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Article

Articulation skills of singing based on the biomechanical coordination of throat muscles

Li Tian

Department of Music, Xi'an Shiyou University, Xi'an 710065, Shaanxi, China; aozhang51905647@163.com

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Abstract: With the development of vocal training in music art, singing skills have been continuously explored and innovated. At present, the articulation skills of singing mostly focus on the surface operations of pronunciation skills such as tongue position, mouth shape, and lip movements, lacking the consideration of throat muscles and their coordination in clear pronunciation. In addition, everyone's pronunciation habits are different, resulting in the low clarity of pronunciation of traditional techniques. This paper used the biomechanical model to analyze the coordination of throat muscles and proposed a systematic and scientific singing pronunciation and articulation training method. The study first built a biomechanical model of throat muscles based on Mooney-Rivlin and CAD, and introduced FEA to perform dynamic simulation on the model to simulate the mechanical behavior of muscle groups under different vocalization states. Then, it took the pharyngeal bones and muscle groups as the research objects, constructed a multi-rigid body dynamics model, and established the dynamic relationship between muscle drive and skeletal movement. Finally, the paper designed personalized singing pronunciation and clarity techniques based on CI, muscle tension distribution, etc. The experiment took 60 healthy singers as subjects, set up an experimental group and multiple control groups, and explored the effectiveness of singing articulation clarity techniques from the perspective of throat muscle biomechanics and visual coordination. The experimental results showed that the pronunciation clarity of the experimental group reached 7 points and the STOI reached 0.84, while the traditional oral resonance training group only scored 5 points and the STOI reached 0.72. The experimental results show that the singing pronunciation clarity technique based on the biomechanical coordination of throat muscles can significantly improve the singing pronunciation clarity and enhance the live listening effect of the singing.

Keywords: throat muscles; biomechanical coordination; articulation skills of singing; multi-rigid body dynamics model; pronunciation clarity

1. Introduction

With the continuous development of singing art, articulation skills have become an indispensable part of singing training [1,2]. When singing, articulation clarity determines the audibility of the lyrics and affects the emotional expression and artistic effect of the song. Traditional vocal training methods usually focus on training techniques such as tongue position, mouth shape, and breathing control [3,4], ignoring the coordination of throat muscles. The coordinated work of throat muscles is crucial for the sound quality control and pronunciation clarity in singing, but traditional methods have failed to systematically study this biomechanical mechanism. In addition, the physiological differences, pronunciation habits and individual characteristics of singers also lead to differences in pronunciation clarity. This paper explores and optimizes the pronunciation clarity techniques in singing from the perspective of the biomechanical coordination of throat muscles, aiming to provide singers with a more scientific and personalized training method.

This paper analyzes the biomechanical coordination of throat muscles and adopts a new singing articulation technique training method. The experiment uses biomechanical modeling technology to simulate the mechanical behavior of throat muscles in different phonation states through the Mooney-Rivlin model and FEA. Combined with the multi-rigid body dynamics model, the dynamic relationship between muscle drive and skeletal movement was explored, and a personalized training method was proposed. Through experiments on 60 healthy singers, the study verified the significant effect of the method in improving the clarity of singing pronunciation and improving the hearing effect. The training method based on the biomechanical synergy of throat muscles has more obvious advantages than traditional pronunciation training methods in improving the clarity of pronunciation and has important application value.

Contributions of this paper:

(1) Based on the Mooney-Rivlin material model and CAD (Computer Aided Design) technology, a biomechanical model of the throat muscles is constructed, and the mechanical behavior of the muscle group is dynamically simulated by combining finite element analysis (FEA). This breaks through the focus on the surface movement of the vocal organs in traditional vocal technique research, and for the first time explores the coordination of throat muscles from a biomechanical perspective, providing a new theoretical framework for clear pronunciation in singing.

(2) This paper uses the multi-body dynamics (MBD) model to establish the dynamic relationship between muscle drive and bone movement, revealing how muscle groups affect the movement state of bones and pronunciation effects through synergy. This provides a more accurate quantitative analysis tool for vocal training and breaks through the limitations of traditional pronunciation technique analysis.

(3) Based on biomechanical synergy analysis, the study designs a personalized singing articulation training method, and verifies its significant advantages in improving pronunciation clarity and enhancing singing effects through experiments.

2. Related work

In singing, the clarity of pronunciation directly affects the expressiveness of the song and the communication effect of the lyrics. Many scholars have begun to study pronunciation clarity techniques from different angles to improve pronunciation clarity. Korner, Norris and other scholars studied the pitch of singing and found that body postures such as the mouth can change the characteristics of vowels and affect the pitch of singing [5,6]. Wang and other scholars explored the effect of vocal training by setting up a breathing mechanism that promotes singing. The results showed that body coordination and mixed breathing training can significantly improve the naturalness of songs [7]. The vocal training method of the Stanislavsky system and the conscious singing form reduce the psychological burden and improve the clarity of pronunciation to a certain extent [8,9]. Zhu and other scholars conducted field surveys to study the singing skills of folk operas and found that breathing control, voice and character portrayal all have a great impact on singing skills [10]. Tsuchimura, Jeanneteau and other scholars analyzed the impact of visual information on the intelligibility of vowels and high notes in songs, indicating that visual information can improve users' intelligibility of vowels and high notes and ensure clear pronunciation of singing [11,12]. The above scholars have proposed a variety of training techniques to improve the clarity of singing and pronunciation, but they have ignored the coordination of throat muscles and their deep influence on pronunciation clarity. Singers still face the problem of unclear pronunciation when applying them in practice, especially when singing fast and difficult songs.

At present, some researchers have tried to introduce biomechanical principles into the field of voice training to analyze the role and coordination of throat muscles. Marin et al. explored the most intense muscle contraction during stuttering and the neuromuscular mechanism that affects muscle activation time and coordination from a biomechanical perspective [13]. Desjardins et al. conducted a biomechanical analysis of primary muscle tension dysphonia and found that physiological muscle tension has a greater stimulating effect on phonation [14]. As a type of external muscle, the neck and laryngeal muscles have a potential role in controlling the fundamental frequency of the vocal cords and promoting vocal hyperfunction [15,16]. Marciniak-Firadza et al. reviewed vocal techniques and found that tension and overexertion of respiratory and laryngeal muscles have a significant impact on the tone and clarity of vocalization [17]. Aydogus et al. studied the effects of vocal warm-up on the acoustic and aerodynamic parameters of the voice, and the results showed that vocal warm-up can improve the objective voice quality [18]. The above scholars studied the application of larynx muscles in the field of vocalization from the perspective of biomechanics, and found that muscle optimization can significantly improve the stability of the voice and the accuracy of pronunciation. However, the researchers failed to systematically consider the coordinated work of muscles during the entire pronunciation process, and there is a large gap in the research on singing pronunciation training from the perspective of biomechanics.

3. Biomechanical analysis of throat muscles and optimization of singing skills

3.1. Biomechanical modeling of pharyngeal muscles

3.1.1. Establishment of the anatomical model of pharyngeal muscles

The anatomical model of pharyngeal muscles includes laryngeal cartilage, larynx, hyoid bone and its related muscle groups. This paper first uses CAD to construct a preliminary three-dimensional model of the pharyngeal muscles, and divides the laryngeal cartilage structure, tongue muscles, laryngeal muscles and other areas into multiple sub-areas, and uses anatomical data to accurately depict the spatial position and morphology of each muscle group.

