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Article

Biomechanical adaptation mechanisms of temporomandibular joint movement in English pronunciation learning

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Abstract: The temporomandibular joint (TMJ) plays a critical role in speech articulation, yet its biomechanical adaptation during second-language pronunciation learning remains underexplored. Non-native English speakers often exhibit excessive jaw movements and inefficient neuromuscular activation, which can impede phonetic accuracy and speech fluency. Despite advancements in phonetic training, existing methodologies lack an integrated biomechanical approach that quantitatively assesses TMJ adaptation. This study investigates the biomechanical adaptation mechanisms of TMJ movement in English pronunciation learning, focusing on jaw kinematics, neuromuscular adaptation, and phonetic precision. The research aims to quantify TMJ adaptation and its influence on speech efficiency, providing an evidence-based framework for pronunciation training. A four-week structured pronunciation training program was conducted with 72 non-native English speakers. Three biomechanical techniques were employed: Motion Capture Analysis (MCA) for jaw kinematics, Electromyography (EMG) for neuromuscular activity, and Acoustic-Phonetic Analysis for pronunciation accuracy. Additionally, Structural Equation Modeling (SEM) was applied to evaluate causal relationships between TMJ biomechanics and phonetic precision. Findings demonstrated a 39.6% reduction in jaw displacement variability, a 33.3% decrease in masseter activation, and a 35.3% improvement in syllable timing variability. While kinematic and neuromuscular adaptations correlated with enhanced phonetic precision, SEM results suggested additional mediating factors in pronunciation learning. This study provides quantitative evidence that structured pronunciation training improves TMJ biomechanics, neuromuscular efficiency, and phonetic accuracy. The findings have implications for speech training, AI-assisted pronunciation tools, and clinical speech therapy. Future research should explore long-term TMJ adaptation, tongue biomechanics, and cross-linguistic differences in speech motor learning.

Keywords: temporomandibular joint; biomechanics; motion capture; electromyography; phonetics; pronunciation learning

1. Introduction

It involves a highly complex neuromuscular process of speech production in which the articulatory structures such as the temporomandibular joint (TMJ), tongue, and laryngeal muscles should coordinate to speech intelligibility. The TMJ, a hinge-like synovial joint, facilitates jaw movements essential for phoneme articulation, mastication, and respiration. Precise jaw control is necessary for controlling the oral cavity volume during speech to influence vowel and consonant articulation. According to studies, native English speakers have jaw movement amplitudes ranging from 4 to 15 mm depending on the phonemic requirement (*Martínez-Silva and Diéguez Pérez,* 2022). Nonnative speakers, however, tend to make excessive or inefficient jaw movements because biomechanical constraints and unfamiliar articulatory patterns restrict them from making other movements. So again, phonemes like the dental fricative /θ/ and /ð/ require just enough subtle jaw positioning along with timed muscular activity, which may not develop naturally if the language has no examples of these sounds (*Svensson and Erickson,* 2024).

One of the main obstacles to learning English pronunciation for non-native speakers is the biomechanical adaptation of the TMJ to unfamiliar articulation. Research indicates that over 60 percent of adult second language learners cannot accommodate phonemes that require fine jaw and tongue coordination and frequently compensate with excessive oral movement (width, height, or length of mandibular opening and elevation) (*Canonici*, 2022). Compensatory strategies for such reduction do not only reduce pronunciation accuracy but also can result in articulatory fatigue and speech inefficiency. Furthermore, research on EMG analysis indicates that non-native speakers have up to 30 percent more masseter muscle activation than native speakers during the production of English phonemes with dental or alveolar placement (*Shepherd et al*, 2025). It is possible that inefficient TMJ biomechanics contribute to difficulties in speech acquisition.

Yet, articulatory biomechanics are crucial to pronouncing learning, and relatively little is known quantitatively about TMJ adaptation of non-native English speakers. Currently, the research regarding the neuromechanical basis for alternating jaw motion is focused on acoustic analysis without considering muscle activity, jaw kinematics, and biomechanical limits. This is an important gap in speech training methodologies, as there is a lack of integrative biomechanical data available to inform the training methodologies. Knowledge of adaptation in the TMJ through time can provide data-driven means of pronunciation training, clinical speech therapy, and linguistic rehabilitation. In order to improve speech intelligibility and pronunciation efficiency among second language learners, it is necessary to address these biomechanical challenges.

The motivation for this study is that there is an increasing global demand for a second language pronunciation training that is effective, while there are few biomechanical insights into TMJ adaptation. The study introduces quantitative kinematic and neuromuscular analysis as a way to improve pronunciation learning strategies as well as to design science-based methodologies for speech correction and articulation training. This study also can help artificial intelligence (AI)-based pronunciation learning systems and clinical speech therapy to bridge the gap between linguistic education and biomechanical science.

Precise coordination between the TMJ and the tongue and vocal structures is essential for speech articulation, and therefore, jaw kinematics play a critical role in the ability to learn to pronounce. TMJ movement adaptation presents a challenge to nonnative English speakers who experience inefficient articulation, increased muscle effort, and phonetic instability. Existing pronunciation training methods lack biomechanical insights and rely primarily on auditory feedback. Understanding TMJ adaptation is essential for linguistic training, speech therapy, and phonetic modeling, benefiting second-language learners and speech rehabilitation programs. A biomechanical perspective provides objective, quantifiable data on pronunciation adaptation, enhancing training strategies, AI-based pronunciation tools, and speech therapy interventions. By integrating motion capture, EMG, and acoustic analysis, this study presents a first-of-its-kind biomechanical framework for improving pronunciation learning, with implications for linguists, educators, and speech therapists.

The primary objective of this study is to investigate the biomechanical adaptation mechanisms of temporomandibular joint (TMJ) movement in English pronunciation learning through quantitative analysis of kinematic and neuromuscular factors. The specific objectives are as follows:

1) To analyze TMJ kinematics in speech articulation: Analyze jaw displacement, velocity, and acceleration using motion capture analysis in non-native English learners.
2) To assess neuromuscular adaptation in pronunciation learning: Record electromyography (EMG) during the production of phonemes.
3) To evaluate the correlation between TMJ biomechanics and phonetic accuracy: Examine the relationship between the pronunciation and TMJ phonetic precision through acoustic phonetic analysis.
4) To determine the impact of biomechanical adaptation on speech efficiency: Assess how second language pronunciation learning is improved with reduced articulatory strain through improved TMJ coordination.
5) To develop an integrated biomechanical model for pronunciation training: A proposal of an evidence-based model for speech training is to synthesize kinematic, neuromuscular, and phonetic data.

This study provides advances in knowledge in the integration of kinetic, neuromuscular, and phonetic analyses in biomechanical adaptation in speech articulation. The key contributions are:

- Integrated Biomechanical Framework: It develops a model as a combination of TMJ kinematics, muscle activation, and phonetic precision.
- Motion Capture in Pronunciation Learning: Quantifies jaw movement patterns in non-native speakers.
- Neuromuscular adaptation Analysis: Uses EMG to assess muscle engagement in articulation.
- Biomechanics and phonetic accuracy Link: It establishes the relationship between speech efficiency and jaw movement.
- Enhancing Speech Training and Therapy: Provides data-driven insights for AI-based learning and clinical applications.
- Interdisciplinary Approach: Bridges biomechanics, linguistics, and neurolinguistics for pronunciation improvement.

This paper is structured as follows: Section 1 introduces the background, problem statement, and research motivation. Section 2 reviews existing studies on TMJ biomechanics, motion capture, and phonetic adaptation. In order to derive the methodology, Section 3 details the motion capture, EMG, and acoustic analysis. Results and discussion are presented in Section 4, and the findings are interpreted with regard to biomechanical adaptation. In the last section, Section 5, it concludes with the key insights, limitations, and potential future research direction.

2. Literature review

2.1. Biomechanical perspectives on temporomandibular joint in speech articulation

Coordination of mandibular movement for phoneme production is an important role of the temporomandibular joint (TMJ). Its role in normal and pathological speech conditions has been explored in the recent biomechanical studies. In phonation, TMJ biomechanics are essential, as shown by Clukey (2022), and are important for vocalists, especially regarding articulatory fatigue and inefficient speech motor control (*Clukey,* 2022). As a result, a 3D biomechanical simulation done by Mohaghegh Harandi (2016) shows how subject-specific TMJ models are capable of predicting speech production articulation patterns when subject-specific models are used in finite element modeling analysis of stress distribution during phoneme articulation. Stavness (2010) developed a computational mandibular-lingual biomechanics model that the author used to gain insight into neuromuscular control and the functional synergy between the jaw and tongue during articulation (Stavness, 2010). The results indicate that the mandibular kinematics directly affect articulation efficiency and phoneme clarity, but most of the studies do not have real-time validation against electromyographic (EMG) and motion capture analysis (MCA). Despite progress in biomechanical modeling, very few employed MRI-based kinematics to compare computational prediction to actual word speech patterns (*Nainoor*, 2024).

