Quantal biomechanical effects in speech postures of the lips

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Why does labial typology look the way it does?

General observation: Languages tend to use different lip shapes for different degrees of labial constriction.

This presentation: We suggest that this is in part due to quantal biomechanical properties of these shapes that allow for robust, feed-forward control.

Let's start by looking at the 451 languages in the UCLA Phonological Segment Inventory Database (UPSID; Maddieson 1984, Maddieson and Precoda 1990)

UPSID labial typology (451 languages)

Though not without exceptions, there's a clear generalization:

- **Labial stops**: 99.8% bilabial (0.2% labiodental)
- **Labial fricatives**: 71% labiodental (29% bilabial)
- **Labial approximants**: 98% rounded (2% labiodental)

Why should this be the case?

A language could produce different degrees of constriction by **varying the activation of a single labial movement:**

- Labial stop: [p]
- Labial fricative: [p̞]
- Labial approximant: [p̞̞]

<u>Languages don’t do this!</u>

Why these mechanisms?

Mechanisms built for a task will be **robust to noisy, everyday conditions**
(e.g., Loeb 2012)

- Allow a **large margin of error**
- Optimize for **feed-forward function** (e.g., Perkell 2012; Guenther 2016)

Speech mechanisms with such properties are associated with the term **quantal**
(e.g., Stevens 1972; Stevens 1989; Stevens and Keyser 2010)

- **Large variation** in input ➔ **little response** in output

Past work on quantal biomechanics

Limited discussion of quantal biomechanical effects

(e.g., Fujimura and Kakita 1979; Fujimura 1989; Perkell et al. 2004; Perkell 2012)

Simulation studies have demonstrated quantal effects in

- The soft palate (Gick et al. 2014; Anderson et al. 2019)
- The larynx (Moisik and Gick 2017)
- Lip rounding with variations in muscle stiffness (Nazari et al. 2011)

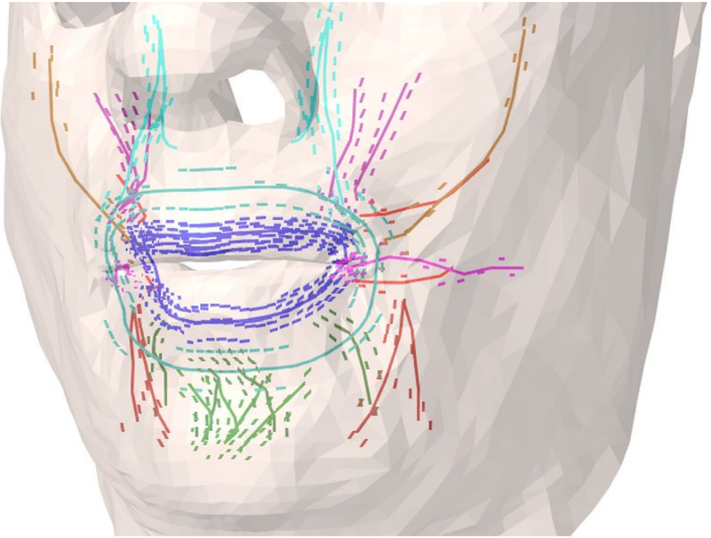
<u>Not all sets of muscle activations exhibit quantality!</u>

(Gick et al. 2014; Moisik and Gick 2017)

The current study

Tests for quantal effects in the three canonical lip postures using a 3D finite-element face model.

- Biomechanical modeling platform Artisynth
  (e.g., Stavness et al. 2012)
- Simulates biomechanics and actions of fixed groupings of muscles
- Passive tissue mechanics, active muscle stress and intrinsic stiffness, volume preservation, gravity



Assumptions & Predictions

<u>Assumptions</u>

- Speech movements are generated by functionally independent groupings of muscles that activate in fixed proportion (**modules**)
  (e.g., Bernstein 1967; Ting et al. 2015)

- Selected in part based on intrinsic quantal biomechanical **robustness**

Assumptions & Predictions

Predictions

Canonical lip modules will be

1. **Robust** across a wide range of **activation levels**
2. **Robust to interference** from surrounding muscles

