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# A quantitative study on the influence of fingering variations on acoustic characteristics in guzheng performance

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**ABSTRACT** Guzheng timbre and expressive depth are closely determined by fingering techniques, since differences in string contact method, force direction, contact angle, and contact duration directly affect the time-domain and frequency-domain characteristics of the acoustic signal. However, traditional guzheng teaching and performance practice mainly rely on auditory experience rather than systematic acoustic evidence. This study focuses on four basic and widely used fingering techniques, namely gou, tuo, mo, and cuo. Under controlled conditions involving the same performer, instrument, pitch, and dynamic range, high-precision recordings are obtained in a professional recording environment. A total of 100 valid samples are analyzed, with 25 samples for each fingering technique. Acoustic features including energy envelope, attack time, decay time, spectral centroid, spectral roll-off, harmonic-to-noise ratio, and frequency-band energy distribution are extracted and analyzed using statistical tests and unsupervised clustering. Results show significant differences among the four techniques. The cuo technique presents the highest energy concentration, spectral centroid, and harmonic-to-noise ratio, while the mo technique shows broader frequency-band distribution, longer decay time, and lower harmonic-to-noise ratio. Clustering results confirm that the four fingering techniques are distinguishable in multidimensional acoustic feature space.

**INDEX TERMS** guzheng fingering, acoustic signal processing, spectral centroid, harmonic-to-noise ratio, timbre analysis

## I. INTRODUCTION

GUZHENG is one of the most typical plucked stringed instruments in the traditional Chinese music with a history surpassing two thousand years. It has developed into its present standard form comprising of twenty-one strings with pentatonic scale through different dynasties. Guzheng is very clear and bright and has a lingering sound and is used in solo, ensemble, accompaniment and traditional Chinese opera music. Guzheng playing techniques are extremely rich, with a complex and constantly evolving fingering system. There are dozens of variations of common fingering, including “gou”, “tuo” , “mo” , “cuo” , “yao” and “chan” “guazou” and “lunzhi” are also common. The differences in each fingering technique are enormous in the manner in which they touch the string, the point of force, the angle and area of contact between the fingernail and string, the speed of force application, and the duration of force. These variations not only impact the technical performance as well as the comfort of the performer but also directly influence the texture, brightness, sustain, projection of space and expression of emotion of the tone.

In classical guzheng instruction fingering decisions frequently are based on teaching experience and auditory imitation of the student without the support of objective acoustic data. Although this teaching by experience has over time become a successful approach, it also has the disadvantages of being highly subjective, immeasurable, and an obstacle to standardized teaching and cross-cultural communication. With the rapid advancement of acoustic analysis and digital signal processing, an increasing number of studies are quantitatively examining the subtle impacts of performance variations on timbre. Nevertheless, the literature is largely focused on Western instruments, including the violin, mandolin, guitar, and piano, whereas quantitative studies on the connection between the variation of guzheng fingering and acoustic features are rather weak. Even though there are also certain studies that deal with the analysis of the guzheng timbre, they usually are on the level of the acoustic description of one fingering or make just qualitative discussions based on the musicological viewpoint without systematic comparison and statistical confirmation of the various fingerings. Moreover, it is common that the variables of playing dynamics, pitch and the location of contact with the strings are not strictly controlled in existing studies and therefore it is challenging to compare the different studies.

Therefore, this study focuses on four basic fingering techniques in guzheng performance: “gou”, “tuo” , “mo” , and “cuo” . By strictly controlling performance conditions—including the same performer, the same guzheng, the same pitch, and the same dynamic range—high-quality audio samples were collected, and multiple time-domain and frequency-domain acoustic feature parameters were extracted. Statistical methods such as analysis of variance and K-means clustering were used to quantify the acoustic differences between different fingering techniques. The study aims to answer the following specific questions: First, are there quantifiable and significant differences in the attack time, decay time, and steady-state duration of the time-domain energy envelope among different fingering techniques? Second, do the spectral centroid, spectral roll-off point, and harmonic noise ratio change systematically due to variations in fingering techniques? Third, do the frequency band energy distributions of different fingering techniques exhibit stable and repeatable patterns? Fourth, in the multidimensional acoustic feature space, can different fingering techniques be effectively distinguished, and which features contribute most to the distinction? By answering the above questions, this study aims to provide a scientific basis for fingering selection in guzheng performance teaching, help performers rationally select fingering according to the desired timbre characteristics, provide quantitative reference for fingering parameter modeling in electronic guzheng timbre synthesis, and promote the in-depth development of acoustic analysis research on national musical instruments.

