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Beyond overload: A biofeedback-based assessment linking postural awareness and sensorimotor control to musculoskeletal health in orchestral musicians

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Abstract. Professional musicians often develop playing-related musculoskeletal disorders (PRMDs) from prolonged static postures, repetitive movements, and chronic biomechanical overload. However, the link between instrumental practice, postural awareness, and sensorimotor control lacks objective, multidimensional investigation. This preliminary study explored these relationships in 28 professional orchestral musicians divided into wind, bowed, and string instrument groups. Participants completed a structured questionnaire investigating musical practice habits, musculoskeletal symptoms, and postural awareness through the validated Postural Awareness Scale (PAS). Functional assessment included flexibility and core endurance tests, while sensorimotor control was quantitatively assessed, for the first time in this target, using the Libra biofeedback-based proprioceptive system. Musculoskeletal pain and discomfort were found to be highly prevalent across all groups, mainly involving the shoulder and spinal anatomical districts. Bowed instrument players showed significantly lower PAS scores than the other groups, suggesting reduced postural awareness associated with sustained asymmetric playing positions. Libra assessments revealed generally poor postural stability, particularly during eyes-closed conditions, indicating increased reliance on visual input for balance regulation and possible proprioceptive deficits. Functional tests also highlighted suboptimal core endurance and flexibility throughout the sample. Overall, findings support the hypothesis that PRMDs result from a complex interaction between cumulative biomechanical overload, reduced postural awareness, and altered sensorimotor control. In this context, specialized kinesiologists might play a pivotal role in prevention and management through tailored proprioceptive training, postural re-education, and adapted conditioning programs integrated into routine musical practice, thereby promoting long-term health, functional efficiency, and performance sustainability in this target population.

Keywords: postural awareness, proprioception, musculoskeletal disorders, biofeedback, adapted kinesiology, professional musicians.

INTRODUCTION

Musical performance requires a highly orchestrated integration of sensorimotor skills, postural regulation, sustained neuromuscular coordination, and complex cognitive processes (Belviso et al., 2026). The repetitive and specialized nature of instrumental practice exposes musicians to substantial physical demands, often comparable to those experienced by athletes in terms of training intensity, precision, and performance pressure (Quarrier, 1993; Ang, Panebianco & Odendaal, 2021; Creech & Hallam, 2003; Currey et al., 2020). However, unlike athletes, musicians often lack structured preventive training, increasing their susceptibility to playing-related musculoskeletal disorders (PRMDs) (Foxman & Burgel, 2006; Chan & Ackermann, 2014; Baadjou et al., 2015). PRMDs, defined as pain, weakness, numbness, or functional impairment affecting performance, represent one of the most prevalent occupational health issues among musicians (Gasenzer et al., 2017; Blanco-Piñeiro, Díaz-Pereira & Martínez, 2017; Cerda-Díaz et al., 2026; Shinde & Borkar, 2021), with consistently high prevalence rates reported across different instrumental groups (Kok et al., 2016; Rotter et al., 2020; Cerda-Díaz et al., 2026). The cervical spine, shoulder girdle, and upper limbs seem to be particularly involved, reflecting the specific biomechanical constraints imposed by instrumental performance (Silva, Lã & Afreixo, 2015; Gómez-Rodríguez et al., 2020; Kochem & Silva, 2018; Steinmetz, Seidel & Muche, 2010). The etiology of PRMDs is complex and multifactorial. Traditional models have emphasized mechanical overload, repetitive strain, and sustained static postures as primary risk factors (Baadjou et al., 2016; Betzl, Kraneburg & Megerle, 2020).

