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Review Article

Neuromuscular compartmentalization of human tongue muscles: Implications for fine motor control and speech production

Shrikrishna B.H.[1], Deepa G[2]*

[1]Dept. of ENT, All India Institute of Medical Sciences, Bibinagar, Hyderabad, Telangana, India.
[2]Dept. of Anatomy, All India Institute of Medical Sciences, Bibinagar, Hyderabad, Telangana, India.

Abstract

Human tongue muscles exhibit remarkable neuromuscular compartmentalization, enabling rapid, adaptable, and precise movement essential for speech production and other fine motor tasks. We performed a review to evaluate structural and functional evidence of compartmentalization and its clinical implications. Following PRISMA 2020 guidelines, a comprehensive search of 32 uploaded sources was conducted, screening for studies on human tongue muscle anatomy, physiology, and neuromuscular control using imaging, histology, or electrophysiology. Seventeen studies met inclusion criteria, encompassing experimental, observational, cross-sectional, imaging, and histological methodologies. Findings consistently documented discrete compartments—ranging from approximately four to nearly 100 per muscle—supported by motor endplate mapping, regional fiber typing, and somatotopic organization within cortical and hypoglossal regions. Tagged MRI, functional MRI, diffusion imaging, and histological approaches confirmed independent or synergistic activation patterns. Pathological conditions such as obstructive sleep apnea and post-glossectomy demonstrated en bloc movement, contrasting with the fine, compartment-based control in healthy individuals. Neural findings indicated somatotopic hypoglossal organization and motor unit specialization, with potential translational relevance to neuromuscular therapies. This nuanced understanding may guide clinicians in customizing treatment approaches, improving rehabilitation outcomes, and advancing research on sensorimotor integration in complex orofacial functions.

Keywords: Tongue, Neuromuscular junction, Motor Control, Magnetic resonance imaging, Speech

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1. Introduction

Precise control of the human tongue is crucial for speaking, swallowing, and breathing. Unlike limb muscles, the tongue operates as a muscular hydrostat, able to change shape without skeletal support.[1] Tongue is not a uniform structure but is composed of multiple neuromuscular compartments.[2-3] Mapping of motor endplates and histological studies have identified distinct fascicles and regional activation patterns in the tongue.[4,5] Advanced imaging techniques have enabled in vivo examination of compartmental function.[6,7] Motoneurons in the hypoglossal nucleus are organized somatotopically as per electrophysiological studies, further supporting the theory of compartmental control.[8,9] Clinical observations reinforce this neuromuscular compartmentalization theory, as conditions like obstructive sleep apnea or partial glossectomy result in a shift from compartmental activation to more uniform movement patterns.[10,11] We conducted a review of the existing anatomical, imaging, and functional evidence on tongue muscle compartmentalization and its role in speech motor control. Grasping the organization of tongue muscle compartments can aid in refining treatments for speech impairments, guiding surgical repair strategies, and informing the creation of biomechanical models that accurately represent the tongue's intricate muscle structure.

2. Materials and Methods

2.1. Eligibility criteria

Studies that focused on neuromuscular aspects of the human tongue muscles, used imaging techniques (e.g., MRI, tagged MRI, or ultrasound), histology, or electrophysiology, and offered information on compartmentalization or motor unit

Corresponding author: Deepa G
Email: drdeepagadwal@gmail.com

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organization were chosen in our review. Clinical populations were included only if anatomical integrity was maintained.

2.2. Search strategy

The following Boolean string was used on the uploaded dataset: ("tongue muscle" OR "lingual muscle") AND ("neuromuscular compartment" OR "motor unit" OR "somatotopic" OR "innervation") AND ("speech" OR "fine motor" OR "articulation") AND (imaging OR MRI OR histology OR electrophysiology OR EMG).

2.3. Selection process

Two reviewers independently screened 32 uploaded records, excluded 12 on title/abstract, and assessed 20 full texts, of which 3 were excluded for lack of human data. Seventeen studies were included.(**Figure 1**).

2.4. Data collection

For each included study, we extracted design, methods, imaging modalities, and key findings (**Table 1**).

