. Half-spaces of a 3D tongue model are clipped in both positive and negative directions. The light gray line in back displays the tongue's default position and shape, and the multicolored line reflects the tongue configuration produced by activating the GGP to 0.3.

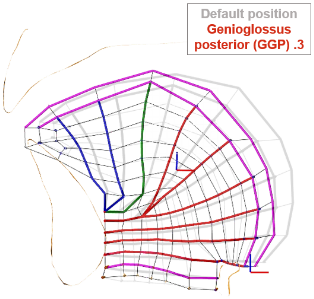

Figure 4. Tongue configuration produced by activation of the genioglossus posterior

Activation of the GGP pulls the tongue body forward, as noted in earlier work. Because the GGP does not extend to the tongue tip (see Figure 1), its activation has no direct effect on the shaping or positioning of the tip. Due to the physiological contact between the tongue tip and body, however, the tongue tip comes out of the mouth as the tongue body moves forward, as in Figure 4. Under this configuration, tongue elevation is mechanically constrained: attempts to raise the tongue body result in further protrusion of the tongue tip. This pattern indicates that additional muscles are required to raise the tongue to the height appropriate for the high vowel /i/, consistent with Hardcastle's (1976) claim that raising the tongue requires the involvement of muscles other than the GGP.

Previous studies (Hardcastle 1976; Epstein et al. 2002; Gick et al. 2013) have suggested that the verticalis (VERT) and transversus (TRANS) muscles contribute to high vowel articulation. In our simulations, however, activation of VERT and TRANS was limited to a maximum of 0.23 when the genioglossus posterior (GGP) was set to 0.3, as higher activation levels produced non-physiological deformation in the ArtiSynth tongue model. Moreover, VERT does not directly elevate the tongue, and although TRANS raises the tongue by narrowing it, the tongue tip continues to protrude from the mouth under this configuration.

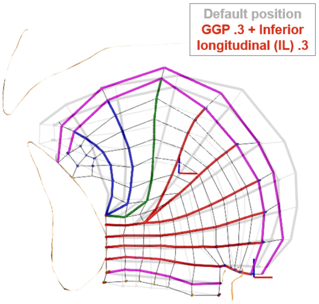

Figure 5. Tongue configuration produced by activating the inferior longitudinal and the genioglossus posterior

The additional muscle required to raise the tongue body while preventing protrusion of the tongue tip was therefore the inferior longitudinal (IL). Figure 5 shows that the tongue forms a bunched shape as a result of the combined activation of the GGP and IL. The bunched shape of the tongue provides two benefits: (i) the tongue tip does not stick out of the mouth, and (ii) the tongue body is elevated. The outcome of this simulation demonstrates that the GGP and IL are the key muscles in the articulation of the front high vowel /i/. This supports earlier electromyography (EMG) research that claimed the IL could be further engaged during the articulation of /i/ as an antagonist for the main muscle, the GGP (MacNeilage and Sholes 1964; Raphael and Bell-Berti 1973).

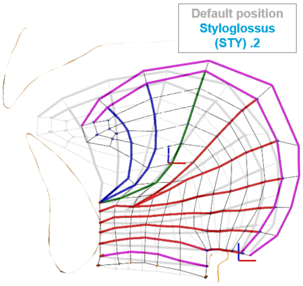

Figure 6. Tongue configuration produced by activating the styloglossus

In the simulation of the non-front high vowel /ɯ/, the styloglossus must be engaged in order to elevate and retract the tongue. Figure 6 shows the tongue shape produced when the styloglossus (STY) is activated to 0.2 on a scale of 0 to 1. In the case of /ɯ/, the degree of activation of this muscle bundle is lower than that of the back high vowel, /u/[1]. When the STY is activated, the entire tongue moves upward and backward. The tongue tip appears lower as a result of tongue body movement because the STY goes from the styloid process below the ear to the tongue tip through the lateral border of the tongue (see Figure 1).

To mimic the low vowel /a/, the tongue must be dragged back and downward. Therefore, it is necessary to activate the hyoglossus. The left panel of Figure 7 shows the tongue shape that results from activating the hyoglossus (HG) to 0.2 on a scale of 0 to 1. The activation of the HG has no direct impact on how the tongue tip is shaped or moved since it is not connected to the tongue tip (see Figure 1). Due to this, shown in Figure 7, when the HG is activated, the tongue tip rises while the tongue body lowers and moves back. To flatten the front and middle part of the tongue, the anterior and middle regions of the genioglossus (GGA and GGM) were stimulated in the simulation, as shown in the right panel of Figure 7.

