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Article

Biomechanical analysis of hand muscle activity and wrist relaxation techniques during piano playing

Qian Yang

Music and Dance Academy, Chongqing Preschool Education College, Chongqing 404100, China; 13709438381@163.com

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Abstract: When playing the piano, there is a complex coordination of movements between the wrists, fingers, elbows, and shoulders. This paper aims to explore the characteristics of hand muscle activity in piano playing through biomechanical analysis and to improve the player's comfort and performance by combining the application of wrist relaxation techniques. Participants with different piano proficiency levels are recruited as experimental subjects, and muscle activity data of players of various levels is collected and analyzed. Surface electromyography (EMG) technology is used to monitor the main muscle activities of the participants dynamically during piano playing, and their features under different playing conditions are analyzed. At the same time, a high-resolution three-dimensional motion capture system is used to analyze the movement efficiency and injury risk of participants' wrists and fingers while playing the piano. Then, the EMG data is integrated with the 3D motion capture data to construct a biomechanical model based on the Newton-Euler method, analyze the relationship between hand movement and muscle load, predict fatigue points during performance, and design relaxation techniques for wrists and fingers. The experiment shows that the *p*-values are all less than 0.05, indicating that relaxation techniques positively affect the electromyographic activity of participants with different piano levels. The wrist relaxation techniques also effectively reduce the risk of injury for participants, indicating that this technique has a positive significance for improving pianists' relaxation level and performance.

Keywords: piano playing; hand muscle activity; wrist relaxation techniques; biomechanical analysis; biomechanical model

1. Introduction

Piano playing is a highly complex artistic activity that requires not only excellent hand coordination but also great strength in all the muscle tissues involved in the activity. Moreover, constant muscle activity can cause significant fatigue in the performer and increase the risk of injury. Traditional academic research often prioritizes the exploration of performance techniques and artistic expression while neglecting the comprehensive and systematic study of the biomechanics of hand muscle activity. A missed opportunity often results in pianists being inadequately prepared to effectively deal with the hand fatigue and tension that may occur during extensive practice, ultimately affecting their overall performance quality. Therefore, it is extremely important to delve deeper into the biomechanical characteristics that control hand muscle activity and to study using various relaxation techniques to enhance the overall experience and relieve discomfort. In the biomechanical study of hand muscles, it is necessary to focus on analyzing the movement load, muscle contraction patterns and joint pressure under different playing tasks, and to quantitatively evaluate them using biomechanical measurement methods. At the same time, "relaxation techniques" as an intervention method to relieve muscle tension and fatigue should break through the limitations of experience and explore application methods by adjusting wrist posture, optimizing touch-key paths, and combining breathing regulation and psychological relaxation. Although relevant research has been explored to some extent, it is still lacking in systematicness, especially in the quantitative assessment of muscle fatigue and the effectiveness of relaxation techniques. There is still a large gap in these areas.

In recent years, the advent of advanced biomechanical analysis techniques has greatly enhanced piano learners' ability to closely examine the state of hand muscle activity during piano performance. By utilizing cutting-edge technological tools such as electromyography (EMG), motion capture systems, and force plates, researchers are now able to monitor muscle activity in real time, facilitating a comprehensive analysis of its relevance to necessary performance skills. The primary advantage inherent in the application of these innovative methods is their ability to provide researchers with quantitative data that can subsequently inform a deeper understanding of the various effects of various performance techniques on muscle activity. As a result, this empirical evidence has enabled scholars to design more scientifically grounded training programs that take into account the biomechanical realities of piano performance, ultimately enabling musicians to perfect their skills while minimizing the risk of injury and enhancing their overall artistic expression.

The purpose of this study is to improve the comfort and performance of the players by conducting a biomechanical analysis of hand muscle activity during piano playing and combining it with wrist relaxation techniques. Combining EMG (Electromyography) and 3D motion capture technology provides unprecedented accuracy and multi-dimensional perspectives for the study of hand muscle activities during piano playing. The wrist relaxation technique reduces muscle tension and joint pressure, thereby enhancing the comfort and expressiveness of playing. It also improves muscle coordination and reduces the risk of muscle fatigue and injury caused by excessive tension and improper posture. The main contribution of this paper is to construct a comprehensive research framework combining biomechanics and performance techniques, which provides a new perspective and basis for future exploration of related fields.

2. Related work

The piano is widely used around the world, and playing it is a highly refined motion [1,2]. Piano playing involves complex cognitive processes, including hand-eye coordination, memory, and the use of creativity [3,4]. Trigulova and Kimsanov [5] emphasized that music hearing not only affected the quality of performance but also had a profound impact on the performer's overall musical understanding and creativity. Therefore, it is recommended that music hearing is improved through ear training and improvisation exercises. Chen and Zheng [6] studied the application of artificial intelligence-based teaching methods in college piano teaching and proposed directions for innovation and exploration. This study showed that using intelligent technology could improve teaching efficiency and personalize students' learning experiences, thereby stimulating students' creativity and performance. Zheng and Leung [7] focused on the development of creativity in piano performance and teaching. Through interviews, he found that cultural background and teaching methods had a significant impact on students' creativity. His research emphasized the need to incorporate more strategies to stimulate creativity into teaching to cultivate students' musical expression. Piano performance is not only a display of skills but also a reflection of personal aesthetics and cultural literacy [8]. Djalalova [9] discussed how piano playing activated students' musical and aesthetic worldview and its impact on music culture. Meng [10] explored expressive movements and their causes in piano playing, emphasizing the relationship between body movement and musical expression. This study helped to better understand the physicality and emotional expression of musical expressiveness. In general, these literatures have explored the multidimensional issues of piano playing and teaching from different perspectives to improve the effectiveness of piano teaching.