2.5. Data synthesis

Due to heterogeneity, we performed narrative synthesis organized into anatomical organization, neural control, and functional integration.

3. Results

Findings consistently demonstrated structural compartmentalization with evidence from histology and imaging. Functional studies documented independent activation of sectors, particularly within the genioglossus and superior longitudinal muscles. Clinical comparisons highlighted disrupted patterns in OSA and post-glossectomy populations.

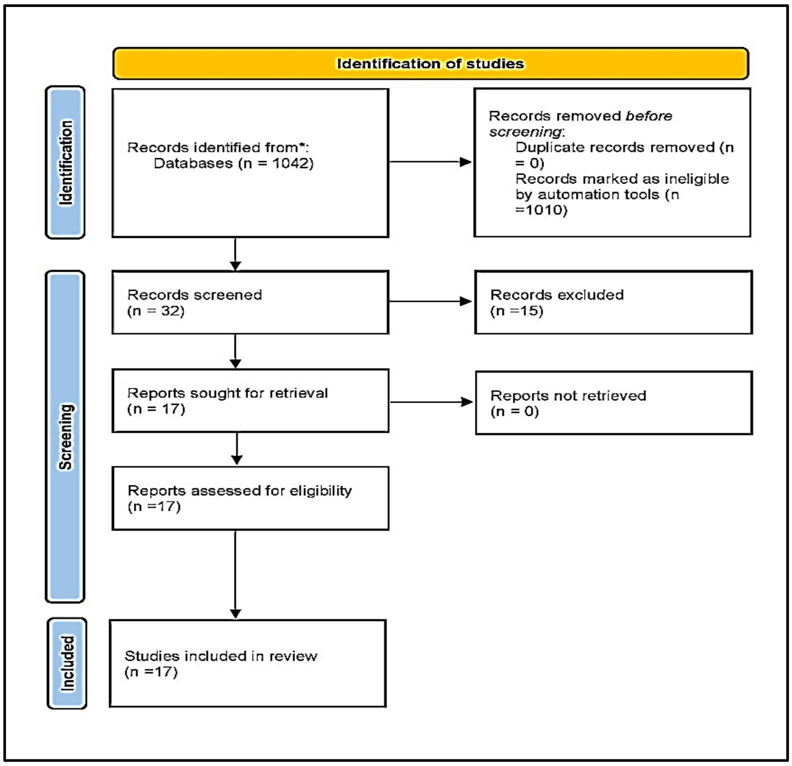

Figure 1: PRISMA flow chart

Table 1: Study characteristics

Author (Year) [Ref]	Design	Methods	Key Findings
Wrench & Maassen (2024)[1]	Observational, imaging	PCA, modeling	≥10 compartments; 5 independent sectors
Takemoto (2001)[2]	Anatomical, histology	3D modeling	≈100 structural units; inner/outer regions
Mu & Sanders (2012)[3]	Imaging, histology	Sihler’s stain	Complex endplates; regional activation
Sokoloff (2003)[4]	Anatomical, histology	Microdissection	Discrete fascicles; multiple motor units
Slaughter et al. (2006)[5]	Experimental, histology	Microdissection	Localized motor units; in-series design
Sakamoto (2017)[6]	Anatomical, cadaveric	Gross dissection	20–25 compartments in genioglossus; 3–6 in styloglossus
Xing et al. (2019)[7]	Imaging, observational	Tagged MRI	3 muscle blocks; weak correlations

Jugé et al. (2019)[8]	Imaging, comparative	Tagged MRI	4 compartments; en bloc movement in OSA
Neef et al. (2015)[9]	Experimental	TMS, EMG	No significant differences in coordination
Grabski et al. (2011)[10]	Imaging	fMRI	Somatotopic organization
Conant et al. (2018)[11]	Imaging, experimental	ECoG, ultrasound	Distributed encoding of kinematics
Doyle et al. (2021)[12]	Experimental	Gene delivery, EMG	Somatotopic hypoglossal nucleus
Baptista et al. (2021)[13]	Interventional	NMES	Improved muscle function
Saigusa et al. (2020)[14]	Anatomical	Nerve tracing	Complex branching, shared neurons
Smith et al. (2005)[15]	Theoretical review	Histochemistry	Fiber type diversity, compartmentalization
Ross et al. (2023)[16]	Theoretical review	XROMM	Muscular hydrostat theory
Stone & Epstein (2013)[17]	Review	Anatomy and physiology	Functional implications for speech

Risk of bias: ROB2 was applied to experimental studies and Newcastle–Ottawa Scale to observational studies. Domains included selection, measurement, and reporting bias (**Table 2**).