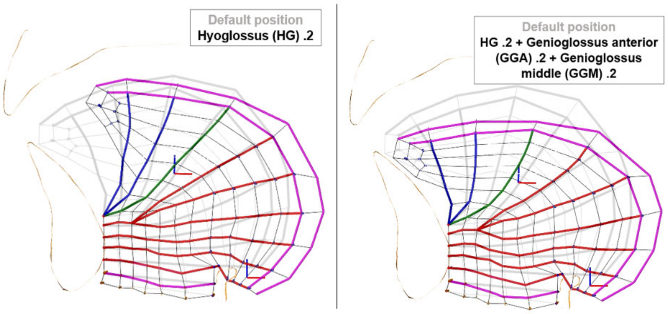

Figure 7. Tongue configurations under hyoglossus-only activation (left) and combined hyoglossus–genioglossus activation (right)

2.2.2. Simulation of a sequence of an alveolar stop and a vowel

The second set of simulations looks at how tongue muscle activation for vowels /i, ɯ, a/ impacts an overlapped /t/ at its maximum constriction point in order to understand the articulatory drive of affrication and palatalization of the alveolar stop /t/ in Japanese. Since the tongue tip and side are the main articulators for /t/, we may assume that the interactions between /i, ɯ, a/ and /t/ will be influenced by the

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[1] In Jang (2020), /u/ was simulated by activating the STY (and the GGP) by .6 using the same ArtiSynth 3D tongue model.

muscles employed to produce those vowels differently.

Although alveolar consonants can be produced apically or sub-laminally (Keating 1991), Ladefoged (1989) suggests that alveolars are more likely to be apical. According to electropalatography (EPG) studies (Nakamura 2001; Kawahara and Matsui 2017; Kochetov 2018), Japanese (denti-)alveolar consonants are articulated by completely sealing the entire alveolar region with the tip and blade of the tongue.Nakamura (2001) describes that /t/ is produced by the central-lateral complete occlusion. Based on this, the Japanese /t/ was simulated by activating the superior longitudinal, which rises and curls the tongue tip or blade backward, and the verticalis, which flattens and laterally widens the tongue. Figure 8 shows the outcome of activating the superior longitudinal (SL) and the verticalis (VERT) to 0.1 on a scale of 0 to 1.

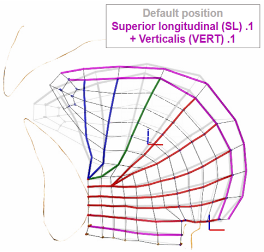

Figure 8. Tongue configuration produced by activating the superior longitudinal and the verticalis

Tautosyllabic sequences of /t/ and the following vowel as potential contexts of affrication and palatalization in Japanese were simulated by adjusting the temporal organization of muscle activations in the ArtiSynth 3D tongue model. Muscular activations for /t/ and the following vowel were simulated to start synchronously in the sequence contexts, according to the paradigm of Articulatory Phonology (Browman and Goldstein 2000). A consonant and a vowel in a CV syllable start at the same time, according to articulatory research that examined the temporal phasing of movements of articulators, such as the lips, tongue tip, and tongue body (Fowler 1980; Löfqvist and Gracco 1999; Goldstein et al. 2007; Nam 2007).

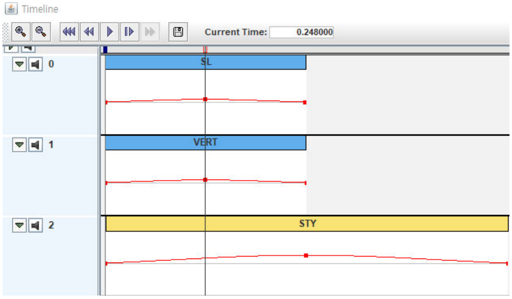

Figure 9. Timeline setting of the /t/+/u/ sequence in the articulatory simulation

The timeline setup for the articulatory simulation of the sequence contexts is shown in Figure 9. In Figure 9, the shorter blue boxes labeled "SL" and "VERT" stand in for the activation of the onset consonant /t/, while the longer yellow box labeled "STY" stands in for the activation of the tautosyllabic vowel /ɯ/. In each box in Figure 9, the horizontal scale displays the length of time that each muscle was activated, and the vertical scale displays the degree of constriction. The duration of tongue muscle activation for vowels was designed to be twice as long as that for /t/ (Fowler 1980). The maximum constriction point of /t/, shown by the black vertical line in the middle of the blue boxes in Figure 9, was used to compare the simulated tongue configurations.