From a biomechanical perspective, professional instrumental practice is characterized by a unique combination of prolonged static loading, highly repetitive fine motor activity, and asymmetric postural configurations, which together generate a distinctive pattern of cumulative mechanical overload. Musicians are required to maintain submaximal but sustained muscle activation over extended periods, often in constrained joint positions that limit physiological variability and recovery (Kok et al., 2017; Rensing, Schemmann & Zalpour, 2018). These conditions promote the development of low-grade chronic fatigue, reduced local circulation, and progressive accumulation of microtrauma within musculoskeletal tissues (Fry, 1986; Sirufo et al., 2022). Instrument-specific demands further exacerbate these biomechanical stresses. For instance, bowed string players typically adopt persistent cervical rotation, lateral flexion, and elevation of the shoulder, associated with prolonged scapular stabilization and asymmetric loading of paravertebral and shoulder girdle muscles (Steinmetz, Seidel & Muche, 2010; Barczyk-Pawelec et al., 2012; Saffert, Melzner & Dendorfer, 2022; Ancillao et al., 2017; Rensing, Schemmann & Zalpour, 2018). Pianists and harpists are exposed to repetitive high-frequency finger movements combined with prolonged sitting and static trunk posture, resulting in continuous activation of both distal and proximal kinetic chains (Ciurana Moñino et al., 2017; Furuya et al., 2011; Chadefaux et al., 2024). Wind instrument players require sustained respiratory effort and increased activation of core musculature, contributing to thoraco-lumbar stabilization demands and altered pressure dynamics (Ackermann & Driscoll, 2010; Chan, Driscoll & Ackermann, 2013; López-Pineda et al., 2023). These conditions lead to non-ergonomic joint alignments and altered load distribution, promoting biomechanical imbalances and maladaptive structural changes over time (Blanco-Piñeiro, Díaz-Pereira & Martínez, 2017; Fernández Paz, Lantarón Caeiro & Soto González, 2020; Rousseau et al., 2023; Barczyk-Pawelec et al., 2012). The coexistence of repetition, force, and static posture creates a cumulative overload scenario in which tissue recovery is insufficient relative to exposure (Rotter et al., 2020; Betzl, Kraneburg & Megerle, 2020). Furthermore, the high level of motor precision required in musical execution tends to reduce movement variability that is a factor associated with increased risk of overuse (Turner et al., 2023). Reduced variability, combined with performance demands and error minimization, may therefore contribute to persistent stereotyped motor patterns and localized overload. At the neuromuscular level, prolonged exposure to these constraints may induce adaptive and maladaptive changes in motor control strategies. Altered muscle recruitment patterns, increased co-contraction, and inefficient coordination between synergistic muscle groups have been observed in musicians with PRMDs (Overton, Du Plessis & Sole, 2018; Silva et al., 2018). These changes likely reflect both peripheral fatigue and central adaptations, suggesting a reorganization of sensorimotor control in response to repetitive strain (Mizrahi, 2020). In this context, proprioception and sensorimotor integration play a crucial role in optimizing postural control and movement efficiency. Accurate proprioceptive input contributes to body schema representation, regulation of postural tone, and fine motor control (Steinmetz, Seidel & Muche, 2010; Smitt & Bird, 2013). Conversely, altered proprioceptive processing may lead to deficient postural strategies, increased muscular stiffness, and suboptimal load distribution, ultimately amplifying biomechanical stress (Carretti, Manetti & Marini, 2025a; Steinmetz, Seidel & Muche, 2010). Emerging evidence has also indicated that musicians with PRMDs exhibit impairments in postural control systems (Rodríguez-Gude, Taboada-Iglesias & Pino-Juste, 2023), further supporting the relevance of sensorimotor control in this target of individuals (Steinmetz, Seidel & Muche, 2010; Garnett, Pijl & Visentin, 2022).

Despite the growing body of literature addressing occupational health risks in musicians, the relationship between biomechanical overload and sensorimotor control alterations remains insufficiently clarified. Most available studies have predominantly focused on epidemiological prevalence, self-reported symptoms, or isolated risk factors, often relying on questionnaire-based approaches without integrating objective functional assessments (Baadjou et al., 2016; Stanhope et al., 2019; Rodríguez-Gude, Taboada-Iglesias & Pino-Juste, 2023). Whereas these contributions have been essential in defining and highlighting the magnitude of the problem, they provide limited insight into the mechanisms linking repetitive biomechanical exposure to altered motor control strategies (Cahalan et al., 2026; Rousseau et al., 2023). Moreover, although postural and ergonomic analyses have been widely investigated, they have been rarely integrated with proprioceptive and sensorimotor dimensions, which are essential for understanding movement regulation in highly skilled performers (Rousseau et al., 2023; Garnett, Pijl & Visentin, 2022). Similarly, neuromuscular studies have documented altered muscle activation patterns in musicians with PRMDs, yet these findings resulted poorly contextualized within a comprehensive framework that includes postural control, sensory integration, and task-specific motor behavior (Overton, Du Plessis & Sole, 2018; Silva et al., 2018). Another important limitation concerns the scarcity of multimodal and quantitative assessment approaches capable of capturing the complexity of instrumental performance. Existing methodologies often rely either on laboratory-based biomechanical analyses with limited ecological validity or on clinical observational tools that may lack sensitivity to detect subtle or early-stage dysfunctions (Ancillao et al., 2017; Schemmann, Rensing & Zalpour, 2018). Consequently, the transition from adaptive motor strategies to maladaptive patterns leading to injury remains poorly understood. In addition, the role of practice-related variables, such as intensity, duration, and cumulative exposure, has been widely acknowledged but insufficiently integrated with objective measures of motor control and postural regulation, hence limiting potential meaningful associations between behavioral load and functional impairment (Kok et al., 2016; Stanhope, Weinstein & Pisaniello, 2020). This gap is particularly relevant in orchestral musicians, who are exposed to prolonged and often non-modifiable performance demands. Therefore, a comprehensive approach that simultaneously considers biomechanical load, sensorimotor control, and related symptomatology is still lacking.

The present preliminary study aims at addressing this gap by adopting a multidimensional assessment framework that combined validated qualitative instruments, standardized motor evaluations, and an innovative biofeedback-based tool to objectively investigate sensorimotor control in relation to musculoskeletal symptoms and practice habits in this target population. This approach might hopefully foster research interest in this still under investigated field through a more mechanistic understanding of PRMDs and contemporarily provide kinesiological preventive/re-educative hints to be stably integrated into instrumental training sessions. Such desirable integration might allow a tailored holistic management of this highly specialized population, thereby contributing to effectively prevent and counteract occupational health issues while safely improving quality of life, artistic performance and long-term career.