Biomechanics not only helps to understand complex biological mechanisms but also lays a solid scientific framework for improving performance in various sports [11,12]. When looking ahead to the prospects of future technological advancements, it is expected that biomechanical analysis can increasingly demonstrate its valuable contributions and applicability in a wider range of fields [13,14]. In a comprehensive review conducted by Pal and Gupta [15], the intricate relationship between biomechanical analysis and joint replacement surgery was carefully examined, demonstrating that the use of biomechanical models to optimize surgical planning could significantly improve the postoperative rehabilitation outcomes of patients undergoing such surgery. Stetzelberger et al. [16] conducted a comprehensive assessment of the structural integrity and functional strength of the round ligament of the hip joint through biomechanical analysis, providing basic data to help understand its key role in maintaining joint stability during dynamic movements. The field of relaxation technology has become a booming market with huge potential applications aimed at relieving physical and psychological stress while improving an individual's overall quality of life [17,18]. The growing interest in the intersection of biomechanics and muscle activity has highlighted the importance of this research in related fields such as sports medicine and rehabilitation [19,20]. A deeper understanding of the mechanisms of change and potential adaptation in muscle activity is essential for optimizing athletic performance, preventing injuries, and developing effective rehabilitation treatments for individuals recovering from physical injuries [21,22]. In a groundbreaking study, Niijima et al. [23] investigated the application of electrical muscle stimulation as a method to modulate and reduce muscle activity during the performance of vibrato techniques, aiming to discover more effective strategies for acquiring motor skills. Berckmans et al. [24] used EMG as a methodological tool to conduct an in-depth exploration of the muscle activity patterns associated with shoulder dysfunction, emphasizing that targeted training of specific muscle groups was essential for promoting the rehabilitation process and restoring functional motor ability. In short, biomechanical analysis of muscle activity during piano playing is conducive to the optimization and application of wrist relaxation techniques.

3. Hand muscle activity and relaxation techniques

3.1. Participant recruitment

Participants are recruited from a music college and local music schools aged between 18 and 45. The recruited subjects are beginners (at least 6 months of piano learning experience, able to play simple pieces proficiently), intermediate players (more than 2 years of piano learning experience, able to play medium-difficulty pieces independently), and advanced players (more than 5 years of piano playing experience, able to play difficult and professional-level pieces, with some stage performance experience).

An online registration system is set up to collect participants' personal information and relevant piano performance experience. Interviews and on-site performance evaluations are conducted for qualified participants.

After the participants are determined, they are informed of the purpose, methods, possible risks, and their rights to the study. Participants are required to sign the informed consent form on a voluntary basis after fully understanding the content of the study and to ensure that they agree to participate in the study and follow the relevant experimental procedures. They need to undergo a physical examination to confirm that they have no history of serious hand diseases or sports injuries and no other health problems that affect their muscle activity.

Based on the interview and assessment results, the final list of participants is confirmed to ensure that there is a sufficient sample size in each level group and that the genders are relatively balanced.

A participant database is established to record each participant's basic information, evaluation results, and related feedback. During the experimental process, it is necessary to maintain regular contact with participants to ensure their enthusiasm and willingness to continue participating in the research. At the same time, the problems encountered by participants during the experiment are collected, and timely feedback and solutions should be provided.

Ethical approval is required for research because it involves the collection of personal information from participants, health examinations, informed consent, and potential physical or psychological risks. It is necessary to ensure that the research process complies with ethical standards and safeguards the rights and safety of participants.

3.2. EMG data acquisition

sEMG technology is used to dynamically monitor the muscle activity of participants during piano playing [25,26]. Participants are required to perform appropriate warm-up exercises before the experiment to reduce muscle tension and ensure that their muscles are in optimal condition.

According to the principle of muscle anatomy, the main muscle groups (fingers, forearms, and wrists) are selected for monitoring. For finger muscle group monitoring, the electrodes are placed on the dorsal and palmar sides of the index and middle fingers. For forearm muscle group monitoring, the electrodes are placed on the radial and ulnar sides of the forearms. For wrist muscle group monitoring, the electrodes are placed near the wrist joint. Before sticking the electrodes, the skin surface is cleaned, and sweat and grease are removed to improve the contact quality between the electrodes and the skin. A bipolar electrode configuration is used to ensure that clear electromyographic signals can be obtained.

In the piano playing environment, the EMG data acquisition system is set up, and the connectivity between the equipment and the participant is ensured. The sampling frequency should be adjusted to 1000 Hz to ensure the ability to capture high-speed movements. At the same time, the appropriate gains are set to ensure that the signal strength is within an acceptable range and avoid signal distortion.

