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Postural adaptations of saxophone players during music performance

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ABSTRACT

Music performance is one of the most refined forms of skilled human behaviour, combining high-level motor and cognitive demands with expressive intentions. We examined how musical features and movement expression affect postural sway in expert saxophone players. Twenty participants (nine female) performed excerpts varying in tempo, rhythmical density, articulation, and technical demands, in standing position, under movement-restricted and expressive-movement conditions. Generalised linear mixed models were used to assess the effects of these factors on centre-of-mass measurements. Results showed that participants swayed faster and travelled longer distances in music with faster tempo and increased rhythmical density, but slower and with reduced mediolateral range when performing tonguing technique (*staccato*). When limited to technical motion, participants still showed increased mediolateral sway during *staccato* passages, suggesting compensatory postural adjustments. Sway frequency was unaffected by movement condition, possibly reflecting an unconscious, task-related motor response. Performances were longer when movement was constrained, highlighting the role of body motion in temporal regulation. Our findings help understand how saxophone players accommodate technical and expressive goals, offering new insights into motor control and multisensory integration during performance.

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Music performance; motor control; dynamic postural sway; centre of mass (CoM); expressive behaviour

1. Introduction

High-level music performance is an exceptional demonstration of the human body's capacities, combining auditory, cognitive, and motor skills. Performing artists have been compared to athletes based on commonalities like practice frequency and intensity, the risk of developing career-threatening playing-related injuries, or exposure to anxiety-inducing events (Dick et al., 2013; Kenny et al., 2014; Quarrier, 1993). However, unlike sports, music performance is driven by artistic goals. This means that although consistent, repeatable motor control is a necessary pre-requisite to achieve musical excellence (McPherson, 2022; Williamon, 2004), it is not enough to produce meaningful interpretations. After mastering technical actions, expert musicians deliberately manipulate their movements to fulfil aural and visual expressive intentions, thus delivering performances complying with cultural and musical standards while adding a personal touch (Shan et al., 2018; Turner et al., 2021). For example, woodwind players lift and circle the instrument's bell to emphasise expressive musical sections (Davidson, 2012; Desmet et al., 2012; Moura & Serra, 2024; Teixeira et al., 2014; Wanderley et al., 2005). If, on the one hand, this gesture helps musicians achieve their projected outcomes by attuning physical expression to musical content, it also visually communicates sound events to the audience (Godøy & Leman, 2010).

The relationship between movements and music is supported by the concept of embodied music cognition (Godøy & Leman, 2010; Leman, 2007), an extension of the embodied cognition framework (Lakoff & Johnson, 2003; Varela et al., 2016). These theories uphold that the body plays a crucial, if not indispensable, role in cognitive processing by acting as a mediator between the environment and the individual's experience. This hypothesis was validated by numerous studies demonstrating that repertoire features are reflected in performers' body movements. Increased motion behaviour

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has been linked to expressive locations (Buck et al., 2013; Davidson, 2007, 2012; Thompson & Luck, 2012), intentional phrasing targets (Desmet et al., 2012), and cadential resolutions (Buck et al., 2013; Chander et al., 2022; Juchniewicz, 2008; MacRitchie et al., 2013; Teixeira et al., 2014). Regarding specific musical features, consistent effects of musical phrasing on musicians' swaying have been reported (Demos et al., 2017); dynamics, harmonic transitions, and melodic phrasing have been associated with bell gestures (Teixeira et al., 2014); and accentuations have triggered impulsive, jerky movements (Dahl, 2004; Dahl et al., 2010; Rasamimanana & Bevilacqua, 2008). Massie-Laberge et al. (2019) discovered that repertoire with a wide range of dynamics and articulations allowed for more amplitude variations, whereas smooth dynamics and articulations, and slow rhythms promoted higher inter-performer variability, hence leading performers to express themselves in more individualised manners. In the rhythm domain, studies have also reported tempo-variant body behaviour (Coorevits et al., 2019), increased movement fluidity in slow tempo (Burger & Wöllner, 2023), and gesture repetition in similar rhythmical structures (Buck et al., 2013; MacRitchie et al., 2013; Wanderley et al., 2005). Furthermore, by developing analytical methodologies enabling the accommodation of musicians' knowledge (e.g. qualitative self-reports), researchers have also been able to correlate resultant music-related movements with *a-priori* interpretative intentions of the performers (Demos et al., 2017; Desmet et al., 2012; Thompson & Luck, 2012; Visi et al., 2020).

