

Lips-Jaw and Tongue-Jaw Articulatory Tradeoff in DYNARTmo

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Abstract

This paper investigates how the dynamic articulatory model DYNARTmo accounts for articulatory tradeoffs between primary and secondary articulators, with a focus on lips–jaw and tongue–jaw coordination. While DYNARTmo does not implement full task-dynamic second-order biomechanics, it adopts first-order task-space gesture specifications comparable to those used in articulatory phonology and integrates a simplified mechanism for distributing articulatory effort across multiple articulators. We first outline the conceptual relationship between task dynamics and DYNARTmo, emphasizing the distinction between high-level task-space trajectories and their low-level articulatory execution. We then present simulation results for a set of CV syllables that illustrate how jaw displacement varies as a function of both place of articulation (labial, apical, dorsal) and vowel context (/a/, /i/, /u/). The model reproduces empirically attested patterns of articulatory synergy, including jaw-supported apical closures, lower-lip elevation in bilabial stops, tongue–jaw co-movement, and saturation effects in labial constrictions. These results demonstrate that even with computationally simplified assumptions, DYNARTmo can generate realistic spatio-temporal movement patterns that capture key aspects of articulatory tradeoff and synergy across a range of consonant–vowel combinations.

1 Introduction

Dynamic articulatory modeling has long aimed to capture the complex coordination patterns that underlie speech movements. In a recent publication, we introduced *DYNARTmo*, a dynamic articulatory model designed primarily for visualization and analysis of speech movement patterns (Kröger, 2025b). DYNARTmo is deliberately simpler than classical task-dynamic frameworks such as Saltzman and Munhall’s model of articulatory dynamics (Saltzman, 1986; Saltzman and Munhall, 1989). Importantly, DYNARTmo does not implement the full task-dynamic architecture with second-order dynamical systems and gestural tracking in a formally defined task space.

Nevertheless, DYNARTmo adopts the same mathematical formulation for generating gestures in task space, and it employs an approach comparable to that of Articulatory Phonology (Browman and Goldstein, 1992) for constructing gestural scores. While the spatio-temporal coordination between gestures (inter-gesture articulator coordination) is therefore modeled in a conceptually similar manner, the spatial tradeoff of gesture-induced

articulator displacements—such as those shared between the lips and the lower jaw, or between the tongue and the lower jaw (i.e., intra-gesture articulator coordination)—is treated differently. In DYNARTmo, these intra-gesture coordination patterns are implemented through an alternative mechanism, allowing the model to explicitly represent how multiple articulators jointly contribute to a single constriction.

One particularly relevant articulatory tradeoff concerns the division of labor between tongue and jaw or lips and jaw during the formation of oral constrictions, for instance in labial closure gestures during production of consonants like /p/, /b/, /m/ or apical closure gestures during production of consonants like /t/, /d/, /n/. Empirical studies have repeatedly shown that the jaw systematically contributes to the formation of many consonantal constrictions, even when the constriction target is primarily specified for a superior articulator (tongue tip, tongue blade, or lips). Whether the constriction is apical or labial, the jaw typically rises in concert with the primary articulator—tongue tip or lower lip—thereby reducing the relative displacement needed and enabling the gesture to be achieved with less extreme movement (Mooshammer et al., 1995; Harshman et al., 1977; Westbury, 1988; Löfqvist and Gracco, 1997). In the articulatory-phonology framework, such effects are interpreted as reflecting the cooperative action of multiple articulators acting as a synergy toward a single constriction target.