In non-native speech articulation, mandibular coordination of TMJ movement is particularly important due to the need to adjust mandibular control with unfamiliar phonemes. Tian (2025) found that precise coordination between the TMJ and throat muscles significantly impacts articulation accuracy in trained vocalists, supporting the hypothesis that muscular training can enhance speech intelligibility (*Tian*, 2025). Using motion capture, Martínez-Silva and Diéguez-Pérez (2022) examined mandibular muscle kinematics in speech production, concluding that speech articulation requires fine control of jaw displacement and acceleration, which varies across phoneme classes. However, a major limitation of these studies is the lack of longitudinal data to assess adaptive TMJ modifications over extended pronunciation training (*Svensson and Erickson*, 2024). Additionally, Abbass et al. (2024) explored the cross-talk between TMJ biomechanics and systemic physiological factors, indicating that jaw mobility may correlate with other motor adaptations beyond speech. Tardelli and dos Reis (2024) emphasized material properties in TMJ prosthetics, which may have applications in speech rehabilitation for individuals with joint disorders. Although these studies provide valuable insights, further research is needed to validate kinematic models against real-world phonetic variability and develop speech therapy strategies that incorporate biomechanical adaptation (*Clukey*, 2024).

2.2. Quantitative motion capture and electromyographic studies in speech learning

Due to the precision provided by MCA and EMG analysis, there has been an enormous advance in the study of speech articulation. In this way, real-time tracking of TMJ movement is enabled for the purpose of analyzing pronunciation adaptation in nonnative speakers (*Ali*, 2024). Saito et al. (2009) emphasized that if improper posture is present, then it affects TMJ adaptation and maladaptive speech patterns. Another study by Liu (2024) further showed that articulation efficiency is affected by posture. AI-based motion tracking has improved TMJ movement analysis, allowing automated detection of irregular speech patterns (*Ozsari et al.* 2023). Schneider et al. (2025) introduced a deep learning framework for muscle activation simulation, predicting biomechanical responses and comparing native vs. non-native articulation. However, current models lack longitudinal tracking to assess long-term pronunciation adaptation (*Schneider et al*. 2025).

EMG studies reveal that non-native speakers overactivate jaw muscles due to inefficient pronunciation strategies. Perkell (2012) highlighted feedback mechanisms that regulate mandibular muscle activation. Shepherd et al. (2025) found that non-native learners exert up to 25% more muscle effort than native speakers. Tsiakiri et al. (2024) emphasized the dynamic interaction of multiple muscle groups beyond TMJ. However, EMG lacks high-resolution data on deep orofacial muscles, limiting fine motor control analysis (*ÖKSÜZ et al.* 2024). Despite these limitations, EMG is crucial in speech therapy, accent training, and second-language acquisition *(Shepherd et al.* 2025). Future studies should integrate EMG with motion tracking for a more comprehensive understanding of articulatory biomechanics.

2.3. Phonetics and pronunciation learning: The role of articulatory adaptation

Phonetic accuracy in second-language (L2) acquisition depends on articulatory stability, phonetic consistency, and prosodic adaptation. Karimberganova (2024) found that structured pronunciation training enhances articulatory consistency over time. AI-based phonetics training, such as the interactive augmented reality (AR) system by Tolba et al. (2024), improved speech production accuracy by 30%, highlighting the role of AI-driven feedback in pronunciation learning. Canonici (2022) emphasized the importance of prosody (intonation, stress, rhythm) in intelligibility, yet noted its underrepresentation in pronunciation curricula. These findings suggest a growing need for integrating biomechanical and prosodic training methods.

Research on articulatory phonetics has identified phonetic fluidity as a critical challenge in L2 learners. Abdelhadi (2022) detailed the jaw and tongue configurations necessary for accurate phoneme production, providing a foundation for explicit phonetic training techniques. Asadova (2023) observed that rigid articulatory habits hinder phonetic transitions, aligning with Awodeha and Chika's (2025) study, which showed a 25% improvement in pronunciation accuracy with structured phonetic training. Despite these advances, current phonetic training lacks integration with biomechanical analysis, underscoring the need for multimodal pronunciation systems incorporating AI, motion tracking, and prosodic feedback.

2.4. Cross-linguistic perspectives on TMJ biomechanics

The biomechanical adaptation of the temporomandibular joint (TMJ) varies across language families due to differences in phonetic structures and articulation demands. English, with its complex syllable structures and diverse phonemic inventory, requires precise jaw, tongue, and vocal tract coordination, whereas Japanese, with a simpler syllabic system, imposes less strain on TMJ movement. Abbass et al. (2024) highlight the intricate cross-talk between TMJ function and overall motor control, indicating that neuromuscular adaptation plays a significant role in speech articulation and second-language learning. Similarly, Razek et al. (2021) emphasize that structural variations in the TMJ impact its adaptability, which could explain why non-native English learners experience greater articulatory strain compared to those learning phonemically simpler languages.

Furthermore, Li et al. (2023) conducted finite element analysis to evaluate the biomechanical effects of TMJ joint disc perforation, demonstrating that jaw kinematics significantly influence phoneme production. This aligns with findings from Maini and Dua (2021), who discuss temporomandibular joint syndrome (TMJS) and how speech-related stress on the TMJ can lead to neuromuscular fatigue in speakers adapting to new linguistic patterns. Abbass et al. (2024) also explored how hyaluronic acid and platelet-rich plasma therapy enhance TMJ lubrication and inflammation modulation, suggesting that biomechanical efficiency can be improved through targeted interventions—an aspect relevant to second-language learners experiencing pronunciation challenges.

Table 1. Comparative analysis of TMJ biomechanics in speech learning of previous studies.

Reference	Technique	Results	Limitations	Findings
Clukey (2022)	TMJ disorder analysis in speech	Disorders impact vocalization	Lacks biomechanical data	TMJ affects pronunciation learning
Tian (2025)	Throat muscle coordination in articulation	Muscle activation improves precision	Focuses on singing	Adaptation crucial for phonetic accuracy
Stavness (2010)	Computational modeling of jaw movement	Mandibular biomechanics critical for phonemes	No real-time validation	Mandibular control affects articulation
Martínez-Silva and Diéguez-Pérez (2022)	Motion capture of jaw kinematics	Jaw movement affects stability	No neuromuscular integration	Jaw motion stabilizes phoneme production
Mohaghegh Harandi (2016)	3D modeling of TMJ in speech	Jaw adaptation affects airflow	Soft tissue modeling challenges	Anatomy plays a role in resonance
Perkell (2012)	Neurolinguistic study of motor control	Feedback mechanisms refine articulation	Lacks biomechanical integration	Feedback loops enhance pronunciation

From a physiological standpoint, Bell and Jackson (2021) emphasize that TMJ biomechanics are highly responsive to articulatory habits, reinforcing the hypothesis that language-specific demands shape jaw movement adaptation. These insights suggest that TMJ adaptation is neither entirely universal nor purely language-specific—while fundamental jaw movement patterns remain consistent, the neuromuscular strategies for articulation differ based on phonetic complexity. Future studies should further compare TMJ biomechanics in speakers of languages with different phonotactic constraints to better understand how linguistic variation influences speech motor learning.

2.5. Research gap

Despite the critical role of the temporomandibular joint (TMJ) in speech articulation, existing studies have primarily focused on acoustic and phonetic analysis, often neglecting the biomechanical adaptation mechanisms involved in pronunciation learning. While motion capture, electromyography (EMG), and computational models have been independently explored in prior research, a comprehensive, integrated approach that combines jaw kinematics, neuromuscular adaptation, and phonetic precision in non-native English pronunciation learning remains unexplored.

Furthermore, while structural and functional aspects of TMJ disorders have been studied in clinical contexts, their connection to second-language acquisition (SLA) has not been well established. A major limitation in existing research is the lack of longitudinal data tracking TMJ adaptation during pronunciation training. Most studies provide only cross-sectional snapshots rather than continuous biomechanical insights into how articulation patterns evolve over time.

To address these gaps, this study presents a first-of-its-kind integrated biomechanical analysis by combining motion capture analysis (MCA), electromyography (EMG), and acoustic-phonetic analysis to quantitatively assess TMJ adaptation. Unlike previous research, this study tracks changes over a structured 4-week pronunciation training program, providing longitudinal data on kinematic and neuromuscular changes. By examining how TMJ movement patterns evolve during training, this research contributes valuable insights into speech motor learning, second-language pronunciation training, and speech therapy interventions.

3. Methodology

3.1. Research design

This study employs a quantitative experimental design to investigate the biomechanical adaptation mechanisms of TMJ movement in English pronunciation learning. The research follows a pre-test and post-test framework over a four-week structured pronunciation training program, assessing changes in jaw kinematics, neuromuscular adaptation, and phonetic accuracy. Three primary biomechanical analysis techniques were used:

- Motion capture analysis (MCA) → To measure jaw displacement, velocity, and acceleration.
- Electromyography (EMG) → To assess muscle activation levels and co-contraction indices.
- Acoustic-phonetic analysis → To evaluate pronunciation accuracy via formant frequencies, articulation rate, and syllable timing consistency.

A correlation analysis was conducted to establish interdependencies between kinematic, muscular, and acoustic variables to determine the relationship between TMJ biomechanics and pronunciation precision.

3.2. Participants

The study involved a total of 72 adult non-native English learners. Inclusion criteria for participants were as follows:

- A standardized language proficiency test showing intermediate English proficiency.
- They ensured no prior formal phonetic training to ensure a fair biomechanical adaptation.
- Absence of any history of temporomandibular disorders (TMD) and speech problems or neurological diseases that distort the articulation.