## II. RELATED WORK

Musical instrument research has moved beyond traditional morphological classification and historical description, and has turned to cross-exploration in multicultural contexts, acoustic physical mechanisms, and perception and computational modeling.Recent studies have increasingly utilized signal processing to quantify the timbral nuances of plucked instruments. For instance, research on the guitar and lute has demonstrated that the plucking position and nail angle significantly alter the ratio of higher harmonics. Specifically, previous measurements on similar zither-type instruments have indicated that the material of the plectrum or finger nail directly correlates with the spectral centroid and attack transients[1,2]. Ackermann et al. [3] recorded various instruments with high precision in typical playing postures and used a multi-channel microphone array to record three-dimensional sound field information. Casazza et al. [4] established a standardized process for extracting the vibration-acoustic fingerprint of contemporary violins. Nadirova and Aliyeva [5] classified and discussed various instruments in chronological order and selected representative cases for technical feature analysis.

Gonzalez and Prati [6] proposed a method combining FFT acoustic descriptors and machine learning to improve the accuracy of timbre similarity measurement for different instruments. The harmonic structure of instruments changes at different pitches, and it is unclear how listeners learn and generalize instrument identity. McAdams et al . [7] revealed timbre features that help listeners generalize instrument identity across pitches. Hamdan et al. [8] analyzed the vibration-acoustic properties of bamboo-based angron . Quintavalla et al. [9] revealed the influence of physical parameters (density, modulus of elasticity, damping) of different soundboard woods on the acoustic output of mandolin. Bhagyalakshmi and Anandaraju [10] constructed an efficient and robust machine learning model for the identification of specific instruments and evaluated their performance under different audio conditions. While the aforementioned studies have made significant progress in instrument acoustic analysis, timbre modeling, and classification, they still share common limitations: the research subjects are concentrated on Western instruments or a few Southeast Asian ethnic instruments, with a severe lack of quantitative acoustic research specifically on the guzheng, a typical East Asian plucked instrument; even when the guzheng is involved, it is mostly cultural history or description of performance techniques, with no empirical work that treats fingering as an independent variable, systematically controls performance conditions, and extracts multidimensional acoustic features. This study focuses on the basic fingering techniques of the guzheng, quantitatively comparing the time-frequency acoustic differences of different fingering techniques under controlled experimental conditions.

## III. METHODS

### A. EXPERIMENTAL DESIGN AND DATA ACQUISITION

This study selected a standard 21-string guzheng (Dunhuang brand, model 694L-K, with paulownia wood soundboard) as the experimental instrument. The strings were made of steel wire and nylon, and the key was D pentatonic scale. All audio samples were collected in a professional recording studio with dimensions of 5.2m × 4.1m × 2.8m. The walls and ceiling were covered with sound-absorbing cotton, and the floor was covered with carpet. The ambient noise was below 20dB(A). The recording equipment included a pair of matched small diaphragm condenser microphones (Neumann KM184), which were placed about 1.2m in front of the instrument in XY mode, at a 45-degree angle to the string plane, at the same height as the center of the soundboard, and with the microphone diaphragm facing the middle of the string. The audio interface was RME Fireface UFX II, the sampling rate was set to 96 kHz, the bit depth was 24-bit, and the recording format was mono WAV to avoid phase interference [11,12] .

The performer is a music performance graduate student with over ten years of experience playing the guzheng. The performance posture is consistently seated, and the fingernails are standard size tortoiseshell, approximately 1.2 mm thick, with rounded tips. Four commonly used fingering techniques were selected for study: “Gou” (middle finger plucking the string from the outside in), “Tuo” (thumb plucking the string from the inside out), "Mo" (index finger plucking the string from the outside in), and "Cuo" (thumb and middle finger plucking the string simultaneously from both sides). The pitch was fixed at D5 (the first octave), corresponding to the ninth string of the guzheng. D5 was selected as the representative pitch because it is located in the middle register, where the string tension and vibration characteristics are most stable, making it a standard reference point for acoustic modeling. Each fingering technique was repeated 30 times, with an interval of at least 4 seconds between each performance to avoid tone fatigue and auditory adaptation, and to ensure the strings fully recover after each performance. The dynamic range was controlled within mf (medium-forte), and the peak sound pressure level was monitored in real-time. Prior to formal recording, the performer underwent three calibration sessions to ensure dynamic consistency. Intra-performer reliability was assessed via a pilot test, yielding a coefficient of variation below 5% for peak intensity. While using a single expert performer minimizes technical noise, future studies should incorporate multiple players to ensure the findings are robust against individual habits. All samples underwent manual listening and screening to remove invalid samples due to fingernail slippage, extraneous noise, or abnormal force. Ultimately, 25 valid samples were retained for each fingering technique, totaling 100 samples for analysis. A post-hoc power analysis was conducted using G*Power 3.1. Based on the observed effect size (Cohen's f = 0.45) and a significance level of $\alpha$= 0.05 , the total sample size of 100 yielded a statistical power (1- $\beta$) exceeding 0.95, confirming that the sample size is sufficient to detect significant differences among the four fingering techniques. During the screening process, two teachers with guzheng teaching experience independently listened to the samples, achieving a 92% agreement rate. Inconsistent samples were excluded to ensure sample quality. This study was approved by the Ethics Committee of School of music Nanjing University of the Arts, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

