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Digital Technology Enables Optimization of Piano Playing Techniques: A Study on Performance Error Identification and Correction Based on Multimodal Acoustic Data

Yishan Zhang
School of Music and Media, Anyang University, Anyang 455000, Henan, China
Corresponding author: Yishan Zhang (e-mail: pinocchio0111@163.com)

ABSTRACT Objective and efficient evaluation of piano performance remains difficult due to the complex interaction among motor control, acoustic characteristics, and artistic expression. To improve the accuracy of performance assessment and training feedback, this study proposes a multimodal acoustic data-driven framework for piano performance error identification and correction. High-precision audio acquisition devices and motion capture sensors are employed to synchronously collect acoustic signals and key-motion parameters, forming a multimodal performance dataset. Based on signal analysis and pattern recognition techniques, an automated error identification model is developed to detect deviations in pitch accuracy, rhythmic stability, and dynamic control. Personalized correction strategies are subsequently generated through visual feedback and adaptive training modules. Experimental evaluation involving learners at different skill levels demonstrates that the proposed system significantly improves technical performance indicators compared with conventional training methods. Furthermore, the analysis reveals strong correlations between performance error patterns and practice behaviors. The proposed framework provides an effective approach for intelligent music education and offers methodological references for acoustic signal processing, multimodal sensing, and pattern recognition applications.

INDEX TERMS multimodal acoustic data, performance error identification, signal processing, multimodal sensing, pattern recognition

I. INTRODUCTION

AS an art form incorporating high technical skill, artistic expression, and complex psychological activities, the basis of optimizing and mastering piano technique remains an integral pursuit where the performer and educator meticulously interlace technical precision with creative depth to produce a flawless tonal tapestry. This mastery demands a seamless integration of movement and mind, mirroring the way advanced processing technologies ensure the structural integrity and aesthetic consistency of a perfectly rendered material. Excellent playing technique not only refers to muscle control of the fingers, namely speed, strength and independence, but also includes a sumptuously large amount of other abilities including small sound control, strict rhythm control and fluent phrasing. In the traditional learning paradigm, technique acquisition and improvement mainly depend on oral between teacher and student, and on repeated practice on the part of the practitioner, and on self-reflection (based on auditory and kinesthetic senses). While this model is full of inherited artistic experience the limitations inherent in this model have been becoming extremely evident. Teacher assessments are inevitably subject to subjective experience momentary attention and personal aesthetic preferences, so that it is impossible to carry out millisecond level, parametric and quantitative comprehensive analysis of every performance. Students are often put in the predicament of “knowing there is a problem, but not knowing exactly what the problem is, its extent, or how to systematically improve it” leading to low practice efficiency and even the creation of difficult to correct erroneous muscle memory.

With the development of information technology rapidly, digital empowerment has emerged as an important driving force for the transformation of traditional fields. In the music industry, from digital audio workstations to AI music composition, technology is transforming the ways sound is created, recorded and disseminated. However at the micro-training level of performance skills, how to utilize the technology to perform indepth intervention is still a topic that requires further exploration. As a problem, good performance can be considered to be the result the real-time coupling of delicate body movements and complex sound effects, and nothing can represent its entirety in only a measure of signal dimensions. Therefore, the acquisition and analysis of any multimodal data integrative of audio and motion (even physiological signals) has become very important and key to understand well the internal mechanisms of performance. By converting an image of the original sound waves produced by the performance, as well as trajectories of the hands and arms into electric signals via high-precision sensors, it is possible to construct a bridge between "action instructions" and "sound results." Furthermore, through the signal processing and machine learning algorithm to mine this data, the error state that is far from the ideal state can be automatically and objectively detected, such as the duration abnormality of a note, abnormal dynamic fluctuations in successive notes, and timbre defects under certain fingerings.

The core proposition of this research is, how to construct systematic frame based on the multimodal acoustic data to realize the high-precision identification of piano playing error, and based on this, form an effective digital correction strategy to empower the optimization process of playing techniques. The expected contributions of this research is: first, to propose and implement a complete technical path combining data acquisition, error identification, and feedback intervention; second, to quantify the advantages of digital correction methods in comparison to traditional methods by means of experimental data; and third, to reveal the possible causes behind the specific playing errors to provide data support for personalized teaching. This research seeks to transition piano education from vague perception to a data-driven paradigm, utilizing precise analytics to refine musical execution with the same rigorous calibration used to monitor tension material and density in automated production. By digitizing these subtle nuances, the study establishes a clearer, more efficient path for performers to advance their skills through a scientifically structured mastery of their craft.