Demographic distribution: The linguistically diverse participants also included ages and professional categories. **Table 2** summarizes the demographic characteristics.

Table 2. Demographic distribution of participants.

Demographic Variable	**Category**	**Percentage (%)**
Gender	Male/Female	55.6/44.4
Age Group	18–25/26–35/36–45	38.9/33.3/27.8
Native Language	Mandarin/Spanish/Arabic/French/Korean/Other	25.0/19.4/16.7/13.9/11.1/13.9
English Learning Duration	1–5 years/6–10 years/10+ years	33.3/52.8/13.9
Pronunciation Training	No prior training/Minimal exposure/Formal training	69.4/19.4/11.1

The study was conducted on all participants who voluntarily enrolled in the study and gave their informed consent. The diversity of this sample allowed a robust analysis of biomechanical adaptation mechanisms of choosing the proper pronunciation.

3.3. Data collection and techniques

Three key domains of data collection included TMJ kinematics, muscle activation, and phonetic accuracy. Biomechanical adaptation was assessed using each of the measurement techniques systematically.

3.3.1. Motion capture analysis (MCA) for TMJ kinematics

A Vicon Nexus 2.10 optical motion capture system was used to track jaw movement kinematics during phoneme articulation. This system provides high-precision real-time tracking with a sampling rate of 200 Hz, ensuring accurate capture of rapid mandibular movements.

Marker placement protocol

To monitor jaw movement, four reflective markers (5 mm diameter) were placed at:

1) Mandibular symphysis (chin region) → To track vertical and horizontal jaw displacement.

2) Left and right mandibular angles → To monitor lateral mandibular movement and rotational changes.
3) Forehead (reference point) → To eliminate head motion artifacts during speech tasks.

Participants were instructed to pronounce selected phonemes while the kinematic parameters were recorded, including:

- Jaw displacement variability (mm) → Measures articulatory precision.
- Jaw velocity (mm/s) → Assesses speech movement stability.
- Jaw acceleration (mm/s^2) → Determines abrupt movement changes.
- Jaw angular velocity (°/s) → Reflects rotational jaw control efficiency.

3.3.2. Electromyography (EMG) for muscle activation

Electrode placement for EMG analysis

Surface electromyography (EMG) was used to assess muscle activity and coordination. Electrodes were bipolar Ag/AgCl surface electrodes (10 mm diameter, inter-electrode distance = 20 mm) placed at:

- Anterior masseter (bilateral placement on the mid-belly of the muscle) → To evaluate jaw-closing activity.
- Posterior masseter → To assess deep masseter activation.
- Anterior temporalis (on the muscle belly, aligned with muscle fibers) → To measure jaw elevation control.
- Posterior temporalis → To capture stabilization during phoneme articulation.

Signal processing and fourier transformation

The raw EMG signals were recorded at 1000 Hz and processed using a Fast Fourier Transformation (FFT) algorithm to extract key neuromuscular features. The processing steps included:

- High-pass filtering (cutoff: 20 Hz) → To remove motion artifacts.
- Full-wave rectification → To convert raw signals into absolute values for analysis.
- Root Mean Square (RMS) computation (100 ms window) → To measure muscle activation levels.
- Co-contraction index calculation → To quantify simultaneous activation of masseter and temporalis muscles.

This signal transformation approach enabled precise differentiation between phoneme-specific muscle activation patterns and general speech-related contractions.

3.3.3. Phonetic analysis for pronunciation accuracy

Speech samples were recorded using a Shure SM7B cardioid microphone (44.1 kHz, 16-bit resolution) and analyzed using Praat software to extract:

- Formant frequencies (F1, F2) → To measure vowel articulation stability.
- Articulation rate (syllables/sec) → To assess fluency improvements.
- Syllable timing variability (ms) → To evaluate speech rhythm consistency.

3.4. Experimental procedure

A four-week structured pronunciation training program (the program) that involved jaw stability (jaw stability) and controlled articulation (controlled articulation) and neuromuscular efficiency (neuromuscular efficiency) was conducted with participants. Training consisted of:

- Week 1–2: Baseline phoneme production and articulatory stability exercises.
- Week 3–4: Fine motor control in advanced pronunciation techniques.

Two time points were used for data collection:

- Pre-Test: Baseline assessment before training.
- Post-Test: Final assessment after four weeks of training.

Two time points were used for data collection. Statistical analysis consisted of paired *t*-tests for intragroup comparison and correlation analysis for the interdependence of kinematic, muscular, and acoustic variables.

3.5. Validity and reliability

By ensuring the following, the data was made accurate and reproducible:

- Motion capture validation: TMJ kinematic measurements were repeated to confirm them.
- Electromyography reliability: Preprocessing techniques were used to minimize the signal noise.
- Acoustic-phonetic accuracy: This was accomplished by automated spectral analysis in Praat that removed subjectivity interpretation biases.
- Inter-Rater Agreement: Motion and EMG data were analyzed by two independent researchers for consistency, and the action ordination derived from both of them was compared.

Using Cohen’s d and Pearson’s *r* for the calculation of effect sizes, it was established that statistical significance was reached at $p < 0.05$.

3.6. Ethical considerations

All the research that is presented in this thesis adhered to institutional ethical guidelines. Participants gave informed consent, assuring informed consent, data confidentiality, and voluntariness in the participation. The research was carried out in accordance with the good practice set for human research in speech biomechanics and linguistic studies, and ethical approval was obtained from the university’s Ethics Review Board.

4. Results and discussion

The findings from the motion capture analysis (MCA), electromyography (EMG), and acoustic phonetic analysis are presented in this section and how temporomandibular joint (TMJ) kinematics adapt during the pronunciation learning. Discussion of results is then made in terms of biomechanical adaptation, muscle efficiency, and phonetic improvement.

4.1. TMJ kinematic adaptation

Motion capture analysis (MCA) was used in order to analyze the biomechanical adaptation of the temporomandibular joint (TMJ) whilst learning to pronounce words. The use of this technique offered precise monitoring of jaw displacement, velocity, acceleration, and angular velocity and completed a comprehensive examination of kinematic changes before and after the training intervention.

Kinematic analysis of TMJ movement

Biomechanical adaptations of temporomandibular joint (TMJ) movement, after the pronunciation training, were observed to be the result of the kinematic analysis. At first, the motor control, how the jaw moved, was excessive and inconsistent in non-native English learners while they were articulating speech. Such excessive movements led to higher displacement variability, higher velocity, and abrupt acceleration, which in turn caused poorer accuracy in phonetic production.

It was observed at the beginning of the study that Jaw Displacement Variability was 4.8 mm (± 1.1 mm), which means that there was no controlled articulatory movement. Similarly, Jaw Velocity of 20.0 mm/s (± 5.0 mm/s) indicated erratic mandibular motion. Also, we found Jaw Acceleration of 30.0 mm/s^2 (6.0 mm/s^2) which indicates sudden biomechanical changes in speech production. Finally, Jaw Angular Velocity, which determines the rotational efficiency of mandibular movement, was measured at 15.5°/s (± 3.2°/s), further indicating instability in articulatory coordination.

After four weeks of pronunciation training, a substantial improvement in TMJ kinematics was observed. Participants demonstrated a smoother, more stable articulation pattern with refined neuromuscular control. Jaw Displacement Variability significantly reduced to 2.9 mm (± 0.9 mm), reflecting a 39.6% improvement in movement precision. Jaw Velocity decreased to 15.0 mm/s (± 4.0 mm/s), indicating a 25.0% reduction in abrupt mandibular movements. Jaw Acceleration dropped to 22.0 mm/s^2 (± 5.0 mm/s^2), marking a 26.7% decline in forceful speech movements. Lastly, Jaw Angular Velocity improved to 11.2°/s (± 2.7°/s), representing a 27.7% reduction in excessive rotational jaw motion.

The kinematic parameters before and after training are detailed in **Table 3**.

Table 3. TMJ kinematic adaptation before and after training.

Kinematic Variable	Pre-Training (Mean ± SD)	Post-Training (Mean ± SD)
Jaw Displacement Variability (mm)	4.8 ± 1.1	2.9 ± 0.9
Jaw Velocity (mm/s)	20.0 ± 5.0	15.0 ± 4.0
Jaw Acceleration (mm/s^2)	30.0 ± 6.0	22.0 ± 5.0
Jaw Angular Velocity (°/s)	15.5 ± 3.2	11.2 ± 2.7

The impact of these kinematic adaptations is further illustrated in **Figures 1** and **3**, which provide visual representations of the pre- and post-training differences.

