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Article

Biomechanical analysis of hand exercises in pianists: Enhancing dexterity through targeted interventions

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Abstract: Background: The incidence of injuries caused by high-intensity repetitive hand movements is relatively high among pianists. Joint stiffness, muscle fatigue, and pain are often associated with the performance process, which, in severe cases, can impact their professional careers. Existing studies mainly focus on performance techniques or simple rehabilitation exercises, lacking systematic hand intervention programs based on biomechanical principles. Additionally, there is still no comprehensive method to quantify and evaluate the actual effects of specialized training. **Objective:** Based on biomechanical principles, this study investigates whether targeted hand training interventions can effectively enhance the flexibility of pianists' finger joints and reduce fatigue and pain caused by overuse. **Methods:** A total of 50 professional pianists with more than five years of performance experience were enrolled and randomized into an intervention group and a control group, with 25 participants in each group. The intervention group received 8 weeks of targeted hand training in addition to routine practice, 5 days per week, 30 min per session. The control group continued their regular performance practice. Joint range of motion, electromyographic (EMG) parameters, grip strength, pinch strength, and fatigue and pain scores were collected at baseline, Week 4, and Week 8. Repeated measures analysis of variance and independent sample *t*-tests were used for comparisons. **Results:** By Week 8, the intervention group showed significantly greater maximum range of motion in the metacarpophalangeal joints, proximal interphalangeal joints, and distal interphalangeal joints compared to the control group ($p < 0.05$). Peak amplitude of the flexor digitorum superficialis, flexor digitorum profundus, extensor digitorum, interosseous muscles, and lumbrical muscles significantly increased ($p < 0.01$). Grip strength and pinch strength were markedly improved compared to the control group ($p < 0.01$), while fatigue and pain scores were significantly reduced ($p < 0.01$). The control group showed no significant improvement in these parameters ($p > 0.05$). **Conclusion:** Targeted hand interventions based on biomechanical principles can effectively improve finger flexibility and reduce fatigue and pain in pianists within a short period, offering substantial application value for preventing performance-related hand injuries.

Keywords: pianists; hand exercises; biomechanics; flexibility

1. Introduction

Epidemiological surveys show that high-intensity repetitive hand movements in piano players have a relatively high incidence of injury, with common symptoms including joint stiffness, tendon pain, and functional decline [1]. In recent years, research has mostly focused on playing techniques or rehabilitation strategies for hand strain, and some literature has proposed that biomechanical interventions have potential value for relieving muscle fatigue and preventing tenosynovitis, etc. [2,3]. However, existing intervention methods mainly focus on basic stretching or simple rehabilitation exercises, lacking systematic biomechanical assessment and quantitative analysis. The exploration of joint load distribution and muscle synergy patterns remains insufficient [4]. Pianists often find it difficult to balance the improvement of playing techniques with the prevention of hand injuries. There remains a research gap regarding specialized training for this group, especially concerning how to maximize the reduction of hand soft tissue injury risk while improving playing stability [5]. During daily practice, performers often encounter insufficient joint range of motion or relatively weak muscle coordination, leading to frequent compensatory movements and pain [6]. Existing methods mostly focus on simple stretching or conventional rehabilitation measures, without fully integrating joint kinematics and electromyographic indicators to precisely evaluate training effects. This makes the effectiveness of targeted strengthening programs lack systematic evidence, and also limits in-depth exploration of improving hand flexibility and preventing injuries [7]. Quantifying hand joint range of motion, peak electromyographic amplitude, and the degree of fatigue pain through scientific methods is key to revealing the patterns of playing movement and proposing intervention strategies [8]. Based on biomechanical considerations, this study designed an eight-week hand intervention training, measuring joint kinematic and electromyographic-related indicators, while also evaluating grip strength, pinch strength, and fatigue pain scores. The novelty of the results lies in clarifying, through quantitative analysis, the coordinated force exertion of the playing muscle groups and the positive changes in joint flexibility, providing a research basis for optimizing pianists' daily practice programs and preventing hand injuries.

2. Research methods

2.1. Study subjects and grouping

Inclusion criteria: (1) Professional or semi-professional piano performers with continuous piano performance training for more than five years, with a daily average playing time of no less than two hours; (2) aged between 18 and 45 years; (3) no history of hand fractures, tendon ruptures, or severe neurological or muscular diseases, and currently no acute hand injuries; (4) agrees to comply with the requirements of this study and signs a written informed consent form; Exclusion criteria: (1) Diagnosed with rheumatoid arthritis or other serious joint pathologies; (2) presence of significant dysfunction in the upper limbs or having recently undergone hand surgery and not fully recovered; (3) unable to complete all tests and training according to the research schedule or experiences severe adverse events during the study leading to withdrawal.

Based on the main effect values obtained from the pilot study, sample size was estimated with the significance level set at 0.05 and the test power set at 0.80, finally determining a total of 50 participants were required. All eligible participants were divided into an intervention group and a control group by block randomization, with 25 participants in each group. The block randomization procedures included stratification by age range (18 to 30 years, 31 to 45 years) and gender, using a computer-generated random sequence within each stratum to assign participants in order to the intervention or control group. To minimize human bias, the study adopted a single-blind design. After group allocation, the researchers involved in the intervention and data collection remained blinded and were unaware of the specific group assignment of the subjects. The data analysis was conducted by an independent third-party statistician. The testing procedures for both the intervention group and the control group were identical and were carried out by the same experimental team to ensure the objectivity and reliability of the study process and outcome evaluation.