II. RELATED WORK

The research perspective on piano performance art continues to expand, and scholars analyze the influence of technique, expressiveness, psychological mechanisms and educational models on performance effectiveness from multiple dimensions. Jia [1] reveals the subtle differences that govern piano performance by analyzing the synergistic effect between piano performance technique and musical expressiveness. Zheng and Leung [2] explore the concept of cultivating creativity in piano performance and teaching based on the Chinese context. Hu [3] believes that emotional expression is the soul of piano performance, which depends not only on superb technique, but also on the performer' s understanding of the work, personal emotional investment and specific performance treatment. Kandemir and Yokuş [4] explore the influence of the variable of learning strategy on two key outcomes of piano learning: self-efficacy and performance success based on educational psychology . Using comparative research method, Jiang [5] reveals the similarities and differences between Chinese and American piano higher education in terms of concept, structure and practice.

Johnson [6] explored the potential value of actor training methods for instrumentalists. Meng [7] systematically analyzed various inducing factors that cause performers to produce specific body postures and movements. Wang et al. [8] proposed a system based on a greedy algorithm that can effectively plan the movements of a robotic hand and achieve a certain degree of automatic piano playing and interaction with people. Jentzsch and Braun [9] explored how different attention instructions affect the performance quality of amateur piano learners, and evaluated their performance accuracy, fluency and expressiveness through objective measurement and expert scoring. Kızılay [10] examined how the Paris Conservatory evolved its piano teaching system in its development, which key figures shaped its tradition, and how broader French culture permeated and influenced its unique piano performance training model. This paper aims to provide a new theoretical basis and practical path for data-driven intelligent piano teaching by synchronously capturing audio and motion parameters, using machine learning models to achieve fine classification and cause tracing of errors, and constructing a dynamic feedback mechanism to drive precise optimization of skills.

III. METHODS

A. CONSTRUCTION OF MULTIMODAL PERFORMANCE DATA ACQUISITION SYSTEM

In order to fully capture the performance state, this study built an environment for synchronous acquisition of audio and kinematic data. Audio acquisition used a professional-grade condenser microphone to record the original piano sound at a sampling rate of 96 kHz and a depth of 24 bits to ensure the capture of the complete acoustic spectrum and transient details. In addition, in order to link sound production with body movement, inertial measurement unit (IMU) sensors were installed at specific locations on the performer's index fingers, thumbs, wrists, and forearms. These sensors synchronously acquired triaxial acceleration, angular velocity and Euler angle data at a frequency of 200 Hz to accurately describe the motion trajectory, speed and posture of key parts of the hand. All sensors and audio interfaces were synchronized at the microsecond level through a unified timecode generator to ensure that each frame of motion data could be accurately aligned with the corresponding audio segment. To address the significant difference between the audio (96 kHz) and motion sensor (200 Hz) sampling rates, this study employs a high-precision interpolation algorithm in the data post-processing stage to uniformly upsample motion data to 96 kHz. This is combined with hardware timestamps for bidirectional matching, thereby achieving fine alignment within the millisecond-level error range and providing a reliable data foundation for subsequent error identification. The acquisition software was customized based on an open source platform, which can display the signal waveform and sensor data stream in real time, and automatically package and store the multi-channel data into a time-aligned data file after the performance, forming the basis of the multimodal dataset for subsequent analysis [11-12].

B. PERFORMANCE ERROR RECOGNITION MODEL BASED ON FEATURE ENGINEERING

After preprocessing the raw data, the core error identification stage begins. First, feature extraction is performed. For the audio aspect, for each musical phrase or note segment, the following features are calculated: the pitch sequence based on the fundamental frequency extraction algorithm and its deviation from the standard pitch in the score; the dynamic envelope obtained through short-time energy analysis and its matching degree with the reference dynamic template, which was jointly marked and determined by three senior piano teachers based on the style of the work, the structure of the musical phrases and the requirements of musical expression, to ensure the artistic rationality of the evaluation criteria; and the overall distance between the actual rhythmic point sequence and the standard rhythmic template, as well as the fluctuation rate of local rhythms, calculated using the dynamic time warping algorithm. For the kinematics aspect, the peak amplitude, average velocity, start and stop delay times of key points, and the coordination index between different finger movements are calculated. These features together constitute a high-dimensional feature vector, used to describe the performance of a single performance in terms of pitch, rhythm, dynamics, and coordination.