Standardized performance tasks are designed, including playing at different forces, speeds, and types of repertoire. Each performance lasts for 5 min without interruption. During the performance, the EMG signals are recorded in real time. After each performance task, a preliminary check of the data is performed. Any signal with artifacts or noise is immediately retested.

The collected EMG data is subjected to a bandpass filter (set to 20 Hz to 500 Hz) to remove low-frequency interference, high-frequency noise, and direct current (DC) components in the signal. The expression is [27,28]:

$$\mathrm{H(f)} = \begin{cases} 0 & \text{if f} < 20\ \text{Hz} \\ 1 & \text{if } 20\text{Hz} \leq \text{f} \leq 500\ \text{Hz} \\ 0 & \text{if f} > 500\ \text{Hz} \end{cases} \tag{1}$$

Filtering out signals below 20 Hz can remove low-frequency interference (such as slow-motion artifacts), while filtering out signals above 500 Hz helps to reduce the influence of equipment or environmental noise.

Then, the EMG signal is normalized, and the expression is as follows:

$$\mathrm{EMG_{norm}}(t) = \frac{\mathrm{EMG}(t) - \mu}{\sigma} \tag{2}$$

μ is the mean of the signal, and σ is the standard deviation of the signal.

Normalization processing eliminates the signal amplitude variations caused by individual differences, making the data from different participants or under different experimental conditions comparable.

The processed EMG data is classified and stored according to the participant number and experimental conditions. The time domain and frequency domain analysis methods are used to explore the characteristics of muscle activity (mean EMG value MEG, peak muscle activity PEG, spectral analysis $P(f)$). The formulas are as follows [29,30]:

$$\begin{cases} \mathrm{MEG} = \dfrac{1}{N}\displaystyle\sum_{i=1}^{N} \mathrm{EMG}_i \\ \mathrm{PEG} = \max(\mathrm{EMG}(t)) \\ P(f) = |\mathrm{FFT}(\mathrm{EMG}(t))|^2 \end{cases} \tag{3}$$

N refers to the number of sampling points, and FFT refers to the fast Fourier transform.

3.3. Three-dimensional motion analysis

A high-resolution three-dimensional motion capture system is used, including multiple high-speed cameras (frequency set to 200 Hz) and motion capture software

[31,32]. The cameras (Vicon Vero 2.2) are distributed around the laboratory to ensure 360° capture of the whole body and local movements.

Reflective markers are placed on key areas of the participants' wrists, fingers, and forearms. The shape and size of the markers must meet the capture system's requirements and should not obstruct the skin to improve the quality of signal reflection. The piano is placed within the capture system's field of view, ensuring that all markers are within the camera's capture angle.

The participants keep a still posture before starting to play. This stage is mainly used to record the initial position and state of each hand joint, providing baseline data for subsequent data analysis. While the participants are playing the piano, the motion capture system is started for data collection. The three-dimensional coordinate data of each marker is recorded in real time. After each performance task, the data quality is checked immediately to ensure that the captured trajectory data is complete and clear. If any problems are found, they are re-measured in time.

EMG data is time-synchronized with motion capture data. Captured 3D coordinate data is converted into corresponding motion parameters (position, velocity, and acceleration).

The software is used to analyze the movement trajectory of wrists and fingers and extract key parameters (range of motion, joint angle change, and movement speed). The average value of each experiment is taken. The number of experiments is set to 5, and 5 different participants are selected for each experiment, as shown in **Figure 1**.

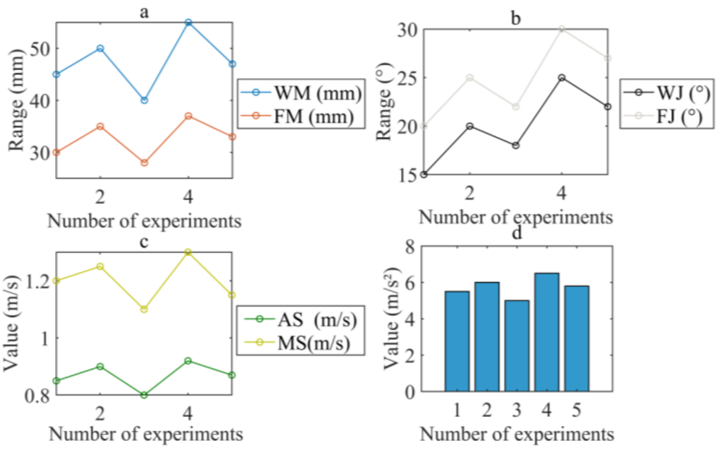

Figure 1. Key parameter data: **(a)** Range of motion data; **(b)** Joint angle change data; **(c)** Average speed and maximum speed data; **(d)** Acceleration data.

In **Figure 1**, WM and FM refer to the range of motion of wrists and fingers, respectively. WJ and FJ refer to the changes in the angles of the wrist and finger joints. AS and MS refer to the average speed and maximum speed, respectively. **Figure 1a–d** shows the changes in the participants' reactions and motor abilities. In each experiment, the range of wrist motion varies from 40 mm to 55 mm, and the range of finger motion varies from 28 mm to 37 mm, showing the flexibility of the wrists and fingers of different participants. The range of wrist joint angle changes is 15° to 25°, while the range of finger joint angle changes is between 20° and 30°, indicating that the flexibility of the fingers during movement is slightly higher than that of the wrists.