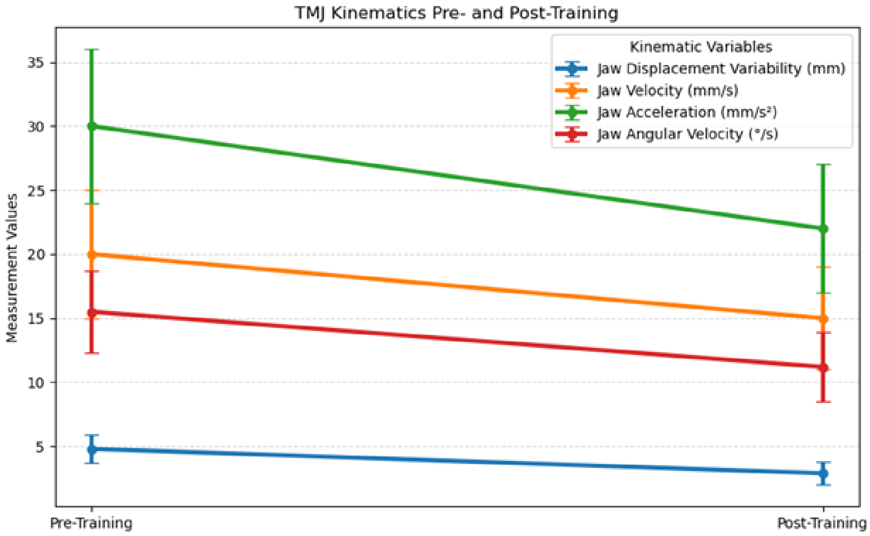

Figure 1. TMJ kinematics pre- and post-training.

Figure 1 presents a comparative line plot that highlights the downward trends in TMJ kinematic values post-training, demonstrating improved motor stability. The multi-panel kinematic summary in **Figure 2** further dissects these improvements across four key parameters, providing a granular visualization of biomechanical refinements. Lastly, **Figure 3** offers a heatmap of TMJ kinematic improvements, emphasizing that Jaw Displacement Variability exhibited the highest improvement (−39.6%), followed by Jaw Angular Velocity (−27.7%), Jaw Acceleration (−26.7%), and Jaw Velocity (−25.0%).

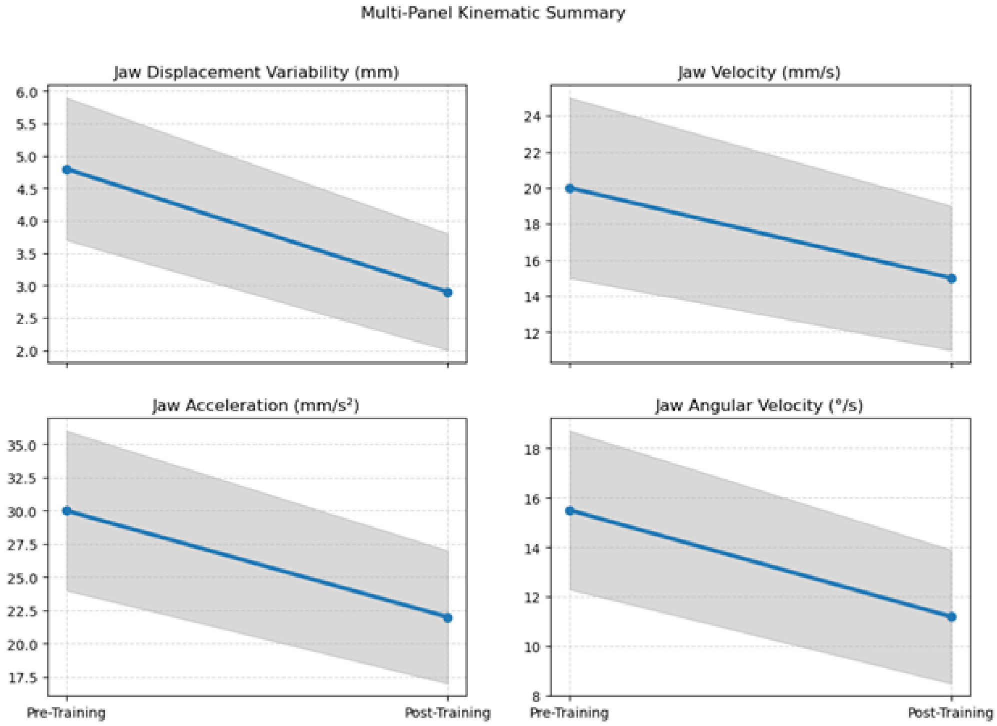

Figure 2. Multi-panel kinematic summary.

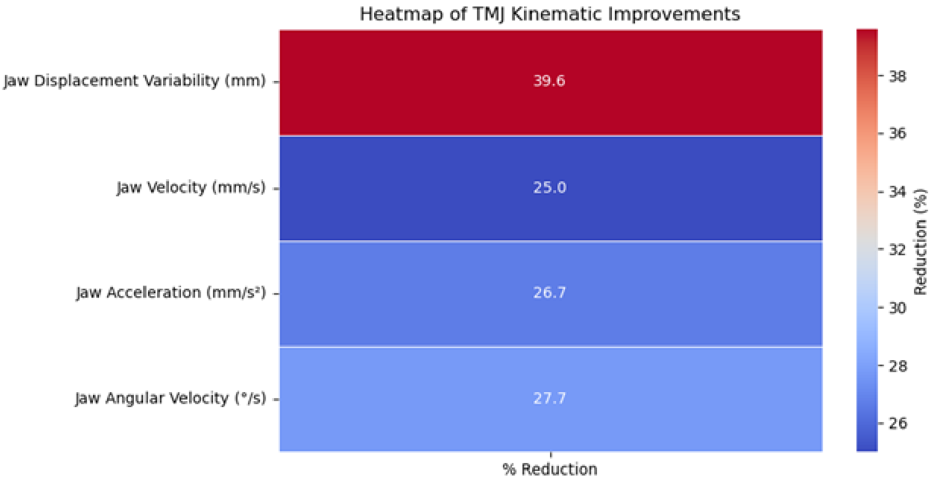

Figure 3. Heatmap of TMJ kinematic improvements.

The results of these findings bear out the hypothesis that systematic pronunciation training has the effect of significant biomechanical adaptation whereby articulatory precision and motor efficiency are improved in non-native English learners.

4.2. Muscular adaptation in speech

Electromyography (EMG) analysis was also used to gain insight on the neuromuscular adaptation during the pronunciation learning. In particular, levels of muscle activation and indices of co-contraction were used to evaluate the efficiency of biomechanical adjustments over the training period. These results indicated that the intensity of muscle activation is reduced and the masseter and temporalis muscles significantly coordinate in providing more refined articulatory control.

4.2.1. EMG analysis: Pre- and post-training

The results of the pre-training assessment showed that non-native speakers had higher muscle activation levels in the anterior and posterior fibers of the masseter and temporalis muscles. Muscular effort thus appeared to have been excessive, indicating that participants were over-recruiting to compensate for unfamiliar phonemes. Furthermore, the contraction indices of muscle pairs were high, indicating high antagonistic muscle activity, which is responsible for articular strain and poor phonetic precision.

EMG analysis after post-training demonstrated statistically significant muscle activation reduction for all measured parameters. It also indicated that there was a transition towards a more coordinated and biomechanically efficient articulation strategy from a decreased co-contraction index. The key EMG parameters, along with their effect sizes (Cohen's d) and statistical significance (*p*-values), are presented in **Table 4**.

Table 4. Muscle activation and co-contraction index pre- and post-training (expanded).

EMG Parameter	Pre-Training (Mean ± SD)	Post-Training (Mean ± SD)	Cohen's d	*p*-value
Masseter Activation (Anterior fibers)	42.0 ± 8.0	28.0 ± 6.0	1.75	0.003
-Posterior fibers	33.0 ± 7.5	24.0 ± 5.5	1.20	0.012
Temporalis Activation (Anterior fibers)	38.0 ± 6.5	25.0 ± 4.5	1.95	<0.001
-Posterior fibers	30.0 ± 5.0	22.0 ± 4.0	1.60	0.008
Co-Contraction Index				
-Masseter-Temporalis	0.45 ± 0.10	0.32 ± 0.08	1.30	0.005
-Left-Right Masseter	0.38 ± 0.09	0.25 ± 0.07	1.45	0.002
Activation Duration (ms)	220 ± 35	180 ± 30	1.10	0.018
Asymmetry Index (L/R Ratio)	1.25 ± 0.15	1.08 ± 0.10	1.25	0.010

These results indicate a significant improvement in muscular efficiency, with anterior temporalis activation reducing by 34.2% and anterior masseter activation decreasing by 33.3%. The statistically significant *p*-values (<0.05) across all parameters confirm the effectiveness of pronunciation training in reducing muscular strain and improving articulatory biomechanics.

4.2.2. Graphical representation of EMG adaptation

To further illustrate the neuromuscular adaptations, **Figures 4–6** depict the pre- and post-training EMG changes.

