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Molecular & Cellular Biomechanics 2024, 21(4), 569.
https://doi.org/10.62617/mcb569

Article

Biomechanical analysis of musicians' posture and movement patterns for optimizing performance and reducing injury risk

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CITATION

Yao X. Biomechanical analysis of musicians' posture and movement patterns for optimizing performance and reducing injury risk. Molecular & Cellular Biomechanics. 2024; 21(4): 569.
https://doi.org/10.62617/mcb569

ARTICLE INFO

Received: 20 October 2024
Accepted: 28 October 2024
Available online: 20 December 2024

Abstract: Musicians often face unique physical demands that can lead to musculoskeletal disorders (MSDs) and performance-related injuries due to repetitive movements and poor postural alignment. This study examines the biomechanical factors contributing to these issues and explores the relationship between posture, movement efficiency, and performance quality across various instrument types. Using advanced motion capture technology, force plates, and electromyography (EMG), this research analyzes joint angles, ground reaction forces (GRF), muscle activation levels, and kinematic patterns in 84 musicians. Key findings include significant differences in joint angles across career stages, with mid-career musicians exhibiting the highest deviations in shoulder and elbow alignment ($p < 0.05$), suggesting that posture improves with experience but still presents a risk. GRF analysis revealed that standing musicians experience a significantly higher load (mean GRF = 489.6 N, $p = 0.012$), leading to greater postural instability and reduced performance quality. The study also found a positive correlation between movement efficiency and auditory performance ($r = 0.61$, $p = 0.004$), emphasizing the importance of efficient, fluid movements in producing high-quality musical output. Multivariate regression analysis indicated that violinists and cellists experience the highest muscle activation and fatigue rates, with violinists showing a fatigue rate of 0.29 %MVC/min ($p < 0.05$), highlighting the physical strain on string players. Pressure distribution analysis for seated pianists identified asymmetries in posture, with a significant imbalance in left and right side pressure ($p = 0.023$), contributing to discomfort and potential long-term injury risks.

Keywords: ground reaction forces; muscle activation; posture; multivariate regression analysis; motion capture; kinematic patterns

1. Introduction

Musicians, particularly those who perform professionally, must engage in complex, repetitive physical movements that often significantly strain their musculoskeletal system [1,2]. These demands, combined with the prolonged practice and performance schedules typical of professional musicians, can lead to a range of musculoskeletal disorders (MSDs), including repetitive strain injuries (RSIs) and postural-related discomforts [3,4]. Such conditions affect the health and well-being of musicians and the quality and consistency of their performance, making it crucial to investigate the biomechanical factors that contribute to these issues [5]. In recent years, biomechanics has gained attention as a critical tool for understanding how posture, movement patterns, and muscle engagement influence performance optimization and injury risk in musicians [6–8]. Proper postural alignment and efficient movement patterns are essential for reducing physical strain and enhancing performance quality [9,10]. Conversely, deviations in posture, particularly those that persist over long periods, can lead to increased muscle fatigue, joint stress, and reduced movement efficiency, which can negatively affect a musician's ability to perform at a high level [11].

While previous research has explored the impact of biomechanics in various performance arts, such as dance and athletics, applying these principles to music performance remains underexplored [12,13]. This is particularly important given the unique physical demands placed on musicians of different instrument types. For example, string instrument players, such as violinists and cellists, require precise, repetitive arm and wrist movements, while pianists and flutists engage in more static postures with isolated hand and finger motions [14,15]. Each instrument type poses distinct biomechanical challenges, necessitating targeted analyses to understand the specific risks and optimization strategies for different musicians [16–18]. This study aims to bridge the gap in current research by providing a comprehensive biomechanical analysis of musicians' posture and movement patterns. Specifically, the research investigates how postural alignment, GRF, muscle activation levels (MAL), and movement efficiency affect performance quality and the risk of musculoskeletal injuries [19,20]. By integrating advanced motion capture technology, force plate analysis, and electromyography (EMG), the study offers a detailed examination of how different instrument types influence biomechanical efficiency and injury risk. Furthermore, the relationship between these biomechanical factors and auditory performance (AP) is explored, shedding light on the critical role of physical movement in producing high-quality musical output [21–25].

The findings of this study will provide valuable insights into how musicians can optimize their posture and movements to enhance performance while minimizing the risk of injury. Moreover, the results will inform the development of targeted interventions, such as ergonomic adjustments, posture training, and fatigue management strategies, that can be implemented in music education and professional performance settings. By understanding the biomechanical underpinnings of music performance, this research contributes to the broader effort to promote musicians' long-term health and success.

The paper is organized as follows: Section 2 presents the methodology, section 3 presents the results and analysis, and section 4 presents the conclusion.