In terms of speed, the average speed fluctuates between 0.8 m/s and 0.92 m/s, and the maximum speed is between 1.1 m/s and 1.3 m/s, with the highest reaching 1.3 m/s, indicating that with the increase in the number of experiments, the participants' motor abilities may have been improved to a certain extent. The acceleration ranges from 5.0 m/s^2 to 6.5 m/s^2, showing how participants' reactions and movement abilities vary across the different experiments.

According to the results of the analysis, the hand movement efficiency, movement pattern, and possible movement injury risks of different participants during performance are identified. Targeted improvement suggestions are put forward to provide data support for the subsequent relaxation technique design. **Table 1** lists details.

Table 1. Movement efficiency and injury risk.

Number of experiments	Efficiency of wrist movement (mm/s)	Efficiency of finger movement (mm/s)	Movement injury risk	Improvement suggestion
1	1	0.75	Medium	Increasing finger flexibility training
2	1.1	0.85	Low	Keeping practicing in the current way
3	0.95	0.7	Medium	Improving wrist flexibility
4	1.2	0.9	Low	Increasing speed control
5	1.05	0.8	Medium	Strengthening fingers

In **Table 1**, the risk of injury is medium in the 1st, 3rd, and 5th experiments, which suggests that participants need to improve their flexibility. The risk of injury is low in the 2nd and 4th experiments, indicating that participants should increase their speed control while maintaining a good state (characterized by high efficiency, coordination, stability, low risk and psychological and physiological relaxation as its main features).

3.4. Biomechanical model construction

The previously collected EMG data and 3D motion capture data are integrated. Time synchronization technology is used to ensure that the two data sets are completely matched in time. The key parameters involved in the biomechanical model (mechanical properties of major muscle groups [33], range of motion of joints, and moment of inertia) are determined.

Based on the Newton-Euler method, the kinetic equation of hand motion is constructed [34,35]. The coordinate system is set to define the motion state of each part of the hand. The kinematic formula is applied to describe the motion trajectories of wrists and fingers:

$$\theta(t) = \theta_0 + \omega t + \frac{1}{2}\alpha t^2 \tag{4}$$

$\theta(t)$ is the angle at time t; θ_0 is the initial angle; ω is the initial angular velocity; α is the angular acceleration.

Combined with the electromyographic activity data, the force exerted by the muscles and its effect on joint movement are calculated. A muscle load calculation module is added to the model to calculate the activity intensity of each major muscle group based on the EMG signal. The effective activity level of the muscle is calculated using the RMS (root mean square) of the electromyographic signal [36,37]. The muscle activity level is combined with the muscle force function determined in the model to analyze the changes in muscle load under different playing conditions.

The muscle fatigue model is added to establish a fatigue dynamic equation related to muscle activity. The physiological characteristics of fatigue are identified through time domain and frequency domain analysis of EMG data and integrated into the biomechanical model. The fatigue threshold and the rate of muscle strength decline after exceeding this threshold are set. The equation is:

$$F_f(t) = F_m(t) \cdot e^{-kt} \tag{5}$$

$F_m(t)$ is the muscle strength after fatigue, and k is the fatigue rate constant.

The fatigue model is combined with the equation of motion to predict the muscle fatigue points that may occur during performance. The computer simulation technology is used to verify the constructed biomechanical model. By simulating the actual performance data of the participants, the consistency between the model output and the actual hand movement and muscle activity is checked. By comparing the simulation results with the experimental data, the model parameters are adjusted to optimize the accuracy of the model.

Based on the output of the biomechanical model, the motion state and muscle load of each hand joint under different playing conditions are analyzed to identify possible sports injury risks. At the same time, the model results are used to guide the design of wrist relaxation techniques, focusing on reducing the frequency of use of high-load muscle groups and optimizing movement patterns.

3.5. Design and application of wrist relaxation techniques

Based on the results of the previous EMG and motion analysis, the main muscle tension areas and their causes are determined. The goals are to reduce muscle tension in the wrists and fingers through relaxation techniques (activating the reflex mechanism against muscle tension and relieving muscle load), improve joint mobility (relaxing the soft tissue and joints around the wrists and reducing the burden caused by fixed postures), promote blood circulation (increasing blood flow to the muscles, eliminating lactic acid, and reducing fatigue), prevent muscle injuries, and improve the comfort and performance of the performer during the performance.

The relaxation techniques consist of controlling breathing rate and depth, promoting relaxation and oxygen supply to the whole body. Targeted relaxation training for the muscles of the forearms, wrists, and fingers. A series of wrist and finger stretching exercises are designed to enhance muscle flexibility and blood circulation.

For specific tense areas, apply the PIR (Post-Isometric Relaxation, post-isometric relaxation) technique. First, perform a slight isometric contraction of the muscles for about 5 s (20%–30% of the maximum strength), then relax and perform passive stretching for 10–15 s. Repeat this process 3–4 times. It is quite common to hold a small ball and gently squeeze it, then release and stretch the fingers.

Before playing, a 5–10 min warm-up is done (deep breathing and light wrist and finger stretching exercises). After playing, a 5–10 min relaxation exercise is arranged.