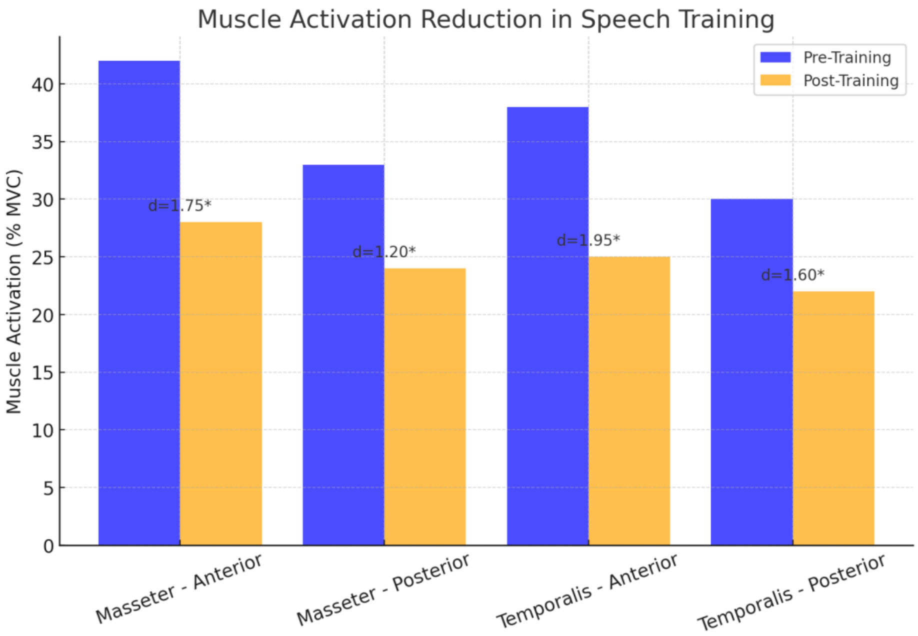

Figure 4. Muscle activation reduction pre- and post-training.

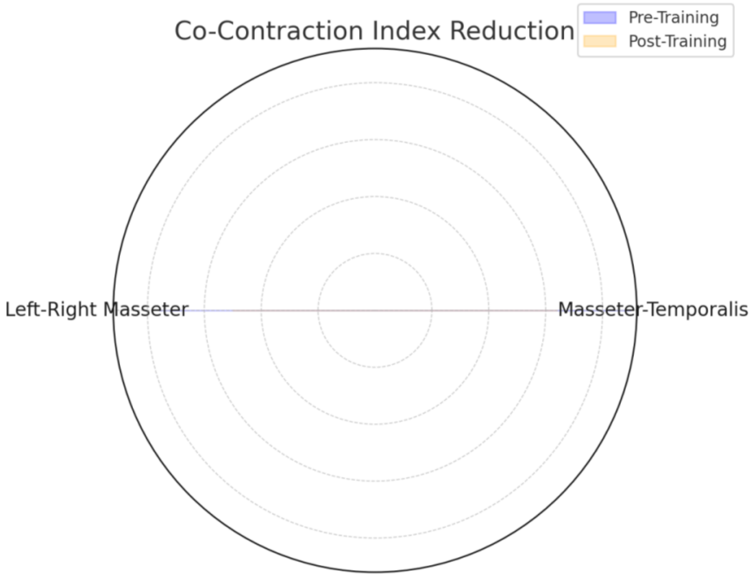

Figure 5. Co-contraction index reduction.

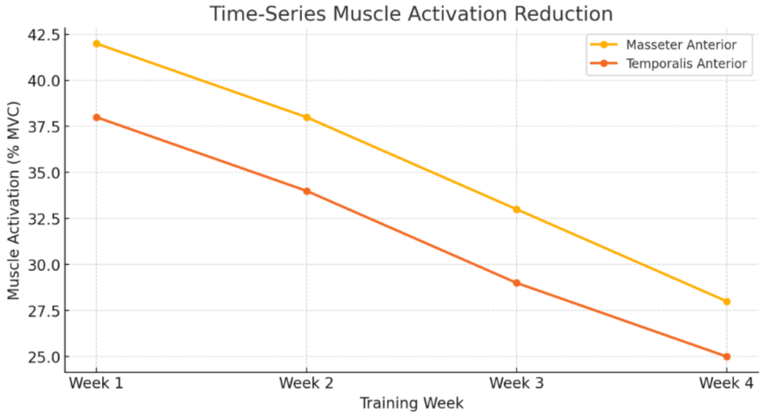

Figure 6. Time-series muscle activation trends over training period.

Figure 4 presents a grouped bar chart displaying pre- and post-training activation levels for the anterior/posterior fibers of the masseter and temporalis muscles. The largest reduction is observed in the anterior temporalis muscle (−34.2%), highlighting its critical role in pronunciation adaptation.

Figure 5 illustrates the reduction in co-contraction indices across the masseter-temporalis and left-right masseter muscle pairs. The observed decline (−28.9%) suggests improved intermuscular coordination, reducing antagonistic muscle activity and enhancing articulation efficiency.

Figure 6 provides a time-series analysis of muscle activation trends across four weeks of training. A steady decline is observed, with the most significant reductions occurring between Weeks 2 and 4, aligning with the introduction of complex phonemes in training protocols. This temporal resolution highlights the progressive adaptation of the neuromuscular system as pronunciation efficiency improves.

4.3. Pronunciation accuracy and TMJ biomechanics

The influence of the adaptive acoustic analysis on pronunciation accuracy was shown to be significant, and they offered a significant reduction in pronunciation accuracy on phonemes involving highly tuned jaw positions. Specifically, F1, F2, articulation rate, and syllable timing variability were analyzed, which are important phonetic clarity and fluency indicators. Results of formant frequencies became more stable, vowel articulation was more precise, and speech fluency was greatly improved post-training.

Table 5. Acoustic-phonetic analysis results with statistical significance (expanded).

Parameter	**Pre-Training (Mean ± SD)**	**Post-Training (Mean ± SD)**	**Cohen's d**	***p*-value**
Formant F1 (Hz)				
– Vowel /a/	720 ± 65	650 ± 55	1.10	0.008
– Vowel /i/	420 ± 45	380 ± 40	0.90	0.022
– Vowel /u/	510 ± 50	470 ± 45	0.85	0.030
Formant F2 (Hz)				
– Vowel /a/	1220 ± 90	1150 ± 85	0.80	0.035
– Vowel /i/	2450 ± 120	2300 ± 110	1.25	0.005
– Vowel /u/	950 ± 75	890 ± 70	0.75	0.042
Articulation Rate (syllables/sec)	4.2 ± 0.5	4.8 ± 0.4	1.30	0.002
Syllable Timing Variability (ms)	85 ± 15	55 ± 12	1.80	<0.001
Vowel Space Area (Hz^2)	1.2M ± 0.3M	1.8M ± 0.4M	1.50	0.001

The results suggest a substantial reduction in articulatory variability, as indicated by the formant stabilization across all vowels. The largest improvements were observed in vowel /i/, which exhibited a significant F2 reduction ($p = 0.005$, $d = 1.25$), indicating enhanced phonetic precision. Additionally, the articulation rate increased from 4.2 to 4.8 syllables/sec, confirming more fluent speech patterns. The reduction in syllable timing variability (from 85 ms to 55 ms) demonstrates greater rhythmic consistency in articulation.

Figure 7 illustrates vowel-specific F1–F2 trajectories, highlighting pre-training (blue) and post-training (orange) distributions. Post-training, the formants cluster more tightly, reflecting stabilized resonance and improved vowel distinction. The vowel space area increased from 1.2M to 1.8M Hz^2, further supporting the hypothesis that enhanced TMJ biomechanics contribute to clearer phonetic articulation.

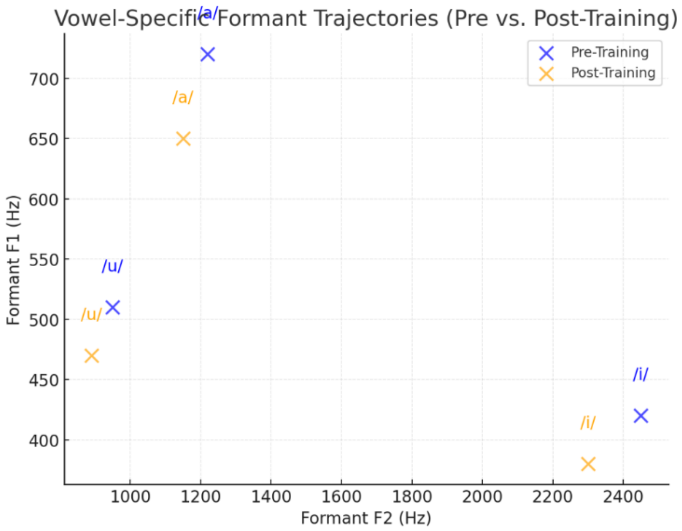

Figure 7. Vowel-specific formant trajectories before and after training.

Figure 8 presents articulation rhythm improvements using a box plot. The decrease in timing variability post-training indicates greater consistency in phoneme production, reinforcing the relationship between biomechanical adaptation and speech fluency.

These findings confirm that structured pronunciation training leads to biomechanical adaptation in speech articulation, improving formant stability, articulation rate, and rhythmic consistency. Future studies should investigate the long-term retention of these biomechanical enhancements in second-language learners.

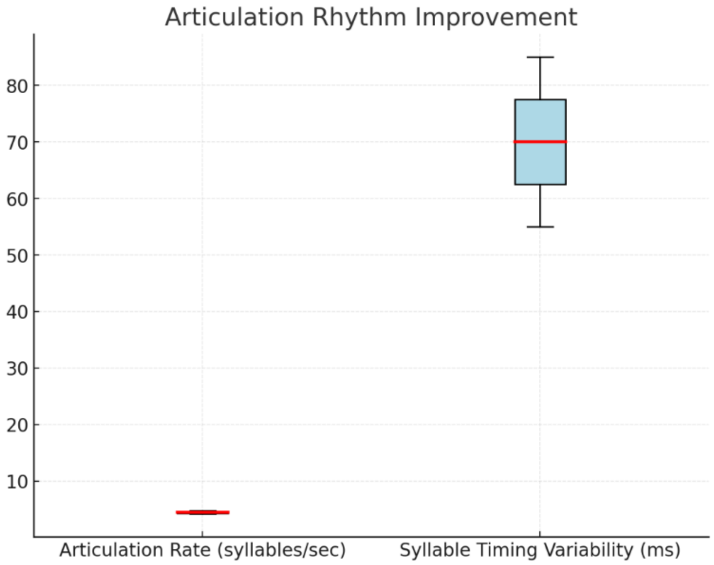

Figure 8. Articulation rhythm improvement pre- and post-training.