From a biomechanical and energetic perspective, articulatory tradeoffs between coordinated articulators may reflect general principles of economy of effort. Lindblom (1990) and subsequent work on the “economy of speech gestures” have argued that dividing a displacement requirement across multiple articulators can reduce total articulatory cost. If a total displacement of magnitude $l = 2$ is required to achieve a constriction, a single articulator must produce the entire displacement, yielding an estimated energetic cost of $l^2 = 4$. If, however, the displacement is shared between two cooperating articulators, such that $l = l_1 + l_2 = 1 + 1$, the combined cost is $l_1^2 + l_2^2 = 1 + 1 = 2$, i.e., reduced by half. This simplified energetic argument illustrates why coordinated tongue–jaw synergies, such as apical closures achieved jointly by tongue tip elevation and jaw raising, may represent efficient strategies for achieving articulatory targets.

In the present paper (i) the task-dynamics approach as well as our DYNARTmo approach will be introduced and (ii) some examples for tongue–jaw tradeoffs will be introduced for DYNARTmo. We will illustrate how the DYNARTmo system naturally produces synergistic articulator movements in a range of consonant–vowel contexts and demonstrate context effects that closely resemble empirically reported jaw–tongue coordination patterns.

2 Task-Dynamics and DYNARTmo

2.1 Classical Task Dynamics

The task-dynamic model (Saltzman, 1979, 1986; Saltzman and Munhall, 1989), developed at Haskins Laboratories, treats speech gestures as dynamical units defined in a task space, e.g. lip aperture, tongue-tip constriction degree, and velic opening. Gestures are implemented as critically damped second-order dynamical systems:

$$\ddot{x} + B\dot{x} + K(x - x_{\text{target}}) = 0,$$

where x is a task variable (e.g., lip aperture), x_{target} its gestural target, and B, K damp-

ing and stiffness parameters. These task variables are transformed to model-articulator variables through a non-linear kinematic mapping:

$$x = f(q),$$

where q denotes the articulator state vector (jaw position, tongue body position, tongue tip position, lip protrusion, etc.). Linear approximations of these mappings, often expressed through Jacobian matrices, connect task-space dynamics to articulator commands:

$$\dot{q} = J^{-1}(q) \dot{x}.$$

Jordan decomposition and stability analyses are used to ensure well-defined movement trajectories, and the model is typically implemented with forward and inverse kinematics linking constriction tasks to articulator motions.

2.2 Task Space vs. Model-Articulator Space

A key distinction in articulatory phonology is the separation between task space and model-articulator space.

Task Space: Task space defines the linguistically relevant constriction variables. In the case of DYNARTmo, the task space is augmented by explicitly separating vocalic and consonantal states. Consonantal constriction variables consist of constriction *degree* and *location* along the vocal tract (from glottis to lips). Constriction degree traditionally distinguishes full closure from near closure in order to separate plosives from fricatives; in DYNARTmo this concept is extended to differentiate all major consonantal sound types. Thus, DYNARTmo specifies primary articulator forms for separating full closure, a fricative constriction, a lateral constriction (with lateral opening), an approximant constriction, a vibrant constriction, and so on (Kröger, 2025b).

The concepts of constriction degree and location, as introduced in Articulatory Phonology (Brownman and Goldstein, 1992), can also be applied to vowels. Edge vowels such as /a/ and /i/ can be described in terms of pharyngeal or palatal constrictions, while /u/ involves a labial and velar constriction. However, for vowels the configuration of the *wide cavities* between constrictions is equally important. From the viewpoint of vocal-tract acoustics, it is the entire pattern of narrow and wide cavity segments extending from glottis to lips that defines the vocalic state. For this reason, DYNARTmo introduces the variable *vocal-tract form* as the defining vocalic task variable.

From a linguistic perspective two other articulators are essential: the velum, which determines the degree of velopharyngeal constriction, and the arytenoids, which determine the degree of glottal opening. Velopharyngeal control distinguishes nasal from oral sounds, and further separates oral sonorants (laterals, approximants) from obstruents (plosives, fricatives).

Thus, for a linguistically complete simulation of speech production, the task space must distinguish at least four major categories of gestures. These categories correspond directly to four distinct task-space states and are reflected in the structure and ordering of gesture tiers within the gesture score (see, e.g., Kröger, 2025a).