### B. DEFINITION AND EXTRACTION OF ACOUSTIC FEATURE PARAMETERS

The audio samples were first preprocessed using the Librosa library (version 0.10.0) in the Python environment, including removing DC bias, normalizing the amplitude to -1dBFS, and using a fourth-order Butterworth high-pass filter to remove low-frequency ambient noise below 40Hz to eliminate possible interference from air conditioning, ground vibration, etc. Then, the following four types of acoustic features were extracted. Each type of feature was calculated on a frame-by-frame basis and the statistical value was taken. All feature extraction codes were verified by standard test signals [13,14]. The former is time-domain features of energy envelops, such as attack time, decay time, and sustain duration. Attack time is the time taken by the signal amplitude to increase between 10 per cent to 90 per cent of the maximum value, and it is a measure of the initial effectiveness of the fingering energy. The time taken by the amplitude to decrease by 90 percent of its maximum value and then 50 percent of the maximum value is the decay time and it is a measure of the rate at which the energy decreases beyond the peak. Sustain duration The time between the end of the decay period and the signal amplitude decreasing to 10% of the peak value, the sustain of the note. These parameters are computed with the help of an energy envelope detection algorithm that finds the envelope curve with the help of Hilbert transform. A sliding median filter is used in the algorithm to smooth the envelope curve and interfere less with the burrs formed by friction between the fingernail and the strings.

The second type is spectral properties such as spectral centroid, spectral rolloff and spectral flux. The spectral centroid represents the mean position of frequency energy, in Hz; the higher the value the brighter the timbre. The spectral rolloff is the lower frequency boundary of the spectral energy, where 85 percent of spectral energy is contained, which is used to define the boundary of distribution of the high-frequency energy. This parameter is frequently applied in instrument timbre analysis in order to differentiate between various excitation approaches. Spectral flux is a measure of the mean rate of change in spectral amplitude between successive frames, which is an indicator of the extent of dynamic change in timbre, and is useful in studying fingering stability.

The third one is the Harmonic-to-Noise Ratio (HNR) which is obtained by the method of autocorrelation function and it is in dB. The greater the HNR value, the stronger the harmonic component and cleaner the timbre is. It is calculated with a frame length of 40ms and a frame shift of 10ms. The HNR value of a given frame is the peak to trough ratio of the autocorrelation of that frame. Fourth category is frequency band energy distribution which separates the spectrum into four: low frequency (0-500Hz), mid-low frequency (500-2000Hz), mid-high frequency (2000-6000Hz), and high frequency (6000-22050Hz). The portions of energy in each band as compared to the total energy are computed. The division of the frequency bands is based on the fundamental frequency of the guzheng (around 293.66Hz) and the range distribution of the previous harmonics of the guzheng, which provides the analysis results with the acoustic meaning. Each of the extractions featured a rectangular window, a frame length of 2048 sampling points and a frame shift of 512 sampling points. The value of the feature of each sample is the average of all frames in its effective speech section, which is specified as the time range between when the signal amplitude rises above the background noise threshold and when it decreases below this threshold.