Simulation 1: Robustness to varying activation

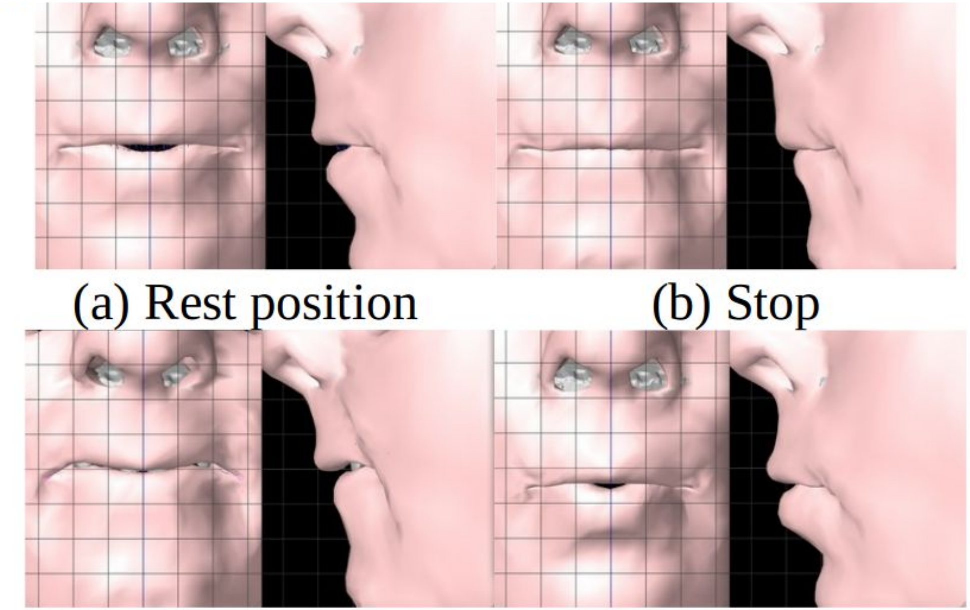
- Defined muscle groupings based on known muscle involvements
  (Lightoller 1925; Stavness et al. 2013)

- Each posture uses a **different set** of muscles (sometimes overlapping)

- No “right” choice: many inputs will contain the necessary mechanic
  (e.g., Loeb 2012)

Simulation 1: Robustness to varying activation

- Activated muscle groupings up to maximum stresses
- Measured opening size at different activation levels