MATERIALS AND METHODS

Participants

The investigated sample comprised 28 musicians, 14 women and 14 men, aged between 21 and 64 years. All participants were professional musicians regularly enrolled in formal musical training programs and/or belonging to orchestras, with an academic background from a conservatoire. Specifically, the study included orchestral musicians with professional experience in instrumental practice, no history of neurological or musculoskeletal disease, and who provided informed consent to adhere to the study. The study was conducted in accordance with the principles of the Declaration of Helsinki of 1975, revised in 2013 (World Medical Association, 2013). Individuals reporting acute pain and recent trauma or surgery at the time of assessment were excluded since such issues might jeopardize balance and safety during sensorimotor tasks. To identify how instrument-specific postures affect sensorimotor control, participants were grouped by instrument type: wind, bowed, and other string instruments. Notably, the string instruments category comprised both harp and harpsichord players since both instruments share a common physical sound-production mechanism based on string plucking – either directly or via a keyboard mechanism – rather than bowing or wind generation. Musicians were recruited through direct contact with various orchestras/music institutions and voluntary participation in the study was promoted via their official communication channels. During this preliminary phase, objectives, operational procedures, organizational and logistical aspects were clearly presented and detailed by an adapted physical activity kinesiologist and approved by the internal review board of each involved music institution. This ensured a clear understanding of the procedures involved prior to the study, promoting informed and responsible participation. In the act of adhering to the study, participants deliberately and consciously gave their consent not only to participate in the planned procedures, but also to data collection, storage, and utilization for scientific publications. In agreement with this form, data were treated, processed, and stored in a completely anonymous way for the purposes of this study. In particular, the obtained information was entered into an electronic datasheet identifying each participant by a unique alphanumeric ID, not mentioning, or making any sensitive data accessible. Given the relatively limited sample size, particularly in the string instrument subgroup, the present investigation should be considered a preliminary exploratory study aimed at generating initial evidence and methodological hints for future larger-scale research.

Qualitative and quantitative evaluations

All study participants filled out a structured questionnaire purposely designed using the Google Forms platform and sent by e-mail in the form of a direct access link to the form. In detail, the first section of the self-administered survey was aimed at collecting sociodemographic and anthropometric data, including age, gender, dominant hand, weight, height and relevant characteristics of musical practice (e.g., played instrument, years of experience, weekly time spent practicing). Regarding the anthropometric aspect, based on the weight and height data provided by each participant, the body mass index was calculated using the formula weight (kg)/height (m^2). The second section examined habits related to instrumental practice, including information regarding the duration of training sessions, the inclusion of warm-up exercises and/or breaks during practice, and any postural training received. Specific purpose-designed questions investigated the self-perception of posture during musical training/performance, as well as the subjective postural awareness. Additional questions were then aimed to identify the presence of pain or physical discomfort associated with musical practice, its frequency and location, or any experienced postural/musculoskeletal issues. Information regarding the level of habitual physical activity and sedentary lifestyle was also collected. Finally, the questionnaire included a section dedicated to assessing postural awareness using the Italian version of the Postural Awareness Scale (PAS), a validated tool designed to investigate the level of subjective perception of postural control in daily activities. The scale consists of 12 items designed to explore both spontaneous and conscious postural awareness. The total score ranges from 12 to 84, with higher values indicating greater sensorimotor awareness (Topino, Gori & Cramer, 2020).