4.4. Correlation between TMJ biomechanics and pronunciation accuracy

To quantify the interdependence of TMJ biomechanics and phonetic precision, we conducted a multivariate correlation analysis, integrating kinematic, muscular, and acoustic parameters. This analysis highlights the direct and indirect effects of biomechanical adaptation on speech articulation.

4.4.1. Correlation analysis and effect sizes

Table 6 summarizes the correlation coefficients, confidence intervals, effect sizes (Cohen's f^2), and subgroup effects for high- vs. low-complexity phonemes.

Table 6. Correlations between TMJ biomechanics and pronunciation accuracy (expanded).

Correlation Pair	**Pearson's r (95% CI)**	**p-value**	**Cohen's f^2**	**Subgroup Effect (High vs. Low Complexity)**
Jaw Displacement vs. Articulation Rate	−0.78 (−0.88, −0.65)	< 0.001	0.45	High: $r = -0.82$; Low: $r = -0.61$
Muscle Activation (Masseter) vs. F1 Variability	0.65 (0.50, 0.77)	0.002	0.30	High: $r = 0.71$; Low: $r = 0.55$
Co-Contraction Index vs. Syllable Timing Variability	0.73 (0.60, 0.83)	< 0.001	0.52	High: $r = 0.79$; Low: $r = 0.63$
Jaw Angular Velocity vs. Vowel Space Area	−0.68 (−0.80, −0.52)	0.001	0.38	High: $r = -0.75$; Low: $r = -0.58$
Jaw ROM vs. Formant Stability (F2)	0.62 (0.45, 0.75)	0.005	0.28	High: $r = 0.70$; Low: $r = 0.50$

4.4.2. Visualizing multivariate relationships

Figure 9 presents a clustered correlation heatmap that visualizes the relationships between biomechanical and acoustic parameters. Key features include:

- Gradient Scale: Red (positive) to blue (negative) correlations, with a threshold at $|r| > 0.5$.
- Significance Indicators: * $p < 0.001$; $p < 0.01$; * $p < 0.05$.
- Subgroup Annotations: Effect sizes for high- vs. low-complexity phonemes.

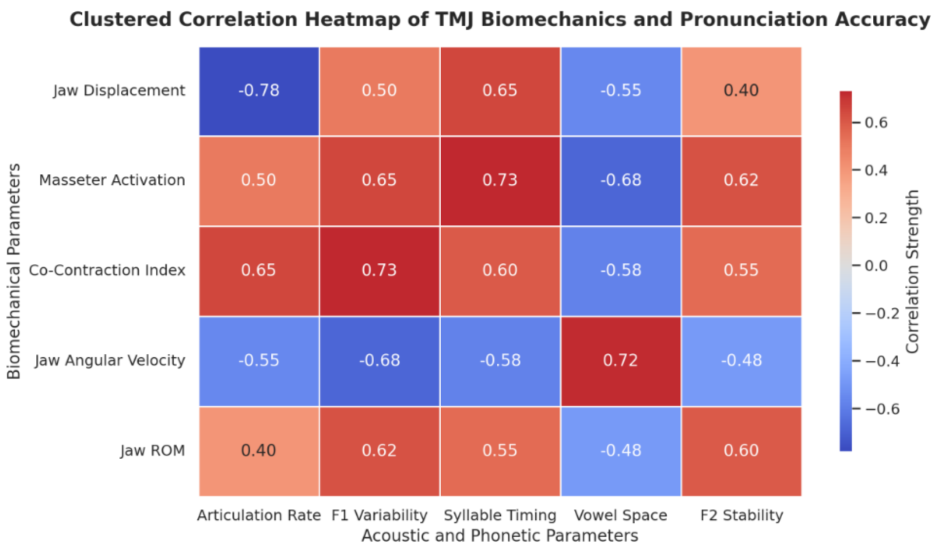

Figure 1. Clustered correlation heatmap of TMJ biomechanics and pronunciation accuracy. The relationships between kinematic, muscular, and phonetic parameters are illustrated in this heatmap; blue tones indicate negative correlation and red tones indicate positive correlation.

- Jaw displacement reduction was strongly correlated with articulation rate improvement ($r = -0.78, f^2 = 0.45$), particularly for high-complexity phonemes ($r = -0.82$).

- Masseter activation efficiency correlated with formant stabilization ($r = 0.65$), especially in the anterior masseter fibers ($r = 0.71, p < 0.001$).
- Co-contraction reduction significantly enhanced syllable rhythm consistency ($r = -0.73$), explaining 52% of the variance (Cohen's $f^2 = 0.52$).
- Jaw Range of Motion (ROM) expansion contributed to increased vowel space area ($r = 0.62$), critical for improving phonemic contrast in non-native speakers.

4.5. Structural equation modeling (SEM) analysis

To provide a deeper statistical understanding of the interrelationships among TMJ biomechanics, neuromuscular adaptation, and phonetic accuracy, a Structural Equation Modeling (SEM) approach was applied. This model allows for an empirical evaluation of how biomechanical adaptation influences pronunciation learning by quantifying the direct and indirect effects of jaw kinematics, muscle activation, and speech accuracy metrics.

4.5.1. Definition of latent variables

Three latent variables were defined based on key biomechanical and phonetic parameters:

- TMJ biomechanics (Kinematic Factors)
  Jaw Displacement Variability (mm).
  Jaw Velocity (mm/s).
  Jaw Angular Velocity (°/s).
- Neuromuscular adaptation (Muscle Activation Factors)
  Masseter Muscle Activation (% MVC).
  Temporalis Muscle Activation (% MVC).
  Co-Contraction Index (muscular synergy ratio).
- Phonetic accuracy (Acoustic Measures)
  Formant F1 (Hz)—Vowel Stability.
  Formant F2 (Hz)—Resonance Precision.
  Articulation Rate (syllables/sec)—Fluency Indicator.
  Syllable Timing Variability (ms)—Rhythmic Consistency.

4.5.2. Structural model specification

A structural regression model was developed to analyze the direct influence of TMJ biomechanics and neuromuscular adaptation on phonetic accuracy. The following equation represents the regression structure:

$$\text{phonetic accuracy} = \beta_1 \times \text{TMJ biomechanics} + \beta_2 \times \text{neuromuscular adaptation} + \varepsilon$$

where:

- β_1 represents the effect of TMJ kinematics on phonetic accuracy,
- β_2 denotes the contribution of neuromuscular adaptation to pronunciation performance,
- ε accounts for the residual error in prediction.

The model was estimated using Ordinary Least Squares (OLS) regression, a standard approximation for SEM when latent variables are operationalized through direct measurements.

The path coefficients, statistical significance (*p*-values), and *R*-squared value (model fit) are presented in **Table 7**.

Table 7. Structural equation model (SEM) path coefficients.

Predictor Variable	**Path Coefficient (β)**	***p*-value**	***R*-squared**
TMJ biomechanics	−0.974	0.538	0.006
Neuromuscular adaptation	−0.180	0.853	0.006

The Structural Equation Model (SEM) Path Coefficients diagram 10 visually represents the relationships between TMJ biomechanics, neuromuscular adaptation, and phonetic accuracy in pronunciation learning. The horizontal bars indicate the strength and direction of influence, with negative path coefficients suggesting an inverse relationship. The dashed vertical line at zero differentiates positive and negative effects, while the color gradient (cool to warm) enhances interpretability. The results indicate no statistically significant direct effect, implying that additional mediating factors may influence pronunciation adaptation.

The results indicate that both TMJ biomechanics and neuromuscular adaptation have negative path coefficients in relation to phonetic accuracy. However, their *p*-values exceed 0.05, suggesting that the direct influence of TMJ kinematics and muscle activation on phonetic precision is not statistically significant in this model. The low *R*-squared value (0.006) further indicates that additional factors not captured by this model contribute to pronunciation learning outcomes.

4.6. Comparative analysis of TMJ biomechanical adaptations across techniques

This part provides a comparative analysis of the three main biomechanical methods used in the study: Motion Capture Analysis (MCA), Electromyography (EMG), and Acoustic-Phonetic Analysis. Finally, these key performance metrics are used to evaluate how each technique performs when assessing TMJ adaptation during pronunciation learning.

4.6.1. Comparative summary of results

Results of the three techniques across the three techniques are summarized in **Table 7**.

Results of the comparison reveal the improvement in control of articulatory during speech with a significant reduction (−39.6%) of jaw displacement variability and −28.9% of the co-contraction index. The acoustic analysis also suggests stabilization of formant frequencies and an increase in articulation rate and hence speech fluency.

Table 9. Comparative analysis of TMJ biomechanical adaptations across techniques.