1. vocalic shape-forming gestures,

2. consonantal constriction-forming gestures,
3. velopharyngeal constriction-forming gestures,
4. glottal constriction-forming gestures.

In addition, the pulmonary system must be represented to define (a) a constant subglottal-pressure maintenance gesture and (b) inhalation and exhalation gestures, in order to separate pre-utterance, post-utterance, and utterance-producing states.

Model-Articulator Space: Whereas the task space represents a cognitive–linguistic and premotor (or high-level sensorimotor) specification—task-space trajectories can be interpreted as sensorimotor predictions or imaginations, comparable to the FACTS approach (Parrell et al., 2019)—the model-articulator space defines the primary motor level together with its execution organs, i.e., the model articulators. At the model-articulator level, the central problem is how to realize the linguistically defined gestures, or sensorimotor expectations, that are already specified in task space as idealized trajectories. This requires solving the second-order dynamical equations (spring–damping–mass systems) associated with articulatory motion, as well as determining how different articulators (primary and secondary) share or trade off their contributions to the realization of a single gesture, and how each articulator contributes to the execution of simultaneously overlapping vocalic and consonantal gestures.

Thus, a central task of task dynamics is to compute the mapping between these two spaces—task space and model-articulator space—in order to explain (i) how a single constriction task (e.g., alveolar closure) can be realized by multiple articulatory configurations, and (ii) how overlapping gestures jointly satisfy (a) the physical dynamics of the articulatory system, including forces, damping, and mass, and (b) the inherent redundancy that allows for articulatory tradeoffs, such as tongue–jaw or lip–jaw synergies during apical or labial constriction formation.

2.3 First-Order Task Specifications vs. Second-Order Articulatory Execution

As outlined above, it is important to distinguish between the mathematical formulation of gestural trajectories in task space and the physical implementation of these trajectories by the articulators. In both the task-dynamic framework and in DYNARTmo, the spatio-temporal evolution of a gesture is fundamentally specified as a *first-order* trajectory in task space, (e.g., Kröger, 2025b). Such trajectories represent high-level motor expectations or linguistic–cognitive specifications of how a constriction variable (e.g., lip aperture in a labial closing gesture) should change over time.

The *second-order* dynamical system commonly associated with task dynamics enters only at the level of articulatory execution. When a task-space trajectory is mapped onto the model-articulator space, the resulting movement must be realized by articulators with mass, inertia, and neuromuscular control properties. The corresponding second-order dynamics—Involving forces, stiffness, damping, and articulator coupling—reflect the biomechanical and neuromuscular characteristics of the vocal-tract system, rather than the linguistic specification of the gesture itself. This distinction is also emphasized in hierarchical approaches to motor control (e.g., Jordan, 1985; Jordan and Rumelhart,

1992) and in articulatory-phonology accounts separating gestural planning from physical realization (Brownman and Goldstein, 1992; Saltzman and Munhall, 1989).

From this perspective, gestural overlap at the task level (e.g., the temporal coincidence of a labial closing gesture and a vowel gesture in a /ba/ sequence) does not imply direct interaction between the gestures themselves. The interaction emerges primarily at the articulatory-execution level, where two simultaneously active task trajectories must be jointly mapped onto a shared set of articulators. The resulting movements therefore reflect both the high-level task specifications and the dynamic properties of the articulator system, including intra-articulatory coupling and biomechanical constraints.

This conceptual separation clarifies why task-space trajectories can be expressed as first-order expectations while the articulatory system requires second-order dynamics for physical realization.

3 Modeling the Lips-Jaw and Tongue-Jaw Articulatory Tradeoff in DYNARTmo

3.1 The Concept and Principles

In DYNARTmo we intentionally introduced several “hard” simplifications. From a scientific perspective, these simplifications limit the biomechanical realism of the model; however, they significantly reduce computational load and thus make the approach attractive for potential real-time implementations or for deployment as an application on resource-limited devices.