After completing the questionnaire, participants underwent a battery of evidence-based motor tests aimed at assessing flexibility, muscular endurance and core stability/strength. All the tests, performed strictly following the official guidelines available in literature, were accurately detailed and then supervised by a specialized kinesiologist. In particular, the V Sit-and-Reach test was administered to assess flexibility of the posterior kinetic chain, peculiarly the hamstring musculature and lower back extensibility. Such evaluative tool is considered a valid field-based alternative to the traditional version of the test, minimizing spinal compression and improving standardization (Hui & Yuen, 2000; Miñarro et al., 2007). Detailing procedures, each participant was asked to assume a seated position on the floor with lower limbs extended and abducted at approximately 30–45°, forming a "V" shape. The heels placed against a baseline marked on the floor, with the zero-point aligned with the heels. The measuring line extended forward along the midline between lower limbs. The subject was requested to place one hand over the other, with arms fully extended, and slowly reach forward along the measuring line, maintaining knee extension, avoiding ballistic movements, and holding the final position for at least 3 seconds. The distance reached beyond the baseline was measured in centimeters. Three attempts were made retaining the best reached value and then comparing it with the reference scores available in literature (Hui & Yuen, 2000; Miñarro et al., 2007). The Sit-Up test was performed as well to evaluate dynamic muscular endurance of the abdominal musculature, particularly the rectus abdominis and hip flexors (Kukić et al., 2022; Bianco et al., 2015). The subject was asked to lie in supine decubitus position on a fitness mat placed on the floor, with bent lower limbs and feet kept parallel and hip-width apart, firmly on the ground. Placing arms outstretched and parallel, hands resting on thighs with palms facing the floor, participant was requested to keep shoulders and head on the mat. From this position, shoulders and upper body had to be lifted just enough to allow the fingertips of both hands rising above knee height and then return to the starting position. The aim of the test was to perform as many correctly executed repetitions as possible in one minute. The achieved reps were then compared with the specific cut-off available in literature (Kukić et al., 2022; Bianco et al., 2015). Subsequently, plank tests were also administered to assess isometric endurance of the core musculature, including rectus and transverse abdominis, obliques, and stabilizing muscles of the lumbar-pelvic region (Tong, Wu & Nie, 2014; Rodríguez-Perea et al., 2025). Specifically, regarding the front plank test, each participant was asked to assume a prone decubitus position, supporting body weight on the forearms and toes. Elbows aligned vertically under the shoulders, forearms parallel, and the body maintained in a straight line from head to heels. The subject was instructed to hold this position as long as possible without compromising alignment (e.g., pelvic drop, excessive lumbar lordosis, or scapular instability). Time was recorded in seconds starting from the moment the correct position was assumed until failure, defined as the inability to maintain the required proper posture (Rodríguez-Perea et al., 2025). Similarly, in the side plank test subject was asked to lie on the floor in lateral decubitus position, supporting the body on one forearm and the lateral face of the foot. The elbow was positioned directly under the shoulder, and the body had to be kept aligned in a straight line. The contralateral arm was placed along the body or on the hip. Both left and right sides were tested by recording time independently for each side, applying the same criteria previously detailed. Reference cut-off values are available in literature for both these tests (Tong, Wu & Nie, 2014).

Finally, the efficiency of sensorimotor control was tested using the Libra sensorized proprioceptive board (Carretti, Manetti & Marini, 2025b), an innovative biofeedback based device designed to provide an accurate and reliable quantitative assessment (Tchórzewski, Jaworski & Bujas, 2010). Specifically, it consists of a sensorized tilting board connectable, via USB, to any computer and specific software interface. The tool is equipped with interchangeable rolling wedges that allow variable oscillation degrees while, through the digital interface, different path patterns can be set and then displayed on the computer screen as a roadway side bounded by two parallel lines. During the swing, whenever such boundaries are approached or overcome, a multimodal feedback is played to signal the departure from the equilibrium position (Tchórzewski, Jaworski & Bujas, 2010). The digital interface also offers a validated preset test called Spielman-De Gunsch (SDG) Test. Such validated trial allows to assess the global postural stability in orthostatic bipedal stance, related to different conditions of visual anchorage: no gaze constraints, straight ahead gaze, and closed eyes (Adamo, Pociask & Goldberg, 2013). During the SDG Test the subject was asked to stand up in orthostatic position on Libra trying to control oscillations by keeping it as parallel to the floor as possible. Specifically, the test includes three consecutive 30-second tasks performed following a linear pathway pattern, presetting a 9/10 difficulty level and 10 cm tilting wedges. At the end of the whole execution, the stability index obtained in each trial can be compared to the 0–100 cut-off values available in the digital database, with lower scores corresponding to higher postural stability (Carretti, Manetti & Marini, 2025b). Clinically, the validated stability index reflects the ability to control postural sway and maintain balance under micro/macro perturbations and different visual anchorage conditions. Therefore, this parameter may represent a crucial outcome for investigating the multimodal complex sensorimotor control of professional musicians. Furthermore, sensorimotor control of the upper body district was investigated using the Libra board in seated position, a specific setting foreseen by the manufacturer and already applied and described in our previous studies (Carretti et al., 2024a, 2024b). In line with the aim of such assessment, Libra was placed on a stable and antislip box, and the subject was instructed to sit over it, keeping arms crossed over chest, with a 90∘ trunk-thigh angle and both legs orthogonal to the ground with feet on a skimmy proprioceptive cushion on the floor. Starting from this position, two tasks were performed, one allowing the board to tilt on frontal plane while the other on sagittal plane. Such variability, simply achieved by changing the Libra positioning from straight-oriented to transverse-oriented, was purposely applied to investigate trunk lateral and antero-posterior stability, respectively (Carretti et al., 2024b). Both tests lasted 1 min and a linear pathway pattern, a maximum difficulty level, and 10 cm tilting wedges were set. Such seated trials were carried out either without the habitually played instrument or in a playing simulated setting assuming the required position. To ensure safety and protect valuable musical instruments, actual instrument use was avoided during these tests. As already detailed for SDG Test, the aim was to keep Libra in balance, parallel to the floor, following the multimodal feedback provided by the digital interface. The achieved performance index was then interpreted using the validated 0–100 cut-off.

Statistical analysis

GraphPad Prism 5 software was used to conduct statistical analysis. One-way analysis of variance (ANOVA) and posthoc Tukey's multiple comparison test were used to compare study groups after Kolmogorov–Smirnov test confirmed the normality of data, which were stated as mean ± standard deviation (SD). Chi-square test was also used for categorical data, which were stated as number/percentage of subjects participating in the study. A p-value of less than 0.05 was deemed statistically significant.