Subsequently, error identification was constructed as a multi-label classification problem. The study collected a large number of performance samples with annotations. The annotations were completed independently by three senior piano teachers, marking the error types present in each performance (such as “rhythm rushing”, “sudden increase in dynamics”). Using these labeled data, a random forest classification model was trained. The advantage of this model is that it can handle high-dimensional features, evaluate the importance of features, and has a good fitting ability for nonlinear relationships [13]. However, piano performance data is essentially time-series data, with a sequential dependency between notes and actions. This study chose random forest primarily because of its advantages, such as high training efficiency on medium-sized datasets, strong interpretability of feature engineering results, and ability to intuitively output feature importance ranking. This facilitates providing learners with clear error attributions, thereby prioritizing the core need for understandable feedback in teaching scenarios. When training the model, the multimodal feature vector is used as input and the error types annotated by experts are used as output labels. The trained model can automatically analyze new performance data and output the possible error types and corresponding confidence probabilities.

C. PERSONALIZED CORRECTION STRATEGY GENERATION AND FEEDBACK INTERFACE DESIGN

Having recognized the mistake, the system does not simply report the problem, but produces a specific correction strategy aimed at fixing the issue. The strategy generation is based on a predefined rule base, which combines the type of an error, the severity of an error (quantified by the degree to which the feature value deviates from the normal range) with the historical data of the learner (common error patterns and progress trajectories) [14-15] . For example, for the identified error of “uneven dynamics of continuous scales”, then the system may find, according to the history data, that the learner generally has the problem of diminuendo when ascending scales by the right hand, and generate a strategy: “Focus on ascending scales by the right hand, practice with the metronome at a speed of 60 beats per minute, pay attention to listening and make sure that the dynamic count value of each note is stable within the preset target range.” To achieve a successful communication of corrective information a specific visual feedback interface was invented. The center section of the interface shows a piano score with color-coded overlays: green indicates correctly executed notes, yellow fifteen replications indicate small deviations and red indicates major mistakes. Clicking on any of the marked notes opens a details window with the exact value of the deviation of the note’ s pitch (in Hertz), duration of the deviation (milliseconds), and dynamics value. One side of the interface has a “Correction Training Room” which gives guided practice based on the strategy generated. For example, for rhythm problems, the system can create an enhanced rhythm track for the learner to follow; for dynamic problems, it can appear on the score a real-time comparison of the dynamics curve and the target curve, making the learner play and adjust accordingly. All the practice sessions are recorded by the system and are used to update the learner model and, therefore, achieve dynamic optimization of the strategy.

IV. RESULTS AND DISCUSSION

To verify the effectiveness of the method, an eight-week controlled experiment was conducted. Forty amateur piano learners with 1 to 5 years of experience were recruited and randomly divided into an experimental group (20 participants) and a control group (20 participants). Both groups practiced the same three test pieces containing scales, arpeggios, chords, and melodic fragments. The experimental group practiced using the system developed in this study once a week, receiving an analysis report from the system after each practice session and completing recommended correction modules. The control group followed a traditional practice model, receiving verbal feedback and guidance from the same teacher once a week. Standardized performance tests were conducted on all participants before the start of the experiment, after the fourth week, and after the eighth week, and data was recorded. The same algorithm was used for post-test analysis to avoid assessment bias.

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

A. SYSTEMATIC IMPROVEMENT OF CORE PERFORMANCE INDICATORS

Quantitative analysis of the data before and after the test showed that the experimental group made statistically significant progress in several core skill indicators. Table 1 summarizes the average performance of the experimental group and the control group in three key indicators before and after the experiment: pitch accuracy, rhythm standard deviation (the smaller the value, the more stable), and dynamic control precision index (defined as the correlation coefficient between the performance dynamic envelope and the reference dynamic template; the closer the value is to 1, the more precise the dynamic change control).