Deep breathing is alternated with progressive muscle relaxation, focusing on the muscles of the wrist and forearm.

During the performance, there is a pause for 1–2 min to do stretching and relaxation exercises after each section to relieve continuous muscle tension.

EMG monitoring and comfort feedback are used to evaluate the effectiveness of relaxation techniques. SPSS (Statistical Package for the Social Sciences) statistical analysis [38,39] is used to compare the differences in electromyographic activity and changes in comfort scores before and after the implementation of relaxation techniques. The specific content and implementation time of relaxation techniques are adjusted based on the feedback results.

Different performers have different habits and needs. In the application of relaxation techniques, through interviews and observations, the specific problems of the performers can be understood, and specific stretching movements and relaxation exercises can be recommended.

A series of training sessions are organized, and professional sports medicine and music psychology experts are invited to provide guidance to promote wrist relaxation techniques more widely. The training content includes the correct implementation methods, precautions, and theoretical basis of the techniques to enhance performers' understanding and application of relaxation techniques.

After a period of implementation, a long-term tracking mechanism is established. Participants are regularly visited to collect their feedback on their actual performance and evaluate the long-term effect and applicability of wrist relaxation techniques. Through regular effect evaluation and feedback correction, the content of relaxation techniques is gradually improved to ensure their scientificity and effectiveness.

4. Experimental verification and analysis

4.1. EMG change analysis

The flowchart of the experimental design is shown in **Figure 2** below.

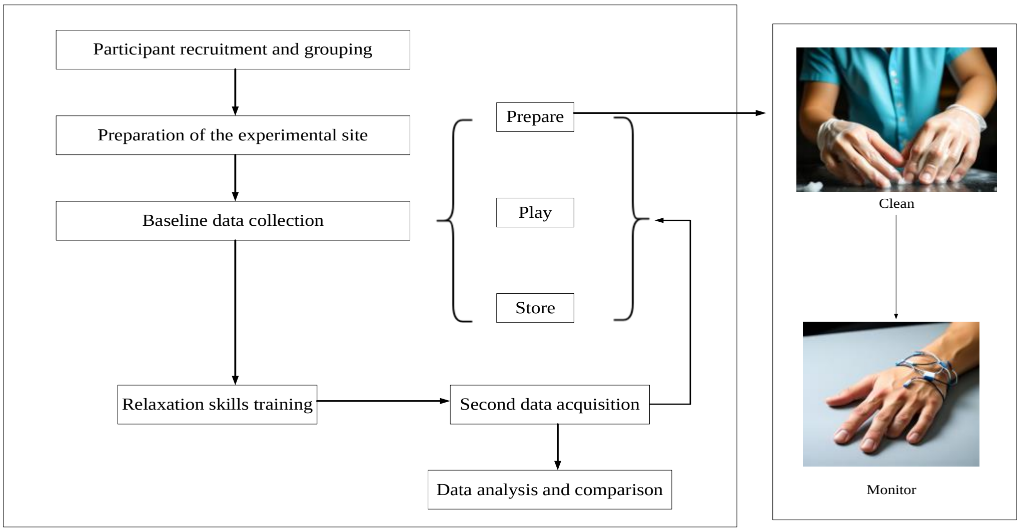

Figure 2. The flowchart of the experimental design.

In **Figure 2**, 30 piano participants recruited are selected for the experiment, including beginners G1 (10 people), intermediate players G2 (10 people), and advanced players G3 (10 people).

The piano and EMG recording equipment is set up in a quiet laboratory. The laboratory temperature should be maintained within 20–25 ℃, and the humidity should be controlled at 40%–60%. Sound insulation devices should be used to minimize external noise interference. Before the experiment, give the participants 10–15 min for adaptation to avoid data deviation caused by tension or anxiety. When collecting baseline data, participants play a 5-minute standard piece of music (Select the technical requirements clear and universal Carny etudes. Set a fixed tempo (120 beats per minute) with a metronome, and participants should play strictly according to the metronome indications to reduce the influence of rhythm differences on muscle activities) without using relaxation techniques. During this process, EMG technology is used to record the electrical activity of the major muscle groups in the participants' hands. The recording frequency is set to 1000 Hz to ensure the accuracy of the data.

After the baseline data collection, all participants receive training in the wrist relaxation technique used in this paper. The training lasts 30 min. After the participants complete the wrist relaxation techniques, the second data collection is conducted. The participants play the same music again, and the recording time is also 5 min. The data is collected using the same EMG technology as the baseline.

PEG, MEG, and spectral features (frequency range and spectral power) of the electromyographic signals are selected for comparison.

The baseline data (designated as D1) is compared with the data after the implementation of relaxation techniques (designated as D2). The changes are analyzed using paired *t*-tests, as shown in **Table 2**. The statistical significance level is set at $p < 0.05$.

Table 2. Changes in electromyographic activity before and after the application of relaxation techniques.