RESULTS

The demographic and anthropometric characteristics of the study participants are detailed in Table 1. Considering the musical instrument played, half of the study sample played bowed instruments, followed by wind instruments and, to a lesser extent, other string instruments such as harp and harpsichord. No statistically significant difference between the three groups (wind instruments, bowed instruments, and string instruments) was observed for the main variables investigated. Specifically, the age-distribution was balanced and there was no difference in the BMI category. Notably, most participants were normal weight, whilst smaller proportion were overweight or underweight. Table 1 summarizes the results related to the current practice of regular physical activity/sport, assessed by question-

Table 1. Demographic/anthropometric data and summary data from questionnaire investigating the current practice of regular physical activity/sport for each of the three study groups.

Variables	Wind instruments (n = 11)	Bowed instruments (n = 14)	String instruments (n = 3)
Age (years), mean ± SD (range)	29.73 ± 8.83 (22–54)	29.57 ± 12.46 (21–64)	29.67 ± 3.51 (26–33)
Sex, n (%)			
Male	7 (63.64)	6 (42.86)	1 (33.33)
Female	4 (36.36)	8 (57.14)	2 (66.67)
BMI category, n (%)			
<18.5 (underweight)	1 (9.09)	2 (14.29)	0 (0.00)
18.5–24.9 (normal weight)	7 (63.64)	6 (42.86)	3 (100.00)
25–29.9 (overweight)	3 (27.27)	6 (42.86)	0 (0.00)
≥ 30 (obese)	0 (0.00)	0 (0.00)	0 (0.00)
Current physical activity/sport practice, n (%)			
Yes	8 (72.73)	7 (50.00)	1 (33.33)
No	3 (27.27)	7 (50.00)	2 (66.67)
Type of physical activity/sport, n			
Walking	4	4	0
Running	1	2	0
Gym	3	2	0
Yoga/Pilates	3	2	1
Swimming	1	1	0
Team sports	0	2	0
Physical activity/sport frequency per week (days), n			
<1	0	4	0
1–2	4	3	0
3–4	1	0	1
7	3	0	0
Average duration of physical activity/sport session (minutes), n			
<30	1	0	1
30–60	7	5	0
>60	0	2	0
Average daily hours spent sitting, n (%)			
1–3	1	1	0
4–6	5	8	2
7–10	5	3	1
Unsure	0	2	0

BMI, body mass index; SD, standard deviation.

naire, with no significant differences observed between three study groups. In particular, most participants reported engaging in regular physical activity or sports, such as walking, running, gym workouts, yoga/Pilates, or swimming. Finally, the range 4–6 hours mainly represented the amount of daily time spent sitting.

Results of postural habits, awareness, and pain associated with musical practice as well as presence of musculoskeletal complaints are shown in Table 2. Overall, the sample comprised musicians with at least 10 years of experience who practice daily. Most musicians reported musculoskeletal pain presence mainly localized to the shoulder or spine, due to the time spent playing and the posture adopted while performing. In particular, the three groups did not differ significantly in their responses. However, it is notable that significant differences in self-reported postural awareness score, assessed by PAS, were found in bowed instrument players compared to wind and string musicians ($p < 0.05$ respectively). In detail, bowed instrument players showed lower postural awareness scores (Table 2).

Furthermore, most participants reported prolonged daily practice sessions with limited interruption hence recalling the presence of cumulative biomechanical overload associated with instrumental performance (data not shown).

Table 3 shows the data of postural stability, assessed by Libra, and the results of functional assessment in the study groups. In particular, the global postural stability, tested using Libra SDG in orthostatic bipedal stance, related to different conditions of visual anchorage (i.e., no gaze constraints, straight ahead gaze, and closed eyes) highlighted poor levels of sensorimotor control in all study groups. Specifically, postural stability tended to worsen during eyes-closed conditions, showing a greater dependence on visual input for balance regulation. Similarly, the trunk stability index in seated position on both frontal and sagittal planes, with and without the musical instrument, did not reveal any statistically significant differences among the three groups of musicians. Moreover, the posterior muscle chain flexibility, measured by the sit-and-reach test, and core stability assessed by plank tests, showed no statistically significant differences among the three study groups. According to the available validated cut-off values, these collective data indicated a poor level of physical fitness. Although overall core endurance values were generally suboptimal across the sample, wind instrument players tended to demonstrate slightly better core strength and endurance performances compared with the other groups.