Based on the anatomical model, the experiment defines 14 major pharyngeal muscle groups, including upper and lower tongue muscles, laryngeal muscles, cricoid cartilage muscles, etc. [19,20]. In the definition of muscle groups, the experiment considers the attachment points, direction, length and tension characteristics of each muscle group, and assigns corresponding material properties to each muscle group and soft tissue, including biomechanical parameters such as elastic modulus and Poisson's ratio.

The mechanical properties of muscles are described by nonlinear hyperelastic model, and the changes in muscle tension are expressed by Mooney-Rivlin model [21–23], as shown in Equation (1).

$$W(A_1, A_2) = C_1(A_1 - 3) + C_2(A_2 - 3) \tag{1}$$

A_1 and A_2 represent the first and second invariants, and C_1 and C_2 represent the elastic behavior constants of the material.

In the biomechanical modeling of throat muscles, the reasonable setting of contact surfaces and constraints is a key step in simulating the interaction between muscle groups during pronunciation.

(1) Contact constraints of cartilage

In the pharynx, there is contact between the cricoid cartilage, thyroid cartilage and other cartilages and the surrounding tissues. The contact of the cartilage is defined by the contact surface friction model, and the calculation Equation of the contact force is shown in Equation (2).

$$F_c = F_N + F_T \tag{2}$$

F_N represents the normal contact force and F_T represents the tangential friction force.

The calculation Equations of F_N and F_T are shown in Equations (3) and (4) respectively.

$$F_N = B\Delta d \tag{3}$$

$$F_T = \alpha F_N \tag{4}$$

B represents the contact stiffness, Δd represents the displacement between the contact surfaces. α represents the friction coefficient.

(2) Muscle tension and traction constraint

Muscles generate tension when they contract or stretch. The experiment uses the muscle tension model to calculate the traction of the muscle. The calculation Equation for muscle tension is shown in Equation (5).

$$T_m = B_m \cdot (D_m - D_0) \tag{5}$$

Among them, B_m represents the stiffness coefficient of the muscle, D_m represents the current length of the muscle. D_0 represents the original length of the muscle, and T_m represents the muscle tension.

In order to ensure that the muscle tension during the simulation is within a certain range, the experiment sets a maximum tension constraint so that the tension of each muscle cannot exceed its physiological limit.

(3) Coordination constraints between laryngeal muscles

The coordination of laryngeal muscle groups is one of the key factors for the clarity of singing pronunciation, and the coordination between different muscle groups needs to be simulated through relative motion constraints. The experiment introduces coordination constraints [24,25] to control the movement direction and amplitude of the two muscle groups during contraction. The expression is shown in Equation (6).

$$\Delta x_{m1,m2} = \beta \Delta y_{m1,m2} \tag{6}$$

$\Delta x_{m1,m2}$ and $\Delta y_{m1,m2}$ represent the relative displacement of the two muscle groups in two directions, and β represents the coordination coefficient.

The biomechanical modeling structure diagram of the throat muscles is shown in **Figure 1**.

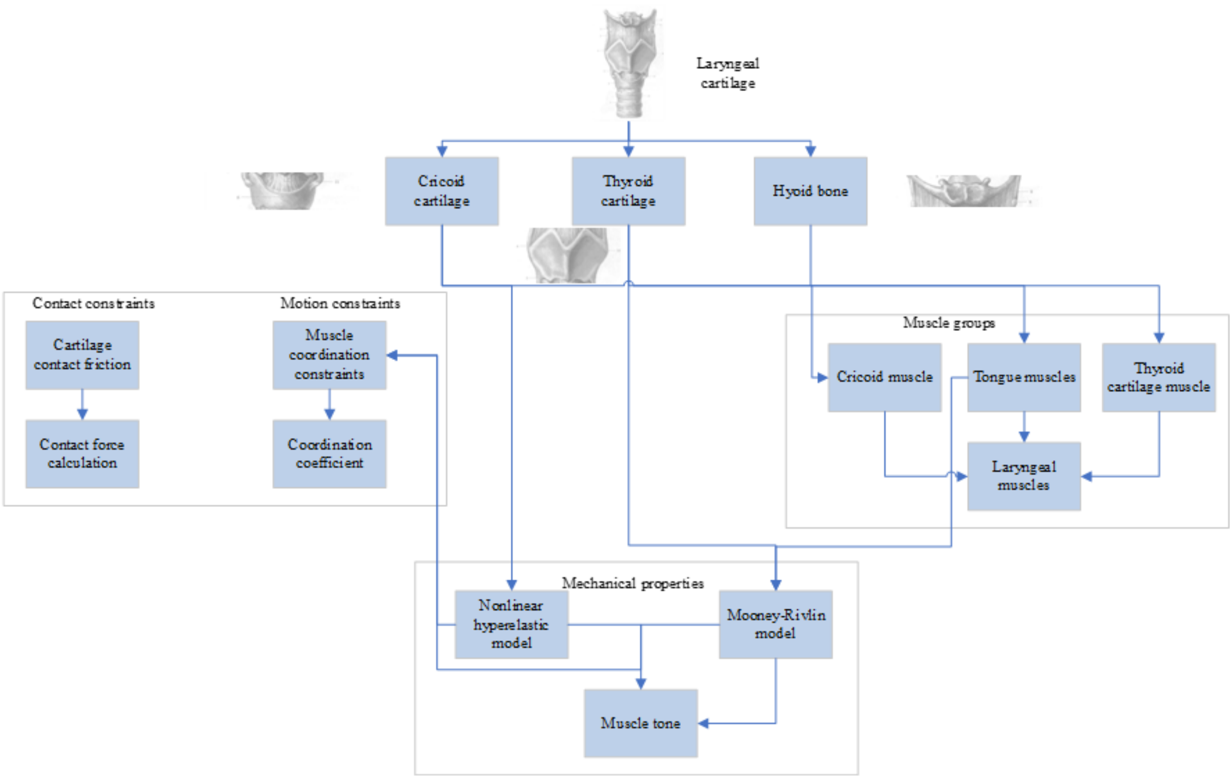


Figure 1. Biomechanical modeling structure of throat muscles.

Figure 1 shows the mechanical properties and interactions of the throat anatomical structure and its related muscle groups. **Figure 1** includes laryngeal cartilage and hyoid bone and several major muscle groups, such as cricoid muscle, thyroid muscle, and tongue muscle. The nonlinear hyperelastic model and Mooney-Rivlin model are used to describe the changes in muscle tension between muscle groups. The overall structure diagram illustrates the dynamic behavior of the throat muscles during the phonation process and their interrelationships, providing theoretical support for further biomechanical analysis and pronunciation optimization.

3.1.2. Finite element analysis

After establishing the collective model, this paper uses FEA technology to perform dynamic simulation on the model [26–28], simulates the mechanical behavior of the throat muscle group under different phonation states, and analyzes the tension, stretch and interaction of the muscles.

In the experiment, a high-order tetrahedral mesh was used to discretize the throat model [29]. At the same time, during the calculation process, ABAQUS software was used as the solution platform, and an explicit solver was used to deal with large deformation and nonlinear problems.

The dynamic equation of the movement of the throat muscles is expressed as shown in Equation (7).

$$E\ddot{\gamma} + Q\dot{\gamma} + B\gamma = F \tag{7}$$

E represents the mass matrix, Q represents the damping matrix, and B represents the stiffness matrix. γ represents the position vector, $\dot{\gamma}$ represents the velocity, $\ddot{\gamma}$ represents the acceleration, and F represents the external force vector.