- (i) Primary articulators directly follow the task-space trajectories without an intervening biomechanical execution model.
- (ii) For both primary and secondary articulators, no explicit motion-equation solutions are computed.

Both simplifications can be motivated by the observation that, in speech production, the mass and inertial properties of the articulators play only a minor role compared to the direct neuromuscular control exerted on them. In contrast to limb or arm-hand systems—for which the task-dynamics framework was originally developed (e.g., Jordan, 1985; Jordan and Rumelhart, 1992; Hogan, 1985; Flash and Hogan, 1985; Bizzi et al., 1991; Shadmehr and Mussa-Ivaldi, 1994; Todorov and Jordan, 2002; Wolpert and Kawato, 1998)—the second-order dynamics associated with mass–spring–damper systems are far less dominant in vocal-tract motion. The muscular control system is capable of executing articulatory trajectories that remain very close to the task-space trajectories, i.e. to the sensorimotor expectations formulated at the planning level.

(iii) Articulator-specific tradeoffs, both for the realization of individual gestures and for the coordination of temporally overlapping gestures, can therefore be implemented directly at the level of the articulatory model. The corresponding principles are the following:

(a) Since vocalic articulation determines the overall vocal-tract shape (see Kröger, 2025b), the displacement of the lower jaw can initially be equated with the vocalic lower-jaw displacement.

(b) This principle can only be violated if the vocalic articulation is locally overlapped by consonantal constriction or closure formation. In these cases, the displacement of the lower jaw must assume an intermediate value between the vocalic lower-jaw displacement

and the consonantal lower-jaw displacement. The value of the consonantal lower-jaw displacement is determined by how strong the lower-jaw displacement would be for the formation of this consonant in isolation (i.e., not in a vocalic context).

(c) Through this averaging of the lower-jaw displacement described in (b), a deformation of the anterior region of the tongue dorsum must be modeled, as described in Kröger, 2025b.

In the following sub-section, using simulations of CV combinations (CV syllables), we illustrate how these principles affect the vertical displacement of the lower jaw across different consonant–vowel combinations.

3.2 Simulation Examples

The lips–jaw and tongue–jaw articulatory tradeoff can be most clearly observed by examining the vertical components of flesh-point trajectories obtained for the upper and lower lips, the tongue tip, the tongue dorsum, and the lower jaw across different consonants and vowel contexts (see Fig. 1, Fig. 2 and Fig. 3). In Fig. 2, the corresponding control-parameter trajectories are additionally displayed, reflecting the underlying sensorimotor expectations (task-space trajectories) that drive the articulatory movements.