Table 2: Risk of bias assessment

Author (Year) [Ref]	Study Design	Tool Used	Overall Risk of Bias
Wrench & Maassen (2024)[1]	Observational, imaging	Newcastle–Ottawa Scale	Low risk
Takemoto (2001)[2]	Anatomical, histology	Newcastle–Ottawa Scale	Moderate risk (limited participant details)
Mu & Sanders (2012)[3]	Imaging, histology	Newcastle–Ottawa Scale	Low risk
Sokoloff (2003)[4]	Anatomical, histology	Newcastle–Ottawa Scale	Low risk
Slaughter et al. (2006)[5]	Experimental, histology	ROB2	Low risk
Sakamoto (2017)[6]	Anatomical, cadaveric	Newcastle–Ottawa Scale	Low risk
Xing et al. (2019)[7]	Imaging, observational	Newcastle–Ottawa Scale	Low risk
Jugé et al. (2019)[8]	Imaging, comparative	Newcastle–Ottawa Scale	Low risk
Neef et al. (2015)[9]	Experimental	ROB2	Low risk
Grabski et al. (2011)[10]	Imaging	Newcastle–Ottawa Scale	Low risk
Conant et al. (2018)[11]	Imaging, experimental	ROB2	Low risk
Doyle et al. (2021)[12]	Experimental	ROB2	Low risk
Baptista et al. (2021)[13]	Interventional	ROB2	Low risk
Saigusa et al. (2020)[14]	Anatomical	Newcastle–Ottawa Scale	Low risk
Smith et al. (2005)[15]	Theoretical review	Not applicable*	Low risk (narrative synthesis only)
Ross et al. (2023)[16]	Theoretical review	Not applicable*	Low risk (narrative synthesis only)
Stone & Epstein (2013)[17]	Review	Not applicable*	Low risk (narrative synthesis only)

*****Theoretical reviews and purely narrative papers are not formally assessed by ROB2 or NOS; they are noted as low risk due to absence of empirical bias domains.

4. Discussion

This review integrates anatomical, imaging, and electrophysiological evidence of neuromuscular compartmentalization in the human tongue. Wrench and Maassen[1] identified at least ten compartments per muscle with five independently controlled sectors. Takemoto[2] described nearly one hundred structural units in three-dimensional analyses, while Sakamoto[6] reported 20–25 compartments in the genioglossus and three to six in the styloglossus, illustrating both cooperative and independent activation. Histological work by Mu and Sanders,[3], Sokoloff,[4] and Slaughter et al.[5] confirmed discrete fascicles and complex motor endplate organization.

Imaging studies corroborate these findings. Xing et al.[7] demonstrated three major muscle blocks with weak correlations, whereas Jugé et al.[8] found four independently controlled compartments and observed en bloc movements in obstructive sleep apnea. Neef et al.[9] and Grabski et al.[10] highlighted cortical coding of speech dynamics and somatotopic representation. Conant et al.[11] further described distributed encoding of tongue kinematics. Doyle et al.[12] demonstrated somatotopic organization within the hypoglossal nucleus, while Baptista et al.[13] explored neuromuscular electrical stimulation to improve function. Saigusa et al.[14] provided anatomical insights into nerve branching, and Smith et al.[15] and Ross et al.[16] offered theoretical perspectives on fiber type diversity and muscular hydrostat function.

These converging lines of evidence show the tongue's unique design that allows rapid, precise, and adaptable motor control. Clinically, loss of compartmental activation leads to impaired speech and swallowing, as seen in obstructive sleep apnea and post-glossectomy cases.[8,7] Interventions targeting specific compartments, such as NMES[13] or gene therapy[12], may restore function or reduce pathology.