The study protocol was approved by the Jilin Normal University Medical Ethics Committee. All participants read and signed an informed consent form before taking part in the experiment.

2.2. Experimental instruments and data collection

The following indicators were collected at Week 0 (baseline), Week 4, and Week 8 for subsequent comparative analysis.

2.2.1. Joint kinematics parameter collection

A Vicon T40S motion capture system (Oxford Metrics, UK) was used, with a sampling rate of 200 frames per second. Circular reflective markers with a diameter of 9 mm were attached to the dorsal side of each finger’s metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, ensuring that the markers would not slip significantly with the finger skin [8]. During the formal test, the subjects played the C major scale in a standard sitting position, with the metronome set at 80 beats per minute, and each performance lasted 60 s. Each subject repeated the performance three times, with a 30-second interval between each. The system collected the flexion and extension angles as well as the angular velocity of the finger joints in real time. The average of the three performances was used for the final statistical analysis.

2.2.2. Muscular mechanics and electromyographic data collection

A Noraxon Ultium EMG system (Noraxon, USA) was used, with a sampling rate of 1000 Hz. Alcohol wipes were used to clean the skin surface of the subjects’ forearm and dorsum of the hand in advance, and hair in the marked areas was removed using a disposable razor. The surface EMG electrodes were vertically attached to the central belly of the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), extensor digitorum (ED), interossei (IO), and lumbrical muscles (LUM), and fixed with medical adhesive tape [9]. The peak amplitude of EMG activity was recorded in millivolts (mV) to evaluate muscle strength output; the duration of EMG activity was recorded in milliseconds (ms) to evaluate the working time of the muscle during the specified performance segment; the ratio of coordinated force among muscle groups was obtained through time-sequence analysis of relative activation among these muscles. The test procedure was consistent with the motion capture process. After completing each performance, the subject rested for 30 s and then performed the second performance. This was repeated three times, and the average was taken.

2.2.3. Other functional measurements

Grip strength was measured using a Jamar hydraulic dynamometer (Patterson Medical, USA), and pinch strength (thumb and index finger) was measured using a Pinch Gauge (B&L Engineering, USA). Each measurement action was maintained for 3 s, measured 3 times in succession, and the maximum value was used for statistical analysis.

Fatigue and pain scores were obtained using a 10 cm Visual Analog Scale (VAS) [10], where 0 indicates no fatigue or no pain, and 10 indicates the most severe level.

2.2.4. Data collection order and environmental control

At each measurement time point, the subjects first performed a 10-minute full-body warm-up. The laboratory temperature was maintained at 22–24 ℃ with a relative humidity of about 50%. The researchers installed the EMG electrodes according to the subject numbering and calibrated the Vicon system. After confirming stable signals, the subjects began the specified scale or movement. Upon completion of the test, the data were saved and the equipment was turned off, after which the next subject's measurement was conducted. Grip strength, pinch strength, and fatigue and pain scores were also measured under the same environmental conditions to ensure measurement consistency and comparability.

2.3. Intervention training program

2.3.1. Hand-specific training in the intervention group

In addition to routine piano practice, the intervention group underwent a continuous 8-week hand-specific training program, with a training frequency of 5 days per week and approximately 30 min per session. Each session included the following three components:

(1) Finger separation and joint range of motion enhancement

A TheraBand (blue resistance level) was used for finger abduction and flexion exercises, 8 to 12 repetitions each time. Each repetition lasted about 3 s, followed by a 3-second rest before the next repetition, for a total of 3 sets. The TheraBand was fixed to a stable support, with the subject seated, shoulders relaxed, and forearms resting on the table. Single-finger or double-finger abduction or flexion movements were performed.

(2) Isometric stability training

While maintaining the metacarpophalangeal joints in a slightly flexed position, each finger applied force against a GripMaster (medium resistance model) for 5 s, then relaxed for 5 s. Each finger completed 3 sets of 10 repetitions. This component primarily enhances the endurance and control of the muscles around the finger joints.

(3) Small muscle group coordination exercises

Both hands were placed on the table, and alternating lifting/tapping between adjacent fingers was performed, mainly engaging the interossei and lumbrical muscles [11]. After completing at least 20 lifts/taps with each hand, the subject switched to the other hand. Each training session repeated 3 sets, with a 15-second rest between sets.

Training load was slightly increased in the 4th week according to individual adaptation. The researchers conducted a weekly face-to-face follow-up with participants to ensure proper movement form and record any adverse reactions.

2.3.2. Control group management

The control group only performed their regular piano practice without any additional hand-specific training. Researchers conducted weekly telephone follow-ups to inquire about hand conditions and practice duration, ensuring no extra intervention measures were introduced. If any hand discomfort occurred, the researchers recorded the specific situation and provided basic advice but did not change the group assignment.

2.4. Data processing and statistical methods

Interpolation compensation and filtering were applied to the motion capture and electromyographic (EMG) signal data to eliminate incidental frame loss and high-frequency noise. After acquisition, the EMG signals were first processed using a 20–450 Hz bandpass filter (4th-order Butterworth filter) to remove low-frequency baseline drift and high-frequency interference. Subsequently, full-wave rectification was performed, and the linear envelope was calculated. To minimize the impact of inter-individual differences, EMG amplitude was normalized before statistical analysis using either maximum voluntary contraction (MVC) or baseline mean values. This process effectively removes environmental noise and EMG artifacts, enhancing the comparability and reliability of the results.