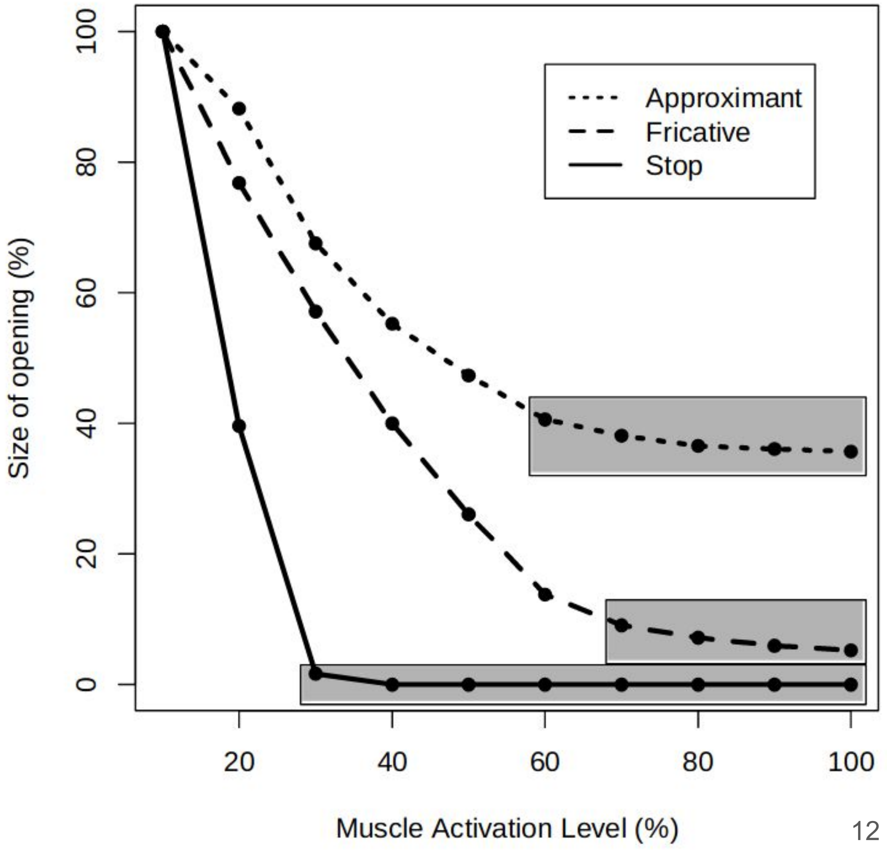


(a) Rest position (b) Stop (c) Fricative (d) Approximant

Simulation 1: Results

<u>Non-linearities occur as predicted!</u>

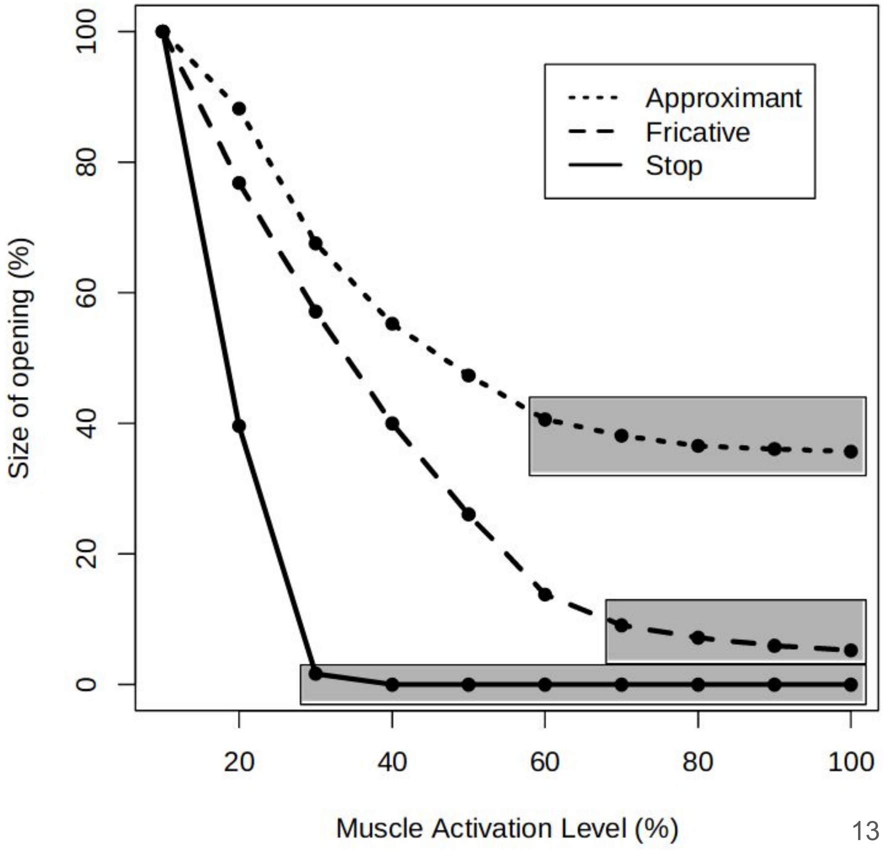
- Grey boxes: areas where 95% of distance to maximum closure has been covered



Simulation 1: Results

Takeaway

All three speech postures are <u>robust to variation in activation levels</u> of relevant muscle groups

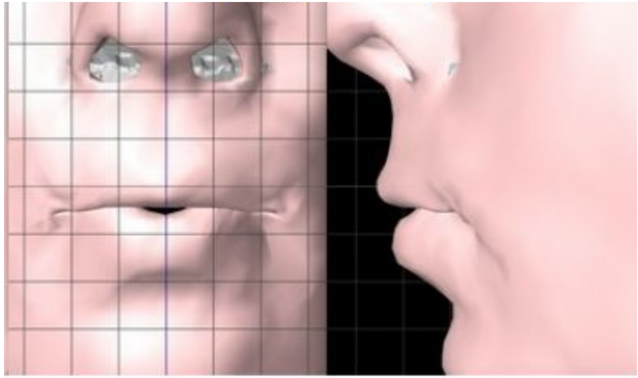


Simulation 2: Robustness to surrounding muscles

Question: Are these postures robust to interference from surrounding muscles?

Focus on approximant (activating OOP)

- No contact, easier to see variable effects



Two types of simulations:

1. Is lip constriction stable when there is surrounding muscle noise?
2. How does degree of OOP activation affect this stability?