The simulated tongue shape at the point of the maximum constriction of /t/ in the context of the following /i/ is shown in Figure 10. The multicolored line reflects the tongue configuration for the /t/ in the context of /i/, which is made by partially overlapping with the activation of the GGP and IL to 0.3. The light gray line in the background shows the tongue configuration for the /t/ in isolation, which is made by activating the SL and VERT to 0.1.

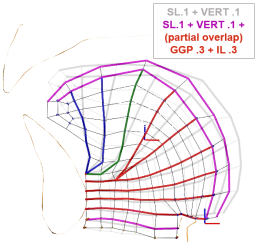

Figure 10. Tongue configuration as the output of simulating /t/+/i/

Figure 10 illustrates how the tongue shape for /t/ in the context of /i/ differs from the tongue shape for /t/ in isolation in that the tongue tip is noticeably lowered and the tongue root is advanced. The vertical position of the tongue body is higher than that of the tongue tip in the context of /i/ because the tongue tip is lowered. The narrow constriction point of the tongue and roof of the mouth moves backward when the highest region of the tongue shifts from the tip to the body. This appears to be the articulatory mechanism behind the palatalization of /t/ before /i/. This is in line with the ultrasound study by Gonzales (2022), which demonstrated that palato-alveolar consonants are produced by moving the tongue body, whereas alveolar consonants are produced by moving the tongue front.

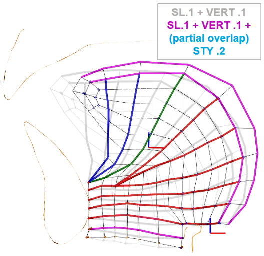

Figure 11. Tongue configuration as the output of simulating /t/+/u/

Figure 11 depicts the simulated tongue shape as it would appear in the context of the following /ɯ/ at the point of maximum constriction of /t/. In the case of /ɯ/, the tongue tip is slightly lowered as it goes backward. The tongue tip's height is still comparable to the tongue body's, unlike in the case of /i/. The alveolar constriction caused by the tongue tip and front can still be expected in this /ɯ/ condition. Because it increases the contact area and degree of constriction between the tongue and the roof of the mouth, the slight lowering of the tongue tip appears to be the articulatory force of the /t/ affrication before /ɯ/.

Figure 12 compares the tongue shape of /t/ in the following /a/ condition (the multicolored line in front) to that of /t/ alone at the point of maximal constriction (the light gray line in back). When it is followed by /a/. the /t/ maintains the same upward orientation of movement as in standalone situations. In the context of /a/, the tongue tip continues to be in a higher position than the tongue body. This explains why in Japanese, /t/ does not alter place or manner before /a/, which has the lowest and the most posterior position of the tongue.

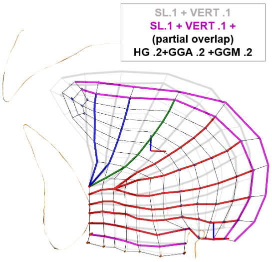

Figure 12. Tongue configuration as the output of simulating /t/+/a/

Based on the real-time MRI IPA data (Toutios et al. 2016), the tongue outlines for the voiceless alveolar stop /t/, the alveolar affricate /ts/ and the voiceless palato-alveolar affricate /tʃ/ are drawn, as shown in Figure 13. Figure 13 demonstrates that, when compared based on the relative height difference between the tip and the body of the tongue, the tongue shapes obtained in the simulations described here of /t/ in the context of /i, ɯ, a/ are similar to the palato-alveolar affricate /tʃ/, the alveolar affricate /ts/, and the alveolar stop /t/, respectively.

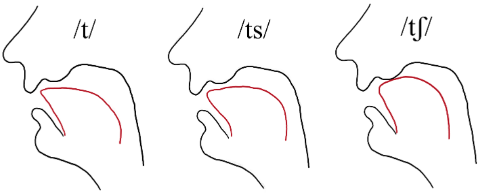

Figure 13. Tongue shape for /t/, /ts/ and /tʃ/ based on the real-time MRI IPA database (Toutios et al. 2016)

The muscle-based understanding of coarticulatory interactions between /t/ and the following vowels helps to explain the pattern of /t/ alternations in Japanese, which could not be made clear by the traditional feature representations. The following section addresses how muscle-based coarticulatory effects can be integrated into phonological computation by proposing an Optimality-Theoretic model in which phonological representations encode constriction orientation in articulation.