For continuous variables, independent sample *t*-tests were used for between-group comparisons, while categorical variables were analyzed using the chi-square test. To control the risk of Type I errors due to multiple comparisons, Bonferroni correction was applied to multiple comparisons of joint range of motion and EMG data, with the significance level adjusted accordingly, considering $p < 0.05$ as significant. All reported *p*-values in this study represent corrected results. Statistical analyses were conducted using SPSS Statistics 25 software.

3. Results

3.1. Comparison of baseline characteristics

Table 1. Baseline demographic and performance characteristics of the intervention group and control group.

Variable	Intervention Group (n = 25)	Control Group (n = 25)	Statistic	p Value
Age (years)	29.56 ± 3.45	28.73 ± 3.15	$t = 0.607$	0.546
Gender (male/female)	12/13	11/14	$\chi^2 = 0.081$	0.776
Years of performance	12.68 ± 1.52	11.72 ± 1.68	$t = 0.806$	0.423
Daily performance time (hours)	3.56 ± 0.45	3.45 ± 0.38	$t = 0.455$	0.651

In this study, the baseline characteristic analysis of the intervention group and the control group showed no statistically significant differences in age, gender composition, years of performance, or daily average performance time (all $p > 0.05$).

The balance of these variables between the intervention and control groups provides a reliable foundation for subsequent comparisons (**Table 1**).

3.2. Changes in joint kinematics indicators

At baseline, there were no significant differences between the two groups in the flexion and extension angles of the MCP, PIP, and DIP joints (*t*-test, $p > 0.05$). After 8 weeks of intervention, the intervention group showed significantly greater maximum flexion and extension angles in all joints than the control group (*t*-test, $p < 0.05$). Notably, the changes in the extension angles of the MCP and DIP joints were significant (*t*-test, $p < 0.01$) (**Table 2**) (**Figure 1**).

Table 2. Comparison of hand joint range of motion (flexion and extension angles) at different time points.

Time Point	Joint	Parameter	Intervention Group (Mean ± SD)	Control Group (Mean ± SD)	*t* Value	Cohen's d	*p* Value
Baseline (0 week)	MCP	Flexion (°)	86.23 ± 7.54	85.41 ± 7.12	0.416	0.08	0.679
	MCP	Extension (°)	14.36 ± 1.53	14.02 ± 1.64	0.296	0.06	0.769
	PIP	Flexion (°)	103.52 ± 9.24	102.43 ± 8.15	0.475	0.10	0.637
	PIP	Extension (°)	9.63 ± 1.06	9.28 ± 1.11	0.519	0.10	0.607
	DIP	Flexion (°)	78.46 ± 6.93	77.21 ± 6.17	0.585	0.12	0.561
	DIP	Extension (°)	5.64 ± 0.79	5.23 ± 0.78	0.656	0.13	0.516
4th week	MCP	Flexion (°)	88.11 ± 7.22	85.52 ± 6.98	1.236	0.25	0.223
	MCP	Extension (°)	15.02 ± 1.58	14.11 ± 1.46	1.85	0.37	0.071
	PIP	Flexion (°)	105.48 ± 8.94	102.56 ± 8.62	1.132	0.23	0.262
	PIP	Extension (°)	9.84 ± 1.13	9.41 ± 1.09	1.308	0.27	0.196
	DIP	Flexion (°)	80.72 ± 6.77	78.63 ± 6.34	1.16	0.25	0.25
	DIP	Extension (°)	6.02 ± 0.84	5.41 ± 0.79	2.301	0.47	0.025
8th week	MCP	Flexion (°)	90.57 ± 7.84	86.43 ± 7.65	2.008	0.40	0.049
	MCP	Extension (°)	16.23 ± 1.45	14.27 ± 1.52	4.136	0.88	< 0.001
	PIP	Flexion (°)	108.63 ± 9.42	103.24 ± 8.97	2.246	0.45	0.028
	PIP	Extension (°)	10.15 ± 1.21	9.26 ± 1.06	2.585	0.52	0.012
	DIP	Flexion (°)	82.61 ± 6.35	79.08 ± 6.54	2.002	0.40	0.049
	DIP	Extension (°)	6.45 ± 0.89	5.58 ± 0.82	3.537	0.75	0.001