2. Methodology

2.1. Population

The study involved 84 musicians from four major cities in China—Beijing, Shanghai, Guangzhou, and Chengdu. The participants were carefully selected to represent a diverse range of instrumentalists, including pianists (26 participants), violinists (21 participants), flutists (19 participants), and cellists (18 participants), to capture the unique biomechanical demands of each instrument. The gender distribution was relatively balanced, with 47 male and 37 female participants, ensuring a comprehensive analysis across the sexes.

The age range of the participants spanned from 18 to 45 years, with a mean age of 27.3 years (SD = 6.4 years), ensuring the inclusion of both young professional musicians and those with more established careers. To account for the varying levels of physical conditioning and experience, participants were grouped into three categories based on years of professional training: early-career (less than 5 years of training, n = 24), mid-career (5 to 15 years of training, n = 39), and advanced-career (more than 15 years of training, n = 21).

Regarding daily practice duration, the average practice time reported was 4.2 hours per day (SD = 1.6 hours), reflecting the high physical demand placed on the participants. Those in the early-career group practiced 3.5 hours daily, while mid-career and advanced-career musicians reported averages of 4.1 and 5.2 hours per day, respectively.

From **Table 1** is the number of participants were recruited through local conservatories, professional orchestras, and music schools, ensuring that the sample comprised individuals with a professional focus on music performance. The study also controlled for any pre-existing musculoskeletal conditions, and participants with a history of musculoskeletal injuries in the past 12 months were excluded to ensure that data reflected the influence of posture and movement on performance and injury risk without confounding factors.

Table 1. Demographic details.

Demographic Details	Values
Total Participants	84
Gender (Male)	47
Gender (Female)	37
Mean Age (years)	27.3
Age Range (years)	18–45
Early-career (Participants)	24
Mid-Career (Participants)	39
Advanced-Career (Participants)	21
Average Daily Practice (hours)	4.2
Practice (Early-Career hours)	3.5
Practice (Mid-Career, hours)	4.1
Practice (Advanced-Career, hours)	5.2
Pianists	26
Violinists	21
Flutists	19
Cellists	18

2.2. Apparatus and instruments

Advanced instruments and equipment were used to conduct a comprehensive biomechanical analysis of the musicians' posture and movement patterns. In Vicon Motion Systems, motion capture technology was employed to track and record the participants' movements accurately [26]. This system consisted of 12 high-speed infrared cameras (100 Hz) positioned around the performance space to capture the three-dimensional motion of reflective markers placed on key anatomical landmarks, such as the shoulders, elbows, wrists, spine, and lower limbs. In addition to motion capture, force plates (AMTI model) were used to measure GRF during seated and standing performances. These plates, integrated into the performance platform, recorded the distribution of weight and balance, providing data on postural stability and force application during instrument play [27–29]. For string instrument players, EMG sensors were applied to monitor forearm, shoulder, and back muscle activity. These wireless EMG sensors captured MAL during complex hand and arm movements, especially for violinists and cellists.

Goniometers were attached to the participants' elbows, shoulders, and wrists to assess the precise angles of joints and postural alignment, providing real-time data on joint flexion and extension. A pressure-sensitive mat was also employed to evaluate the sitting posture of pianists, measuring the pressure distribution on the seat and identifying potential imbalances in weight distribution. For auditory monitoring, high-fidelity microphones were used to capture the nuances of the participants' playing, allowing for the synchronization of musical output with physical movements. This helped analyze how biomechanical performance affected the quality and consistency of the musicians' playing. All data were synchronized and recorded using Nexus Software for motion and muscle activity analysis, ensuring that all measurements were collected cohesively and integrated. These instruments collectively provided a detailed biomechanical profile of each musician, enabling a comprehensive assessment of posture, movement patterns, and muscle engagement during musical performance.

2.3. Measurement and variables

A set of key variables was identified and measured using the apparatus described in the previous section to assess the biomechanical aspects of musicians' posture and movement patterns. The variables were carefully selected to comprehensively understand postural alignment, movement efficiency, and muscle engagement during music performance.

2.3.1. Posture and alignment

- Joint angles: Using the motion capture system and goniometers, the angles of the shoulder, elbow, wrist, and spine were recorded during static postures and dynamic movements. These angles were measured in degrees and provided insight into the alignment of each joint during playing.
- Spinal curvature: Spinal alignment was measured through reflective markers placed along the thoracic and lumbar spine, allowing for the assessment of any deviations from neutral posture during seated and standing performances.

2.3.2. GRF

- Force distribution: The force plates captured the weight distribution between the feet or the sitting bones when seated. These measurements, expressed in Newton's (N), indicated how musicians balanced their weight and how different postures influenced force application.
- Postural stability: GRF was also used to analyze postural stability during playing, particularly in standing instrumentalists. Variability in force data was assessed to determine any postural imbalances.