DISCUSSION

To our knowledge, the present study is the first to provide a multidimensional insight into the complex interaction between biomechanical load, postural habits, and sensorimotor control in orchestral musicians, supporting the hypothesis that these factors are strictly interconnected and collectively contribute to the development of PRMDs. The high prevalence of self-reported pain and discomfort observed in all the instrumental groups investigated is consistent with the extensive literature documenting musculoskeletal complaints as one of the most common occupational health issues in musicians (Kok et al., 2016; Rotter et al., 2020; Gómez-Rodríguez et al., 2020; Cerda-Díaz et al., 2026). In particular, the predominance of shoulder, cervical, and spinal involvement aligns with previous findings highlighting the upper body as the most exposed district due to sustained asymmetric postures and repetitive motor patterns (Silva, Lã & Afreixo, 2015; Kochem & Silva, 2018; Gómez-Rodríguez et al., 2020). From a behavioral perspective, the data collected through the questionnaire revealed a substantial exposure to risk factors traditionally associated with PRMDs, including prolonged daily practice, limited variability in posture, and high weekly playing frequency. Notably, most musicians reported practicing 4-6 hours per day with minimal interruption, reinforcing the link between cumulative overload and insufficient recovery time described in earlier studies (Baadjou et al., 2016; Betzl, Kraneburg & Megerle, 2020). The observed association between practice duration and impaired postural control highlighted the role of training load. Prolonged practice without adequate recovery leads to neuromuscular fatigue, which impairs proprioceptive acuity and increase postural sway. This finding is aligned with research indicating that workload management represents a critical factor in the prevention of PRMDs (Baadjou et al., 2016; Amaral Corrêa et al., 2018). Additionally, the frequent adoption of non-neutral trunk and head alignments, such as forward inclination, lateral flexion, and rotation, confirmed the persistence of instrument-specific postural constraints already documented in the literature (Barczyk-Pawelec et al., 2012; Fernández Paz, Lantarón Caeiro & Soto González, 2020; Rousseau et al., 2023). These maladaptive postures, when maintained over time, may alter load distribution and contribute to microtrauma accumulation, ultimately leading to chronic dysfunctions (Fry, 1986; Sirufo et al., 2022). In fact, it has been demonstrated that instrument-specific biomechanical constraints play a crucial role in shaping these adaptations, significantly compromising proprioception efficiency and postural control (Barczyk-

Table 2. Summary data from questionnaire focusing on the postural habits, awareness, and pain associated with musical practice as well as presence of musculoskeletal complaints.

Variables	Wind instruments (n = 11)	Bowed instruments (n = 14)	String instruments (n = 3)
Handedness, n (%)			
Right-handed	9 (81.82)	13 (92.86)	3 (100.00)
Left-handed	1 (9.09)	1 (7.14)	0 (0.00)
Mixed-handed	1 (9.09)	0 (0.00)	0 (0.00)
Years of musical experience, n (%)			
1–9	1 (9.09)	1 (7.14)	0 (0.00)
10–20	6 (54.55)	10 (71.43)	2 (66.67)
> 20	4 (36.36)	3 (21.43)	1 (33.33)
Weekly frequency of playing on a daily, n (%)			
1–2	0 (0.00)	0 (0.00)	0 (0.00)
3–4	0 (0.00)	2 (14.29)	0 (0.00)
5–6	4 (36.36)	4 (28.57)	0 (0.00)
7	7 (63.64)	8 (57.14)	3 (100.00)
Average hours of musical playing, n (%)			
< 1	0 (0.00)	0 (0.00)	0 (0.00)
1–2	3 (27.27)	2 (14.29)	0 (0.00)
3–4	6 (54.55)	7 (50.00)	2 (66.67)
5–6	2 (18.18)	5 (35.71)	0 (0.00)
> 6	0 (0.00)	0 (0.00)	1 (33.33)
Posture adopted while playing, n (%)			
Sitting	7 (63.64)	5 (35.71)	3 (100.00)
Static standing	4 (36.36)	3 (21.43)	0 (0.00)
Dynamic standing	0 (0.00)	6 (42.86)	0 (0.00)
Trunk alignment while sitting playing, n			
Straight	1	2	2
Slightly leaning forwards	5	2	1
Slightly leaning backwards	1	1	0
No attention to posture	0	0	0
Trunk alignment while standing playing, n			
Straight and aligned	2	1	0
Flexion	0	3	0
Lateral flexion	2	1	0
Unbalanced to one side	0	4	0
No attention to posture	0	0	0
Head alignment (orientation) while playing, n (%)			
Neutral position	4 (36.36)	2 (14.29)	0 (0.00)
Flexion	5 (45.45)	1 (7.14)	2 (66.67)
Lateral flexion	2 (18.18)	6 (42.86)	1 (33.33)
Rotation	0 (0.00)	4 (28.57)	0 (0.00)
No attention to posture	0 (0.00)	1 (7.14)	0 (0.00)
Pain/discomfort presence, n (%)			
Yes	8 (72.73)	12 (85.71)	2 (66.67)
No	3 (27.27)	2 (14.29)	1 (33.33)
Body localization, n			
Neck	3	4	0
Shoulder	8	7	1
Spine	2	7	0
Arm	0	3	0
Wrist	2	1	1
Hand	1	2	0

(Continued)

Table 2. (Continued).