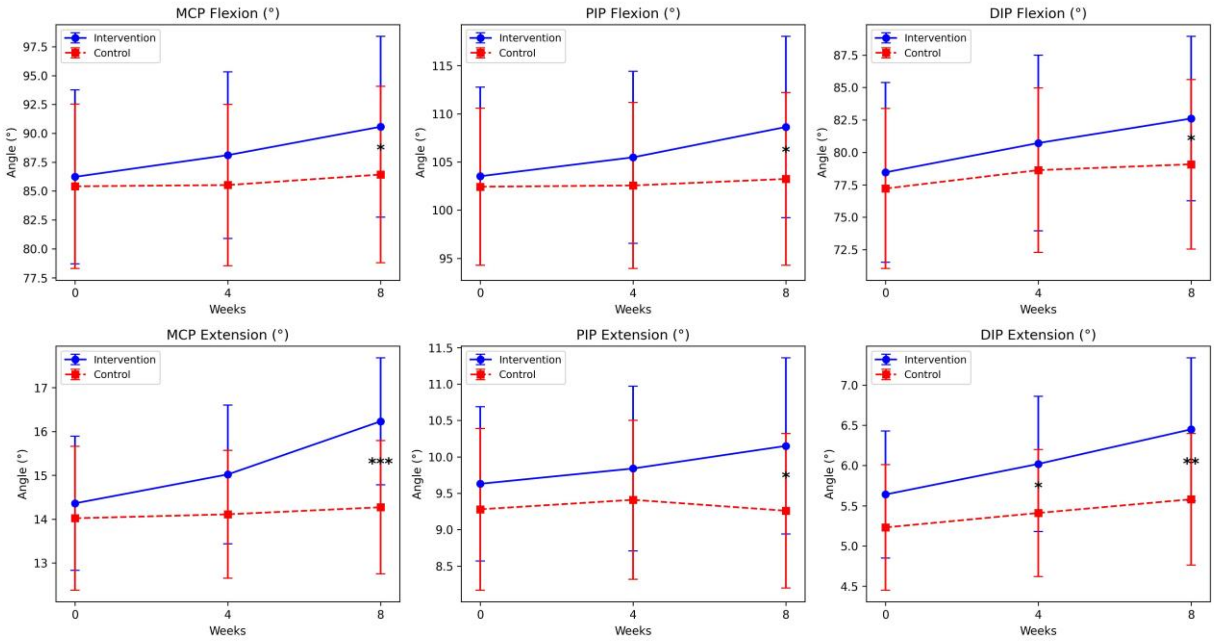

Figure 1. Changes in hand joint range of motion at different time points.

Data were analyzed using independent samples *t* test. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.3. Comparison of EMG characteristics

At baseline, there were no statistically significant differences in the peak amplitude and duration of each muscle group between the two groups (*t*-test, $p > 0.05$). After 8 weeks of intervention, the intervention group showed significantly higher peak amplitudes of the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), extensor digitorum (ED), interossei (IO), and lumbrical muscles (LUM) compared to the control group ($p < 0.01$). There were no significant differences in duration changes for some muscle groups (*t*-test, $p > 0.05$) (**Table 3**) (**Figure 2**).

Table 3. Comparison of EMG activity peak amplitude and duration (FDS, FDP, ED, IO, LUM).

Time Point	Muscle Group	Index	Intervention Group (Mean ± SD)	Control Group (Mean ± SD)	*t* Value	Cohen's d	*p* Value
Baseline (0 week)	FDS	Peak Amplitude (mV)	0.54 ± 0.04	0.52 ± 0.05	0.451	0.09	0.654
	FDS	Duration (ms)	345.12 ± 32.31	348.47 ± 30.25	0.425	0.08	0.673
	FDP	Peak Amplitude (mV)	0.61 ± 0.06	0.59 ± 0.05	0.591	0.12	0.558
	FDP	Duration (ms)	372.45 ± 34.21	370.29 ± 35.17	0.243	0.05	0.809
	ED	Peak Amplitude (mV)	0.47 ± 0.04	0.49 ± 0.05	0.716	0.14	0.478
	ED	Duration (ms)	339.87 ± 30.24	340.76 ± 31.51	0.118	0.03	0.906
	IO	Peak Amplitude (mV)	0.39 ± 0.03	0.37 ± 0.03	1.023	0.2	0.312
	IO	Duration (ms)	329.65 ± 27.68	327.81 ± 28.02	0.206	0.04	0.837
	LUM	Peak Amplitude (mV)	0.42 ± 0.03	0.43 ± 0.04	0.567	0.11	0.574

Table 3. (*Continued*).

Time Point	**Muscle Group**	**Index**	**Intervention Group (Mean ± SD)**	**Control Group (Mean ± SD)**	***t* Value**	**Cohen's d**	***p* Value**
Baseline (0 week)	LUM	Duration (ms)	360.29 ± 33.14	358.18 ± 31.82	0.245	0.05	0.807
4th week	FDS	Peak Amplitude (mV)	0.58 ± 0.05	0.53 ± 0.04	1.91	0.38	0.063
	FDS	Duration (ms)	357.64 ± 32.77	349.33 ± 29.96	1.004	0.20	0.320
	FDP	Peak Amplitude (mV)	0.65 ± 0.06	0.60 ± 0.05	2.172	0.44	0.034
	FDP	Duration (ms)	384.21 ± 34.02	375.46 ± 35.87	1.049	0.21	0.298
	ED	Peak Amplitude (mV)	0.51 ± 0.04	0.48 ± 0.05	1.142	0.23	0.260
	ED	Duration (ms)	343.08 ± 31.86	341.25 ± 30.57	0.222	0.05	0.825
	IO	Peak Amplitude (mV)	0.43 ± 0.04	0.39 ± 0.03	2.041	0.41	0.045
	IO	Duration (ms)	334.71 ± 28.44	330.05 ± 29.61	0.581	0.12	0.563
	LUM	Peak Amplitude (mV)	0.46 ± 0.04	0.44 ± 0.04	1.311	0.26	0.195
	LUM	Duration (ms)	367.24 ± 31.29	361.87 ± 30.58	0.621	0.12	0.538
8th week	FDS	Peak Amplitude (mV)	0.71 ± 0.06	0.62 ± 0.05	4.001	0.80	< 0.001
	FDS	Duration (ms)	368.15 ± 32.69	350.62 ± 29.53	2.281	0.46	0.027
	FDP	Peak Amplitude (mV)	0.76 ± 0.07	0.65 ± 0.06	4.91	0.92	< 0.001
	FDP	Duration (ms)	395.23 ± 34.55	379.48 ± 33.09	1.803	0.36	0.078
	ED	Peak Amplitude (mV)	0.59 ± 0.05	0.53 ± 0.05	2.922	0.59	0.005
	ED	Duration (ms)	352.76 ± 31.21	340.18 ± 31.36	1.371	0.28	0.177
	IO	Peak Amplitude (mV)	0.47 ± 0.04	0.41 ± 0.03	3.552	0.71	0.001
	IO	Duration (ms)	344.12 ± 29.51	333.62 ± 28.43	1.409	0.29	0.167
	LUM	Peak Amplitude (mV)	0.52 ± 0.05	0.45 ± 0.04	3.326	0.67	0.002
	LUM	Duration (ms)	376.51 ± 32.84	362.49 ± 31.27	1.668	0.34	0.102