Group	Index	D1 (mean ± standard deviation)	D2 (mean ± standard deviation)	*p* value
G1	PEG (μV)	150 ± 20	130 ± 15	0.022
	MEG (μV)	80 ± 10	60 ± 8	0.015
	Frequency range (Hz)	100 ± 5	90 ± 4	0.010
	Spectral power (μV²)	2000 ± 300	1500 ± 250	0.020
G2	PEG (μV)	180 ± 25	160 ± 20	0.030
	MEG (μV)	90 ± 12	70 ± 9	0.018
	Frequency range (Hz)	110 ± 6	100 ± 5	0.012
	Spectral power (μV²)	2200 ± 350	1700 ± 300	0.025
G3	PEG (μV)	200 ± 30	180 ± 25	0.028
	MEG (μV)	100 ± 15	80 ± 10	0.014
	Frequency range (Hz)	120 ± 7	110 ± 6	0.008
	Spectral power (μV²)	2500 ± 400	2000 ± 350	0.018

In **Table 2**, the beginner group shows significant decreases in all indicators, and the *p*-values are all less than 0.05, indicating that relaxation techniques have a positive effect on the electromyographic activity of beginners. The intermediate and advanced performers also show significant decreases after the implementation of relaxation techniques, and the *p*-values are all less than 0.05, indicating a similar trend.

When beginners play, they tend to have excessive extra muscle activities. Relaxation techniques can significantly reduce these redundant activities. For advanced players, they already have efficient muscle control and the optimization space of relaxation techniques is relatively small. Therefore, the reduction range is limited.

In summary, the wrist relaxation techniques effectively reduce the participants' electromyographic activity, indicating that this technique has a positive significance for improving the performers' relaxation levels and performance.

4.2. Comfort evaluation

An experimental questionnaire is compiled (Employ the NASA-TLX framework to design subjective rating items for fatigue and comfort sensation), including subjective ratings of hand comfort, fatigue, relaxation, and overall playing experience during playing, using a five-point Likert rating. From the perspective of the overall performance score, an improvement in the participants' performance experience does not necessarily mean that their performances are closer to the score or more artistic. The quality of music performance can be further verified by recording the performance audio and combining it with the professional scoring from external experts.

The design of the self-assessment scale refers to existing muscle fatigue and psychological comfort assessment tools to ensure that the questions are specific and targeted.

8 participants are randomly selected to play the designated music for 5 min without using relaxation techniques and complete the comfort questionnaire and scale. After 30 min of wrist relaxation technique training, the participants play the same music again and fill in the same questionnaire.

The experimental sequence is randomly assigned to avoid interference from learning effects. The data collection time for each group is arranged at the same time of the day to minimize the differences in physiological rhythms.

After collecting questionnaire and scale data, the average scores of D1 and D2 are counted, and the changes in the comfort score of each group are calculated, as shown in **Figure 3**.

Figure 3 shows the changes in the scores of hand comfort, fatigue, relaxation, and overall performance experience of the 8 participants before and after the intervention. **Figure 3a–e** shows the effectiveness of relaxation techniques in improving the participants' playing experience and comfort, especially in improving hand comfort and relaxation. Overall, these changes reveal the positive impact of relaxation techniques on the participants' emotional and physiological states.