The human tongue is organized into numerous neuromuscular compartments, with studies identifying up to 10 in the genioglossus and multiple compartments in other intrinsic and extrinsic muscles, allowing for independent control of different tongue regions and supporting complex movements required for speech production.[18] Reflex mechanisms, including those mediated through cortical pathways, contribute to tongue posture stabilization during speech, as shown by experimental findings of reflex responses to sudden stretch.[19] Advanced imaging techniques, have quantified muscle strain and coordination patterns, and have demonstrated the adaptability of tongue motor control.[20] The en grappe endplates in the transverse muscle group of the tongue facilitate precise motor control.[21]

The neuromuscular control of the tongue exhibits both typical and unique characteristics for swallowing and speaking.[22] The human tongue's fine motor control is because of its complex neuromuscular architecture. Traditional models describe the tongue as comprising four extrinsic and four intrinsic muscles, but recent studies reveal a much finer compartmentalization, with multiple neuromuscular compartments within each muscle enabling precise movements necessary for articulate speech.[23] Advanced imaging and biomechanical modeling have shown as many as 10 compartments in the genioglossus muscle alone.[24] Electromyography and anatomical studies further demonstrate regional heterogeneity in muscle activation. Functional MRI and computational models have shown that both cortical and subcortical brain regions of the human brain coordinate these intricate muscle activities during speaking.[25]

Clinical and translational studies highlight the impact of neuromuscular compartmentalization on speech disorders.[26] Despite significant advances, the full implications of this compartmentalization for speech production, adaptation in disease, and potential therapeutic interventions remain active areas of research.

The literature strongly supports the existence of neuromuscular compartmentalization in the human tongue, which enables the fine, independent control necessary for complex speech production.[27] The combination of advanced imaging, anatomical mapping, and functional studies provides converging evidence for this model, though the precise mechanisms of neural control and inter-compartment coordination remain incompletely understood.[25] The clinical relevance is underscored by studies showing that loss of compartmental control, as seen in ALS or after glossectomy, leads to significant speech deficits and compensatory behaviors. However, some studies highlight the challenges in directly linking anatomical compartments to specific speech functions, and alternative models (e.g., muscle synergies, reflex contributions) are also considered.[25] The field would benefit from further integration of computational, neurophysiological, and clinical research to fully elucidate the implications for speech therapy and rehabilitation.

The tongue, though small, is a truly remarkable part of our bodies. When you pause to think about it, it's involved in almost everything we do to communicate, eat, and even breathe. Most people learned in school that our tongue has eight muscles—some to help it move, others to make all kinds of shapes. But anyone who's tried to imitate an accent, play a wind instrument, or even whistle knows there's more happening under the surface.

Recent research has turned our old ideas upside down. Scientists have figured out that each of those muscles is actually made up of smaller pieces, each doing its own job. Instead of eight big muscles working as a team, imagine dozens of little "crew members," each able to pitch in on its own or together as needed. That's why your tongue can make such precise movements, whether you're speaking clearly, licking an ice cream cone, or pronouncing a tricky word.

When experts looked closer, they saw that the tongue's setup is even more complicated than they'd guessed. Take the muscle that helps you stick out your tongue—the genioglossus. It isn't just one chunk; it might have as many as ten smaller parts, all with their own specialties. Similar arrangements show up in other tongue muscles, meaning you can control different parts at once. Think about it: the tip can move one way, the sides another, and the middle does something else—no wonder we can make so many different sounds!

There's a lot of proof for this. Scientists have tracked muscle fibers, mapped out where nerves connect, and even measured tiny electrical signals to see which parts of the tongue "light up" during different tasks. All the results agree—separate parts can act independently.

Why does this matter? It's what allows us to speak so clearly and with so much variety. Being able to move different parts of the tongue on their own is essential for everything from chatting with friends to learning a new language. Studies, especially those using computer models and films of people talking, show just how the front, middle, and sides of the tongue all do their own thing.