Simulation 2: Type 1

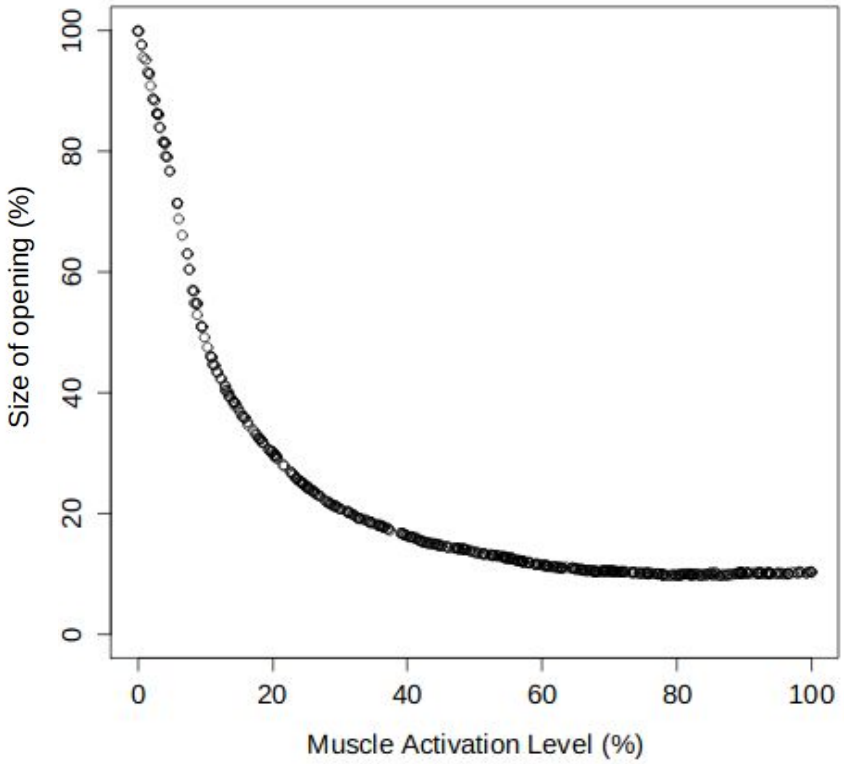
Sampled OOP activation ~ $U(0\%, 100\%)$

1. Without activation of surrounding muscles (same as Sim. 1)

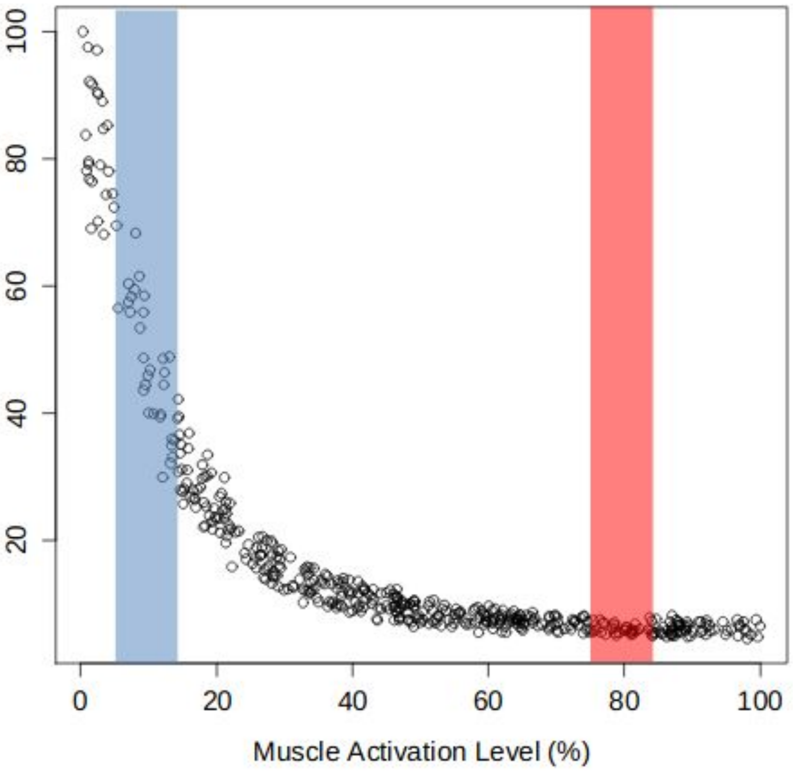
2. With activation of surrounding muscles ~ $U(0\%, 10\%)$