TABLE 1. Comparison of core performance indicators before and after the experiment

Group	Index	Pre-test average	Post-test average	Increase
Experimental group	Pitch accuracy	78.2%	92.7%	+14.5 percentage points
Experimental group	Pace standard deviation (ms)	45.3	28.1	-17.2 ms
Experimental group	Dynamic control accuracy index	0.65	0.86	+0.21
Control group	Pitch accuracy	79.1%	85.4%	+6.3 percentage points
Control group	Pace standard deviation (ms)	43.8	37.5	-6.3 ms
Control group	Dynamic control accuracy index	0.67	0.75	+0.08

The experimental group showed significantly better improvements than the control group across all three metrics. Particularly in rhythm stability and dynamic control, the experimental group demonstrated remarkable improvement (rhythm stability was 2.7 times that of the control group). This indicates that accurate identification and immediate feedback based on multimodal data can help trainees detect and correct subtle fluctuations and inaccuracies in dynamic control that are difficult to detect using traditional methods more quickly and effectively. The objective data provided by the system (such as specific milliseconds and dynamic deviation values) replaces vague adjectives (such as "a bit fast" or "a bit weak"), making training objectives clear and measurable, thereby greatly improving the directness and efficiency of training.

B. ERROR PATTERN ANALYSIS AND THE EFFECTIVENESS OF PERSONALIZED CORRECTION

Another advantage of the system is its ability to continuously track and analyze individual error patterns. Table 2 shows the distribution of the top three most common error types identified by the system for all members of the experimental group during the experiment, and their elimination rates after targeted correction.

TABLE 2. Identification and Correction Effects of Common Error Types in the Experimental Group

Error type	Frequency of occurrence (total number of occurrences)	The system recommends the main corrective strategies.	Error elimination rate after eight weeks
Complex rhythmic time unevenness	18	Layered rhythm training and visualization of time value comparison	88.9%
Uneven force when pressing the keys simultaneously on chords	16	Single-note dynamics calibration exercises and slow chord arpeggio practice emphasizing balance	93.8%
Some notes in a fast scale are blurred ("missed notes")	15	Extremely slow high finger lift exercises and motion trajectory smoothness training	86.7%

Table 2 reveals several deep-seated skill problems commonly found among amateur learners but often overlooked. For example, "imbalanced dynamics when pressing keys simultaneously on chords" often results in a muddy sound and a lack of prominence in the main melody. Traditional teaching might vaguely point out that "the sound is not clean," but the system can precisely identify which notes have an imbalanced dynamic ratio and correct it through targeted practice, achieving an elimination rate as high as 93.8%. This demonstrates that digital identification is not only about discovering errors but also about finely classifying them, enabling corrective measures to move from a "general" approach to a "point-to-point" one, significantly improving the accuracy and success rate of intervention.

C. LONG-TERM TRAINING EFFECTIVENESS AND SKILL INTERNALIZATION

To understand the sustainability of the effects, a follow-up test without systematic assistance was conducted on the experimental group four weeks after the experiment ended. The test piece is a new piece that has not been practiced before, but it has been independently evaluated by three senior piano teachers. Its technical difficulty coefficient (5.3 $\pm$ 0.2) and core skill requirements (scales, arpeggios, dynamics control) are different from the baseline test piece (difficulty coefficient 5.1 $\pm$ 0.1, the difference is not statistically significant, $t(38) = 0.89$, $p = 0.38$) is highly matched, ensuring the rationality of the comparison. Before the formal experiment, all participants had not been exposed to the new work. The researcher collected the baseline performance of the experimental group on the new work through a pre-performance (without feedback). The results showed that its sight-reading accuracy, self-correction efficiency and other indicators were basically the same as the baseline test scores before the experiment ($p > 0.05$), proving that the initial cognitive difficulty of the two groups of works was comparable. Table 3 compares the performance of the experimental group in this follow-up test with their performance in the pre-test at the beginning of the experiment (based on pieces of similar difficulty).