A heterogeneous range of motion measures has been used to analyse musicians' movements. While some refer to isolated gestures or body locations, e.g. angles of the knee (Moura et al., 2023) and hip (Haugen et al., 2023), head's distance travelled (Bishop et al., 2019; Massie-Laberge et al., 2019) or bell velocity (Teixeira et al., 2014), others represent global movement, like body sway estimations based on head markers (Chang et al., 2017, 2019) or full-body contraction indexes (Visi et al., 2020). Surprisingly, few studies used traditional postural control assessments based on the Center of Mass, CoM (Visi et al., 2020), Center of Gravity, CoG (Turner et al., 2021), or Center of Pressure, CoP (Demos et al., 2017). In fact, in a recent review focused on musicians' postural assessment during playing, only one out of 27 studies used CoP variables (Rousseau et al., 2023). In addition, we found one study comparing the CoP's postural sway of musicians and nonmusicians in a standing position, revealing postural misalignments in the musician group, most likely explained by instrument-specific playing postures (Nusseck & Spahn, 2020).

Music performance requires a constant, codependent interplay between gross and fine motor control systems. Gross control of the body, trunk, and arms provides the stabilisation needed to execute the fine finger movements required for sound production (Shan et al., 2018). Hence, studying dynamic full-body postural control can provide useful insights on how musicians interact with musical works and their instruments throughout a performance. Nonetheless, in-performance posture analysis remains understudied, as multiple studies adopt reductionist approaches directed to local movements, such as mechanical scale exercises (Mann et al., 2023), chords (Turner et al., 2023) or keystrokes (Goebl, 2017; Goebl et al., 2005). Turner et al. investigated the postural strategies of piano players by considering the mutual influence of trunk and hands (Turner et al., 2022), as well as CoG shifts and joint angles of the trunk, shoulders, elbow and wrists (Turner et al., 2021). In line with these authors (Turner et al., 2021, 2022), we recognise that although understanding the biomechanics of technical gestures is undoubtedly important, research can benefit from an art-centred approach – one that accounts for both mechanical efficiency and the expressive, embodied aspects of musical experience. Analysing performance as a full-body task, considering the interaction between gross and fine movements, through musical excerpts drawn from well-known repertoire enables researchers to preserve natural, expressive and context-dependent motor behaviours that are often constrained in purely biomechanical or decontextualised tasks. This integrated perspective supports a more holistic understanding of musical expertise and its translation into movement.

Few studies have examined how music features influence performers' postural sway. Existing research has primarily focused on how body sway relates to within-excerpt features such as musical phrasing (Broughton & Davidson, 2016; Davidson, 2012; Demos et al., 2017), togetherness (Chang et al., 2017), and group emotional intention (Chang et al., 2019), rather than on how specific musical parameters (e.g. tempo, rhythmic density) affect postural control during performance. To support this direction, findings from music listening research offer relevant context. Studies have shown that musical genre and pulse- and rhythm-related features influence spontaneous body sway during listening (e.g. pulse and rhythmical clarity induce increased sway and facilitate synchronisation, see Burger et al., 2010, 2013; Coste et al., 2018; González Sánchez et al., 2018). While some results remain challenging to interpret (e.g. tempo was not significant in Burger et al., 2013), the overall trend suggests that music can modulate motor behaviour, providing a rationale for investigating whether similar effects arise during active performance.

To address this research gap, we analysed saxophone players' dynamic postural sway during the performance of four musical excerpts varying in the level of rhythmical density, tempo, articulation, and technical difficulty. Nine postural control variables characterising CoM dynamics, commonly used in posturography, were examined to investigate oscillations in swaying space, velocity, and frequency with respect to the musical demands. The following hypotheses were constructed considering previous findings.