Simulation 2: Type 1 Results

No surrounding noise



Surrounding noise



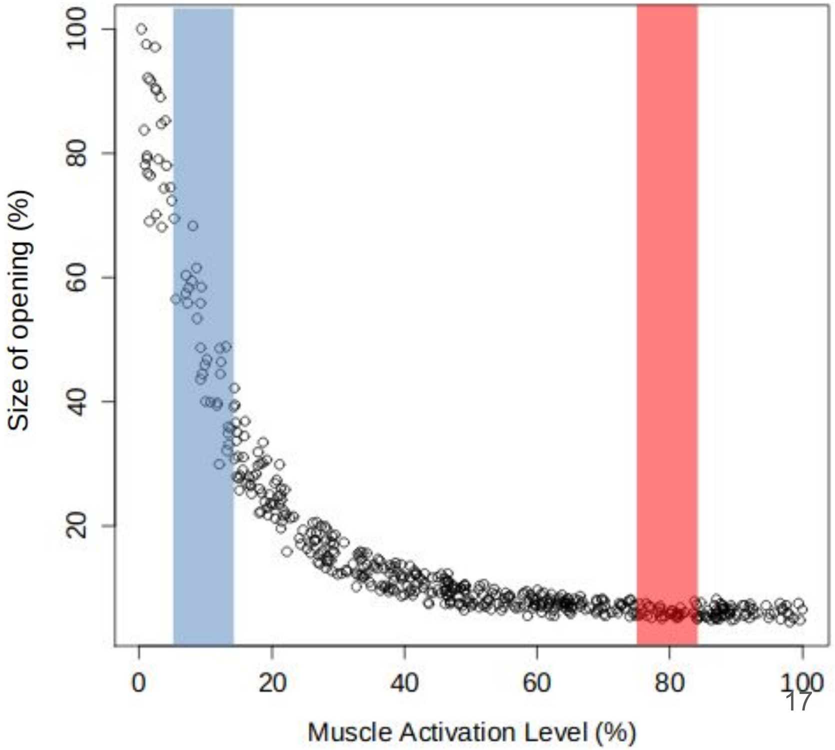
Simulation 2: Type 2

Sampled OOP activation from **two distributions**

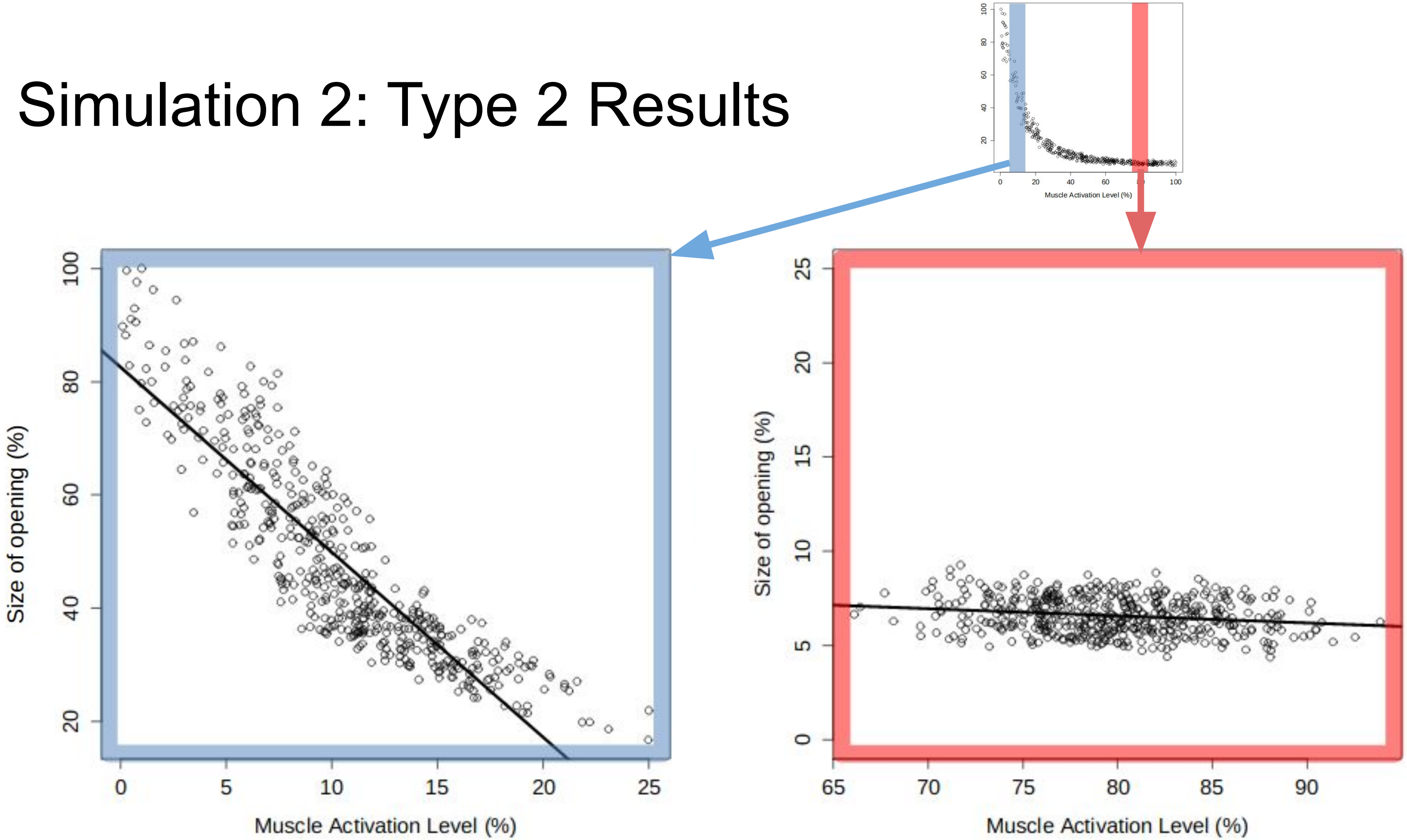
1. Low activation ~ *N(<u>10%</u>; 10%)*