TABLE 3. Evaluation of Skill Transfer and Long-Term Retention Effects in the Experimental Group

Evaluation Project	Pre-experimental test (baseline)	Post-experiment follow-up tests (without system assistance)	Change
Sight-reading accuracy in one performance	62.5%	80.3%	+17.8 percentage points
Self-correction efficiency (average time to detect and correct errors)	28.4 seconds	15.7 seconds	-12.7 seconds
Subjective scoring of performance fluency (blind teacher evaluation, out of 10)	5.8	7.9	+2.1 points

Even without real-time system feedback, the experimental group members showed a significant improvement in accuracy on their first performance of new pieces compared to the baseline before the experiment, indicating that the skill improvements gained through systematic training have a certain degree of transferability. More importantly, the substantial increase in "self-correction efficiency" suggests that learners do not merely rely on the system to "tell" them of errors, but rather, through long-term, precise feedback, they internalize the standards and judgment abilities for perceiving the "correct performance state," thus enabling them to more quickly identify problems and make adjustments. The improvement in teachers' subjective evaluations further confirms the positive impact of skill optimization from the overall level of artistic performance. This demonstrates the ultimate goal of this method: not to make performers permanently dependent on machines, but to use machines as efficient "coaches" to accelerate the formation of accurate internal auditory perception and motor control, ultimately achieving the autonomous internalization and improvement of abilities.

D. COMPREHENSIVE DISCUSSION

The results of this study collectively show that the digital intervention framework based on multimodal acoustic data has great advantage in many dimensions of optimization of the technique of piano performance. Its core value is in the application of the show improvement of the performance process from a "black box" to a "white box". Many vague and generalized evaluations in the traditional model (such as "poor musicality" or "rough technique") are divided into specific, quantifiable parameter issues ("the dotted rhythm value in measure 12 is 15% shorter" or "the average dynamic range of the left hand accompaniment is 3dB higher than the melody of the right hand"). This decomposition makes the practice objectives very clear, adds to cognitive load, and enables practitioners to focus their attention on solving specific problems.

However, the research also has to discuss the limitations. First of all, the system is currently well able to detect and correct rather objective technical parameters associated to the conformity of musical scores (pitch, rhythm, dynamic balance) but it is still difficult to effectively quantify and guide the higher-level musical expressive elements e.g. the appropriate change of timbre, the use of the rubato, the personalised treatment of syntax etc. These areas are still ones that require the artistry and experience of teachers. Second, the power of the system depends on the assumption that the learner has some basic abilities in sight-reading and is willing to use scientific methods in their practicing. For learners who have very low levels of motivation or vastly different ways of thinking, the results may be impoverished. Future work could explore the use of incorporating more physiological signals (such as electromyography and electroencephalography) to understand the neuromuscular mechanism behind performance of the music and attempt to combine generative models to provide examples of creative reference for musical expressive training.

V. CONCLUSION

This study validates an effective solution to optimize piano performance through digital technologies, utilizing multimodal acoustic data analysis to monitor and refine the sonic texture with the same rigorous precision applied to characterizing fineness and uniformity. This systematic approach ensures that every material auditory layer is meticulously calibrated, providing a data-driven foundation for perfecting complex musical craftsmanship. From building a technical framework combining synchronous data acquisition, multi-feature error identification, and personalized feedback intervention, abstract performance quality issues were effectively converted into measurable, analysable, and interventionisable concrete goals. Quantitative results from controlled experiments indicate the significant improvement in learners' performance of core skills indicators including pitch accuracy, rhythmic stability, and dynamic control compared to traditional teaching feedback models. Further in-depth analysis shows the system does not only efficiently detect common errors, and also has a high elimination rate through specific correction strategies which encourage skill internalization and transfer, making learners ensure higher self-monitoring and corrective ability even without system assistance. This study confirms that digital technology serves to reinforce rather than replace the humanistic essence of piano instruction, acting as a high-precision sensor that monitors the consistency and tension of every musical thread to compensate for traditional limitations in accuracy and personalization. This integration functions as a sophisticated finishing process, ensuring that the raw artistic material is refined with the same technical immediacy required to produce a flawless, high-grade performance. It partially frees teachers of the heavy burden of basic, repetitive error correction work, as they need to use their time and energy better for inspiring artistic imagination, and for musical literacy.

AUTHOR CONTRIBUTIONS

Yishan Zhang designed, collected and analyzed the data, and drafted the manuscript. Yishan Zhang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Yishan Zhang 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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