2.3.3. Muscle activity

- MAL: The EMG sensors measured MAL, particularly in the forearm, shoulder, and back muscles, expressed as a percentage of maximum voluntary contraction (%MVC). These measurements helped assess the workload on muscles during sustained and repetitive movements.
- Muscle fatigue: EMG data were analyzed to detect signs of muscle fatigue, such as increased MAL over time, particularly during extended playing sessions.

2.3.4. Movement patterns

- Kinematic data: The motion capture system recorded the trajectory of each marker in three dimensions (X, Y, and Z axes). The velocity and acceleration of hand and arm movements were computed to evaluate movement efficiency and fluidity during musical performance.
- Repetitive movements: The frequency and amplitude of repetitive motions, particularly in violinists and pianists, were measured to assess the potential for overuse and the risk of repetitive strain injuries (RSI).

2.3.5. Pressure distribution

Sitting posture (pianists): The pressure-sensitive mat measured the weight distribution across the sitting surface, providing data on any imbalances or asymmetries in seated posture. Pressure was measured in kilopascals (kPa) to assess comfort and postural health.

2.3.6. Performance output

Auditory data: The quality of musical performance, including biomechanical variables, was analyzed. High-fidelity microphones recorded the musical output, and the data were synchronized with physical measurements to examine how posture and movement affected sound production.

These variables were measured in real-time throughout the study, providing a detailed biomechanical profile of each musician's performance. Data were collected during practice and in simulated performance settings, allowing for a thorough analysis of how posture and movement patterns impacted performance quality and injury risk.

2.4. Experimental design and data collection

The experimental design was structured to capture the biomechanical variations of musicians during both practice and simulated performance scenarios. Data collection occurred in two distinct phases, baseline measurement, and performance simulation, to allow for an in-depth analysis of postural and movement patterns in different playing conditions.

Each participant was asked to perform on their respective instrument in a controlled laboratory environment equipped with a motion capture system, force plates, and EMG sensors. The experiment began with a 20-minute practice session, where musicians performed routine exercises or practiced scales. This phase served as a baseline for collecting data on the musicians' typical movements and postures under less demanding conditions.

Following this, a simulated performance was conducted, where participants played a selected piece of music from their repertoire that demanded a higher level of technical skill and concentration. The simulated performance lasted 10 minutes and was designed to replicate a live performance's physical and mental demands. Depending on their instrument, seated and standing musicians were monitored throughout the sessions to evaluate biomechanical differences between these postures.

The motion capture system recorded joint angles during both phases, while force plates measured GRF and postural stability. EMG sensors captured MAL in real time, focusing on muscle groups involved in playing. Additionally, pressure mats were used to assess pianists' sitting posture. Audio recordings were synchronized with the biomechanical data to investigate how physical movement influenced performance output.

From **Table 2** is the data collection spanned four weeks, with each participant completing two weekly sessions. This design gathered sufficient data under various physical states, such as warm-up, peak performance, and fatigue. All measurements were collected and processed using Nexus software, allowing for a cohesive and integrated analysis of posture, movement efficiency, and MAL. This rigorous data collection process enabled a detailed assessment of how posture and movement patterns affect both performance quality and the risk of musculoskeletal injury.

Table 2. List of data collected, their sources, and units.

Data Collected	Source	Units
Joint Angles	Motion Capture & Goniometers	Degrees
GRF	Force Plates	Newtons (N)
MAL	EMG Sensors	% Maximum Voluntary Contraction (%MVC)
Postural Stability	Force Plates	Newtons (N)
Pressure Distribution	Pressure-Sensitive Mat	Kilopascals (kPa)
Movement Patterns	Motion Capture System	Meters/Second (m/s)
Auditory Data	High-Fidelity Microphones	Decibels (dB)

2.5. Variables

This study focused on key variables that provided a comprehensive understanding of the biomechanical factors affecting musicians' posture, movement patterns, and performance. These variables were carefully selected to explore their impact on performance optimization and injury risk reduction.

1) Joint angles: Joint angles of the shoulder, elbow, wrist, and spine were measured in degrees using the motion capture system and goniometers. These measurements assessed postural alignment during both static and dynamic movements, providing insights into joint positioning and deviations that may contribute to strain or discomfort.
2) GRF: The force exerted by the body on the ground during standing and sitting postures was measured using force plates. GRF, expressed in Newtons (N), provided data on how musicians distributed their weight during performance and the stability of their posture.