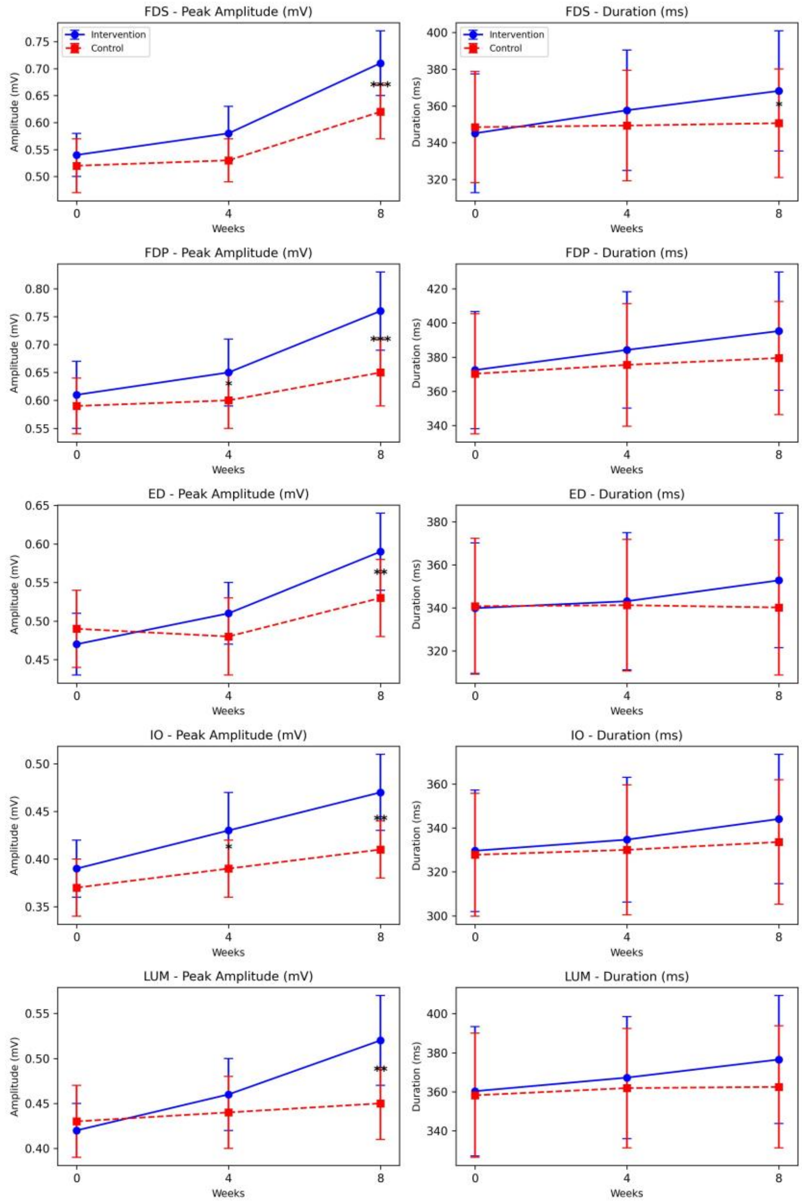

Figure 2. EMG peak amplitude and duration for FDS, FDP, ED, IO, and LUM.

Data were analyzed using independent samples *t* test. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.4. Hand strength and functional assessment

At baseline, there were no statistically significant differences between the intervention group and the control group in grip strength and each pinch strength indicator (*t*-test, $p > 0.05$). By the 4th week, significant differences had emerged in some indicators (*t*-test, $p < 0.05$). After 8 weeks of intervention, the intervention group's grip strength, thumb-index finger pinch strength, and three-finger pinch strength were significantly higher than those of the control group (*t*-test, $p < 0.01$) (**Table 4**) (**Figure 3**).

Table 4. Comparison of grip strength and pinch strength before and after intervention.

Time Point	Measurement Indicator	Intervention Group (Mean ± SD)	Control Group (Mean ± SD)	*t* Value	Cohen's d	*p* Value
Baseline (0 week)	Grip Strength (kg)	29.43 ± 2.14	29.21 ± 2.21	0.289	0.06	0.774
	Thumb-Index Finger Pinch (kg)	7.62 ± 0.64	7.58 ± 0.61	0.221	0.05	0.826
	Three-Finger Pinch (kg)	9.43 ± 0.74	9.48 ± 0.72	0.27	0.06	0.788
4th week	Grip Strength (kg)	31.16 ± 2.46	29.64 ± 2.19	1.875	0.38	0.066
	Thumb-Index Finger Pinch (kg)	8.03 ± 0.68	7.64 ± 0.62	1.913	0.39	0.061
	Three-Finger Pinch (kg)	10.02 ± 0.88	9.54 ± 0.71	2.144	0.45	0.036
8th week	Grip Strength (kg)	33.68 ± 2.74	30.12 ± 2.47	3.374	0.69	0.001
	Thumb-Index Finger Pinch (kg)	8.81 ± 0.72	7.77 ± 0.63	5.028	1.08	< 0.001
	Three-Finger Pinch (kg)	10.73 ± 0.96	9.62 ± 0.74	3.813	0.78	< 0.001