3.1.3. Model parameter optimization

The objective function is established based on parameters such as muscle tension, pronunciation clarity, and coordination. The expression of the objective function is shown in Equation (8).

$$F_{op} = \delta \sum_{i=1}^{n} (|T_i - T_{ir}|^2) + \varepsilon(\sum_{j=1}^{m} |CA_j - CA_{jr}|^2) \tag{8}$$

T_i represents the simulated measured muscle tension, and T_{ir} represents the actual measured muscle tension. CA_j and CA_{jr} represent the simulated and actual coordination indexes, respectively. δ and ε represent weighting coefficients, and n and m represent the number of muscle groups and the coordination degree.

The Particle Swarm Optimization (PSO) algorithm was used to solve the objective function in the experiment [30,31]. The PSO algorithm uses the movement of simulated particles in the search space to find the optimal solution, and through continuous iteration, updates the speed and position of the particles to optimize the model parameters. The expression of model parameter optimization is shown in Equation (9).

$$u_i^{k+1} = \vartheta u_i^k + \mu_1 \pi_1 (p_i^k - x_i^k) + \mu_2 \pi_2 (o^k - x_i^k) \tag{9}$$

u_i^{k+1} represents the iteration speed of the particle at the k+1th time, and x_i^k represents the current position of the particle. p_i^k and o^k represent the individual optimal solution and the global optimal solution, respectively. ϑ represents the inertia weight, μ_1 and μ_2 represent the learning factors, and π_1 and π_2 represent random numbers.

After multiple optimization steps, this paper obtains a model that is more in line with actual physiological characteristics and can more accurately simulate the dynamic behavior of throat muscles during pronunciation.

The PSO hyperparameter settings are shown in **Table 1**.

Table 1. Hyperparameters.

Parameters	Value	Parameters	Value
Number of particles	100	Social factor	1.5
Maximum number of iterations	300	Maximum speed	1.0
Inertia weight	1.0	Minimum speed	0.1
Learning factor	1.5	Random number	0~1

In **Table 1**, it can be seen that the number of particles in the hyperparameters of PSO in the model parameter optimization is 100, the maximum number of iterations is 300, and the inertia weight is 1.0. The learning factor and social factor are both 1.5, the maximum speed and minimum speed are 1.0 and 0.1 respectively, and the random number is 0 to 1.

3.2. Throat muscle coordination

3.2.1. Construction of multi-rigid body dynamics model

Based on the anatomical model of throat muscles, this paper constructs a multi-rigid body dynamics model in order to accurately describe the dynamic behavior of throat muscles [32,33]. The multi-rigid body dynamics model takes the throat bones and muscle groups as the research objects, and realizes the full simulation of the muscle group movement state during pronunciation by establishing the dynamic relationship between muscle drive and bone movement.

(1) Dynamics model framework

The experiment uses the Lagrange dynamics method to express the motion equation. The Lagrange equation is expressed as shown in Equation (10).

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\rho}_i}) - \frac{\partial L}{\partial \dot{\rho}_i} = R_i \tag{10}$$

L represents the Lagrangian function, ρ_i represents the generalized coordinates, and R_i represents the generalized force.

(2) Rigid body modeling of bone structure

This paper takes the cricoid cartilage, thyroid cartilage and hyoid bone as the main rigid body units, uses hinge joints to simulate their connection relationships, and adds Lagrangian multipliers to introduce joint constraints into the motion equation. The motion equation is expressed as shown in Equation (11).

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\rho}_i}) - \frac{\partial L}{\partial \dot{\rho}_i} + \tau_c^T \sigma = R \tag{11}$$

σ represents the Lagrange multiplier, and τ_c^T represents the joint constraint, whose value is 0.

(3) Muscle drive unit modeling

In the model, each muscle is regarded as a spring-damper unit, and its mechanical behavior is defined as a nonlinear elastic system. The active tension of the muscle is expressed as shown in Equation (12).

$$F_m = F_{\max} \cdot \cos(\omega) \cdot exp(-(\frac{D_m - D_o}{\zeta})^2) + \theta \cdot i_m \tag{12}$$

$F_{\max}$ represents the maximum muscle force, ζ represents the standard deviation of length change, θ represents the damping coefficient, and ω represents the angle between the muscle contraction direction and the movement direction.

3.2.2. Calculation of muscle load distribution

(1) Inverse dynamics calculation

In the dynamics framework, the experiment uses the inverse dynamics method to solve the muscle force. The calculation Equation for solving the muscle force is shown in Equation (13).

$$F_{mu} = J(\gamma)^T \cdot \sigma \tag{13}$$

$J(\gamma)^T$ represents the Jacobian matrix of the joint coordinates.

(2) Solution optimization of muscle load distribution

In order to ensure that the calculation results are consistent with the physiological characteristics of muscles, this paper introduces a quadratic programming algorithm to solve the multi-solution problem and minimize the total force sum of squares, as shown in Equation (14).

$$F = \min \sum_{i=1}^{n} F_i^2 \tag{14}$$

F_i is a non-negative number.

(3) Calculation of time-varying load

In dynamic simulation, the study generates a time-varying load curve by calculating the muscle force distribution at different time points frame by frame. The muscle load time series expression is shown in Equation (15).

$$F_m(t) = F_{m,a}(t) + F_{m,p}(t) \tag{15}$$

$F_{m,a}(t)$ represents the tension generated by active contraction, and $F_{m,p}(t)$ represents the tension generated by passive muscle stretching.

3.2.3. Quantification of synergy

In order to quantify the synergy of the throat muscle groups during pronunciation, this paper introduces the Coordination Index (CI) to analyze the muscle synergy pattern through statistical and mechanical methods. The calculation Equation of CI is shown in Equation (16).

$$\mathrm{CI} = \frac{1}{n(n-1)} \sum_{i=1}^{n} \sum_{j=1, j \neq \mathrm{i}}^{n} \mathrm{corr}(F_i(t), F_j(t)) \tag{16}$$

$\mathrm{corr}(F_i(t), F_j(t))$ represents the Pearson correlation coefficient of the muscle force time series.

The study used wavelet transform to analyze the distribution of muscle load in the time-frequency domain [34,35] and capture the dynamic characteristics of muscle synergy. The expression of wavelet transform is shown in Equation (17).

$$V_f(a,b) = \int_{-\infty}^{\infty} F(t)\kappa^*(\frac{t-b}{a})dt \tag{17}$$

a and b represent scale and translation parameters respectively, and κ^* represents the mother wavelet function.

3.3. Design of personalized singing pronunciation and clarity techniques

Based on the analysis of throat muscles, this paper designs training techniques with three goals: improving the coordination of throat muscle groups, enhancing the tension control ability of specific muscles, and improving muscle endurance.

(1) Muscle group coordination training

The experiment uses muscle CI to train highly coordinated muscle groups as a group. If the CI of the laryngeal muscles and cricoid cartilage muscles is high, resonant pronunciation exercises are set to emphasize the coordinated actions of the two.

In the wavelet transform analysis of the time-frequency distribution of muscle load, frequency division training tasks are designed. The long sound exercises of low-frequency vibration pronunciation “a” and “o” are alternately performed with the “ti-ti-ti” exercises of high-frequency vibration pronunciation with fast syllable switching to enhance the coordination flexibility of muscles.