3. Assimilation of constriction orientation of the tongue

3.1. Gestural representation of [t, ts, tɕ] and [i, ɯ, a]

The results of EPG studies show that Japanese (denti-)alveolar [t] is apico-laminal with constriction of both tip and blade of the tongue (Nakamura 2001; Kawahara and Matsui 2017; Kochetov 2018). The stop and fricative components of affricates [ts, tɕ] are homorganic in the approach and release phases within each sound, according to Nakamura (2001). The alveolar region is where the stop component of [ts] is produced. Japanese speakers' [s] articulation displays both apical and apico-laminal realizations in the denti-alveolar region, but the apico-laminal realization shows stronger stability. When compared to that of [ts], the stop component of the alveolo-palatal affricate [tɕ] exhibits a considerable increase in contact and retraction of the constriction location. The configurational pattern of the stop occlusion of [tɕ] is more similar to that of the raisinggesture of the tongue dorsum in the alveopalatal nasal [ɲ̟]. The alveolo-palatal fricative [ɕ] makes up the fricative component of [tɕ]. The tongue blade and (medio-)dorsum work together to create the narrowing constriction for the lamino-dorso [ɕ] in the postalveolar and pre-palatal regions (Nakamura 2001).

In the study of Japanese [ts], the position of the tongue body has not been mentioned. Related to the high coarticulatory resistance of fricatives with adjacent vowels (Byrd 1994; Recasens and Rodríguez 2017), however, we can expect the high position of the tongue body. This is because in the environment of adjacent low vowels, fricatives prevent the tongue body from lowering due to the aerodynamic requirements for frication noise generation by a narrow channel along the palate (Keating 1990; Badin et al. 2019). In line with the prediction, the MRI IPA dataset (Toutios et al. 2016), however, shows that tongue body is raised not only in the articulation of the palato-alveolar affricate [tʃ], but also in the articulation of the alveolar affricate [ts] (see Figure 13). In the case of [ts], the height of the tongue body is similar to that of the tongue tip.

Table 1. Gestural representation of Japanese [t, ts, tɕ]

Articulator	Tongue Tip			Tongue Body
Parameter	CL	CD	CO	CO
[t]	Alveolar	Closure	Up	Down
[ts]	Alveolar	Closure→narrow	Up	Up
[tɕ]	Post-alveolar	Closure→narrow	Down	Up

The Articulatory Phonology framework conceptualizes sounds as articulatory movements of constricting organs, and the movements are defined as “gestures” with a specific goal (Browman and Goldstein 1986). The tongue’s tip is the most flexible and dynamicarticulator (Derrick et al. 2014). Coronal constrictions can vary in location, degree, and orientation (or, put it another way, the posture of the tongue tip). Based on the results of previous articulatory studies, Japanese [t, ts, tɕ]can be represented using gestures of the tongue as in Table1. In Table1, ‘CL’ and ‘CD’ represents the constriction location and constriction degree parameters, respectively.

The (phonological or phonetic) contrast between apicals, with constriction of the tongue tip, and laminals, with anterior constriction of the tongue blade as well as flattening or lowering of the tongue tip, is one universally recognized characteristic of coronal obstruents (Bladon and Nolan 1977; Butcher and Tabain 2004; Flemming 2003). The constriction orientation of the tongue tip is up for apicals, and down for laminals (Browman and Goldstein 1989; Gafos 1999). In the proposed representation of Japanese [t, ts, tɕ], the constriction orientation (‘CO’ in Table 1) of apico-laminal [t, ts] is ‘up’ and that of [tɕ] produced by the blade and (medio-)dorsum of the tongue is ‘down’.

The concept of constriction orientation is here extended to tongue body gestures. Extending the notion of constriction orientation to the tongue body departs from standard articulatory-phonological usage, in which CO is typically associated with the tongue tip. This extension is motivated by the biomechanical results of the present simulations, which show that relative vertical orientation between the tongue tip and body constitutes a stable and phonologically relevant dimension of tongue shape. The proposed tongue body constriction orientation (TBCO) is therefore not an arbitrary abstraction, but a formalization of a mechanically grounded articulatory relation. Because the tongue body is not as flexible as the tongue tip, the constriction orientation is strongly associated to the constriction degree: ‘up’ of TBCO corresponds to ‘narrow’ of the tongue body constriction degree (TBCD) and ‘down’ of TBCO corresponds to ‘wide’ of TBCD. TBCO is used instead of TBCD in representations to highlight the fact that the COs of the tongue's tip and body characterize the shape of the tongue as a result of muscle activation during articulation. As TBCO specification for the apico-laminal stop [t], TBCO is specified as ‘down’. Even with the constriction of the tongue blade, the height of the tongue tip is still higher than the height of the tongue body. The proposed representations of Japanese affricates [ts, tɕ] have the same ‘up’ value of TBCO because they are produced with the high position of the tongue body. Affricates [ts] and [tɕ] have different gestural specifications of TTCL and TTCO.