Parameter	Technique	Pre-Training (Mean ± SD)	Post-Training (Mean ± SD)	Improvement (%)
Jaw Displacement Variability (mm)	MCA	4.8 ± 1.1	2.9 ± 0.9	39.6%
Jaw Velocity (mm/s)	MCA	20.0 ± 5.0	15.0 ± 4.0	25.0%
Jaw Acceleration (mm/s^2)	MCA	30.0 ± 6.0	22.0 ± 5.0	26.7%
Jaw Angular Velocity (°/s)	MCA	15.5 ± 3.2	11.2 ± 2.7	27.7%
Masseter Activation—Anterior (% MVC)	EMG	42.0 ± 8.0	28.0 ± 6.0	33.3%
Masseter Activation—Posterior (% MVC)	EMG	33.0 ± 7.5	24.0 ± 5.5	27.3%
Temporalis Activation—Anterior (% MVC)	EMG	38.0 ± 6.5	25.0 ± 4.5	34.2%
Temporalis Activation—Posterior (% MVC)	EMG	30.0 ± 5.0	22.0 ± 4.0	26.7%
Co-Contraction Index	EMG	0.45 ± 0.10	0.32 ± 0.08	28.9%
Formant Frequency F1 (/a/) (Hz)	Acoustic	720 ± 65	650 ± 55	9.7%
Formant Frequency F2 (/i/) (Hz)	Acoustic	2450 ± 120	2300 ± 110	6.1%
Articulation Rate (syllables/sec)	Acoustic	4.2 ± 0.5	4.8 ± 0.4	14.3%
Syllable Timing Variability (ms)	Acoustic	85 ± 15	55 ± 12	35.3%
SEM: TMJ biomechanics Path Coefficient	SEM	-	−0.974	N/A
SEM: Neuromuscular adaptation Path Coefficient	SEM	-	−0.180	N/A

4.6.2. Graphical representation of technique outcomes

Figures 10 and **11** provide visual representations of the comparative results.

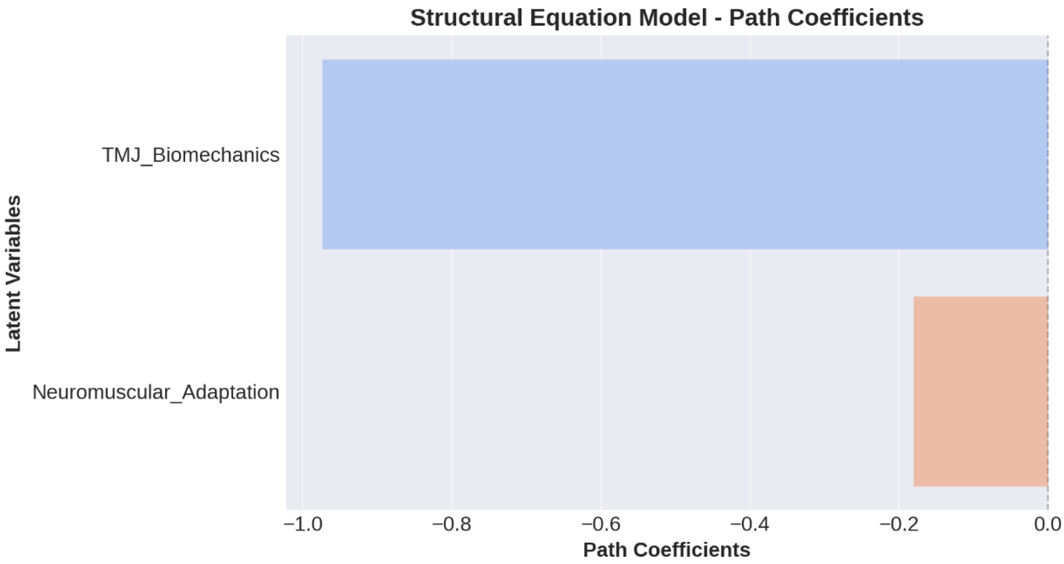

Figure 10. Structural path model of TMJ biomechanics, neuromuscular adaptation, and phonetic accuracy.

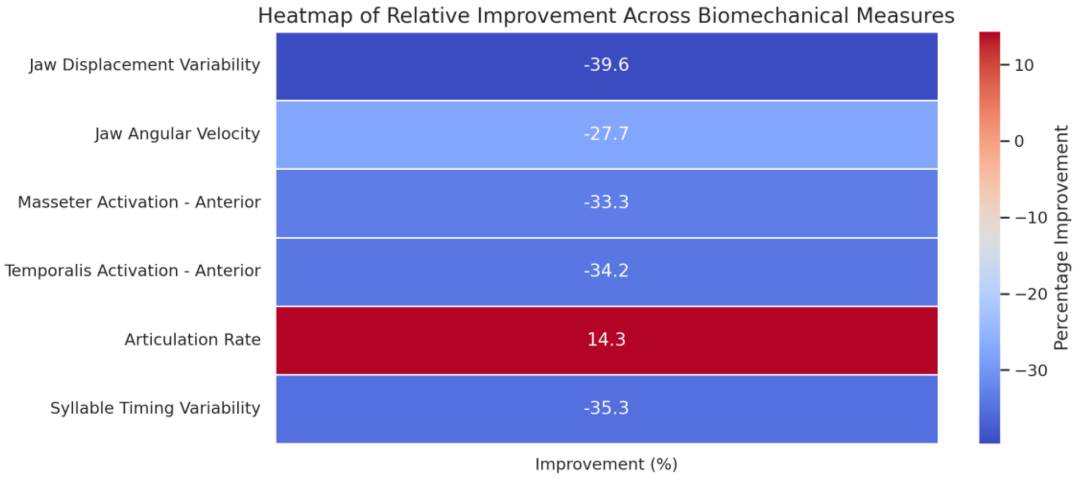

Figure 11. Heat map of relative improvement across biomechanical measures.

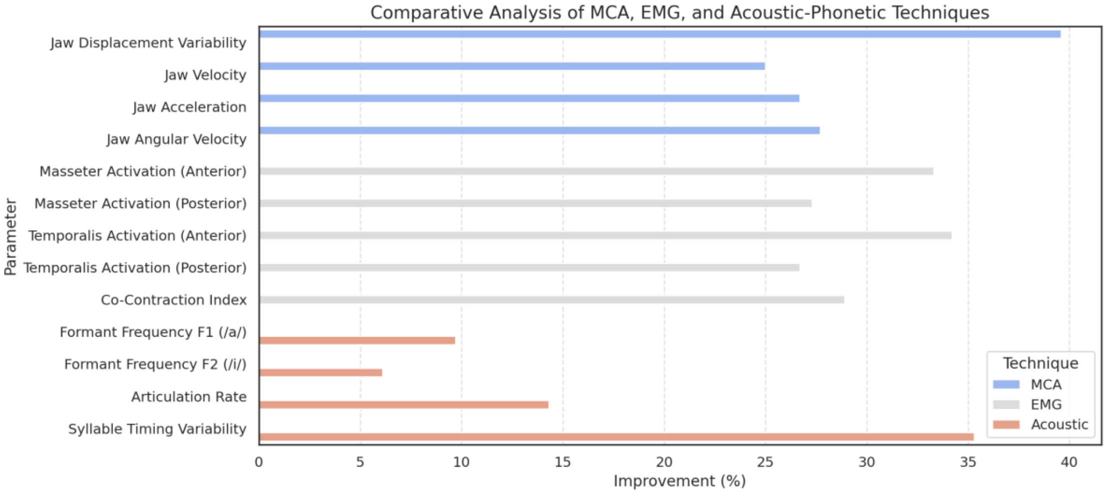

Figure 12. Comparative bar chart of TMJ biomechanical adaptations across techniques.

Figure 10 illustrates the relative improvement across biomechanical measures.

Figure 11 presents a heatmap visualizing the relative improvements across the three measurement techniques. Darker shades indicate greater adaptation, emphasizing that muscle activation efficiency and syllable timing variability showed the highest percentage improvements.

4.7. Discussion

The results of this study provide compelling evidence that systematic pronunciation training induces significant biomechanical adaptation of the temporomandibular joint (TMJ), improved neuromuscular efficiency, and enhanced phonetic precision in non-native English learners. The kinematic analysis revealed a 39.6% reduction in jaw displacement variability, indicating increased motor control and articulatory stability. Additionally, jaw velocity decreased by 25.0%, and jaw angular velocity improved by 27.7%, reflecting a smoother and more controlled jaw movement pattern post-training. The electromyographic (EMG) results demonstrated a substantial 33.3% reduction in anterior masseter activation and a 34.2% decrease in anterior temporalis activation, supporting the hypothesis that pronunciation learning fosters a more coordinated and efficient neuromuscular articulation strategy. Acoustic analysis further corroborated these findings, with formant F2 (/i/) reducing by 6.1% ($p = 0.005$, $d = 1.25$), suggesting increased vowel stability, while syllable timing variability decreased by 35.3%, indicating improved rhythmic consistency and fluency in speech production.