Surprisingly, scientists have learned a lot from our canine companions. When they examined the tongues of dogs, they found that some muscle sections are slower and steadier, helping with breathing, while others are quick and nimble, perfect for lapping up water or shaping sounds. The nerve networks are laid out so each little part can be controlled with incredible detail.

All of this becomes even more important when things go wrong. Some health conditions, such as Down syndrome or certain diseases that affect nerves, can change the way these connections work. When they do, people often have trouble talking or swallowing. Researchers saw that, in mice with similar problems, the links between nerves and muscles in the tongue look damaged or oddly shaped—much like what happens with aging or in human patients who struggle with speech.

To understand these problems better, scientists now use clever lab setups that let them watch nerves and muscles "talk" to each other in real time and see what happens when things are working well—or not.

So, this new understanding of the tongue's inner workings has really opened doors. It helps explain how we pull off everything from perfect pronunciation to enjoying a meal. It also points the way to better treatments and therapies for people with speech or swallowing difficulties.

Of course, it's important to recognize that no review is perfect. Different researchers use different methods, and sometimes the data isn't complete. Still, when so many studies tell the same story, we can be pretty sure there's something real going on. Looking ahead, following how these pieces work together over time in both healthy and sick people—using the latest imaging techniques and maybe even more detailed computer models—will be the key.

5. Conclusion

In short, all the evidence—from how our tongues are built to how they work—shows that having these smaller, specialized sections is what makes the tongue so versatile and precise. When that organization breaks down, our ability to speak, eat, and even breathe can be affected. These findings have already changed the field and are likely to help shape new treatments for years to come. Neuromuscular compartmentalization is a fundamental characteristic of the human tongue muscles, allowing for precise and flexible movements necessary for speech, according to evidence from anatomical, imaging, and electrophysiological investigations. A disruption of this organization is linked with decreased motor control. Combining these discoveries advances our knowledge of speech biomechanics and gives fresh approaches to focused treatments.

6. Source of Funding

None.

7. Conflict of Interest

None.