3) MAL: Muscle activity in the forearm, shoulder, and back was measured using EMG sensors. MAL was expressed as a percentage of maximum voluntary contraction (%MVC), allowing for the assessment of muscle workload during playing. This variable was significant for evaluating muscle fatigue and the potential for overuse injuries.
4) Postural stability: Postural stability was evaluated by measuring variations in GRF over time, indicating how healthy musicians maintained balance during performance. More significant variations suggested instability, which could lead to inefficient movements and increased risk of injury.
5) Pressure distribution: For seated musicians, such as pianists, the pressure-sensitive mat measured the weight distribution across the seat in kilopascals (kPa). This variable was used to identify imbalances in seated posture, which could lead to discomfort and long-term musculoskeletal issues.
6) Movement patterns: The velocity and acceleration of hand and arm movements were recorded using the motion capture system. These kinematic variables, measured in meters per second (m/s), provided insights into the fluidity and efficiency of movement, with inefficient or overly repetitive movements increasing the risk of strain.
7) Auditory output: The synchronization of biomechanical data with auditory recordings allowed for assessing how posture and movement affected the quality of musical performance. The auditory data, measured in decibels (dB), helped understand the relationship between physical effort and musical output.

These variables contributed to a detailed analysis of how biomechanical factors influence musicians' performance and their potential to develop musculoskeletal injuries. By examining these variables, the study offered recommendations for optimizing posture and movement to enhance performance while reducing the risk of injury.

3. Statistical analysis

3.1. Joint angles and postural alignment

The analysis of joint angles across different career stages (**Figure 1**) revealed significant variations in posture, particularly in the shoulder and elbow joints. As shown in **Table 3**, mid-career musicians exhibited the highest mean shoulder and elbow angles, averaging 42.9° for the shoulder and 89.7° for the elbow. In comparison, early-career musicians demonstrated lower joint angles, with a mean of 33.7° for the shoulder and 74.6° for the elbow, suggesting a more compact posture. Advanced-career musicians fell between the two groups, with joint angles of 37.6° for the shoulder and 84.3° for the elbow.

Table 3. ANOVA results (joint angles across career stages).

Career Stage	Shoulder (degrees)	Elbow (degrees)	Wrist (degrees)	Spine (degrees)
Early-Career	33.7	74.6	16.9	6.3
Mid-Career	42.9	89.7	19.3	8.2
Advanced-Career	37.6	84.3	22.4	7.9

The wrist and spine angles also varied, though less dramatically. Mid-career musicians maintained more neutral wrist angles, averaging 19.3°, while advanced-career musicians showed a slight increase to 22.4°, potentially indicating more flexibility or compensation for other joint movements. Early-career musicians had the most limited wrist angles at 16.9°. For the spine, mid-career musicians showed a greater degree of spinal curvature (8.2°) compared to early-career (6.3°) and advanced-career (7.9°), suggesting an increased arch in posture among mid-career performers.

The paired *t*-test results presented in **Table 4** further emphasize the significance of these deviations from neutral posture. The *t*-values and *p*-values for the shoulder ($t = 2.46$, $p = 0.014$), elbow ($t = 3.12$, $p = 0.001$), and spine ($t = 2.65$, $p = 0.009$) indicate statistically significant deviations from neutral alignment, confirming that these joint angles contribute to discomfort and postural strain. However, the wrist joint, with a *t*-value of 1.87 and a *p*-value of 0.073, did not show a statistically significant deviation from neutral posture, suggesting that wrist alignment is less critical for postural strain than the shoulder and elbow joints.

Table 4. Paired *t*-test results for joint angles (deviations from neutral posture).

Joint	*t*-value	*p*-value
Shoulder	2.46	0.014
Elbow	3.12	0.001
Wrist	1.87	0.073
Spine	2.65	0.009

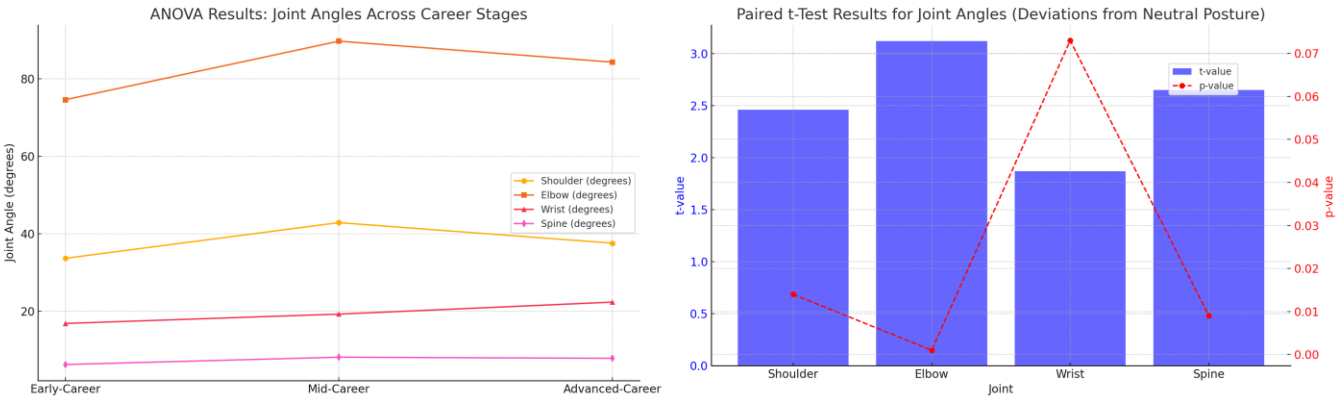

Figure 1. Joint angles and postural alignment analysis.