2. High activation ~ *N(<u>80%</u>; 10%)*

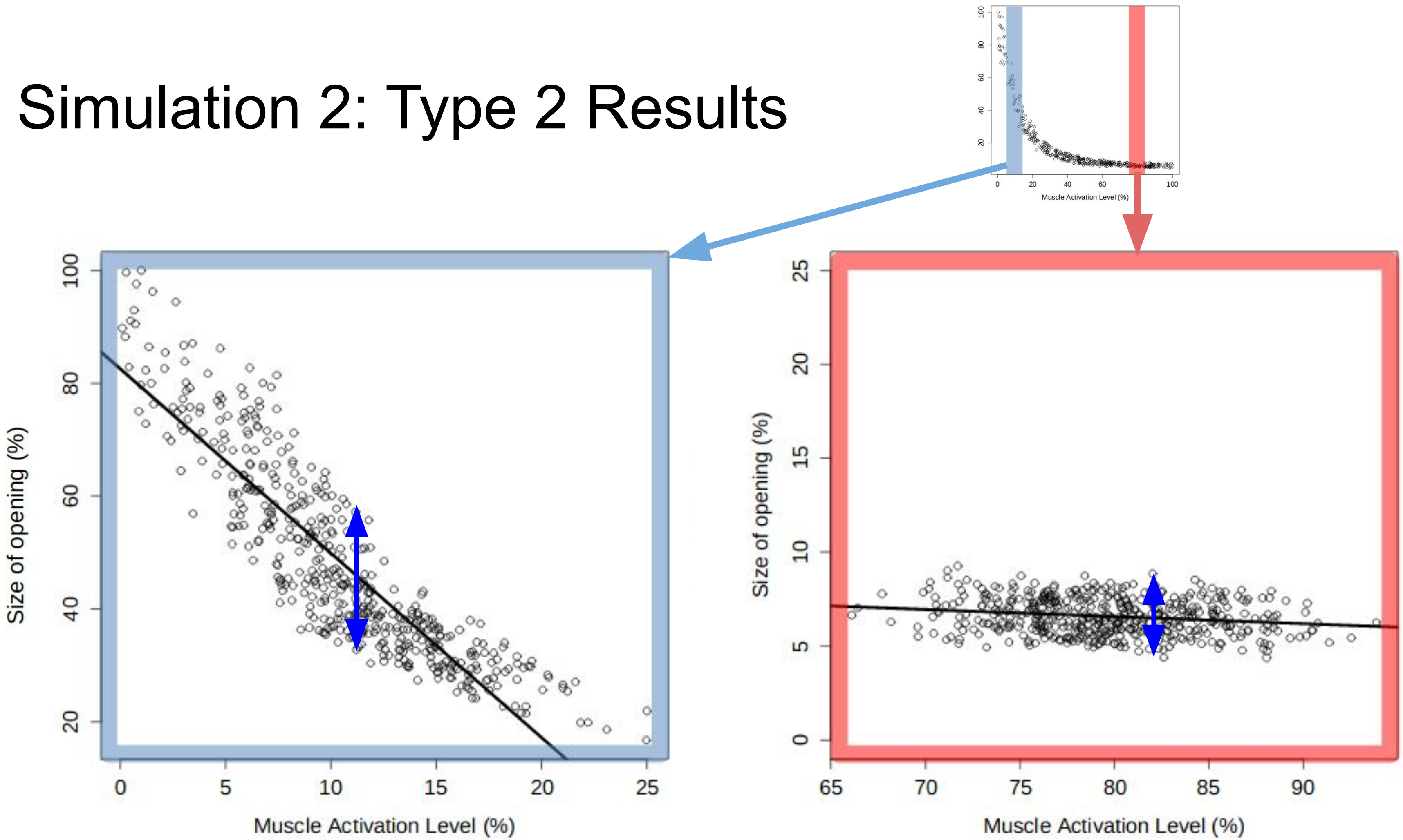
Other muscles ~ *U(0%, 10%)*



Simulation 2: Type 2 Results



Simulation 2: Type 2 Results



Simulation 2: Type 2 Results

Higher OOP activation reduces interference from surrounding muscles

- Variability in **high activation** region is significantly lower

The **high activation** region falls in the quantal region in Simulation 1!

- Same region is **robust** to both intrinsic and extrinsic activation noise

Discussion

Why don’t we see labial inventories that look like [p], [p̞], [p̞̞]?

- The regions in which frication and approximation are achievable using this configuration are biomechanically unstable.

The sets of muscles associated with the three canonical lip postures are:

1. Robust to intrinsic activation noise (Simulation 1)
2. Robust to extrinsic noise from surrounding muscles (Simulation 2)

Discussion