(2) Tension adjustment training

By analyzing the distribution of muscle tension, this paper found that insufficient or excessive tension of specific muscles, such as the cricoid cartilage, can significantly affect the clarity of voice. The experiment set up a light tone voice task, such as “ha”, and adjusted the pronunciation strength to maintain a reasonable tension range. If the cricoid cartilage muscle tension is found to be insufficient, a continuous ascending scale training is designed, gradually increasing from the bass “do” to the treble “sol”, gradually increasing the pitch and improving muscle tension.

(3) Dynamic load endurance training

In dynamic load endurance training, the pronunciation environment of different speaking speeds is simulated, starting from the slow pronunciation of monosyllable long sound “la-la-la”, and gradually transitioning to the fast pronunciation of continuous polysyllables “ma-me-mi-mo”.

(4) Integrated training of breathing and voice

The dynamic modeling results of throat muscles can be combined to study and design breathing and voice synchronization training techniques.

Deep inhalation and light pronunciation: The low-load state in the dynamic model can be simulated. The trainee takes a deep breath and then releases the airflow quickly, while using the long sound “ha” to practice the ability of the throat muscles to control the airflow.

Combination of breathing and syllables: It can design continuous pronunciation exercises of “ha-he-ho-hu”, gradually increase the number and speed of syllables, and improve the responsiveness of throat muscles.

4. Evaluation experiment of singing articulation skills

4.1. Experimental environment

Hardware configuration: Intel Xeon Platinum 8280, NVIDIA Tesla V100 GPU (Graphics Processing Unit), 128 GB DDR4 (Double-Data-Rate Fourth), 2 TB SSD (Solid State Disk).

Software platform: ABAQUS platform, Simulink, OpenSim, Windows 10.

Data acquisition equipment: Delsys Trigno wireless EMG system, Vicon 3D motion capture system, Honeywell micro pressure sensor.

4.2. Experimental data and preprocessing

The experimental data are derived from the EMG (electromyography) signals of cricoid cartilage, thyroid cartilage, tongue muscles, etc., of 60 healthy singers, the movement trajectory of laryngeal cartilage, the changes in airflow in the pharynx and air pressure during pronunciation, etc. All singers had no serious laryngeal diseases or other medical history that affected pronunciation, and signed informed consent forms before the experiment and obtained approval from the ethics committee. A total of 2150 sets of data were collected from March to June 2024. Some of the original data are shown in **Table 2**.

Table 2. Partial experimental data.

Singer number	Cricoid muscle EMG signal (μV)	Thyroid muscle EMG signal (μV)	Tongue muscle EMG signal (μV)	Laryngeal cartilage movement trajectory (mm)	Airflow (L/s)	Air pressure (Pa)
1	25.4	18.7	22.3	5.2	0.15	45.6
2	28.9	21.5	19.8	4.8	0.18	43.2
3	30.1	22.1	24.4	5.4	0.17	47.3
4	24.5	20.2	23.7	5	0.16	44.1
5	26.8	19.9	21	4.9	0.14	42.8
6	27.3	20.6	20.5	5.1	0.19	46
7	29.2	21.8	22.7	5.3	0.2	44.5
8	28.4	22.3	25	4.7	0.18	43.9
9	26.2	19.5	23.2	5.2	0.16	45
10	30.5	23.1	20.8	5	0.17	44.3

In **Table 2**, the data of 10 singers at a certain point in time are visualized, including cricoid muscle EMG signal, thyroid cartilage muscle EMG signal, tongue muscle EMG signal, laryngeal cartilage movement trajectory, airflow, air pressure, etc.

Data preprocessing

(1) Data cleaning

For outliers in the data, the experiment can remove abnormal data points that exceed three times the standard deviation. For missing data caused by signal loss or experimental equipment problems, interpolation is used to fill in the gaps.

(2) Signal filtering

This paper uses a Butterworth low-pass filter and sets the cutoff frequency to 50 Hz to remove high-frequency noise. For low-frequency noise, the experiment uses a high-pass filter and sets its cutoff frequency to 10 Hz to remove low-frequency interference from the environment and equipment.

(3) Signal normalization

In order to eliminate the influence of individual differences and signal amplitude differences between different singers, the study normalized the maximum value of each group of signals to between 0 and 1 to achieve normalization processing and ensure that the data is compared and analyzed under the same dimension.

4.3. Evaluation indicators

STOI (Short-Time Objective Intelligibility):

$$\mathrm{STOI} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{corr}(s_i(n), \hat{s}_i(n)) \tag{18}$$

$s_i(n)$ represents the original speech signal, and $\hat{s}_i(n)$ represents the distorted speech signal.

PESQ (Perceptual evaluation of speech quality):

$$\mathrm{PESQ} = f(s_i, \hat{s}_i) \tag{19}$$

f represents the function calculated by the speech quality model.

SegSNR (Segment Signal-to-Noise Ratio):

$$\mathrm{SegSNR} = 10 \cdot \log_{10}\left(\frac{\sum_{t=1}^{N} x(t)^2}{\sum_{t=1}^{N}[y(t) - x(t)]^2}\right) \tag{20}$$

$x(t)$ represents the tth sample of the original speech signal, $y(t)$ represents the sample in the distorted language, and *N* represents the signal length.

4.4. Experimental design

The experimental goal is to analyze the relationship between the coordination of throat muscles and the clarity of singing articulation, and to evaluate the impact of the training method based on biomechanical analysis on the clarity of singers' pronunciation.

The experimental group is divided into two groups, namely the experimental group and the control group. In the experimental group, participants can undergo personalized singing training based on biomechanical analysis, including muscle group coordination training, tension adjustment training, dynamic load endurance training, and breathing and vocalization integration training, with 10 people in each group. In the control group, there are five groups, pitch training, breath control, oral resonance training, oral tongue position adjustment, oral opening and closing training, with 10 people in each group.

The experimental steps are as follows:

(1) Before the experiment began, all participants were given a baseline test, including recording their natural singing and a preliminary assessment of their muscle electrical activity, laryngeal movement trajectory, and articulation clarity.

(2) Based on the results of the preliminary assessment, a personalized training plan was designed for each experimental group member to optimize their muscle coordination, tension control, and vocal endurance.

(3) The experimental group and the control group can be trained according to their respective training plans. After each training session, data collection can be conducted to record physiological parameters such as electromyographic signals, motion trajectories, airflow, and air pressure, and pronunciation clarity can be evaluated at the same time.

(4) After the above steps, the changes in pronunciation clarity of the two groups of participants before and after training can be statistically analyzed.

5. Singing pronunciation clarity evaluation and optimization effect

5.1. Accuracy of biomechanical modeling of throat muscles

In order to explore the accuracy of biomechanical modeling of different throat muscles, this paper conducts comparative analysis on the established models at different time steps from the perspectives of MAE (Mean Absolute Error), MSE (Mean Square Error), and RMSE (Root Mean Square Error). The results are shown in **Figure 2**.

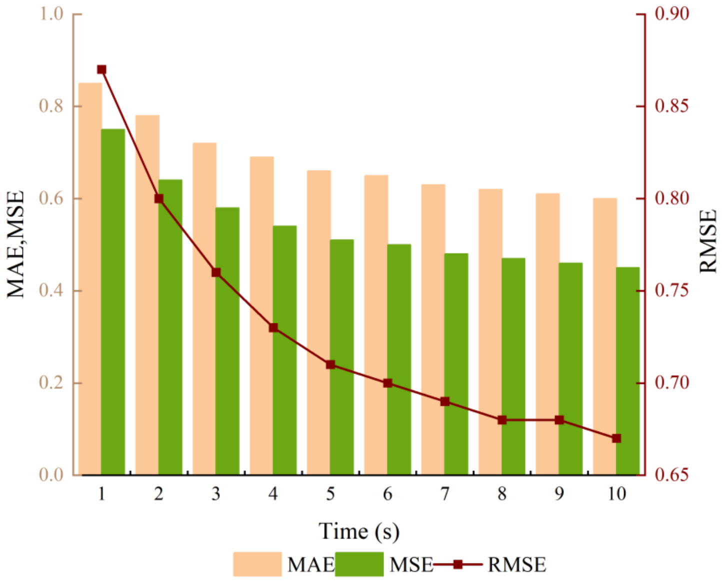


Figure 2. Accuracy of the modeling of the biomechanics of the pharyngeal muscles.