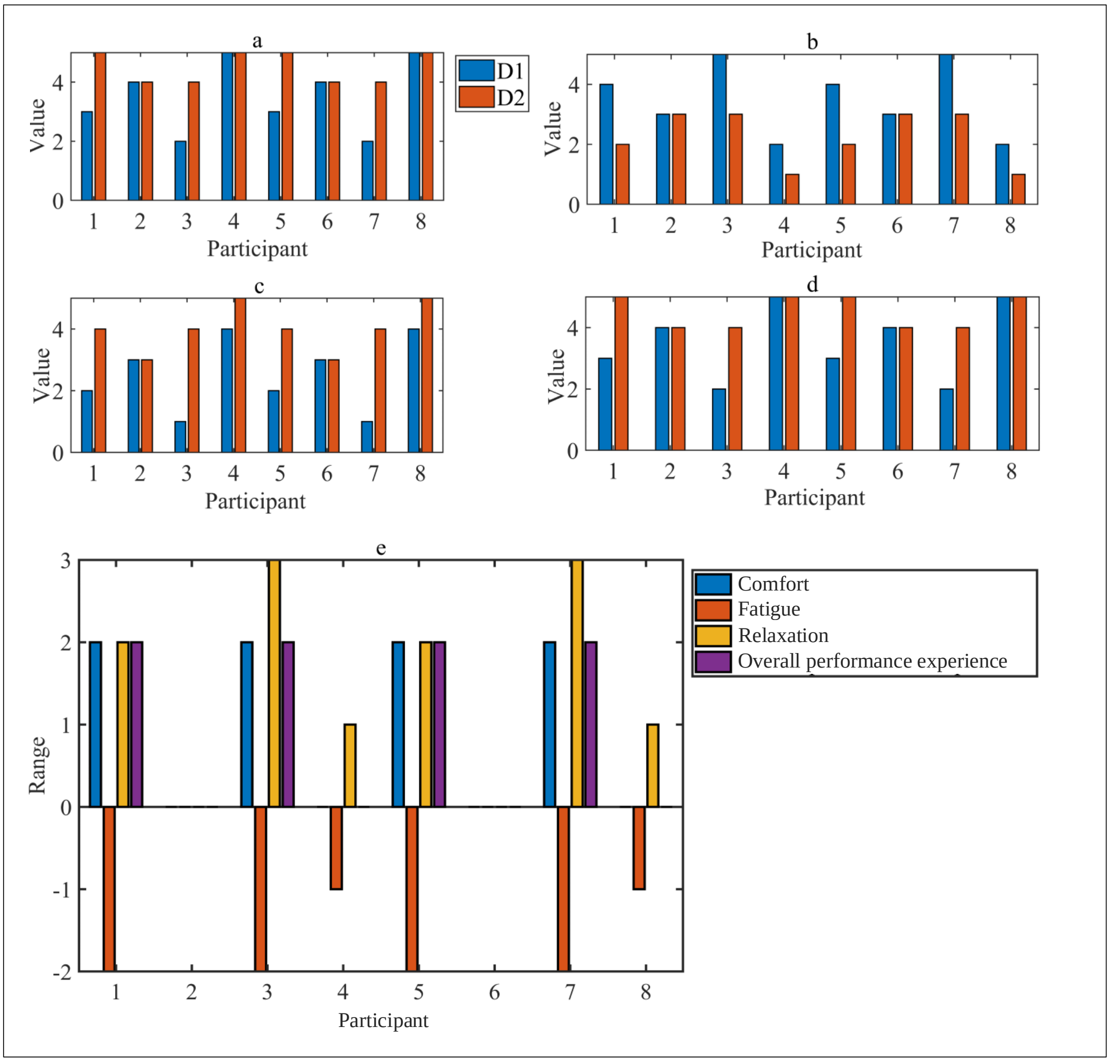

Figure 3. Comfort rating and changes (unit: points): **(a)** Hand comfort rating (unit: points); **(b)** Fatigue rating (unit: points); **(c)** Relaxation rating (unit: points); **(d)** Overall performance experience rating (unit: points); **(e)** Rating changes (unit: points).

4.3. Injury risk evaluation

Before the experiment, all participants undergo a baseline assessment. The electromyographic activity of the major muscle groups of the hands of the participants in a static state (It does not mean that the muscles are completely at rest, but rather that they are in a state of low-level activity) and during light playing (represented by J1 and J2, respectively) is recorded. They fill out a questionnaire about the degree and frequency of self-perceived fatigue, using a 1–10 point scale to record subjective fatigue. The participants are divided into two groups, an experimental group and a control group, with 15 people in each group. **Table 3** lists the baseline data.

Table 3. Baseline data records of the experimental group and the control group.

Group	**J1 (μV)**	**J2 (μV)**	**J3 (points)**	**J4 (h)**
Experimental group	12.4 ± 3.1	34.2 ± 5.0	6.3 ± 1.2	12.5 ± 3.4
Control group	12.1 ± 3.0	33.8 ± 4.8	6.1 ± 1.3	13.0 ± 3.6

In **Table 3**, J3 represents the subjective fatigue score, and J4 represents the weekly playing frequency. The baseline assessment data of participants in different groups is similar in range and has no significant differences.

The experimental group receives the wrist relaxation technique training provided in this paper for 4 weeks, 3 times a week, 30 min each time. The control group does not receive any special training. They maintain regular playing habits and record their playing behaviors and self-perceptions.

A mid-term evaluation is conducted in the second week of the experiment, repeating the steps of baseline data collection, recording J1, J2, and J3 and adding the average fatigue change value J5, to observe changes in muscle fatigue and tension, as shown in **Table 4**.

Table 4. Changes in electromyographic activity and subjective fatigue scores in the two groups in the mid-term evaluation.

Group	J1 (μV)	J2 (μV)	J3 (points)	J5 (points)
Experimental group	11.3 ± 2.9	31.5 ± 4.7	5.4 ± 1.1	−0.9 ± 0.5
Control group	12.0 ± 3.1	33.6 ± 4.9	6.0 ± 1.2	−0.1 ± 0.3

Table 4 shows the changes in electromyographic activity and subjective fatigue scores of the experimental and control groups in the mid-term evaluation. The electromyographic activity of the experimental group decreases compared with the baseline data, both in the static state and in the light playing, showing a trend of muscle relaxation. In terms of subjective fatigue scores, the experimental group also decreases significantly compared with the baseline, further reflecting the reduction of participants' fatigue. The average fatigue change value is −0.9 ± 0.5, showing a positive improvement effect. The control group has a slight increase in static electromyographic activity and electromyographic activity in light playing compared with the baseline data, and the subjective fatigue score decreases, but the change is small.

After the experiment, all participants continue to record under the same conditions to compare the changes in electromyographic activity before and after the experiment. The fatigue questionnaire is re-filled. It is recorded whether the participants experience any discomfort or injury during the experiment, and the frequency of occurrence and severity are evaluated. **Figure 4** and **Table 5** show the relevant data.