Suggests a biomechanical contribution to typological distribution of labial sounds.

What about bilabial fricatives?

- The mechanism for bilabial fricative constriction may not be the same as for bilabial stop closure (e.g., lip compression; Okada 1991)
- Serves as competing alternative to labiodental fricatives

Discussion

Bears on theories of speech organization and motor control

- Degree of constriction and involved articulators are <u>not independent parameters!</u>
- Primitive units of organization are **modular muscle groupings** that **activate in a fixed proportion** to achieve a **particular functional goal**
  (e.g., Bernstein 1967; Safavynia and Ting 2013; Gick and Stavness 2013; Ting et al. 2015)

Understanding these structures provides explanatory power for linguistic phenomena.

Thank you!

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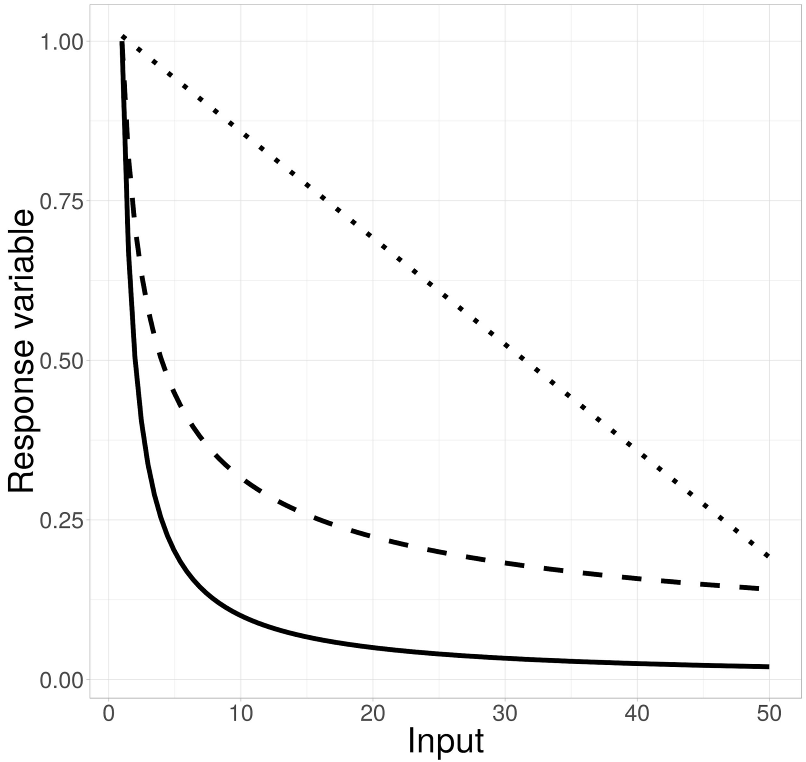
Quantal regions