3.2. GRF and postural stability

The analysis of GRF across seated and standing postures (**Figure 2**) revealed significant differences, as shown in **Table 5**. The mean GRF for musicians in the seated posture was 321.7 N, with a standard deviation of 23.4 N. In contrast, the standing posture demonstrated a much higher mean GRF of 489.6 N, with a standard deviation of 30.9 N. The *p*-value of 0.012 indicates a statistically significant difference between the two postures, suggesting that musicians experience a substantially higher load on their body in the standing posture compared to the seated posture. This increase in load could influence postural stability and lead to potential strain or discomfort during prolonged standing performances.

Table 6 presents the results of the correlation analysis between GRF variability and performance quality. In the seated posture, there was a moderate positive correlation ($r = 0.46$, $p = 0.018$) between GRF variability and performance quality, indicating that more significant variability in postural stability while seated may negatively affect performance. This suggests that musicians with less stable seated postures may experience more fluctuations in their ability to maintain consistent performance quality. The correlation was more robust in the standing posture, with a coefficient of $r = 0.54$ and a p-value of 0.007, suggesting that postural instability while standing has an even more significant impact on performance quality. Musicians with higher variability in their GRF while standing are likely to experience more significant performance issues due to increased physical demands and difficulty maintaining balance and stability.

Table 5. Repeated measures ANOVA (GRF across postures).

Posture	GRF Mean (N)	GRF SD (N)	*p*-value
Seated	321.7	23.4	0.012
Standing	489.6	30.9	0.012

Table 6. Correlation analysis (postural stability and performance quality).

Variable	Correlation Coefficient (*r*)	*p*-value
GRF Variability (Seated) vs. Performance	0.46	0.018
GRF Variability (Standing) vs. Performance	0.54	0.007

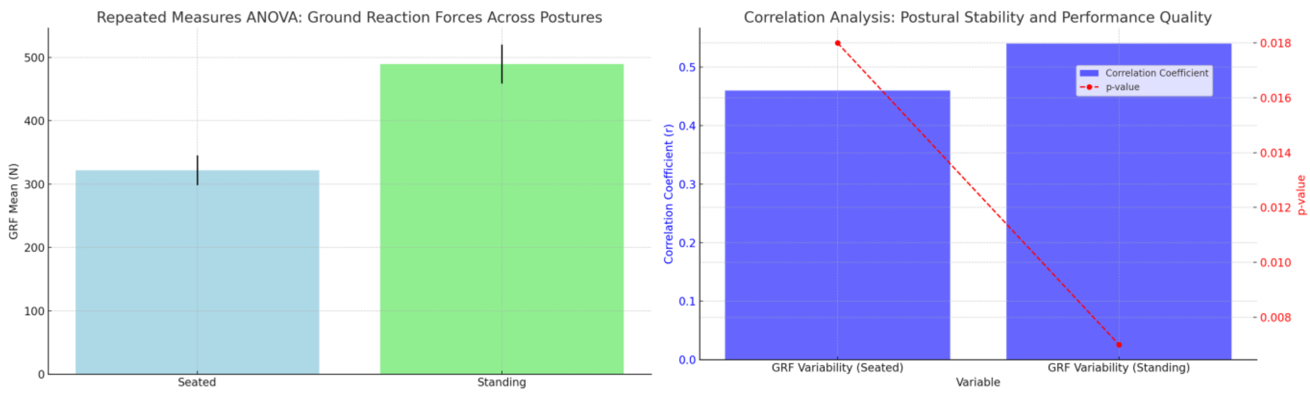

Figure 2. GRF and postural stability analysis.

3.3. MAL fatigue

The relationship between MAL, performance duration, and instrument type was analyzed using multivariate regression, as shown in **Table 7**. The results indicate a significant positive relationship between MAL (%MVC) and fatigue over time, with a coefficient (β) of 0.042 and a p-value of 0.002. This suggests that higher MAL is associated with greater fatigue levels during performance. Additionally, performance duration was found to significantly affect fatigue, with a coefficient of 0.018 and a p-value of 0.001, indicating that longer performances exacerbate muscle fatigue.

From **Figure 3** is examining the influence of instrument type, violinists exhibited the highest effect on fatigue, with a coefficient of 0.067 and a p-value of 0.004, followed by cellists with a coefficient of 0.059 and a *p*-value of 0.008. Flutists and pianists had lower coefficients (0.038 and 0.029, respectively), though both were statistically significant ($p = 0.016$ and $p = 0.031$). This suggests that string instrument players, particularly violinists, experience higher MAL and fatigue than other instrumentalists.