Using the same gestural framework, Japanese [i, ɯ, a] can be represented as in Table 2. Following that [ɯ] is produced by narrowing the lips without protrusion (Ito et al. 2006), the lip gestures for [ɯ] are not specified.

Table 2. Gestural representation of Japanese vowels [i, ɯ, a]

Articulator	Tongue Tip	Tongue Body	
Parameter	CO	CL	CO
[i]	Down (andretract)	Palatal	Up
[ɯ]		Pre-velar	Up
[a]		Velar	Down

The articulatory simulation results show that in order to produce the high front vowel /i/, beside fronting of the tongue body, additional lowering and retraction of the tongue tip is crucial (see 2.2.1). For this reason, the proposed representation of /i/ involves TTCO ‘down (andretract)’, as shown in Table 2.

Based on the proposed gestural representation of coronal consonants and vowels, the alternation patterns of /t/ in coarticulation with the following tautosyllabic vowels can be summarized as in Table 3.

Table 3. Japanese /t/ alternation patterns based on the gestural representation

		/t/	
		TTCO: Up	TBCO: Down
[i]	TTCO: Down	TTCO: Down and TBCO: Up →[tɕ]	
	TBCO: Up		
[ɯ]	TTCO: -	TTCO: Up and TBCO: Up → [ts]	
	TBCO: Up		
[a]	TTCO: -	TTCO: Up and TBCO: Down → [t]	
	TBCO: Down		

The coarticulation case of /t/ and /i/ (see the first row in Table 3) demonstrates that when the gestural values of a coarticulated tautosyllabic consonant and vowel conflict, the consonant value is assimilated to the vowel value. This is due to the fact that the articulatory duration of a vowel is twice that of a consonant as its onset initiated synchronously (see Figure 9). Since /t/ and /i/ have conflicting TTCO and TBCO values, /t/ receives the 'Down' for TTCO and ‘Up’ for TBCO from /i/. This results in the palatalization of /t/. In the coarticulation of /ɯ, a/ with /t/, the TTCO value of /t/ is maintained because the vowel lacks a TTCO specification. In the case of TBCO, the vowel values remain unchanged in coarticulatory situations because the consonant lacks a corresponding specification. /t/ acquires the 'Up' specification for TBCO while retaining the 'Up' specification for TTCO during coarticulation with /ɯ/. This results in /t/ becoming [ts]. During coarticulation with /a/, /t/ acquires a 'Down' specification for TBCO while keeping a 'Up' specification for TTCO. As a result, /t/ is realized as [t]. To summarize, using the proposed gestural representations, the patterns of Japanese /t/ alternations can bedefined as the assimilation of CO specifications between tautosyllabic onset consonants and vowels.

3.2. Optimality theoretic explanation on Japanese /t/ realizations

For a formal analysis of Japanese /t/ alternations, we employ the Optimality Theory (henceforth, OT) framework (Prince and Smolensky 1993; McCarthy and Prince 1993, 1995). Using violable constraints and their ranking, the OT can determine the internal connections between seemingly unrelated phenomena. There are two types of constraints: markedness constraints and faithfulness constraints. Markedness constraints limit the possible output of a given input, while faithfulness constraints limit the possible differences between an input and its output candidates.

As shown in section 3.1, palatalization and affrication of /t/ in Japanese can be defined as the CO assimilation of onset and nucleus within the same syllable. AGREE-σ [CV(CO), the primary markedness constraint used in this study, requires tautosyllabic onset and nucleus in the output to be specified for the same CO value (Lombardi 1999; Baković 2000), as defined in (1). This constraint penalizes the tautosyllabic [ti] because [t] is specified as ‘Up’ for TTCO and ‘Down’ for TBCO while [i] is specified as ‘Down’ and ‘Up’.

(1) AGREE-σ[CV(CO): Assign one violation mark for every pair of tautosyllabic onset and nucleus whose members differ in their specification for the tongue constriction orientation.