In **Figure 2**, overall, the MAE, MSE, and RMSE have similar trends at different time steps. As time goes by, the error of the model gradually decreases, which shows that the model has a high accuracy in simulating the biomechanics of the pharyngeal muscles. In terms of MAE, from the 1st to the 5th second, MAE decreased from 0.85 to 0.66, and then decreased to 0.65 after the 6th second, and stabilized in the time step after the 7th second. MAE and RMSE showed a rapid downward trend in the first 5 s, with MSE decreasing from 0.75 to 0.51 and RMSE decreasing from 0.87 to 0.71, and gradually stabilized in the last 5 seconds. **Figure 2** shows that the model fitting effect begins to stabilize after reaching a certain level, so that the throat muscle biomechanical modeling achieves good simulation performance.

5.2. Comparison of singing pronunciation clarity before and after training

The experiment collects raw data from different singers and divides them into different groups. The baseline data before training and the results after training of the experimental group were compared, and the results are shown in **Figure 3**. The participants in the experimental group received personalized singing training based on biomechanical analysis, including muscle group coordination training, tension regulation training, dynamic load endurance training, and breathing and voice integration training. In **Figure 3**, the articulation clarity of singing is evaluated by combining expert scoring and objective quantitative indicators. The expert scoring dimensions are divided into pronunciation accuracy, clarity, and fluency. The Likert 5 scale is used, with two questions in each direction, 10 points for each dimension, and a total score of 30 points. Objective quantitative indicators include STOI, PESQ, and SegSNR.

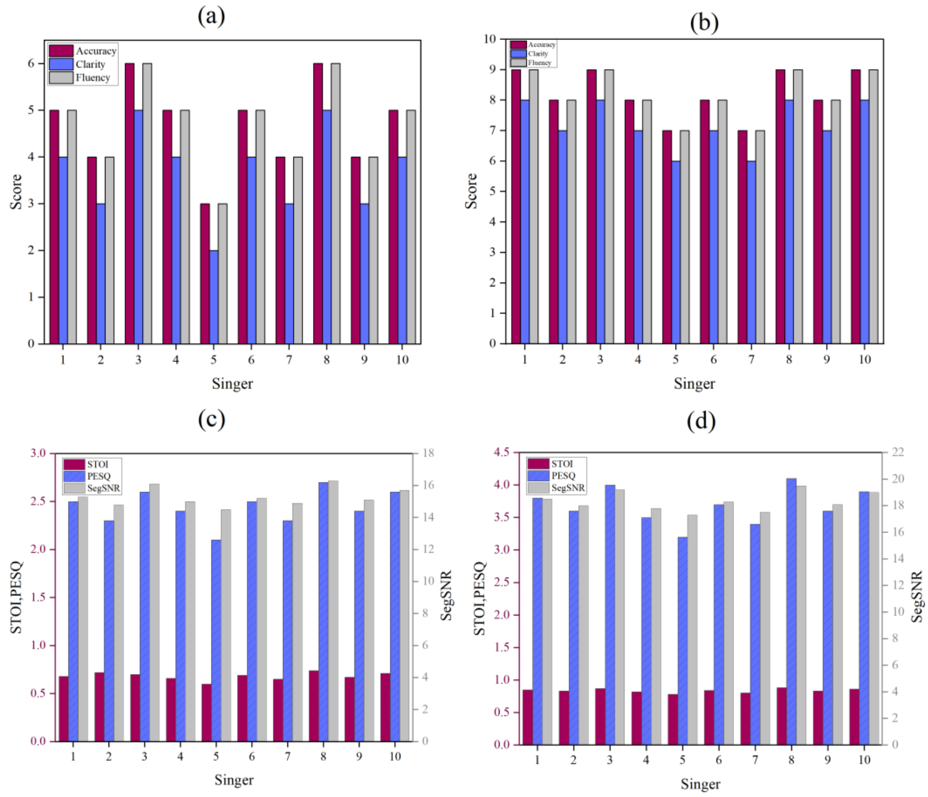


Figure 3. Comparison of pronunciation clarity before and after training. **(a)** Pronunciation accuracy, clarity, and fluency comparison before training; **(b)** Pronunciation accuracy, clarity, and fluency comparison after training; **(c)** STOI, PESQ, and SegSNR comparison before training; **(d)** STOI, PESQ, and SegSNR comparison after training.

In **Figure 3a**, the distribution of scores before training is relatively scattered, showing that the basic levels of different singers vary greatly. Before training, the singers' articulation clarity assessment scores were all low, and the singers' scores in the accuracy, clarity, and fluency dimensions were all less than 6 points. The first singer's pronunciation accuracy reached 5, clarity reached 4, and fluency reached 5; the second singer's scores were even lower, only 4, 3, and 4 respectively. In **Figure 3b**, after personalized biomechanical analysis training, all singers' scores in the three dimensions were significantly improved. The pronunciation accuracy of the first singer improved from 5 to 9, the clarity improved from 4 to 8, and the fluency improved from 5 to 9. The score of the fifth singer improved from 3 to 7 in accuracy, 2 to 6 in clarity, and 3 to 7 in fluency.

In **Figure 3c**, all singers had low scores on the objective indicators before training. Singer 1 has an STOI of 0.68, a PESQ of 2.5, and a SegSNR of 15.3; Singer 5 performs the worst, with an STOI of only 0.6, a PESQ of 2.1, and a SegSNR of 14.5. In **Figure**

3d, after personalized training, Singer 1's STOI improves from 0.68 to 0.85, PESQ from 2.5 to 3.8, and SegSNR from 15.3 to 18.5. Singer 8 achieved the best result, with STOI reaching 0.88, PESQ 4.1, and SegSNR 19.5. Singer 5 had the lowest result, but also improved significantly, with STOI increasing from 0.6 to 0.78, PESQ from 2.1 to 3.2, and SegSNR from 14.5 to 17.3.

Overall, the clarity scores of most singers after training were above 7 points, and the accuracy and fluency also reached 8 points or above, which shows that the training effect is significant. The experimental group's personalized singing training, combined with the training method of biomechanical analysis, enables singers to effectively regulate and control the movement of vocal organs such as tongue muscles and laryngeal muscles, enhance the coordination and endurance of core vocal muscles such as tongue muscles and laryngeal muscles, and optimize the accuracy and clarity of vocalization.

5.3. Correlation analysis between muscle activity and articulation clarity

There is a close relationship between muscle activity and articulation clarity. In order to further explore the relationship between the two, the correlation between the intensity of different muscle group activities and articulation clarity is analyzed. The results of the correlation analysis between muscle activity and articulation clarity are shown in **Figure 4**. In **Figure 4**, articulation clarity is quantified using STOI.