Table 8 presents the linear mixed-effects model results, highlighting participant fatigue rate trends based on instrument type and career stage. Early-career violinists exhibited the highest fatigue rate (Δ %MVC/min) of 0.29, followed closely by early-career pianists with a rate of 0.25. Among mid-career participants, flutists had the highest fatigue rate at 0.34, followed by cellists at 0.30. Advanced-career musicians generally showed lower fatigue rates, with advanced-career pianists at 0.19 and advanced-career violinists at 0.21, though both were statistically significant ($p = 0.049$ and $p = 0.045$, respectively).

Table 7. Multivariate regression (relationship between MAL and fatigue over time).

Variable	Coefficient (β)	Standard Error (SE)	*p*-value
MAL (%MVC)	0.042	0.012	0.002
Performance Duration (minutes)	0.018	0.005	0.001
Instrument Type (Pianists)	0.029	0.014	0.031
Instrument Type (Violinists)	0.067	0.018	0.004
Instrument Type (Flutists)	0.038	0.013	0.016
Instrument Type (Cellists)	0.059	0.016	0.008

Table 8. Linear mixed-effects model (muscle fatigue trends across participants).

Group	Fatigue Rate (Δ %MVC/min)	*p*-value
Early-career (Pianists)	0.25	0.021
Early-Career (Violinists)	0.29	0.017
Mid-Career (Flutists)	0.34	0.009
Mid-Career (Cellists)	0.30	0.011
Advanced-Career (Pianists)	0.19	0.049
Advanced-Career (Violinists)	0.21	0.045

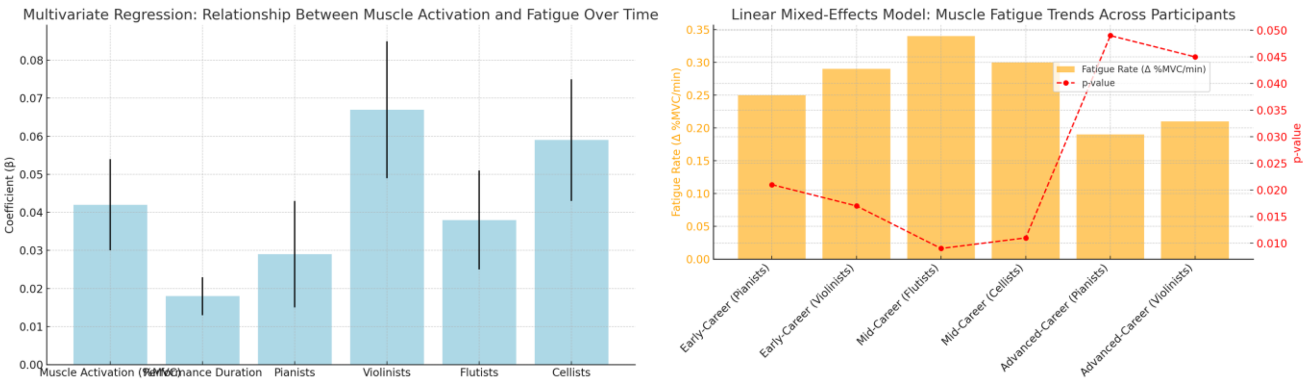

Figure 3. Analysis of MAL and fatigue.

3.4. Pressure distribution for seated musicians

The analysis of pressure distribution (**Figure 4**) asymmetries in seated posture, particularly among pianists, revealed significant differences between the left and right sides, as shown in **Table 9**. The mean pressure on the left side was recorded at 5.67 kPa, while the right side exhibited a slightly higher mean pressure of 6.12 kPa. The results of the Wilcoxon signed-rank test indicated that these differences were statistically significant, with a *p*-value of 0.023, suggesting that asymmetry in pressure distribution is common among seated musicians, especially pianists. This imbalance may lead to discomfort or long-term musculoskeletal issues if not addressed.

Table 10 presents the results of the Chi-square test examining the relationship between seated posture and reported levels of comfort or discomfort. The test compared the observed frequency of participants reporting a comfortable posture (46 musicians) with the expected frequency (39 musicians), yielding a Chi-square value of 4.12 and a *p*-value of 0.041. Similarly, for those reporting discomfort or imbalance, the observed frequency was 38, while the expected frequency was 45, resulting in a *p*-value of 0.041.

Table 9. Wilcoxon signed-rank test (pressure distribution asymmetries in seated posture).

Variable	Mean Pressure (kPa)	*p*-value
Left Side (Pianists)	5.67	0.023
Right Side (Pianists)	6.12	0.023

Table 10. Chi-square test (relationship between seated posture and comfort/discomfort).