As this study focuses on CO assimilation, the primary faithfulness constraints are those that preserve CO values. IDENT(CO) is violated whenever an input CO value differs from its corresponding output CO value (McCarthy and Prince 1995), as defined in (2).

(2) IDENT(CO): Assign one violation mark for every CO value in the input that is different from its corresponding CO value in the output.

A family of the IDENT(CO) constraint preserves CO values under general or particular conditions. In Japanese /t/ alternations, the CO value of onset /t/ is assimilated to the tautosyllabic vowel. To avoid vocalic alternation, we divide the IDENT(CO) constraint into two specific ones, IDENT-C(CO) and IDENT-V(CO) for consonants and vowels respectively, and assume that IDENT-V(CO) dominates IDENT-C(CO) in Japanese grammar.

When IDENT-C(CO) ranks higher than AGREE-σ[CV(CO), tautosyllabic sequences of a consonant and a vowel (henceforth, CV) with different CO values are permitted. This is because the violation of faithfulness ranks higher than the violation of markedness. When IDENT-C(CO) is ranked lower than AGREE-σ[CV(CO), tautosyllabic CV sequences with different CO values are not accepted and CO assimilation can be applied to correct the markedness violation. Given that /t/ is palatalized in Japanese, we can conclude that AGREE-σ[CV(CO) dominates IDENT-C(CO) in Japanese phonological grammar.

The interaction between IDENT-C(CO) and AGREE-CV(CO) does not, however, reveal any information regarding changes in the place of articulation brought on by Japanese /t/ palatalization. In Japanese, The (denti-)alveolar /t/ is palatalized and becomes the alveolo-palatal [tɕ] in the context of /i/. To penalize palatalization without place change, Flemming (2003) proposed the constraints *PalatalizedDental and *PalatalizedAlveolar against palatalized laminal dentals and alveolars. These constraints are based on cross-linguistic data indicating that coronal palatalization induces place retraction to post-alveolar positions in addition to laminalization (Keating 1991, 1993).

In this study, we utilize a markedness constraint requiring palatalized laminal consonants to be post-alveolar. The constraint *[TTdown, TBup, +anterior] is defined as in (3)[2]. Dental and alveolar places of articulation are represented using the featural representation [+anterior] for simplification.

(3) *[TTdown, TBup, +anterior]: Assign one violation mark for every segment whose constriction orientation values contain both 'Down' for the tongue tip and 'Up' for the tongue body when its constriction location is anterior ('Dental' or 'Alveolar').

Since Japanese palatalization causes change in the place of articulation of /t/ from (denti-)alveolar to alveolo-palatal, we can infer that the markedness constraint *[TTdown, TBup, +anterior] also outranks the faithfulness constraint IDENT-C(CO). To sum up, the constraint ranking for Japanese /t/ alternations is as in (4).

(4) *[TTdown, TBup, +anterior], AGREE-σ[CV(CO) >> IDENT-C(CO)

In OT, multiple violations of a lower-ranked constraint are less severe than one violation of a higher-ranked constraint. The constraint ranking in (4) enables the derivation of all /t/ alternations observed in Japanese. Tableau 1 shows the derivation of /t/ palatalization in the context of tautosyllabic /i/.

In Tableau1, the faithful output candidate (a) gets two violation marks for AGREE-σ[CV(CO) because [t] and [i] have different CO values for both TT ('up' and 'down', respectively) and TB ('down' and 'up'). The affrication output candidate (b) violates AGREE-σ[CV(CO) because [ts] and [i] differ in TTCO values ('up' and 'down', respectively). The markedness constraint *[TTdown, TBup, +anterior] penalizes the output candidate (c) with a palatalized alveolar. The candidate violates IDENT-C(CO) two times due to changes in CO values of both TT and TB. The palatalized candidate (d) also violates IDENT-C(CO) two times for the same reason, but it does not violate any higher-ranked constraints. Therefore, the candidate (d), [tɕi] becomes the realized output for /ti/.

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[2] This constraint is not restricted to palatalization. This constraint can also explain the posterior location of articulation of the 'bunched' /r/ relative to the retroflex /r/ (Catford 2001).