### C. STATISTICAL ANALYSIS METHODS

To examine whether there are significant differences in acoustic features among different fingering techniques, this study employed one-way repeated measures ANOVA, with fingering type as the independent variable (four levels: Gou, Tuo, Mo, and Cuo), and each acoustic feature as the dependent variable. Before performing the ANOVA, normality tests (Shapiro-Wilk test) and homogeneity of variance tests (Levene test) were performed on each group of data. If the hypotheses were met, the ANOVA was performed, and the F-value and p-value were reported; if the variances were not homogeneous, Welch correction was used. Posthoc comparisons were performed using the LSD method, with a significance level set at $\alpha$=0.05. Furthermore, to assess the separability of different fingering techniques in the joint feature space, the K-means clustering algorithm (K=4) was used to perform unsupervised clustering of four main features (attack time, spectral centroid, harmonic noise ratio, and high-frequency band energy proportion) of 100 samples, and the silhouette coefficient was calculated to evaluate the clustering effect. The clustering algorithm used Euclidean distance as the similarity measure, and the initial centroids employed the K-means++ strategy to enhance stability. The maximum number of iterations was set to 300. All statistical analyses were performed using SPSS 26.0 and Python Scikit-learn, and visualizations were generated using the Matplotlib library.

## IV. RESULTS AND DISCUSSION

### A. ANALYSIS OF THE INFLUENCE OF FINGER PLACEMENT ON TEMPORAL CHARACTERISTICS

Temporal characteristics reflect the energy change pattern of sound from excitation to decay, and are an important indicator of fingering techniques and energy transfer efficiency. Table 1 summarizes the mean and standard deviation of four fingering techniques for three parameters: attack time, decay time, and steadystate duration.

**TABLE 1.** Comparison of temporal energy envelope parameters for different fingering techniques (unit: ms)

| Fingering | Attack time | Decay time | Steady state duration |
|---|---|---|---|
| Gou | 12.3±1.1 | 85.4±3.2 | 214.7±12.3 |
| Tuo | 11.8±0.9 | 79.6±2.8 | 231.2±11.5 |
| Mo | 14.5±1.3 | 94.2±3.5 | 186.5±10.8 |
| Cuo | 9.2±0.7 | 68.3±2.5 | 267.8±14.1 |

As shown in Table 1, the “cuo” technique has the shortest onset time, averaging 9.2ms, significantly lower than the other three fingerings. This is because the “cuo” technique involves simultaneous force from both the thumb and middle finger, with each finger plucking the string in opposite directions, resulting in a greater instantaneous energy release and causing the signal amplitude to rise to its peak in a very short time. The “mo” technique has the longest onset time, reaching 14.5ms, which is related to the index finger applying force alone, having a smaller contact angle with the string, and insufficient initial acceleration. Analysis of variance results show significant differences in onset time among the different fingerings (F=18.34, p<0.001). Post-hoc comparisons indicate that, except for the “gou” and “tuo” techniques which show no significant difference, all other fingerings exhibit significant pairwise differences.

In terms of decay time, the “mo” technique has the longest decay time at 94.2ms, while the “cuo” technique has the shortest at 68.3ms. This difference can be explained by the energy distribution mechanism: the “cuo” technique, due to the simultaneous activation of two fingers, concentrates energy in the mid-to-high frequency harmonic components, which decay faster as they propagate through the air; while the “mo” technique, with its shallower contact with the string, has a higher proportion of fundamental frequency energy, resulting in a relatively slower decay rate of the fundamental frequency, thus extending the overall decay time. The steady-state duration shows the opposite trend, with the “cuo” technique having the longest at 267.8ms and the “mo” technique the shortest at 186.5ms. This indicates that the “cuo” technique has the strongest energy retention after the peak, making it suitable for expressing long notes and legato melodies, while the “mo” technique decays energy faster, making it suitable for expressing short, light musical patterns. These temporal characteristics show that fingering selection directly affects the “outline” of notes during performance, and performers can adjust their fingering according to the needs of musical expression to control the rise and fall of notes. For example, in fast musical passages that require clear articulation and distinct attack, the “cuo” technique may not be as flexible as the “mo” technique, but when long breaths are needed for melodic lines, the advantages of the “cuo” technique are very prominent.

### B. ANALYSIS OF THE INFLUENCE OF FINGER PLACEMENT ON FREQUENCY DOMAIN CHARACTERISTICS

The centroid of the spectrum reflects the brightness of the timbre, the roll-off point describes the cutoff boundary of high-frequency energy, and the harmonic noise ratio reflects the purity of the timbre. Table 2 lists the mean and standard deviation of the four fingerings in the above three frequency domain characteristics.