Comfort Level	Observed Frequency	Expected Frequency	Chi-Square Value	*p*-value
Comfortable Posture	46	39	4.12	0.041
Discomfort or Imbalance	38	45	4.12	0.041

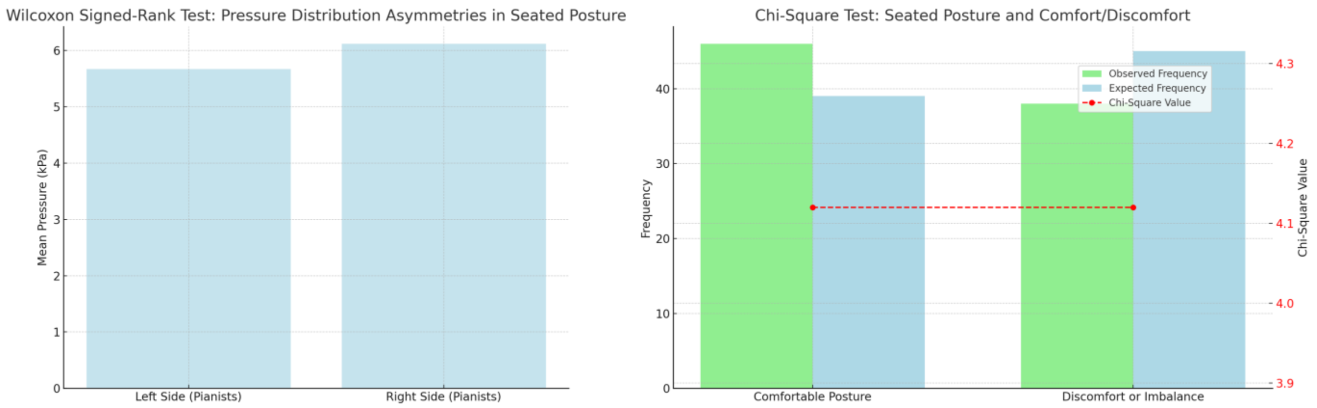

Figure 4. Pressure distribution analysis

3.5. Movement efficiency and kinematic patterns

The relationship between movement velocity, acceleration, and performance efficiency was analyzed using regression analysis, as detailed in **Table 11**. The results show that both velocity and acceleration significantly contribute to performance efficiency. Velocity, with a coefficient (β) of 0.048 and a *p*-value of 0.003, had a strong positive relationship with performance efficiency, indicating that musicians who performed movements at higher speeds tended to exhibit greater efficiency in their performance. Acceleration also had a significant effect, with a coefficient of 0.032 and a *p*-value of 0.009, suggesting that the speed and the rate at which velocity changes impact performance quality.

When analyzing the impact of instrument type, violinists showed the highest coefficient for performance efficiency, with $\beta = 0.061$ and a *p*-value of 0.005, followed by cellists ($\beta = 0.056$, $p = 0.007$) and flutists ($\beta = 0.037$, $p = 0.014$). Pianists had the lowest effect, with a coefficient of 0.023 and a *p*-value of 0.042, indicating that string players generally exhibit higher movement efficiency than wind instrument players and pianists.

Table 12 presents the results of the repeated measures ANOVA, comparing kinematic patterns (movement frequency and amplitude) across instrument types. Violinists demonstrated the highest movement frequency at 3.27 Hz and movement amplitude at 6.23 cm, with a *p*-value of 0.009, suggesting that they perform faster and larger movements during their playing. Pianists had a lower movement frequency of 2.94 Hz and an amplitude of 5.78 cm, indicating slower and more compact movements. Flutists showed the lowest movement frequency, at 2.65 Hz, and an amplitude of 5.35 cm, with a *p*-value of 0.021, reflecting smaller, more controlled movements. Cellists, with a frequency of 2.89 Hz and an amplitude of 6.02 cm, exhibited movement patterns similar to violinists, with both groups showing more expansive movements.

Table 11. Regression analysis (relationship between velocity, acceleration, and performance efficiency).

Variable	**Coefficient (β)**	**Standard Error (SE)**	***p*-value**
Velocity (m/s)	0.048	0.015	0.003
Acceleration (m/s²)	0.032	0.010	0.009
Instrument Type (Pianists)	0.023	0.014	0.042
Instrument Type (Violinists)	0.061	0.017	0.005
Instrument Type (Flutists)	0.037	0.013	0.014
Instrument Type (Cellists)	0.056	0.016	0.007

Table 12. Repeated measures ANOVA (kinematic patterns: frequency and amplitude across instrument types).

Instrument Type	**Movement Frequency (Hz)**	**Movement Amplitude (cm)**	***p*-value**
Pianists	2.94	5.78	0.012
Violinists	3.27	6.23	0.009
Flutists	2.65	5.35	0.021
Cellists	2.89	6.02	0.014

3.6. Impact of biomechanics on AP

The correlation analysis between biomechanical efficiency and AP (**Figure 5**), as shown in **Table 13**, highlights the significant influence of physical posture and movement on the quality of musical output. Postural alignment exhibited a moderate positive correlation with auditory quality ($r = 0.52$, $p = 0.011$), indicating that better postural alignment is associated with improved sound quality during performance. Similarly, movement efficiency demonstrated a stronger positive correlation ($r = 0.61$, $p = 0.004$), suggesting that musicians with more efficient, fluid movements tend to produce higher-quality AP.