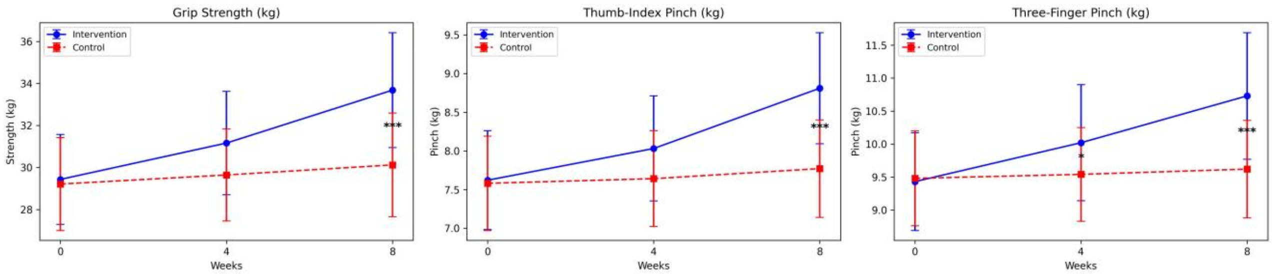

Figure 3. Comparison of grip strength and pinch strength before and after intervention.

Data were analyzed using independent samples *t* test. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.5. Changes in fatigue and pain scores

At baseline, there were no statistically significant differences in fatigue and pain scores between the two groups (*t*-test, $p > 0.05$). Throughout the intervention, the control group exhibited minimal changes in these scores, whereas the intervention group's scores at the 4th and 8th weeks were significantly lower than those of the control group (*t*-test, $p < 0.05$) and showed a gradual decline (**Table 5**) (**Figure 4**).

Table 5. Changes in fatigue and pain scores during the intervention.

Time Point	Intervention Group (Mean ± SD)	Control Group (Mean ± SD)	*t* Value	Cohen's d	*p* Value
Baseline (0 week)	4.31 ± 0.56	4.26 ± 0.51	0.341	0.07	0.734
4th week	3.65 ± 0.59	4.19 ± 0.53	2.424	0.48	0.021
8th week	2.52 ± 0.51	4.16 ± 0.50	7.126	1.43	< 0.001

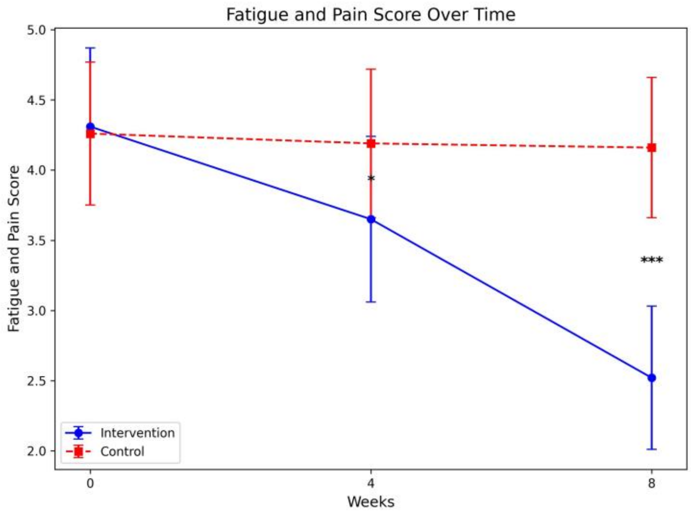

Figure 4. Changes in fatigue and pain scores during the intervention.

Data were analyzed using independent samples *t* test. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

4. Discussion

This study found that after eight weeks of intervention, the intervention group demonstrated significantly better flexion and extension ranges of the metacarpophalangeal joints, proximal interphalangeal joints, and distal interphalangeal joints compared to the control group. The increased range of motion indicates that the soft tissues and muscle groups around the joints have obtained better compliance and coordination through continuous training [12,13]. The improvement in flexibility not only facilitates the smooth execution of difficult fingerings during piano performance but may also reduce fatigue and pain caused by joint stiffness or compensatory movements. Moderate enhancement of joint activity has a potential protective effect on joint cartilage and ligaments, reducing the risk of local inflammation and adhesions [14]. From a biomechanical perspective, precise specialized training enables the hand joints to maintain a good movement trajectory under high repetitive loads, helping to reduce tendon friction and joint stress concentration. The results suggest that a reasonable combination of exercise patterns and daily practice can help prevent the gradual accumulation of hand dysfunction while improving performance. This improvement has practical guiding significance for the fine motor control of the fingers. If performers can maintain moderate training and scientific rest, they may reduce soft tissue wear in the process of completing more technical movements [15]. Changes in joint flexibility may accumulate over long-term training, thereby helping pianists maintain a more enduring performance state. This trend is worthy of further investigation.