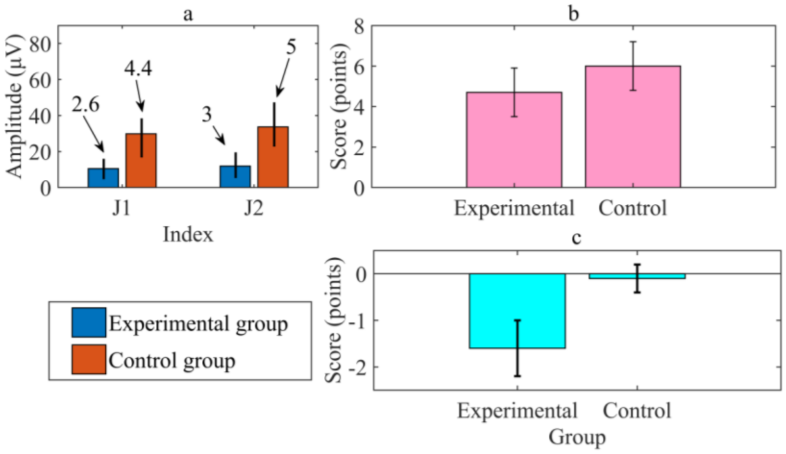

Figure 4. Changes in electromyographic activity and fatigue scores of the two groups after the experiment: **(a)** Changes in electromyographic activity; **(b)** Subjective fatigue score; **(c)** Changes in fatigue score.

Figure 4 shows the changes in the electromyographic activity and fatigue scores of the two groups after the experiment. According to the **Figure 4a–c**, the electromyographic activity of the experimental group is lower than that of the control group in both the static state and the light playing, indicating that the muscle tension of the experimental group is lower in the static state. In addition, in terms of subjective fatigue scores, the scores of the experimental group are significantly lower than those of the control group, suggesting that the experimental group feels less fatigued. The magnitude of the change in fatigue scores also shows significant differences, indicating that the experimental group has a more significant improvement in fatigue after implementing relaxation techniques.

Table 5. Statistics of injuries during the experiment.

Group	**The injured (person)**	**Injury incidence rate**	**Average injury frequency (times/person)**
Experimental group	1	6.70%	0.2 ± 0.1
Control group	4	26.70%	0.8 ± 0.3

In **Table 5**, the experimental group still has the fewest number of injured people during the experiment, only 1 person, and the injury incidence and average injury frequency are the lowest. The incidence of injury in the control group was 26.70%, with an average injury frequency per person being 0.8 ± 0.3 times. This indicates that the experimental group achieved a more effective reduction in injury risk under the intervention condition.

SPSS is used to perform paired t-tests to compare the changes in electromyographic activity between the experimental group and the control group before and after the application of relaxation techniques. The mean and standard deviation of the subjective fatigue score of each group are calculated, and an independent sample *t*-test is performed to compare the significant differences in fatigue between the two groups.

The injury incidence of participants in each group during the experiment is counted, and the injuries between the experimental group and the control group are compared. The chi-square test is used to analyze the difference in injury risk, as shown in **Table 6**.

Table 6. Chi-square test and t-test analysis results.

Index	Testing method	Degree of freedom (df)	Statistical value (χ^2/t)	Significance level
J1	Paired *t*-test	28	4.25	0.001**
J2	Paired *t*-test	28	5.12	0.000**
J3	Independent sample *t*-test	28	−3.86	0.002**
J6	Chi-square test	1	5.33	0.021*

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$.

In **Table 6**, J6 refers to the injury incidence rate. The results show that the electromyographic activity of both the experimental and control groups changes significantly, which is statistically significant (degree of freedom df = 28; J1: $t = 4.25$, $p = 0.001$**; J2: $t = 5.12$, $p = 0.000$**). This indicates that relaxation techniques are effective in reducing electromyographic activity. J3, which carries out an independent sample t-test, shows that the fatigue score of the experimental group is significantly lower than that of the control group (df = 28; $t = -3.86$, $p = 0.002$**), indicating that the relaxation techniques of the experimental group are more effective in reducing the fatigue of the participants. The chi-square test is used to analyze the difference in injury risk (J6). The results show that there is a significant difference in the incidence of injury between the experimental and control groups (degree of freedom df = 1; $\chi^2 = 5.33$, $p = 0.021$*), which means that the experimental group has a lower risk of injury. In summary, these results support the effectiveness of relaxation techniques and their positive effects on reducing muscle activity, fatigue, and injury risk. Relaxation techniques reduce muscle tension and electrical activity by regulating neuromuscular responses, thereby lowering the activity intensity of specific muscle groups. This leads to an improvement in joint range of motion, a more balanced distribution of muscle loads, and a reduction in fatigue generation.

5. Conclusion

This paper integrates EMG and 3D motion capture systems to construct a biomechanical model based on the Newton-Euler method and deeply analyzes the characteristics of hand muscle activity in piano playing and the influence of wrist relaxation techniques. Pianists of different levels are recruited, and their electromyographic activity, comfort, and injury risk data before and after the application of relaxation techniques are collected and compared. The results indicate that wrist relaxation techniques significantly reduce the intensity of electromyographic activity in each group, improve hand comfort, and effectively reduce the risk of injury. However, this study is limited to short-term observations in a laboratory environment and fails to fully consider the effects of long-term training effects and individual differences on the results. Future research can further explore the application of relaxation techniques in actual performance environments and customize more effective training programs for personalized needs. At the same time, more diverse music performance forms can be combined to provide more comprehensive scientific guidance and support for pianists.

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