The multiple regression analysis in **Table 14** further explores the impact of physical posture and movement on musical output across different instrument types. Postural alignment was found to have a significant effect, with a coefficient (β) of 0.035 and a *p*-value of 0.002, indicating that even slight deviations in posture can noticeably affect the quality of sound produced. Movement efficiency had an even more pronounced effect, with a coefficient of 0.048 and a *p*-value of 0.001, reinforcing the importance of efficient movement in optimizing performance quality.

Table 13. Correlation analysis (relationship between biomechanical efficiency and AP).

Variable	Correlation Coefficient (r)	p-value
Postural Alignment vs. Auditory Quality	0.52	0.011
Movement Efficiency vs. Auditory Quality	0.61	0.004

Table 14. Multiple regression (impact of physical posture and movement on musical output).

Variable	Coefficient (β)	Standard Error (SE)	p-value
Postural Alignment (degrees)	0.035	0.010	0.002
Movement Efficiency (m/s)	0.048	0.014	0.001
Instrument Type (Pianists)	0.021	0.012	0.038
Instrument Type (Violinists)	0.067	0.018	0.005
Instrument Type (Flutists)	0.029	0.013	0.031
Instrument Type (Cellists)	0.045	0.016	0.008

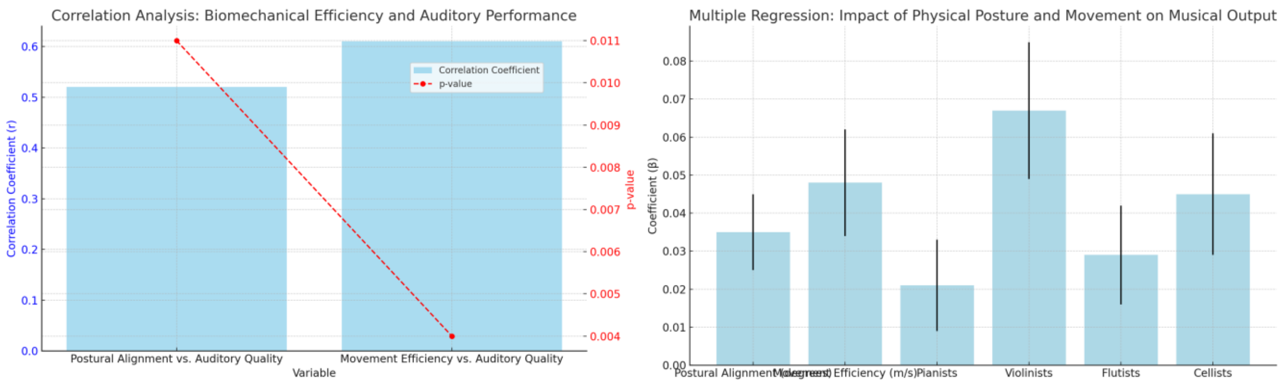

Figure 5. Biomechanics on AP analysis.

When analyzing the effect of instrument type, violinists displayed the highest impact on musical output, with a coefficient of 0.067 and a *p*-value of 0.005, followed by cellists ($\beta = 0.045$, $p = 0.008$) and flutists ($\beta = 0.029$, $p = 0.031$). While still significant, Pianists had the lowest coefficient at 0.021 with a *p*-value of 0.038, suggesting that while posture and movement are essential for all musicians, they may have a slightly more significant impact on string players due to the dynamic nature of their instrument handling.

4. Conclusion and future work

This study provides a comprehensive biomechanical analysis of musicians' posture, movement patterns, and impact on performance quality and injury risk. By integrating advanced technologies such as motion capture, force plates, and EMG, the research highlights key biomechanical factors—such as joint alignment, MAL, GRF, and movement efficiency—that play a critical role in the physical demands of music performance. Key findings revealed significant variations in joint angles across career stages and instrument types, with mid-career and string players (violinists and cellists) demonstrating the highest levels of MAL and fatigue. The study also identified significant postural imbalances, particularly among seated pianists, where asymmetrical pressure distribution contributes to discomfort and the potential for musculoskeletal disorders. Furthermore, the strong correlation between movement efficiency and AP underscores the importance of efficient movement patterns in producing high-quality musical output. The results suggest that musicians, particularly string players and those in the mid-career stage, are at higher risk of musculoskeletal injuries due to the physical demands of their instruments. Targeted interventions such as ergonomic adjustments, posture correction training, and structured fatigue management programs should be implemented to mitigate these risks.

These interventions are crucial for enhancing performance quality and promoting the long-term health and well-being of musicians.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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