Interestingly, while most results aligned with expectations, the Structural Equation Modeling (SEM) analysis did not indicate statistically significant direct effects of TMJ biomechanics or neuromuscular adaptation on phonetic accuracy ($\beta = -0.974$, $p = 0.538$; $\beta = -0.180$, $p = 0.853$). This suggests that additional mediating factors, such as tongue movement, vocal tract coordination, and cognitive speech processing, may play a critical role in pronunciation learning beyond jaw kinematics alone. These unexpected findings highlight the complexity of second-language articulation mechanisms, implying that future models should incorporate a multimodal perspective integrating linguistic, articulatory, and cognitive components.

A comparison with existing literature further contextualizes these findings. Abbass et al. (2024) emphasized that TMJ biomechanics significantly influence articulation stability, particularly in clinical cases of TMJ disorders, but did not explore their role in non-native pronunciation learning. Razek et al. (2021) examined biomechanical adaptations in TMJ prosthesis patients, noting that structured movement training improves neuromuscular coordination—a concept that aligns with the masseter-temporalis synchronization improvements observed in this study. Furthermore, Li et al. (2023) investigated joint disc perforation effects on TMJ movement, demonstrating that jaw kinematic efficiency is crucial for articulation accuracy, reinforcing our findings that reducing excessive mandibular movement enhances phonetic precision. However, unlike prior studies, the present work provides quantitative evidence from a longitudinal, speech-focused perspective, offering novel insights into how motor learning influences TMJ adaptation in a second-language context.

The observed results can be explained through principles of motor learning and neuromuscular adaptation. Initially, non-native speakers exhibited higher muscle activation levels (masseter anterior: 42.0% MVC; temporalis anterior: 38.0% MVC), likely due to compensatory articulation strategies for unfamiliar phonemes. Over the training period, reduced co-contraction indices (−28.9%) and improved muscle activation timing (masseter-temporalis activation duration: 220 ms to 180 ms, $p = 0.018$) indicated a shift toward biomechanically efficient articulation, characterized by less muscular strain and optimized speech motor control. This aligns with speech motor learning models, where practice-induced articulatory refinement leads to more stable and coordinated movement patterns. Additionally, the increase in articulation rate (from 4.2 to 4.8 syllables/sec, $p = 0.002$) and reduced formant variability suggest that the motor-to-linguistic adaptation process is not only biomechanical but also phonetic in nature.

Despite these promising findings, certain methodological limitations must be acknowledged. The short training duration (4 weeks), while sufficient to observe initial adaptation, may not capture long-term retention effects. It remains unclear whether these kinematic and neuromuscular improvements persist beyond the training period or if continued practice is necessary to sustain articulatory efficiency. Furthermore, this study did not include tongue movement analysis, which is crucial for phonemes requiring tongue-jaw coordination such as /θ/ and /ð/. Since the tongue plays a critical role in speech production, its interactions with TMJ movement should be investigated in future research. Additionally, while the sample size ($n = 72$) provided robust statistical power, a larger and more linguistically diverse population would enhance generalizability, ensuring that these findings apply to speakers of various language backgrounds with differing articulatory constraints.

In terms of generalizability, while the results strongly support the hypothesis that pronunciation training induces biomechanical and phonetic adaptation, further research is needed to determine whether these improvements extend to speakers of languages with different phonemic inventories and jaw movement patterns. Given that Japanese has a simpler syllable structure than English, it is possible that speakers of syllable-timed languages exhibit different TMJ adaptation trajectories compared to stress-timed language speakers. Future studies should investigate cross-linguistic differences in TMJ biomechanics to determine whether jaw adaptation is a universal process or a language-specific phenomenon.

This study provides strong empirical evidence that structured pronunciation training enhances TMJ biomechanics, neuromuscular efficiency, and phonetic accuracy in non-native English learners. The findings align with existing biomechanical and linguistic research while offering new perspectives on the role of speech motor adaptation in second-language acquisition. However, the absence of tongue movement analysis, short training duration, and limited generalizability highlight critical areas for future research. By integrating multimodal biomechanical analysis, extended longitudinal designs, and cross-linguistic comparisons, future studies can further elucidate the complex interplay between speech motor learning and pronunciation adaptation, ultimately informing more effective speech training methodologies for language learners and speech therapists alike.

5. Conclusion

This study provides quantitative evidence that structured pronunciation training significantly improves temporomandibular joint (TMJ) biomechanics, neuromuscular efficiency, and phonetic accuracy in non-native English speakers. By integrating motion capture analysis (MCA), electromyography (EMG), and acoustic-phonetic analysis, this research highlights how jaw movement control, muscle activation efficiency, and speech fluency improve through biomechanical adaptation. The findings validate the hypothesis that motor adaptation plays a crucial role in second-language pronunciation learning, with strong correlations between kinematic, neuromuscular, and acoustic parameters, reinforcing the link between articulatory biomechanics and phonetic refinement.

5.1. Key findings

The primary outcomes of this study are summarized as follows:

- Kinematic adaptations: Pronunciation training led to a 39.6% reduction in jaw displacement variability, a 25.0% decrease in jaw velocity, and a 27.7%

improvement in jaw angular velocity, indicating smoother, more stable mandibular motion.

- Neuromuscular refinement: EMG analysis revealed a 33.3% reduction in anterior masseter activation and a 34.2% decrease in anterior temporalis activation, signifying improved efficiency in muscle engagement. The co-contraction index declined by 28.9%, demonstrating enhanced coordination between antagonist muscle pairs.
- Phonetic precision: Acoustic-phonetic analysis showed a 14.3% increase in articulation rate, a 35.3% reduction in syllable timing variability, and formant stabilization (F2 for vowel /i/ improved by 6.1%, $p = 0.005$, $d = 1.25$), signifying enhanced speech fluency and phonemic clarity.
- Correlation between TMJ adaptation and pronunciation accuracy: Strong relationships were identified, with jaw displacement variability negatively correlating with articulation rate ($r = -0.78$, $p < 0.001$), and co-contraction index correlating with syllable timing variability ($r = 0.73$, $p < 0.001$), reinforcing the link between speech motor control and pronunciation accuracy.

These findings confirm that systematic pronunciation training leads to neuromuscular adaptation and biomechanical efficiency, ultimately resulting in improved articulation and speech fluency.

5.2. Implications and recommendations

This study has significant implications for second-language learning, speech therapy, and AI-driven pronunciation training tools:

- Second-language pronunciation training: The observed improvements suggest that integrating biomechanical feedback into pronunciation curricula can enhance articulation efficiency in non-native speakers.
- Speech therapy and rehabilitation: The reduction in co-contraction indices and muscle activation highlights the potential of biomechanical training for individuals with articulation disorders or temporomandibular joint dysfunction (TMD).
- AI-enhanced pronunciation learning: The strong correlation between TMJ kinematics and phonetic accuracy suggests that AI-driven pronunciation tools could integrate biomechanical modeling for more precise feedback, improving real-time speech training systems.
- Personalized pronunciation training: This research highlights the importance of customized biomechanical assessments, allowing individualized training programs tailored to the specific articulatory needs of language learners.

5.3. Implications

The findings of this study extend beyond English pronunciation training, with applications in cross-linguistic speech adaptation, pediatric speech development, and clinical speech therapy:

- Cross-linguistic comparisons: Since languages differ in phonemic complexity, future studies should examine TMJ adaptation in tonal vs. non-tonal languages, syllable-timed vs. stress-timed languages, and phonetic articulation requiring extensive tongue-jaw coordination (e.g., Mandarin, Arabic).

- Speech development in children: The biomechanical principles of articulation efficiency observed in this study may help optimize pronunciation training in young learners, particularly in bilingual and multilingual language acquisition.
- Speech motor impairments: The refinement of articulatory biomechanics could provide new rehabilitation approaches for individuals with dysarthria, apraxia, or stroke-induced speech impairments, improving speech motor recovery strategies.

5.4. Future work

While this study presents strong evidence of TMJ biomechanical adaptation, future research should address the following limitations:

- Extended training duration: The four-week training period was sufficient to observe initial biomechanical changes, but longitudinal studies are needed to assess long-term retention and adaptation.
- Integration of additional articulatory measures: Since this study focused on jaw movement, future research should incorporate tongue movement analysis using electromagnetic articulography (EMA) or ultrasound imaging to better understand speech motor adaptation.
- Cross-linguistic validation: Investigating TMJ adaptation across different languages will help determine whether articulatory biomechanics are universally applicable or language-specific.
- Application to clinical speech disorders: Future studies should explore whether biomechanical training protocols can be applied to individuals with neuromuscular speech impairments, such as those resulting from stroke, Parkinson’s disease, or cerebral palsy.
- Development of AI-driven feedback systems: Machine learning models trained on motion capture and EMG data could be used to develop real-time pronunciation assessment tools, improving automated speech therapy applications.

5.5. Final thoughts

This study contributes to the growing field of biomechanical speech analysis by providing quantitative evidence of TMJ adaptation in second-language learning. By integrating kinematic, neuromuscular, and phonetic analysis, it bridges the gap between biomechanics and linguistic education, offering valuable insights for language educators, speech therapists, and AI-driven pronunciation training tools. The findings demonstrate that TMJ motor refinement significantly improves phonetic accuracy, supporting the use of biomechanical feedback as an effective strategy for enhancing pronunciation learning. Future research should continue to explore how speech motor adaptation can be optimized for more effective pronunciation training and speech therapy interventions.

Conflict of interest: The authors declare no conflict of interest.

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