In this study, EMG detection showed that the intervention group had a significantly increased peak amplitude of the flexor digitorum superficialis, flexor digitorum profundus, extensor digitorum, interossei, and lumbrical muscles, while the duration did not exhibit a noticeable extension, indicating a stronger instantaneous force-generating capacity under the same or higher performance load. The enhancement of this capacity maintains a higher level of hand movement stability and reduces compensation by non-target muscle groups [16]. According to the specialized training program, while improving key-press accuracy and force generation efficiency, it avoids excessive stress on unilateral muscle groups or local joints [17]. The results suggest that by strengthening the coordinated force generation pattern, finger movement efficiency can be maximized, providing a feasible approach to preventing tendinitis, tenosynovitis, and other potential injuries. The biomechanical concept combines local muscle training with inter-finger movement control, enabling each finger to maintain sensitivity and coordination during rapid performances or wide-span switches. The increase in peak amplitude indicates that when the core muscle group fatigue level is relatively low, effective output can still be maintained [18]; the lack of significant change in duration suggests that the balance between short-term explosive power and endurance has been optimized. If performers adopt this model over the long term, they can achieve a more reasonable distribution of muscle load during high-intensity practice and reduce the external force impact on the joints [19]. A force generation strategy that emphasizes both high efficiency and low injury risk not only optimizes performance technique but also has practical value in integrating rehabilitation and prevention, laying a foundation for further in-depth research on biomechanical patterns in the performance process.

The study results show that the significant improvements in grip strength and pinch strength in the intervention group indicate that targeted hand training effectively enhanced overall hand strength and inter-finger coordination. This improvement in strength provides a more solid mechanical foundation for piano performance, enabling better control and precision during rapid and complex movement transitions [20]. Coupled with the significant decrease in fatigue and pain scores, it can be inferred that the training not only reduced the sense of muscle fatigue caused by high-intensity performance but also alleviated the discomfort of hand pain. In contrast, the control group showed minimal changes in scores throughout the intervention period, reflecting the stability of their "habitual level" and further highlighting the effectiveness of the specialized intervention. This dual intervention model, by improving muscle strength and joint flexibility, may prevent multiple aspects of performance-related hand injuries, including common issues such as tenosynovitis, ganglion cysts, and carpal tunnel syndrome. Further analysis of the electromyographic (EMG) data of the IO (interosseous muscles) and LUM (lumbrical muscles) reveals a more coordinated activation pattern in the intervention group, suggesting their crucial role in regulating finger stability and inter-finger force distribution. The interosseous muscles primarily control finger abduction and adduction, while the lumbrical muscles assist in finger flexion and fine motor control. Coordinated activation helps balance inter-finger load and reduces unnecessary compensatory movements, thereby lowering the risk of overuse injuries to specific joints or muscle groups. This mechanism complements the improvement in joint flexibility, enabling performers to maintain accuracy and comfort even during high-frequency or large-span transitions. These findings further support the value of specialized training in enhancing muscle synergy and preventing performance-related injuries, providing a basis for future applications in clinical rehabilitation or other populations engaged in fine hand tasks. The study suggests that enhancing inter-finger strength and movement coordination can reduce excessive compensation by small hand muscles, thereby lowering the risk of joint and soft tissue damage from long-term high-load performance. The reduction in fatigue and pain not only helps improve performance but also extends pianists' professional careers, allowing them to maintain an optimal working state under high-intensity conditions [21]. This training model provides a preventive strategy that may be referenced by other populations engaged in high-intensity hand operations and has potential for broader application in clinical rehabilitation and functional training. There is a mutually restrictive relationship among finger flexibility, muscle fatigue, and pain. High-intensity or prolonged playing leads to muscle overuse, resulting in fatigue and pain signals, which often inhibit the range of motion of interphalangeal joints. This restriction forces performers to adopt compensatory movements, further exacerbating local muscle fatigue and soreness. Moderately improving joint flexibility and coordination helps distribute local hand loads, reducing stress on soft tissues and tendons, thereby slowing down the accumulation of fatigue and the onset of pain. When muscle groups exert force synergistically under optimal mechanical conditions, ineffective or excessive muscle fiber recruitment can be avoided, making playing movements smoother, which also helps mitigate the negative effects of fatigue and pain.

It should be noted that the improvement of hand flexibility involves not only the enhancement of local muscle strength and joint mobility but also the refined control of inter-finger movements by the central nervous system. Repetitive and targeted hand training may induce plastic changes in the cortical motor areas and spinal pathways, increasing the efficiency of neural excitation transmission and improving the precision of inter-finger muscle activation. Existing literature has shown that motor training can enhance corticospinal excitability and remodel sensorimotor integration, further strengthening speed and coordination. Future studies integrating neuroelectrophysiological or functional imaging techniques to systematically evaluate the impact of training on central mechanisms will help elucidate the physiological basis of interventions in movement pattern optimization and injury prevention.

Despite the rigorous approach in participant recruitment, data collection, and intervention design, this study still has some limitations. The eight-week intervention period was relatively short and could only assess short-term training effects, making it impossible to fully reveal the long-term impact of the intervention on hand function. Particularly in the performance careers of professional pianists, training outcomes may vary depending on continuity and frequency. Although the sample size was estimated through a pilot study and met statistical requirements, the diversity of the participants was insufficient, failing to fully consider differences in performance specialties, training habits of pianists from different sectors, and individual variations in hand anatomy. This may limit the general applicability of the results. Additionally, this study focused on key biomechanical parameters such as hand joint range of motion and electromyographic signals, without incorporating more comprehensive indicators like myofascial tension, nerve conduction velocity, and psychosomatic fatigue data, which may be of great significance for understanding the mechanism of hand movement and preventing long-term injuries. Future research may extend the follow-up period, recruit more diverse participants, and include high-resolution imaging and neurophysiological data to further reveal the overall impact of intervention on the complex biomechanical mechanisms of the hand. By combining multiple perspectives—performance techniques, rest strategies, and rehabilitation interventions—pianists and other high-intensity hand users can be provided with more precise and effective preventive and optimization strategies, laying a stronger scientific foundation for related research fields.