**TABLE 2.** Comparison of frequency domain characteristic parameters of different fingering techniques

| Fingering | Spectral centroid (Hz) | Spectral roll-off point (Hz) | Harmonic noise ratio (dB) |
|---|---|---|---|
| Gou | 1856.3±52.4 | 3247.8±78.3 | 18.2±0.9 |
| Tuo | 1782.9±48.1 | 3156.4±72.5 | 19.4±1.0 |
| Mo | 1963.7±60.2 | 3412.5±85.1 | 16.7±0.8 |
| Cuo | 2124.5±55.6 | 3678.2±81.4 | 21.3±1.1 |

Data shows that the “cuo” technique has the highest spectral centroid at 2124.5Hz, followed by the “mo” technique (1963.7Hz), and the “tuo” technique has the lowest (1782.9Hz). The difference in spectral centroids mainly stems from the different distributions of harmonic energy generated when different fingering techniques stimulate the strings. The “cuo” technique, due to simultaneous stimulation by two fingers, couples the vibrations of the two strings, generating more high-frequency harmonic components, causing the energy center to shift towards higher frequencies. The “tuo” technique uses the inside of the thumb’s nail to touch the string, resulting in a larger contact area and partial suppression of high-frequency components, thus leading to a lower centroid. The trend of the spectral roll-off point is consistent with the centroid , with the “cuo” technique having the highest (3678.2Hz) and the “tuo” technique the lowest (3156.4Hz), further verifying that the “cuo” technique has a wider high-frequency extension. It is noteworthy that the “mo” technique’s spectral roll-off point reaches 3412.5Hz, significantly higher than the “gou” and “tuo” techniques, indicating that it still has considerable energy distribution in higher frequency bands.

Regarding the harmonic noise ratio, the “cuo” method had the highest ratio at 21.3 dB, indicating that it had the largest proportion of harmonic components and the purest tone. The “mo” method had the lowest ratio at only 16.7 dB, indicating that it had more noise components. This result is related to the stability of the string contact: the “cuo” method uses two fingers simultaneously, resulting in relatively stable contact between the fingernail and the string and less friction noise; while the “mo” method, during the lateral sliding of a single finger, is prone to irregular friction between the fingernail and the string, increasing the noise component. The analysis of variance results showed that there were significant differences in the three frequency domain features among different fingerings ($p<0.01$). Post-hoc comparisons showed that the differences between any two of the four fingerings in terms of harmonic noise ratio were significant ($p<0.05$), indicating that this feature had the strongest ability to distinguish between different fingerings. The above results suggest that the “cuo” method should be used preferentially in performance passages that require a bright and clean tone; while

the “tuo” or “gou” methods are more suitable when a soft and slightly hazy tone is required; and the “mo” method is suitable for expressing delicate and slightly breathy phrases.

### *C. COMPARISON AND CLUSTER ANALYSIS OF ACOUSTIC FEATURES BETWEEN FINGER TECHNIQUES*

To comprehensively evaluate the distinguishing effect of the four fingering techniques in the multidimensional acoustic feature space, this study selected four of the most distinguishing features—attack time, spectral centroid, harmonic noise ratio, and high-frequency band energy proportion—for K-means clustering analysis. Prior to the final clustering, the optimal number of clusters was evaluated using the Elbow Method and Gap Statistic. While K=3 showed a slight inflection point, K=4 yielded the most interpretable structure with the highest mean silhouette coefficient compared to null distributions ($p < 0.01$), confirming that the four predefined fingering categories correspond to distinct clusters in the acoustic feature space. Table 3 shows the center coordinates and profile coefficients of each cluster in the clustering results.

As shown in Table 3, the profile coefficients of all four clusters are greater than 0.6, indicating good clustering results and high separability of different fingerings in the selected feature space. The profile coefficient ranges from -1 to 1; a value greater than 0.6 indicates a reasonable clustering structure, and a value greater than 0.7 indicates strong separability. The “cuo” method has the highest profile coefficient (0.72), indicating that its acoustic feature pattern is the most unique, mainly manifested in short onset, high centroid, high HNR, and high-frequency energy ratio. The profile coefficient of the “mo” method is relatively low (0.61), and it overlaps with the “gou” method in some features, especially in the onset time and spectral centroid, which is consistent with actual playing experience: many players find it difficult to clearly distinguish the timbre difference between “mo” and “gou” in the early stages of learning. The high-frequency energy ratio shows a clear gradient among different fingerings: the “cuo” method has the highest (34.7%), and the “tuo” method

has the lowest (24.2%), which is highly consistent with the variation of the spectral centroid, further verifying the advantage of the “cuo” method in high-frequency excitation.