Variables	Wind instruments (n = 11)	Bowed instruments (n = 14)	String instruments (n = 3)
Pain/discomfort onset frequency, n			
Always	1	3	0
Often	6	5	1
Rarely	1	4	1
Never	0	0	0
Osteoarticular disorder presence, n (%)			
Yes	4 (36.36)	5 (35.71)	0 (0.00)
No	7 (63.64)	9 (64.29)	3 (100.00)
Symptom presence in the last month, n (%)			
Yes	2 (50.00)	3 (60.00)	0 (0.00)
No	2 (50.00)	2 (40.00)	0 (0.00)
Symptom presence in the past week, n (%)			
Yes	2 (50.00)	3 (60.00)	0 (0.00)
No	2 (50.00)	2 (40.00)	0 (0.00)
Functional impact on instrumental performance, n (%)			
Yes	3 (75.00)	5 (100.00)	0 (0.00)
No	1 (25.00)	0 (0.00)	0 (0.00)
Symptom attribution to the instrument playing, n (%)			
Yes	3 (75.00)	2 (40.00)	0 (0.00)
No	0 (0.00)	1 (20.00)	0 (0.00)
Unsure	1 (25.00)	2 (40.00)	0 (0.00)
Postural Awareness Scale (total score), mean (SD)	52.81 (9.90)	41.85 (11.12)*	60 (8.88)

SD, standard deviation; *$p < 0.05$ compared to wind and string instruments.

Table 3. Mean scores of anatomo-functional and sensorimotor control assessments for each of the three study groups.

Variables	Wind instruments Mean ± SD	Bowed instruments Mean ± SD	String instruments Mean ± SD
Libra SDG test, index			
No gaze constraint	17.14 ± 1.83	16.07 ± 1.79	16.82 ± 1.96
Straight ahead gaze	16.20 ± 2.17	15.51 ± 2.96	15.94 ± 0.42
Closed eyes	17.96 ± 1.91	17.76 ± 1.59	17.18 ± 0.72
Libra seated tests, index			
Frontal plane trunk stability	0.78 ± 1.05	0.48 ± 0.23	0.48 ± 0.23
Frontal plane trunk stability with musical instrument	0.96 ± 1.85	0.42 ± 0.21	0.35 ± 0.05
Sagittal plane trunk stability	1.77 ± 4.70	0.40 ± 0.58	0.47 ± 0.46
Sagittal plane trunk stability with musical instrument	0.55 ± 0.89	0.40 ± 0.58	0.35 ± 0.18
V Sit-and-reach test, centimeters	41.54 ± 14.27	34.93 ± 17.12	31.43 ± 11.57
Sit-up, n repetition/min	23.00 ± 7.80	20.71 ± 8.64	16.66 ± 2.08
Plank, seconds			
Front	100.72 ± 37.55	79.28 ± 42.76	92 ± 28.79
Right	48.09 ± 22.89	43.71 ± 24.95	33.33 ± 5.5
Left	54.36 ± 20.03	41 ± 25.63	44.66 ± 16.92

SDG, Spielman-De Gunsch; SD, standard deviation.

Pawelec et al., 2012; Blanco-Piñeiro, Díaz-Pereira & Martínez, 2017; Ancillao et al., 2017; Rensing, Schemmann & Zalpour, 2018). Specifically concerning postural awareness, measured by PAS, the relatively heterogeneous scores observed among the instrumental groups investigated suggested that subjective perception of posture may vary depending on instrument-specific demands. In particular, bowed instrument players showed lower postural awareness scores, suggesting a possible association between sustained asymmetric playing positions and reduced subjective perception of posture and body alignment. This aspect is particularly relevant considering that reduced body awareness has been associated with inefficient motor strategies and increased injury risk (Smitt & Bird, 2013; Garnett, Pijl & Visentin, 2022). The gap between high biomechanical stress and moderate postural awareness may impair self-regulation, perpetuating harmful motor habits in this target of individuals. The functional motor assessments by validated tasks further supported such interpretation. Although flexibility and core endurance values did not show statistically significant differences between groups, a general trend toward suboptimal performance, particularly in core stability tests, can be observed. Despite this overall deficit, wind instrument players showed better values in core strength and endurance thus remarking the link between instrument-specific posture and somatosensory adjustments. Given that core parameters are essential for maintaining postural control and distributing mechanical loads efficiently, a conscious recruitment of this anatomo-functional district becomes crucial during instrumental performance (Ackermann & Driscoll, 2010; Chan, Driscoll & Ackermann, 2013). Insufficient conditioning of stabilizing musculature may thus exacerbate compensatory strategies and increase local stress on peripheral segments, as also suggested by studies demonstrating the beneficial effects of targeted exercise programs in reducing pain and improving function in musicians (Lundborg & Grooten, 2018; Mirshahi et al., 2023).