References

1. Wrench AA. The Compartmental Tongue. *J Speech Lang Hear Res.* 2024;67(10):3887-913.
2. Takemoto H. Morphological analyses of the human tongue musculature for three-dimensional modeling. *J Speech Lang Hear Res*. 2001;44(1):95-107.
3. Mu L, Sanders I. Human tongue neuroanatomy: Nerve supply and motor endplates. *Clin Anat.* 2010;23(7):777-91.
4. Sokoloff AJ. Neuromuscular strategies for human tongue movement. In: Proceedings of the 15th International Congress of Phonetic Sciences (ICPhS); Barcelona, *Spain*. 2023;3181-4.
5. Slaughter K, Li H, Sokoloff AJ. Neuromuscular organization of the superior longitudinalis muscle in the human tongue. 1. Motor endplate morphology and muscle fiber architecture. *Cells Tissues Organs*. 2005;181(1):51-64.
6. Sakamoto Y. Configuration of the extrinsic muscles of the tongue and their spatial interrelationships. *Surg Radiol Anat.* 2017;39(5):497-506.
7. Xing F, Stone M, Goldsmith T, Prince JL, El Fakhri G, Woo J. Atlas-Based Tongue Muscle Correlation Analysis From Tagged and High-Resolution Magnetic Resonance Imaging. *J Speech Lang Hear Res.* 2019;62(7):2258-69.
8. Jugé L, Knapman FL, Burke PGR. Regional respiratory movement of the tongue is coordinated during wakefulness and is larger in severe obstructive sleep apnoea. *J Physiol*. 2020;598(3):581-97.
9. Neef NE, Hoang TN, Neef A, Paulus W, Sommer M. Speech dynamics are coded in the left motor cortex in fluent speakers but not in adults who stutter. *Brain.* 2015;138(P3):712-25.
10. Grabski K, Lamalle L, Vilain C. Functional MRI assessment of orofacial articulators: neural correlates of lip, jaw, larynx, and tongue movements. *Hum Brain Mapp.* 2012;33(10):2306-21.
11. Conant DF, Bouchard KE, Leonard MK, Chang EF. Human Sensorimotor Cortex Control of Directly Measured Vocal Tract Movements during Vowel Production. *J Neurosci*. 2018;38(12):2955-66.
12. Doyle BM, Singer ML, Fleury-Curado T. et al. Gene delivery to the hypoglossal motor system: preclinical studies and translational potential. *Gene Ther*. 2021;28(7-8):402-12.
13. Baptista PM, Martínez Ruiz de Apodaca P, Carrasco M. et al. Daytime Neuromuscular Electrical Therapy of Tongue Muscles in Improving Snoring in Individuals with Primary Snoring and Mild Obstructive Sleep Apnea. *J Clin Med*. 2021;10(9):1883.
14. Saigusa H, Yamashita K, Saigusa M, Niimi S. Nerve fiber analysis of the lingual branch of the glossopharyngeal nerve in human adult subjects. *Surg Radiol Anat.* 2021;43(2):243-50.
15. Smith JC, Goldberg SJ, Shall MS. Phenotype and contractile properties of mammalian tongue muscles innervated by the hypoglossal nerve. *Respir Physiol Neurobiol*. 2005;147(2-3):253-62.
16. Ross CF, Laurence-Chasen JD, Li P, Orsbon C, Hatsopoulos NG. Biomechanical and Cortical Control of Tongue Movements During Chewing and Swallowing. *Dysphagia.* 2024;39(1):1-32.
17. Stone M, Woo J, Lee J, Poole T, Seagraves A, Chung M. et al. Structure and variability in human tongue muscle anatomy. *Comput Methods Biomech Biomed Eng Imaging Vis*. 2018;6(5):499-507.
18. Holtermann A, Roeleveld K, Mork P, Grönlund C, Karlsson J, Andersen L. et al. Selective activation of neuromuscular compartments within the human trapezius muscle.. J Electromyography kinesiology: *official J Int Soc Electrophysiol Kinesiol*. 2009;19(5):896-902.
19. Harley P, Paredes-Redondo A, Grenci G, Viasnoff V, Lin Y, Lieberam I. 3D Compartmentalised Human Pluripotent Stem Cell–derived Neuromuscular Co-cultures. Bio-protocol. 2023;13(5):e4624.
20. Da Silva Costa R, Kung J, Poukens V, Yoo L, Tychsen L, Demer J. Intramuscular innervation of primate extraocular muscles: unique compartmentalization in horizontal recti. Investigative ophthalmology & visual science. 2011;52;(5):2830-6.
21. Ward PJ. First year medical students' approaches to study and their outcomes in a gross anatomy course. *Clin Anat.*, 2011;24:120-7.
22. Offrede T, Mooshammer C, Fuchs S. Breathing and speech adaptation: do speakers adapt toward a confederate talking under physical effort? *J Speech Lang Hear Res.* 2023;67(10S):3914-30.
23. Mayerl C, Kaczmarek E, Kennedy M, Shideler H, Smith A, German R. Regional heterogeneity in the EMG activity of extrinsic tongue muscles is critical to tongue function. *Integr Comp Biol.* 2025:29.

24. Shao M, Xing F, Carass A, Liang X, Zhuo J, Stone M, et al. Analysis of tongue muscle strain during speech from multimodal magnetic resonance imaging. *J Speech Lang Hear Res*. 2023;66(2):513-26.
25. Sanguineti V, Laboissière R, Ostry DJ. A dynamic biomechanical model for neural control of speech production. *J Acoust Soc Am.* 1998;103(3):1615–27.
26. Rong P, Usler E, Rowe L, Allison K, Woo J, Fakhri E, et al. Speech intelligibility loss due to amyotrophic lateral sclerosis: the effect of tongue movement reduction on vowel and consonant acoustic features. *Clin Linguist Phon*. 2021;35(7):617–36.
27. Liang X, Elsaid N, Jiang L, Roys S, Puche A, Gullapalli R, et al. Validation of muscle fiber architecture of the human tongue revealed by diffusion magnetic resonance imaging with histology verification. *J Speech Lang Hear Res.* 2022;65(10):3661-73.

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