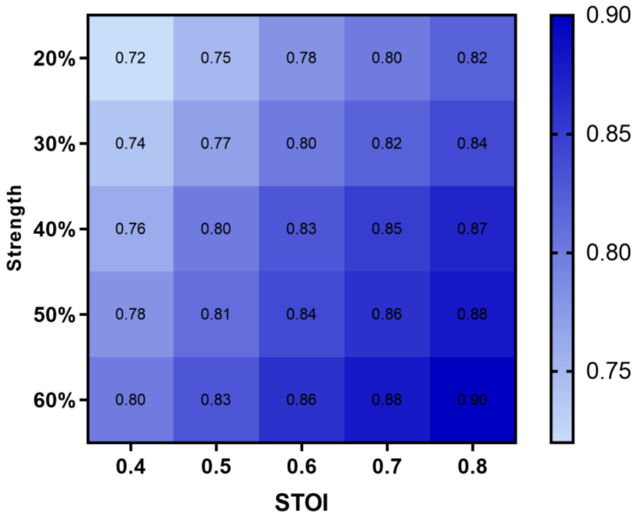


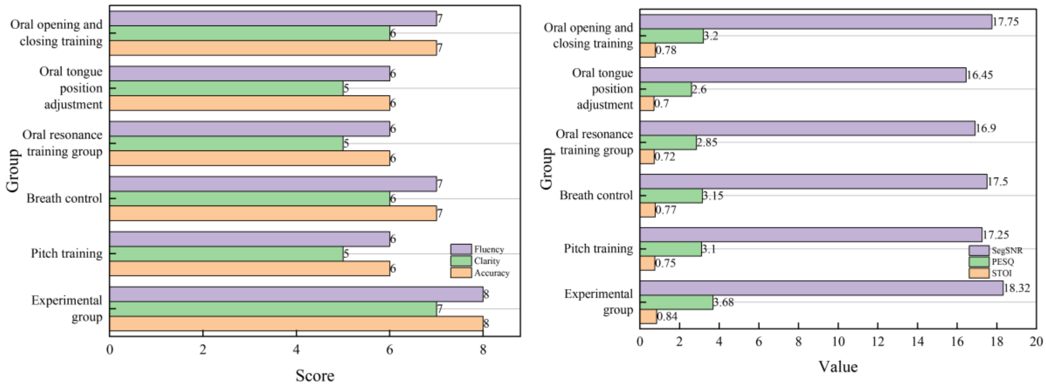
Figure 4. Correlation between muscle activity and articulation clarity.

In **Figure 4**, there is an obvious positive correlation between muscle activity intensity and articulation clarity, and the correlation coefficient gradually increases with the increase of muscle activity intensity. The horizontal axis represents the quantitative index STOI of singing articulation clarity, and the vertical axis represents the intensity of muscle group activity.

At 20% muscle activity intensity, the correlation coefficient of STOI gradually increases from 0.72 to 0.82. At 60% muscle activity intensity, the correlation coefficient of STOI increased from 0.8 to 0.9, a significant increase. The correlation coefficients of low muscle activity intensities of 20% and 30% were slightly lower than those of high activity intensities of 50% and 60%, indicating that low-intensity muscle activity has a relatively limited effect on improving pronunciation clarity, but it also has a certain promoting effect.

5.4. Comparison of singing articulation clarity between the experimental group and the control group

Participants in the experimental group received personalized singing training based on biomechanical analysis, including muscle group coordination training, tension regulation training, dynamic load endurance training, and breathing and voice integration training. In the control group, there are five groups: pitch training, breath control, oral resonance training, oral tongue position adjustment, and oral opening and closing training. The comparison results of the singing articulation clarity between the experimental group and the control group are shown in **Figure 5**.



(a) (b)

Figure 5. Comparison of pronunciation clarity between the experimental group and the control group. **(a)** Comparison of pronunciation accuracy, clarity, and fluency between the experimental group and the control group; **(b)** Comparison of STOI, PESQ, and SegSNR between the experimental group and the control group.

In **Figure 5a**, it can be seen that the pronunciation accuracy, clarity, and fluency of the experimental group are significantly higher than those of the control group. The experimental group achieved 8, 7 and 8 in pronunciation accuracy, clarity and fluency respectively, while the three indicators of the control group were all lower. The pronunciation accuracy of the pitch training group and the breath control group were 6 and 7, the clarity was 5 and 6, and the fluency was 6 and 7. The pronunciation accuracy and clarity of the oral resonance training group and the oral tongue position adjustment group were both 6 and 5. This shows that the experimental group adopted a comprehensive training method based on biomechanical analysis, which improved the singers' control over vocal muscles, enhanced the coordination between breathing and vocalization, and improved the clarity of singing and pronunciation.

In **Figure 5b**, it is further found that the STOI value of the experimental group reached 0.84, PESQ reached 3.68, and SegSNR reached 18.32. The experimental group was significantly better than the control groups in all objective quantitative indicators. In summary, the personalized comprehensive training method based on biomechanical analysis can greatly improve the clarity of singing pronunciation from the perspective of the biomechanical coordination of throat muscles.

5.5. Dynamic relationship between CI value and pronunciation clarity

The dynamic relationship between CI value and pronunciation clarity is shown in **Figure 6**.

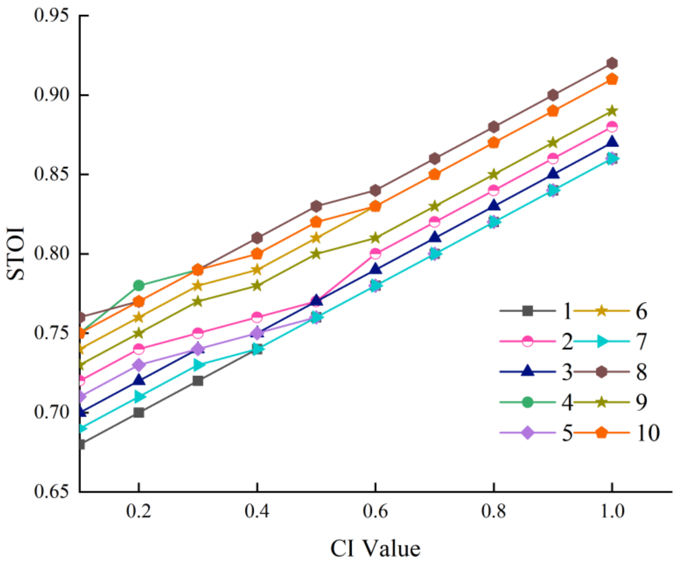


Figure 6. Dynamic relationship between CI value and articulation clarity.

In **Figure 6**, the CI value indicates the degree of coordination of key muscles during articulation. As the CI value increases, the articulation clarity gradually improves. When the CI value gradually increases from 0.1 to 1.0, the STOI value increases overall. When the CI value is high, the growth of STOI slows down to some extent. It can be seen that under high CI values, the marginal improvement of synergy gradually weakens the impact of STOI growth. This shows that optimizing muscle synergy is the key to improving articulation clarity, but attention should be paid to the marginal decrease in training efficiency.

5.6. Biomechanical changes of different techniques under singing conditions

In order to explore the biomechanical changes of different skills under singing conditions, the experiment takes the singers after personalized tension adjustment training as an example, and statistically analyzes the stress peak, average stress, maximum displacement amplitude, maximum joint rotation amplitude and other parameters under different muscles. The biomechanical changes after personalized tension adjustment training are shown in **Table 3**. In **Table 3**, the muscles include tongue muscles, laryngeal muscles, pharyngeal muscles, and cricoid muscles.