The main innovative contribution of the present study lies in the objective assessment of sensorimotor control through the validated biofeedback-based Libra system. The relatively homogeneous SDG test scores across groups suggest a generally preserved global postural stability under visual conditions. Conversely, during eyes-closed tasks, altered postural control patterns have been evidenced, hence suggesting that musicians might exhibit deficits in proprioceptive integration, relying more heavily on visual input to maintain stability. Similar findings have been reported in individuals with chronic musculoskeletal pain, where sensory reweighting mechanisms become altered, leading to reduced adaptability (Rodríguez-Gude, Taboada-Iglesias & Pino-Juste, 2023). From a neurophysiological standpoint, these alterations may reflect changes in central processing of sensory information. Indeed, prolonged exposure to repetitive and constrained motor tasks can lead to plastic adaptations within the central nervous system, potentially reinforcing suboptimal movement patterns (Overton, Du Plessis & Sole, 2018; Belviso et al., 2026). Contemporarily, slight differences emerged when analyzing trunk stability during dynamic seated tasks on Libra board, particularly when comparing conditions with and without simulated instrument playing. The observed variability in the performance index, with and without playing simulation, may reflect the task-related adaptations to complex postural demands imposed by instrument-specific positions. These findings support the hypothesis that sensorimotor control is task-dependent and may lead to maladaptive adjustments under ecologically relevant conditions, where biomechanical and cognitive demands are combined for extended periods (Steinmetz, Seidel & Muche, 2010; Mizrahi, 2020). In this context, the increased stability index during not playing conditions can be interpreted as an indicator of reduced adaptability of the sensorimotor system when exposed to habitual featured constraints (Overton, Du Plessis & Sole, 2018; Silva et al., 2018). Furthermore, the relationship between pain and impaired postural control observed in the investigated sample highlighted a bidirectional interaction. Pain can modify motor output through protective mechanisms, such as increased stiffness and reduced movement variability, which in turn may increase mechanical stress on tissues (Betzl, Kraneburg & Megerle, 2020). This dangerous vicious cycle might contribute to the persistence and chronicity of symptoms. Finally, a relevant aspect concerns the relationship between physical activity and musculoskeletal health. Although a relatively high proportion of participants reported engaging in regular physical activity, this did not appear sufficient to prevent the occurrence of pain and discomfort. Consistent with previous studies, this finding suggests that generic physical activity alone might not be adequate to counteract the specific biomechanical demands of musical performance (Baadjou et al., 2015; Roos et al., 2024). Instead, tailored kinesiologist-led strategies focusing on posture and proprioception should be integrated into music training sessions to reduce injury risk (Árnason, Briem & Árnason, 2018; Adamčák et al., 2025; Baadjou et al., 2018; Roos et al., 2024). Nevertheless, barriers to implementation remain significant, including lack of time, motivation, and institutional support (Ajidahun et al., 2019). Therefore, a multidisciplinary approach actively involving different specialized professionals, educators and performers is essential to effectively address these issues.

Taken together, the results of this study support the growing body of literature advocating for preventive interventions that address not only ergonomic factors but also sensorimotor function in the health management of professional musicians, thus reinforcing the need for a comprehensive and integrative evidence-based approach. Unlike previous research predominantly based on self-reported data or isolated assessments, the present multidimensional framework might provide a more detailed characterization of the mechanisms underlying PRMDs. In particular, the integration of objective biofeedback-based measurements with subjective and functional evaluations may represent a promising methodological advancement in this field, concretely addressing some of the limitations highlighted by recent reviews (Stanhope et al., 2019; Rousseau et al., 2023). However, some limitations should be acknowledged. The relatively small sample size and the unbalanced distribution among instrumental groups may limit the generalizability of the findings. Moreover, the cross-sectional study design does not allow causal relationships to be established between exposure variables and outcomes. Future investigations should therefore adopt longitudinal designs and larger samples to better investigate the temporal evolution of sensorimotor adaptations and their role in the onset and prevention of PRMDs. In particular, it would be valuable to determine whether structured proprioceptive and postural re-education programs might positively modify PAS scores, improve the Libra-derived stability index, and reduce the incidence and severity of PRMDs over time. Applying a kinesiological perspective, a dose-response approach would be useful to provide standardized and instrument-tailored recommendations.

CONCLUSIONS

In conclusion, our investigation supports the concept that PRMDs in musicians emerge from an interplay between biomechanical constraints, reduced postural awareness, and lack of sensorimotor education. Accordingly, tailored interventions should incorporate proprioceptive training, postural re-education, and body awareness techniques, as well as structured physical conditioning programs designed, led and monitored by specialized kinesiologists (Baadjou et al., 2018; Carretti et al., 2024a; Roos et al., 2024). Regular integration of health education into music curricula may enhance early recognition of risk factors and promote long-term musculoskeletal health in this vulnerable target of individuals (Adamčák et al., 2025; Árnason, Briem & Árnason, 2018). While addressing barriers to implementation remains a critical challenge, both at institutional and individual levels (Ajidahun et al., 2019), concretely fostering such holistic approach might represent a key step toward the development of targeted and enjoyable protocols to preserve overall health, artistic performance, and career sustainability in this highly specialized population.

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AUTHOR CONTRIBUTIONS

GC: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. TL: Methodology, Formal analysis, Data curation, Investigation, Writing – original draft, Writing – review & editing. MM (Mirko Manetti): Formal analysis, Data curation, Writing – original draft, Writing – review & editing. MM (Mirca Marini): Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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