A region of a function in which **large variation (error)** in one dimension effects **little response** in some other (task) dimension



- Solid line: strongly quantal
- Dashed line: fairly quantal
- Dotted line: not quantal

Simulation 1 & 2: Muscle sets and ranges

	OOPs	OOPi	OOMs	OOMi	MENT	RIS	LLSAN	LLS
Bilabial	–	–	30	30	20	20	–	–
Labiodental	–	–	–	26	26	26	36	50
Rounded	40	40	–	–	–	–	–	–

Table 1: Maximum muscle stress (kPA) used for the three lip constrictions.

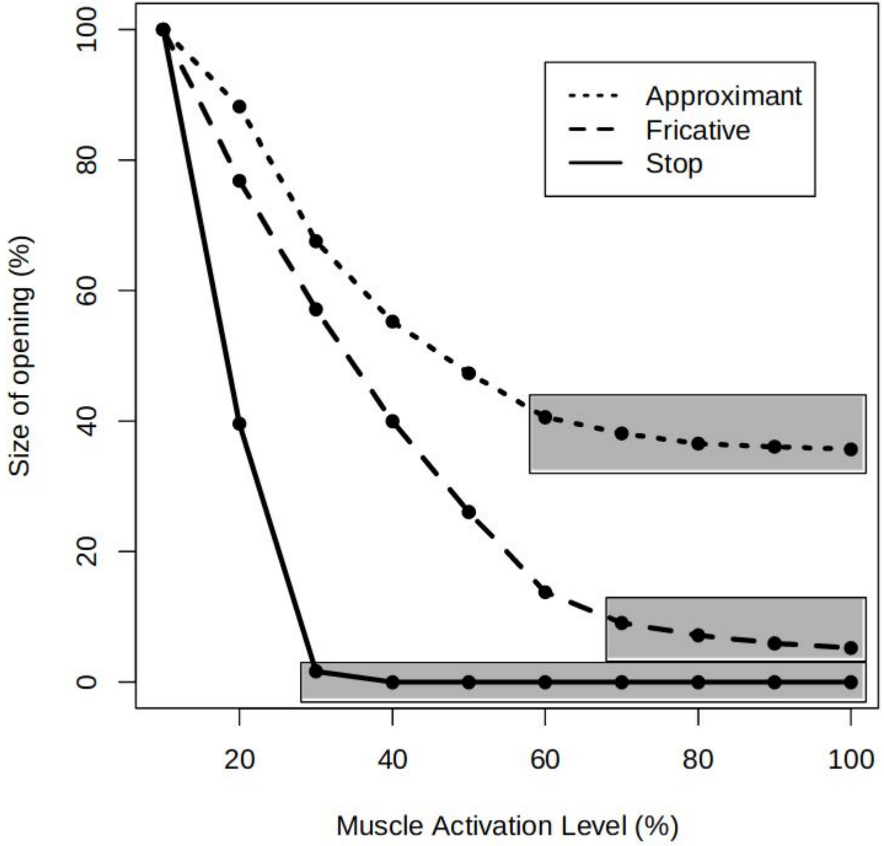
OOMs/i: superior/inferior marginal orbicularis oris
OOPs/i: superior/inferior peripheral orbicularis oris
MENT: mentalis
RIS: risorius
LLSAN: levator labii superioris alaeque nasi
LLS: levator labii superioris

Simulation 2 noise muscles: above muscles, plus depressor anguli oris, buccinator, depressor labii inferior, levator anguli oris, zygomaticus

Simulation 1: Q-scores

The **Q-score** of a function quantifies quantality (Moisik and Gick 2017):

- Compares first derivative in earlier and later ranges
- Based on heuristics in Moisik & Gick (2017):
  - Stop is *strongly quantal*
  - Fricative and approximant are *moderately quantal*



Simulation 1 & 2: Calculating opening size

Simulation 1: Count pixels in coronal images, convert to mm^2

- Labiodental calculated between lower lip and upper teeth
- Other sounds between lower lip and upper lip

Simulation 2: Calculate minimum opening size along a series of cutting planes

- Necessary because of large number of simulations

Probabilistic sampling of inputs done using the BatchSim tool