In **Table 3**, before training, the biomechanical parameters of each muscle showed lower stress and smaller displacement and rotation range. The peak stress of the tongue muscle reached 120.45 Pa, the maximum displacement reached 6.74 mm, and the maximum rotation range of the joint was 10.24°. The peak stress and maximum rotation range of the pharyngeal muscle reached 210.84 Pa and 14.56°, respectively, indicating that the pharyngeal muscle bears a larger stress load and range of motion. Without personalized tension adjustment training, the activities of different muscle groups are unbalanced. The pharyngeal muscles are subjected to higher stress and activity range due to overwork, while the cricoid cartilage muscle is weaker, with a stress peak of only 150.92 Pa and a rotation angle of 9.87°.

Table 3. Biomechanical changes after personalized tension regulation training.

	Muscle	Peak stress (Pa)	Average stress (Pa)	Maximum displacement (mm)	Maximum joint rotation (°)
Before training	Tongue muscles	120.45	85.32	6.74	10.24
	Laryngeal muscles	180.63	135.49	7.23	12.36
	Pharyngeal muscles	210.84	162.76	8.01	14.56
	Cricoid muscles	150.92	110.55	5.84	9.87
After training	Muscle	Peak stress (Pa)	Average stress (Pa)	Maximum displacement (mm)	Maximum joint rotation (°)
	Tongue muscles	138.12	92.67	7.32	11.36
	Laryngeal muscles	195.54	145.32	8.15	13.28
	Pharyngeal muscles	230.72	173.65	8.76	15.43
	Cricoid muscles	165.81	120.37	6.45	10.62

After training, the biomechanical parameters of each muscle are generally improved, and the stress, displacement and joint rotation range are all increased. The peak stress of the tongue muscle increased from 120.45 Pa to 138.12 Pa, and the maximum displacement increased from 6.74 mm to 7.32 mm. The peak stress of the pharyngeal muscle increased from 210.84 Pa to 230.72 Pa, and the maximum rotation angle of the joint increased from 14.56° to 15.43°. This shows that after personalized tension adjustment training, the strength and activity of each muscle group have been balanced and enhanced. It is the personalized training that improves the coordination and tension distribution between muscles and optimizes the overall vocal biomechanics.

5.7. Differences in pronunciation habits among different individuals

The differences in pronunciation habits among different individuals are shown in **Table 4**.

Table 4. Differences in pronunciation habits among different individuals.

Singer	Pronunciation habits	Pronunciation accuracy	Clarity	Fluency
1	Tense type	7	6	6
2	Relaxed type	6	7	7
3	Anterior type	8	9	8
4	Reverse type	5	5	6
5	Resonant type	9	9	9
6	Asymmetric type	6	6	5
7	Tongue muscle dominant type	7	7	6
8	Tense type	8	7	7
9	Relaxed type	6	6	7
10	Tense type	7	6	6

In **Table 4**, the singer with resonant pronunciation (Singer 5) scored the highest in all indicators, with pronunciation accuracy, clarity and fluency all scoring 9 points. It can be seen that this pronunciation habit can significantly improve singing performance. Singers with tense (singers 1, 8, 10) and relaxed (singers 2, 9) pronunciation performed worse in clarity and fluency, especially tense singers, whose pronunciation accuracy was the lowest at 7 The minimum score for clarity and fluency is 6. It is precisely due to tension that the control of the throat muscles is unstable, affecting the clarity and fluency of the voice. The front type (Singer 3) showed high pronunciation accuracy and clarity, reaching scores of 8 and 9, indicating that this pronunciation habit helps improve the projection and brightness of the voice. The singer with asymmetrical pronunciation (Singer 6) had the lowest score among all scores, with accuracy, clarity and fluency of 6, 6 and 5 respectively. This is related to poor coordination of the throat muscles, resulting in poor pronunciation. Poor stability. Overall, the differences in pronunciation habits reflect differences in throat muscles, vocal cord tension, and vocal organ control capabilities.

5.8. The adaptability of different music styles to the training method in this article

The adaptability results of different music styles to the training method in this article are shown in **Table 5**.

Table 5. The adaptability of different music styles to the training method in this paper.

Music style	Pronunciation accuracy	Clarity	Fluency
Classical music	9	9	8
Pop music	8	8	9
Jazz music	7	8	9
Folk music	8	9	8
Rock music	7	7	8

In **Table 5**, classical music scored 9 points in pronunciation accuracy and 9 points in clarity, indicating that the training method in this paper performs well for classical music that requires high-precision pronunciation, while fluency is slightly lower, only 8 points, precisely because of the strict requirements of classical music on rhythm and pitch. Pop music scored the highest in fluency, reaching 9 points, and has strong adaptability, thanks to the free expression and fewer pitch restrictions of this style, but pronunciation accuracy and clarity are slightly inferior, both 8 points. Jazz music scored relatively balanced, but only 7 points in pronunciation accuracy. Folk music achieved clarity of 9 points and pronunciation accuracy of 8 points. Rock music scored the lowest in accuracy of 7 points and clarity of 7 points, which is related to its emphasis on the expression of emotion and volume, and pays less attention to precise pronunciation skills, but fluency reached 8 points, with good performance. Overall, the training method in this paper shows good adaptability in most music styles, especially in music types that focus on pitch and clarity.

5.9. The influence of different psychological factors on singing pronunciation skills

The results of the influence of different psychological factors on singing pronunciation skills are shown in **Table 6**.

Table 6. The influence of different psychological factors on singing pronunciation skills.

Psychological factors	Pronunciation accuracy	Clarity	Fluency
Anxiety	6	5	5
Confidence	9	9	9
Happiness	8	8	9
Depression	5	4	5
Tension	6	6	5

It can be seen from **Table 6** that psychological factors have a significant impact on singing pronunciation skills. Confidence is the most favorable psychological factor, which can significantly improve the accuracy, clarity and fluency of pronunciation. The scores are all 9 points, indicating that confidence helps singers stay relaxed and effectively control their vocalizations. Pleasant emotions also lead to better pronunciation performance, with accuracy and clarity scoring 8 points, and fluency scoring 9 points, indicating that happy emotions contribute to the natural flow of the voice. Anxiety and tension have a negative impact on singing. Anxiety leads to pronunciation accuracy of 6 points, and lower clarity and fluency, both of which are 5 points. Nervousness reduces fluency to 5 points. It can be seen that nervousness can interfere with singing performance. Depressed mood is the most unfavorable, with low accuracy, clarity and fluency, especially clarity, which is only 4 points, indicating that depressive mood seriously affects pronunciation skills.

6. Experimental discussion

This study starts from the biomechanical coordination of throat muscles and deeply explores the training effect of singing articulation skills. The accuracy of throat muscle biomechanical modeling gradually improves over time, the error gradually decreases, and the stability and accuracy of the model are effectively verified. After personalized training, the singers' articulation clarity was significantly improved, with a significant improvement in pronunciation accuracy, clarity, and fluency. Moreover, after training, the singers' objective quantitative indicators STOI, PESQ, and SegSNR all showed significant positive improvements, with the training group showing more obvious differences compared to the control group in terms of STOI and SegSNR. The positive correlation between muscle activity intensity and articulation clarity further supports the effectiveness of the training method. Overall, the training method of singing articulation clarity skills based on the biomechanical coordination of throat muscles allows singers to regulate and control the movement of tongue muscles, laryngeal muscles and other vocal organs, enhance the coordination and endurance of core vocal muscles such as tongue muscles and laryngeal muscles, and optimize the accuracy and clarity of vocalization.