5. Conclusion

The results of this study indicate that, through targeted hand exercises based on biomechanical principles, pianists experience a marked improvement in joint range of motion and coordinated muscle force generation, accompanied by enhanced grip and pinch strength as well as significantly reduced fatigue and pain scores. In the short term, this training intervention provides a stable and safe force-generating foundation for groups who engage in high-intensity hand use, allowing performers to maintain an optimal state during complex movement transitions and prolonged performances. The data support the practical value of this intervention strategy in improving performance and preventing common hand injuries, while also laying the groundwork for future studies aimed at extending the intervention duration, exploring multiple biomechanical indicators, and expanding sample heterogeneity.

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

References

1. Ye S, Lee Y, Lee K, Park HS. Evaluation of sensors for finger joint angle estimation on soft robotic hand rehabilitation device. The Korean Society of Mechanical Engineers. 2023.
2. Bai Q, Dong L, Wang H, et al. ZM suture combined with early functional exercise can promote finger functional recovery in patients with finger flexor tendon rupture. American Journal of Translational Research. 2023; 15(9): 5683–5690.
3. Kaito M, Takanori O, Shinichi F. The plyometric activity as a conditioning to enhance strength and precision of the finger movements in pianists. Scientific Reports. 2022; 12(1): 22267.
4. Pozzo R, Gärtner H. The coordination between pedal and finger forces during piano playing in classical passage with respect to the quality of sound. International Journal of Psychophysiology. 2021; 168(S): S159–S159.
5. Kimoto Y, Hirano M, Furuya S. Adaptation of the corticomuscular and biomechanical systems of pianists. Cerebral Cortex. 2021; 32(4): 709–724.
6. Manning MC, Siminoski A, Schutz M. Exploring the effects of effectors: Finger synchronization aids rhythm perception similarly in both pianists and non-pianists. Music Perception: An interdisciplinary journal. 2020; 37(3): 196–207.
7. Takahashi N, Furuya S, Koike H. Soft exoskeleton glove with human anatomical architecture: Production of dexterous finger movements and skillful piano performance. IEEE Transactions on Haptics. 2020; 13(4).
8. Pu S, Pei Y, Chang J. Decoupling finger joint motion in an exoskeletal hand: A design for robot-assisted rehabilitation. IEEE Transactions on Industrial Electronics. 2020; 67(1): 686–697.
9. Kang T, Lee J, Park D, et al. Effects of a finger exercise program on hand function in automobile workers with hand osteoarthritis: A randomized controlled trial. Hand Surgery and Rehabilitation. 2019; 38(1): 59–66.
10. Singh N, Saini0 M, Anand S, et al. Robotic exoskeleton for wrist and fingers joint in post-stroke neuro-rehabilitation for low-resource settings. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2019; 27(12): 2369–2377.
11. Bella DS, Palmer C. Rate effects on timing, key velocity, and finger kinematics in piano performance. PLoS ONE. 2017; 6(6): e20518.
12. Kimoto Y, Hirano M, Furuya S. Adaptation of the corticomuscular and biomechanical systems of pianists. Cerebral Cortex. 2021; 32(4): 709–724.

13. Turner C, Visentin P, Sha G. Wrist internal loading and tempo-dependent, effort-reducing motor behaviour strategies for two elite pianists. Medical Problems of Performing Artists. 2021; 36(3): 141–149. doi: 10.21091/mppa.2021.3017
14. Kimoto Y, Oku T, Furuya S. Neuromuscular and biomechanical functions subserving finger dexterity in musicians. Scientific Reports. 2019; 9: 12224. doi: 10.1038/s41598-019-48718-9
15. Takamizawa R, Kenway L. An analysis of musculoskeletal disorder risk factors associated with common pedagogical principles of the Lhevinne and Taubman piano schools: A literature review. Research Studies in Music Education. 2023; 46(3). doi: 10.1177/1321103x231200195
16. Farzana S, AshishMathew A. Effect of finger and hand exercises among amateur pianist. Indian Journal of Forensic Medicine & Toxicology. 2021; 15(1): 591.
17. Kimoto Y, Oku T, Furuya, S. Neuromuscular and biomechanical functions subserving finger dexterity in musicians. bioRxiv. 2019. doi: 10.1101/625558
18. Yu H, Luo X. The healing effects of piano practice-induced hand muscle injury. Computational and Mathematical Methods in Medicine. 2022. doi: 0.1155/2022/1020504
19. Li Y, Wu M, Zhang Y, et al. PIANO: A parametric hand bone model from magnetic resonance imaging. Proceedings of the Thirtieth International Joint Conference on Artificial Intelligenc. 2021. doi: 10.24963/ijcai.2021/113
20. Novosiadla I. Psychophysiological factors of effective development of piano technique of future music teachers. Scientific Bulletin of Mukachevo State University Series “Pedagogy and Psychology”. 2023; 9(1). doi: 10.52534/msu-pp1.2023.47
21. Vergel V, Núñez P, Suárez C. Biomechanical analysis of grip strength in upper limb rehabilitation. Journal of Physics: Conference Series. 2022; 2153. doi: 10.1088/1742-6596/2153/1/012019