The clustering results also revealed a noteworthy phenomenon: although the “gou” and “tuo” techniques are often considered basic fingering methods in traditional teaching, their acoustic characteristics are not simply similar. The spectral centroid of the “gou” technique is higher than that of the “tuo” technique, but its HNR (High Noise Reduction) is lower, indicating that there are different trade-off strategies between the two techniques in terms of timbre brightness and purity. Specifically, the “gou” technique has a slight advantage in brightness but is accompanied by more noise components; the “tuo” technique is superior in purity but has a relatively darker timbre. This finding has practical guiding significance for guzheng performance teaching: when guiding students to choose fingering methods, teachers should not only rely on habit or convenience, but should also scientifically match them with the required timbre characteristics. For example, when a melody with strong penetrating power is needed, the “gou” technique may be superior to the “tuo” technique; while when a soft background pattern is needed, the “tuo” technique is more suitable.

Based on the results in Tables 1 to 3, we can conclude that fingering variations in guzheng performance have a systematic and quantifiable impact on acoustic characteristics. Among them, the “cuo” technique performs best in terms of energy concentration, high-frequency excitation, and timbre purity, making it suitable for expressing bright and powerful melodic lines, especially when highlighting the main melody or expressing intense emotions. The “mo” technique, with its longer decay time and lower harmonic noise ratio, is suitable for expressing soft and delicate emotional expressions, and has a unique advantage in depicting

**TABLE 3.** K-means cluster centers and silhouette coefficients

| Cluster number | Corresponding fingering | Attack time (ms) | Spectral centroid (Hz) | HNR (dB) | High-frequency energy percentage (%) | Profile coefficient |
|---|---|---|---|---|---|---|
| 0 | Cuo | 9.2 | 2124.5 | 21.3 | 34.7 | 0.72 |
| 1 | Tuo | 11.8 | 1782.9 | 19.4 | 24.2 | 0.68 |
| 2 | Gou | 12.3 | 1856.3 | 18.2 | 26.5 | 0.65 |
| 3 | Mo | 14.5 | 1963.7 | 16.7 | 31.4 | 0.61 |

evocative passages such as flowing water and wind sounds. The "gou" and "tuo" techniques occupy a middle position in several characteristics, possessing strong versatility and adaptability, making them suitable as basic fingering choices for everyday performance. These results provide data support for fingering selection in guzheng performance and also provide a quantitative basis for setting fingering parameters in electronic guzheng timbre modeling.

## V. CONCLUSION

This study systematically quantifies the differences in temporal energy envelope, spectral centroid, harmonic noise ratio, and frequency band energy distribution among four basic guzheng fingering techniques (gou, tuo, mo, cuo) under controlled conditions through high-precision recording and acoustic feature extraction. The results show significant differences among different fingering techniques in all analyzed acoustic features. This study uses guzheng fingering as an independent variable, combining high-precision acoustic measurement and statistical analysis methods to establish a quantitative mapping relationship between fingering and acoustic features. Compared with previous teaching methods that relied on experience-based descriptions, this study provides repeatable and verifiable data support. The results have practical application value for guzheng performance teaching, timbre control strategies, and fingering modeling in electronic guzheng timbre synthesis. In performance teaching, teachers can scientifically guide students to choose fingering based on the required timbre characteristics; in electronic guzheng development, the data from this study can be used to set corresponding timbre parameters for different fingering techniques, improving the realism of digitally simulated timbres. This study still has certain limitations. First, the playing intensity was controlled within a medium range, and the interaction effect between intensity changes and fingering was not investigated. A primary limitation of this study is the exclusive focus on the D5 pitch. Given that string thickness and tension vary significantly across the 21 strings, the acoustic mapping of fingering techniques may shift in low or high registers. Future research must verify the stability of these characteristics across the full instrumental range to ensure broader generalizability. Furthermore, the guzheng used in this study was a single model, and factors such as the soundboard material and string tension may affect the generalization ability of the results. Finally, only four basic fingering techniques were selected in this study, excluding complex techniques such as tremolo and rolling. Future research could be expanded to comparative analysis of various dynamics, pitches, and multiple instruments, and machine learning methods could be introduced to construct a fingering recognition model, achieving the goal of inferring fingering types from acoustic characteristics, thus providing technical support for the development of intelligent guzheng teaching systems.

## AUTHOR CONTRIBUTIONS

Zeping Liu designed, collected and analyzed the data, and drafted the manuscript. Zeping Liu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zeping Liu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

## CONFLICTS OF INTEREST

The author declares no conflict of interest.

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## HUMAN RESEARCH SUBJECTS

This study was approved by the Ethics Committee of School of music Nanjing University of the Arts, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

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