In the experimental results, the experimental group showed significantly higher pronunciation intelligibility and stronger speech intelligibility, while the traditional oral resonance training group was worse. The main reason is that the training method used by the experimental group is based on the biomechanical synergy of throat muscles, which fully considers the dynamic behavior and coordination of throat muscles, while traditional training methods focus on surface operations such as tongue position, mouth shape, and lip movements. . Traditional methods ignore the important role of the throat muscles in the pronunciation process, resulting in limited improvement in pronunciation clarity. The training method based on the biomechanical model accurately adjusts the coordination of the throat muscles by simulating the synergy and mechanical behavior of muscle groups, significantly improving the clarity of pronunciation and speech intelligibility. The finite element analysis and multi-rigid body dynamic model used in the experiment enable the mechanical behavior of the throat muscles to be accurately simulated and optimized, providing a scientific basis for personalized training programs, thereby effectively improving the singer's pronunciation clarity.

This paper establishes a biomechanical model of throat muscles and combines it with personalized training to accurately identify the impact of muscle activity on pronunciation clarity during singing, providing a scientific basis for the optimization of singing skills. Personalized training enhances the singer's ability to control the vocal organs, improves the coordination and endurance of the vocal muscles, and helps the singer improve the clarity of pronunciation during singing. From the perspective of biomechanics, this study provides a new singing training method. Compared with traditional voice training methods, it has the advantages of being more precise and personalized, and can better meet the training needs of different singers, providing a theoretical basis and practical guidance for vocal teaching and singing training.

This study has made significant progress in the analysis of biomechanical synergy of throat muscles, but there are still certain limitations.

(1) In terms of sample selection, the experimental subjects of this study were only 60 healthy singers, and they were mainly professional singers or individuals with certain singing experience, which will affect the broad applicability of the results. Singers of different ages, genders and vocal habits will have great differences in muscle coordination and vocal habits. Future research will consider a wider sample population to verify the generalizability of this training method to different groups.

(2) The impact of individual differences on the results cannot be ignored. Everyone's throat muscle structure, vocal habits and physiological characteristics are different, which will lead to differences in the effects of the same training method on different individuals. In practical applications, personalized adjustments need to be made according to the specific conditions of each singer to achieve the best training effect. This article uses a more accurate biomechanical modeling and simulation method. However, there may be many nonlinear factors that cannot be fully simulated in the actual vocalization process, such as emotions, environmental factors, etc. These factors will affect the stability and repeatability of the training effect. sex.

7. Case studies

In this study, multiple case studies were used to demonstrate the practical application effect of the singing articulation articulation skills training method based on the biomechanical synergy of throat muscles.

Case 1: Li, male, 26 years old, vocal student

Li is a professional vocal music student who has participated in many stage performances. However, he often has problems with unclear articulation when singing fast songs. Especially in high-pitched and fast-changing pronunciations, the pronunciation of words is blurred, which affects the expressiveness of the song. The experimental group adopted a training method based on the biomechanical synergy of throat muscles. During the experiment, Li received customized training for three months. The training content includes: using a biomechanical model to analyze the coordination of Li's throat muscles, setting personalized muscle tension distribution and coordination, simulating the mechanical behavior in different vocal states, and optimizing his articulation and pronunciation.

The experimental results are as follows: Li's pronunciation clarity was significantly improved during the song singing after training, especially in the fast lyrics part, the pronunciation was clearer and smoother, and the blurred pronunciation was significantly reduced. In the articulation clarity score, Li improved from 5 points before training to 7 points, and the STOI value increased from 0.72 to 0.85, indicating an overall improvement in articulation clarity and sound quality. Later in the experiment, during Li's live performance, feedback showed that fans' understanding of the lyrics and the conveying effect of the song's emotions were greatly improved.

Case 2: Wang, female, 30 years old, professional singer

Wang is a professional singer with long-term performance experience, but there is still a problem of inconsistent pronunciation when singing songs of different styles. Especially in songs with strong emotional expressions, the articulation clarity sometimes decreases. Wang participated in a two-month personalized singing pronunciation training. The training method combined biomechanical analysis and muscle tension optimization, focusing on the synergy and coordination of muscle groups, and improved the dynamic performance of the throat muscles during pronunciation.

Experimental results: After training, Wang's pronunciation clarity was significantly improved, especially when singing high-pitched parts, the originally blurred pronunciation was effectively improved. The articulation clarity score increased from 5.5 points before training to 7 points, and the STOI value increased from 0.75 to 0.82, indicating that her pronunciation clarity has been enhanced in the entire range of sounds. When singing, Wang reported that his voice quality was more stable and his pronunciation flexibility had also improved. When switching between high and low notes, the pronunciation of words was more clear and discernible.

Case 3: Zhang, male, 20 years old, music major

Zhang is an undergraduate majoring in music and has just started receiving vocal training. In the initial training, Zhang had a serious problem of unclear articulation, especially when singing fast lyrics, incoherent pronunciation and slurred speech often occurred. Through two months of training, a collaborative training method based on biomechanics was used, combined with the FEA simulation model, to optimize Zhang's throat muscle coordination and muscle tension distribution.

Experimental results: After training, Zhang's pronunciation clarity improved significantly, especially when he pronounced the words quickly, the lyrics were easier to understand by the audience. The articulation clarity score increased from 4.5 points before training to 6.5 points, and the STOI value increased from 0.68 to 0.80, indicating that the singer's pronunciation clarity has been significantly improved. Zhang reported that he was more confident during the singing process, and the clarity of pronunciation and the stability of the tone had been significantly improved, especially in singing difficult songs.

The singing articulation articulation skills training method based on the biomechanical synergy of throat muscles has shown good results among singers of different levels. Whether they are professional singers, professional singers or music majors, personalized training methods can be effective Improve the clarity of articulation and optimize the sound quality and singing skills of singing. Combining biomechanical analysis and dynamic simulation, it can provide each singer with a more precise training program and significantly enhance their singing effects, especially in high notes and fast pronunciation parts. Research and use of these actual cases have been verified as a method of improving singing skills with broad application prospects.

8. Conclusions

This paper designs a systematic training method by constructing a biomechanical model of throat muscles and performing multi-rigid body dynamics analysis. The study simulates the mechanical behavior of throat muscles under different phonation states and reveals the important influence of muscle synergy on singing clarity. The experimental results show that the training based on this method is significantly better than the traditional oral resonance training in improving the clarity of singing articulation and enhancing the auditory effect of pronunciation. This study has achieved some positive results, but there are also some shortcomings. Individual differences are not fully considered, and there is a lack of analysis of the impact on long-term effects.

Future research:

(1) The current experiment only selected 60 healthy singers, which is a small sample size and only covers healthy individuals. Future research can expand the sample size to include individuals of different ages, genders, singing styles, and vocal cord diseases to further verify the applicability of the biomechanical model in a wider population. For singers with different language and cultural backgrounds, the impact of different pronunciation habits on the coordination of throat muscles can be studied to improve the universality of the model.

(2) This study did not fully consider individual differences, such as throat structure, muscle group size, and tension regulation ability. Future research can use personalized imaging data, such as CT and MRI scans, to model the physiological characteristics of each singer, combined with personalized biomechanical modeling methods, to further optimize articulation clarity techniques.

(3) This study provides an immediate improvement in articulation clarity, but lacks long-term tracking of training effects. Future research can evaluate the sustained effect of this training method on singers' voice clarity, sound quality stability, etc. through long-term tracking experiments to determine whether it is feasible for long-term application.

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