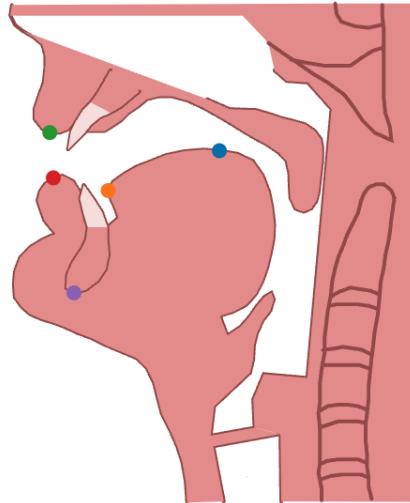
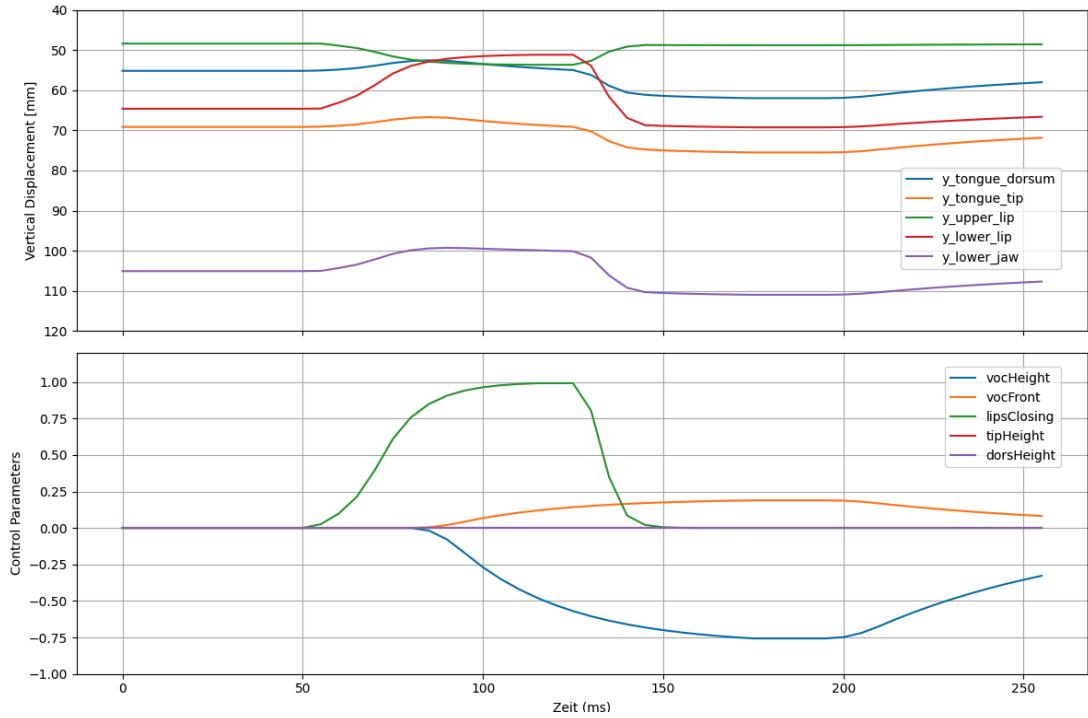


Figure 1: DYNARTmo flesh point locations for upper and lower lip (green, red), tongue tip (orange), tongue dorsum (blue), and the lower jaw (purple) displayed in midsagittal view. Colors of flesh points are identical with colors of flesh point trajectories displayed in Fig. 2 and Fig. 3.

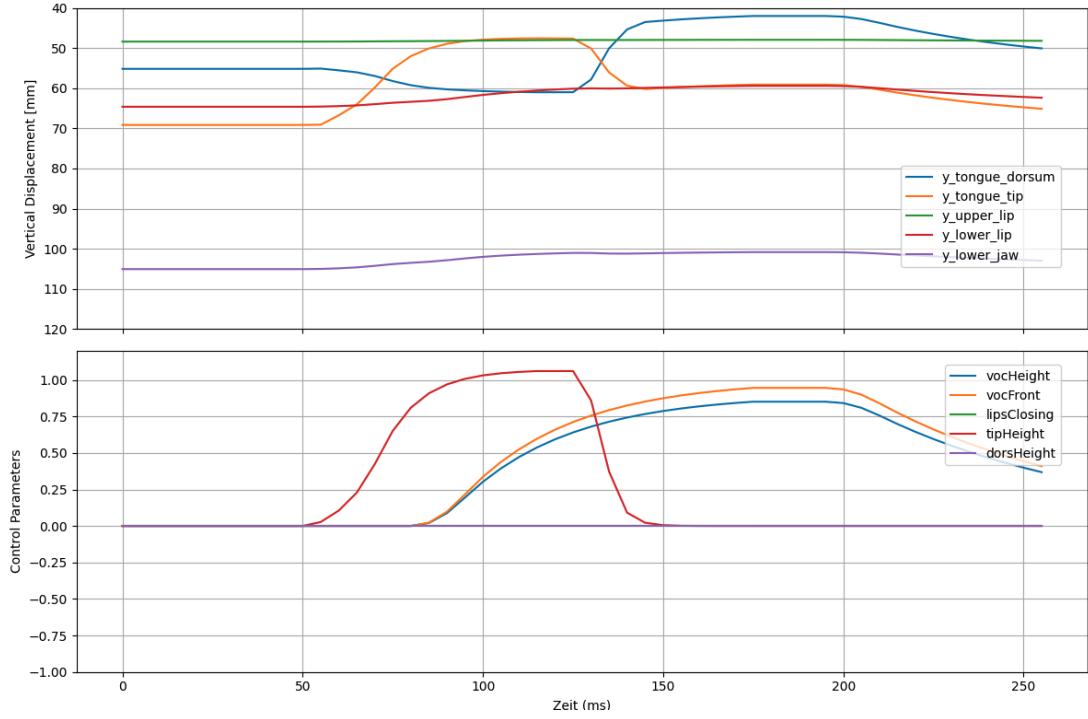
The example syllable /pa/ (Fig. 2a) illustrates the following:

(i) In the upper part of Fig. 2a (vertical displacement of flesh points) we can see that the lower jaw position at the end of the syllable is lower than the vocalic neutral position at the beginning of the syllable (i.e., before the onset of consonantal closure formation). This reflects vocalic articulation, because the end of the syllable corresponds to the vocalic /a/ posture. During consonant production, however, a high lower-jaw position is reached. This highlights the contribution of lower-jaw elevation to the of the lower lip during the production of the consonantal closure for /p/.

(ii) The lower part of Fig. 2a (control parameters; task space paraemters) demonstrates the full independence of the consonantal and vocalic control parameters during syllable production: The lip closing sensorimotor demand does not interact with sensorimotor



(a) Flesh point and control parameter trajectories for /pa/.



(b) Flesh point and control parameter trajectories for /ti/.

Figure 2: Flesh point trajectories (vertical displacement) and control parameter trajectories (reflecting task space sensorimotor expectations) generated by DYNARTmo for two syllables; top: /pa/; bottom: /ti/.

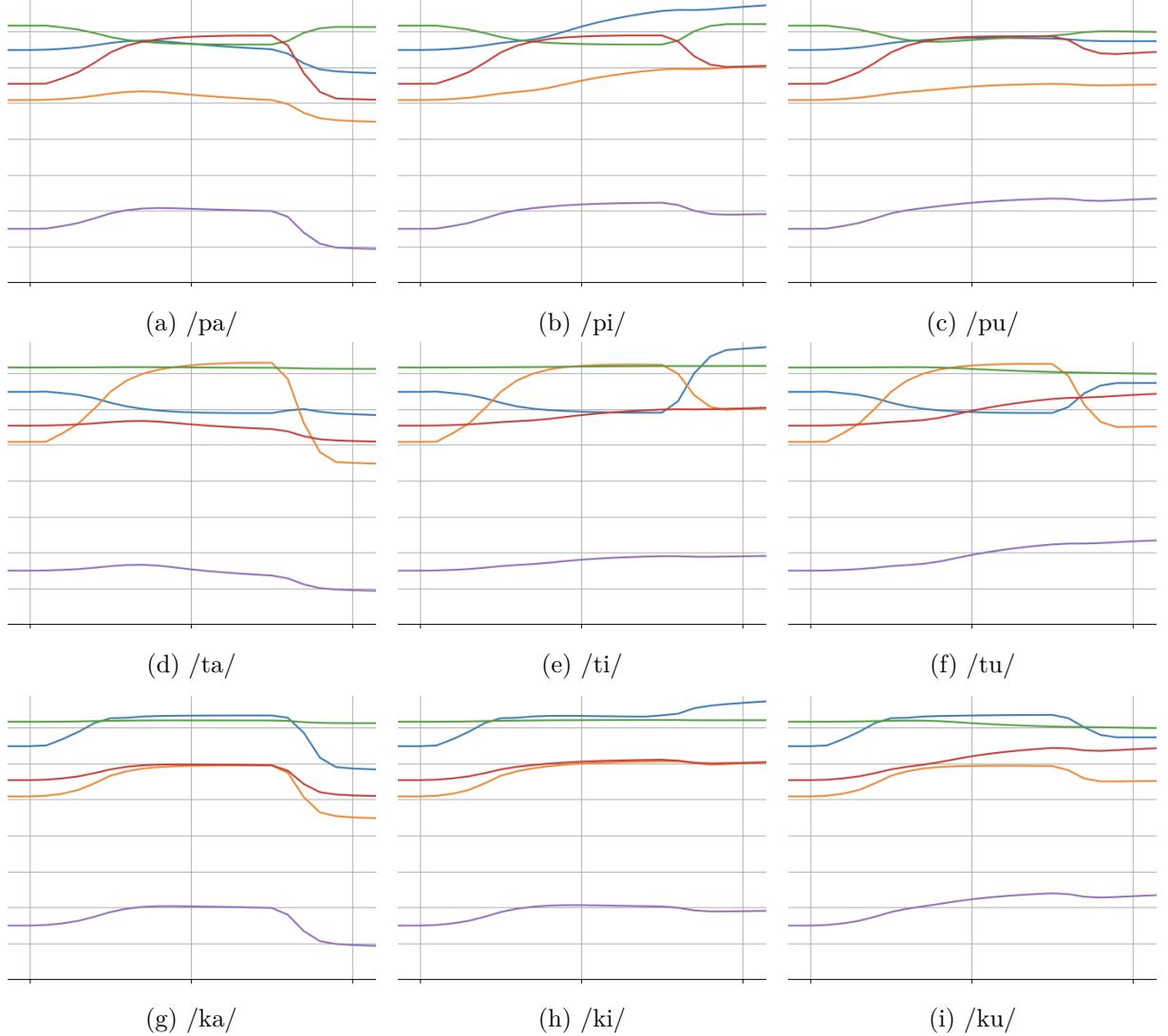


Figure 3: Vertical displacement trajectories of flesh-point for nine CV syllables. Columns: different vowel contexts: /Ca/, /Ci/, /Cu/; Rows: different intitial consonant: /pV/, /tV/, /kV/; blue: tongue dorsum; orange: tongue tip; green: upper lips; red: lower lips; magenta: lower jaw. Time interval is $t = 40$ msec to $t = 160$ msec (c.f. Fig. 2)

demands for vocalic height or vocalic fronting for later vowel production. Thus, the gesture interaction as well as gestural articulator tradeoff is not initiated at this level.