Tableau 1. Japanese /t/ palatalization before the tautosyllabic /i/: /t/ → [tɕ]

/t + i/ [alveolar, TTup, TBdown] [palatal, TTdown, TBup]	*[TTdown, TBup, +anterior]	AGREE-σ[CV(CO)	IDENT-C(CO)
a. (faithful output: [t]) [alveolar, TTup, TBdown][i]		*!*	
b. (affrication: [ts]) [alveolar, TTup, TBup][i]		*!	*
c. (palatalized alveolar) [alveolar, TTdown, TBup][i]	*!		**
☛ d. (palatalization: [tɕ]) [post-alveolar, TTdown, TBup][i]			**

Tableau 2. Japanese /t/ affrication before the tautosyllabic /ɯ/: /t/ → [ts]

/t + ɯ/ [alveolar, TTup, TBdown] [pre-velar, TBup]	*[TTdown, TBup, +anterior]	AGREE-σ[CV(CO)	IDENT-C(CO)
a. (faithful output: [t]) [alveolar, TTup, TBdown][ɯ]		*!	
☛ b. (affrication: [ts]) [alveolar, TTup, TBup][ɯ]			*
c. (palatalized alveolar) [alveolar, TTdown, TBup][ɯ]	*!		**!
d. (palatalization: [tɕ]) [post-alveolar, TTdown, TBup][ɯ]			**!

Japanese /t/ affrication in the context of tautosyllabic /ɯ/ is derived as in Tableau 2. The faithful output candidate (a) obtains a violation marks for AGREE-σ[CV(CO) due to different TBCO values of [t] and [ɯ]. The palatalized alveolar candidate (c) gets a violation mark for *[TTdown, TBup, +anterior]. Since the other candidates (b) and (d) do not violate those high-ranked constraints, the candidates (a) and (c) cannot be the winner of Tableau 2. The candidate (b) with an affricated [ts] violates IDENT-C(CO) by a value change in TBCO from 'down' to 'up'. The candidate (d) with a palatalized [tɕ] violates IDENT-C(CO) two times by value changes in both TTCO and TBCO. With a less number of violation of the same constraint, the affrication candidate (b) becomes the realized output in the context of /ɯ/.

Tableau 3 shows that /t/ is realized as [t] in the context of tautosyllabic [a]. The winning candidate (a) with a faithful [t] does not violate any constraint in Tableau

3. The affrication candidate (b) violates AGREE-σ[CV(CO) because [t] has ‘up’ and [a] has ‘down’ as TBCO specifications. The candidate (b) also violates IDENT-C(CO) due to the value change in TBCO from ‘down’ of /t/ to ‘up’ of [ts]. The palatalized alveolar candidate (c) violates all of the three constraints. The markedness constraint *[TTdown, TBup, +anterior] penalize the palatalized alveolar having [TTdown, TBup] specifications. Another markedness constraint AGREE-σ[CV(CO) assigns a violation mark to the difference of TBCO values of palatalized alveolar (‘up’) and a low vowel [a] (‘down’). The faithfulness constraint IDENT-C(CO) assigns two violation marks for the candidate (c) due to changes in TTCO and TBCO values. The constraints AGREE-σ[CV(CO) and IDENT-C(CO) assign the same number of violation marks for the palatalized candidate (d) for the same reasons. The candidate (d), however, does not violate *[TTdown, TBup, +anterior].

Tableau 3. Japanese /t/ realization before the tautosyllabic /a/: /t/ → [t]

/t + a/ [alveolar, TTup, TBdown] [velar, TBdown]	*[TTdown, TBup, +anterior]	AGREE-σ[CV(CO)	IDENT-C(CO)
☛ a. (faithful output: [t]) [alveolar, TTup, TBdown][a]			
b. (affrication: [ts]) [alveolar, TTup, TBup][a]		*!	*
c. (palatalized alveolar) [alveolar, TTdown, TBup][a]	*!	*	**
d. (palatalization: [tɕ]) [post-alveolar, TTdown, TBup] [a]		*!	**

In terms of muscular articulation for middle vowels such as [e, o], activating the hyoglossus (HG) is essential for lowering the tongue body. The HG is the primary muscle used to produce the low vowel [a]. In our proposal, middle vowels [e, o] have [TBCO 'Down'] in addition to [TBCO 'Up'][3] in their gestural specification. As shown in Tableau 4, the realization of [t] in the context of [e] is deduced as [t]. The violation profiles of Tableau 4 and Tableau 3 are identical. The same will apply to the case of [o].

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[3] This is similar to the concept of the Element Theory (Harris and Lindsey 1995). If we define the element A to correspond the muscular activation lowering the tongue body, then middle vowels [e, o] can be represented as I+A and U+A, respectively.