- H1
  Based on studies reporting musicians aligning their movements to the beat and rhythmical structures (Buck et al., 2013; Burger & Wöllner, 2023; Coorevits et al., 2019; MacRitchie et al., 2013; Wanderley et al., 2005), we predicted that sway velocity and frequency would be positively associated with rhythmical density (e.g. recurrent discrete rhythmical events promoting recurrent, faster sway) and tempo (e.g. slower music promoting slower, less frequent sway).
- H2
  Given that accents lead musicians to perform jerky movements (Dahl, 2004; Dahl et al., 2010; Rasamimanana & Bevilacqua, 2008), we predicted that shorter, faster swaying would emerge in music containing constant accents (*staccato* articulation).
- H3
  Technical difficulty leads performers to reduce motion amplitude and focus on sound-producing gestures (Massie-Laberge et al., 2019; Nusseck & Wanderley, 2009; Wanderley et al., 2005). Thus, we predicted that sway amplitude, velocity, and frequency would decrease in excerpts with increased technical demands (high rhythmical density and/ or *staccato* articulation).

Furthermore, to explore the potential functions underlying swaying patterns, we compared expressive performances to baseline immobile performances. Following previous literature (e.g. Davidson, 1993; Thompson & Luck, 2012), we predicted that expressive conditions reflected increased motion patterns when compared to immobile conditions. However, it has also been reported that musicians are unable to fully restrict their movements when playing immobile (Massie-Laberge et al., 2019; Wanderley et al., 2005). Therefore, considering that the postural control variables hereby studied were novel to musicians' motion research and provided detail down to the micromotion level, we adopted an analytical model allowing to compare the two conditions, postulating that, if differences emerged, they could reveal core postural control behaviours for technical execution. The effects of musical expertise (university students vs. professionals) and participants were also accounted for in the analysis.

2. Materials and methods

2.1. Participants

Twenty alto saxophone players (mean ± SD: age = 26.3 ± 5.4 years; body mass index = 22.8 ± 3.7 kg/m2; 9 female) were recruited via convenience sampling. To guarantee high levels of musical expertise, participants met the criteria of having a minimum of 10 years of regular saxophone practice (mean ± SD: 16.9 ± 5.6 years) and following higher education degrees in saxophone performance. As a result, 12 participants were professionals with established careers, and 8 were university students finishing bachelor's and master's degrees in saxophone performance. Additionally, participants reported not having any known musculoskeletal or neurological impairments. Before the data collection, participants were sent an informative participation document along with the informed consent, which they signed before starting the recording session. This study was approved by the Ethics Committee for Health of the Universidade Católica Portuguesa (CES-UCP) under protocol number 137/2021.

2.2. Apparatus

Data used in this study were reused from a larger existing database originally collected and described in Moura et al. (2022), which was developed for a qualitative observational analysis. In the present study, a subset of this dataset was analysed quantitatively to examine postural control variables. Motion data were recorded at 240 Hz using a Vicon optical motion capture system with nine T40S-NR18 infrared cameras. The marker position setup used included 67 retroreflective markers (58 in body landmarks and 9 in the saxophone, reported in detail in Table 1). Additionally, audio and video were recorded, respectively, with a Zoom H4N recorder and a Canon EOS 100D with an 18–55 mm lens.

2.3. Musical repertoire

The musical excerpts used in this study were: E1 and E2, respectively, bars 53–66 and 84–92 from Concerto in Eb Op. 109 by Glazunov (Glazunov&, 1936); E3, bars 21–35 from Rhapsodie by Debussy (Debussy, 1998; composed in 1903) and E4, bars 1–39 from the 3rd movement of Sonata Op. 19 by Creston (Creston, 1945). To select the excerpts, we conducted an *a-priori* survey of pieces included in international schools' curricula

Table 1. Anatomic landmarks for the skin and saxophone markers.