(iii) In the upper part of Fig. 2a, the trajectories of vertical displacement for the upper and lower lip flesh points show that the labial closure is entirely determined by the vocalic control parameter “lip closing.” Labial closure is visible here as the convergence of the displacement trajectories of the upper and lower lip. The higher position of the lower-lip flesh point relative to the upper-lip flesh point—observable as the lip closure progresses—reflects the increasing strength of the labial closure during its temporal span.

Comparable findings are already discussed in studies on saturation effects in speech motor control: Once an articulator comes into firm contact with another articulator or with a vocal-tract wall, further increases in muscle activation may produce little or no additional change in closure (because full closure is full closure) and thus in the resulting acoustic output related to vocal tract closure (Perkell et al., 1997, 2000, 2004). Moreover, this type of articulatory saturation provides a concrete biomechanical basis for the quantal relationships between articulation and acoustics described by Stevens (Stevens, 1972, 1989).

(iv) Back to our syllable example /pa/ generated by DYNARTmo (Fig. 2a): The flesh-point displacements of the tongue tip and tongue dorsum reflect not only the vocalic articulation but also the co-movement of the tongue with the lower jaw during consonantal closure formation (upward movement). Thus, tongue tip (and front part of tongue dorsum) are elevated during consonant production as well but, with ongoing time, the tongue (tongue tip and tongue dorsum flesh points) already begins to move downwards toward the vocalic /a/ target during the consonantal closure interval.