Tableau 4. Japanese /t/ realization before the tautosyllabic /e/: /t/ → [t]

/t + e/ [alveolar, TTup, TBdown] [palatal, TBupandTBdown]	*[TTdown, TBup, +anterior]	AGREE-σ[CV(CO)	IDENT-C(CO)
☛ a. (faithful output: [t]) [alveolar, TTup, TBdown][e]			
b. (affrication: [ts]) [alveolar, TTup, TBup][e]		*!	*
c. (palatalized alveolar) [alveolar, TTdown, TBup][e]	*!	*	**
d. (palatalization: [tɕ]) [post-alveolar, TTdown, TBup] [e]		*!	**

4. Conclusion

In Japanese, within a syllable, /t/ is palatalized and realized as [tɕ] before /i/, affricated as [ts] before /ɯ/, and remains unchanged before /a/. These alternation patterns are difficult to explain using conventional featural approaches, because a front vowel /i/ induces a posterior shift in place of articulation whereas a non-front vowel /ɯ/ does not. This study has shown that a muscle-based approach offers a unified explanation of these alternations. Using a 3D tongue model, we conducted articulatory simulations by manipulating patterns of muscle activation associated with the vowels /i, ɯ, a/. The simulations demonstrate that the shape of the tongue during the articulation of /t/ varies systematically depending on the coarticulated tautosyllabic vowel, because each vowel recruits a different configuration of tongue muscles.

For /i/, activation of the inferior longitudinal muscle is required to raise the tongue body without protrusion, which lowers and retracts the tongue tip. In the coarticulation of tautosyllabic /t/ and /i/, this yields a configuration in which the tongue body is higher than the tip, producing a palatalized outcome. For /ɯ/, the styloglossus elevates and retracts the entire tongue; due to the physical coupling between tongue body and tip, both move together, resulting in affrication without palatalization. For /a/, the hyoglossus and genioglossus shape the tongue body without directly affecting the tongue tip, which remains relatively high, yielding an unaltered [t].

These muscular interactions can be represented in terms of gestural values of constriction orientation for the tongue tip and body. The alternations of Japanese

/t/ can thus be formalized as assimilations in constriction orientation between tautosyllabic consonants and vowels. Within an Optimality-Theoretic framework, this yields a simple grammar in which constraints on constriction orientation dominate faithfulness[4], deriving the observed alternation patterns: *[TTdown, TBup, +anterior], AGREE-σ[CV(CO) >> IDENT-C(CO).

Several limitations of this study should be acknowledged. First, the simulations are based on a single anatomical tongue model and do not incorporate direct articulatory data from Japanese speakers. In actual speech, speakers vary in tongue length, thickness, flexibility, and muscular development, and such anatomical differences can directly influence articulatory strategies. Because the present study employs a fixed model, it cannot capture this inter-speaker variability, and the results should not be interpreted as representative of all Japanese speakers' articulatory patterns. Second, muscle activation levels are implemented as normalized exciter values rather than physiologically calibrated measurements. This abstraction, while standard in biomechanical modeling, necessarily omits fine-grained aspects of neuromuscular control. Consequently, the simulations are not intended to provide quantitatively precise predictions of articulatory trajectories or a fully parameterized physiological model of Japanese speech production. These limitations mean that the present results should be interpreted with caution: the model does not aim at faithful anatomical reproduction, nor does it claim empirical exhaustiveness.

Despite these limitations, the significance of this study lies in demonstrating the mechanistic plausibility of a muscle-based explanation for Japanese /t/-alternations. The model is intentionally simplified; nevertheless, even this minimal system generates tongue configurations that structurally correspond to the empirically attested categories [tʃ], [ts], and [t] in different vowel contexts. This convergence is important precisely because the model is not finely tuned to Japanese-specific anatomy. It shows that the observed asymmetry can emerge from general biomechanical interactions among tongue muscles under different vowel-specific demands.

By integrating biomechanical simulation with an Optimality-Theoretic analysis of constriction orientation, this study bridges articulatory modeling and phonological explanation. Rather than stipulating language-specific rules or descriptive constraints,

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[4] Labrune (2012) notes that we can observe non-affricated and non-palatalized [t] before the high vocoids in recent loanwords, e.g. 'tea bag' [tiːbaggɯ]. This can be explained that in the Japanese grammar for recent loanwords, IDENT-C(CO) outranks AGREE-σ[CV(CO).

it demonstrates how muscle-based articulatory tendencies can be systematically incorporated into formal phonological analysis. The contribution of the present work thus lies not in empirical completeness, but in conceptual integration: it provides a framework in which deep articulatory mechanisms can be interpreted as inputs to phonological computation, opening a new avenue for understanding phonological patterns that resist conventional accounts.

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