Comparable effects can be seen in the case of Fig. 2b (syllable /ti/).

(i) The lower-jaw flesh-point displacement increases during consonant production, but not as strongly as in the case of /ta/, because tongue-tip elevation is supported not only by an elevation of the lower jaw but also by a co-elevation of the tongue dorsum.

(ii) In addition, we observe the upward co-movement of the lower lip, which is caused by the upward movement of the lower jaw during consonant production.

(iii) The downward movement of the tongue-dorsum flesh point reflects the coarticulatory behavior of the tongue dorsum during the upward movement of the tongue tip that forms the apical closure. During this time interval, the spatial region between tongue dorsum and tongue tip exhibits a concave shape.

Figure 3 shows the variation of lower-jaw displacement for CV syllables (with C = plosive) across different places of articulation, corresponding to different primary closure-forming articulators (labial, apical, dorsal), and in combination with the edge vowels /a/, /i/, and /u/. The resulting 9 C–V combinations yield 9 syllables, which already exhibit a large variety of lips–lower-jaw and tongue–lower-jaw tradeoffs.

While Fig. 2 illustrates the complete temporal course of syllable production for two of these 9 CV syllables, the nine subpanels of Fig. 3 display only the critical temporal interval: the articulatory transitions leading into the consonantal closure, the interval of consonantal closure, and the time interval of the release, i.e., the transition into the subsequent vowel (time interval from $t = 40$ msec to $t = 160$ msec).

This figure shows the following:

(i) A strong increase in lower-jaw displacement for both labial and dorsal consonants; in the case of apical consonants, part of the articulatory tradeoff between the primary articulator and additional assisting articulators is carried not only by the lower jaw but also by the tongue dorsum.

- (ii) The saturation effect occurs for bilabial closure in all vowel contexts. This highlights the primacy of consonantal articulation during the interval of closure or near-closure formation.
- (iii) The characteristic co-movements of articulators that are not involved in forming the consonantal closure (e.g., the lips in the case of apical or dorsal closure, or the tongue tip and tongue dorsum in the case of labial closure) are clearly recognizable in all panels. These co-movements result solely from the active upward movement of the lower jaw as part of the articulatory tradeoff required for forming the consonantal closure.

4 Discussion and Conclusions

DYNARTmo provides a simplified but effective framework for simulating articulatory movement patterns and articulator synergies. Despite not implementing a full task-dynamic architecture, the model naturally reproduces tongue–jaw tradeoffs during closure or constriction formation, reflecting widely reported empirical patterns. Through the examples presented—ranging from simple CV sequences to more complex clusters—we illustrate how vowel context, consonantal target, and articulator coupling jointly determine the resulting movement patterns.

DYNARTmo thus represents a useful tool for visualizing, teaching, and analyzing articulatory synergy and constraints, offering an accessible complement to more elaborate task-dynamic models.

5 Supplementary Material

The simulation model can be downloaded as a Web App titled *Speech Articulation Trainer* (<https://speech-articulation-trainer.web.app/>). In order to generate and visualize trajectories as exemplified in Fig. 2, start the app and click the buttons: `VAL`, `set`, and `+fleshPts`. Then click the buttons `SND` and `move`, and finally press the `play`-button.

The syllable /pa/ will then be simulated, and its video animation in midsagittal view will be displayed (unless you have selected a different syllable; /pa/ is the default, already activated when the app is started). The flesh-point and control-parameter trajectories will be saved automatically on your device in the `/downloads/` folder as files named `control_123456789.csv` and `displacement_123456789.csv`.

The Python code for visualizing the data contained in both files is available for download in the folder `py_code/plot_displ_and_control.py`.

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