Head and Trunk	Upper Limb	Lower Limb	Saxophone
Vertex	Acromion: lateral border and posterior angle	Great trochanter	Mouthpiece
Pterion (R, L)	Humeral shaft[1,2]	Femoral shaft[1]	Neck (R, L)
Glabella	Epicondyle: lateral and medial	Femoral epicondyle:lateral and medial	Bottom point
Sternal notch	Forearm[1,2]	Tibial shaft[1]	Anterior body[1]
7th cervical vertebra	Ulna and radius: styloid process	Malleolus: lateral and medial	Bell (4 markers)
Scapula: superior and inferior angle (R, L)	2nd and 5th metacarpal: head	Posterior calcaneal tuberosity	
Iliac spine: posterior superior(R, L)		1st, 3rd, and 5th metatarsals: head	
Iliac crest: anterior-superior(R, L)			

Note: R, right; L, left.
[1] Midpoints.
[2] One marker on the right arm and two markers on the left.

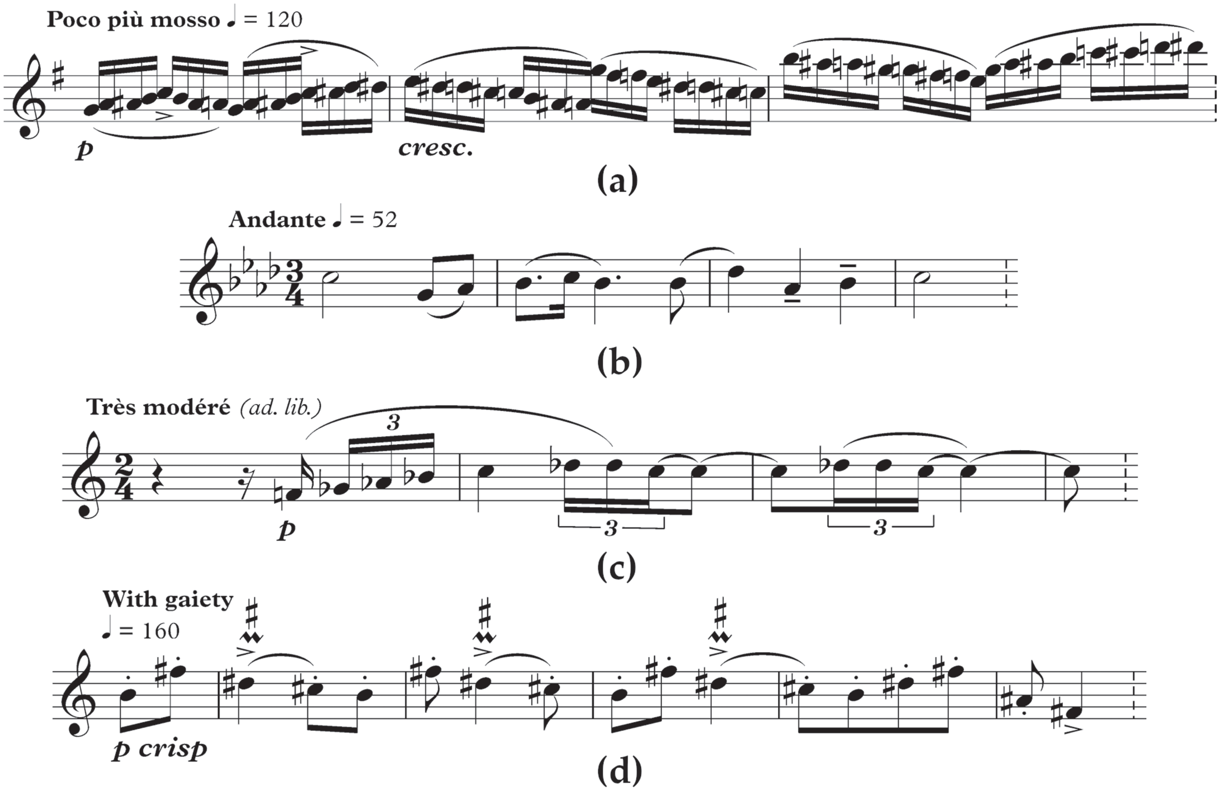

Figure 1. Illustrative fragments of the musical excerpts used in this study. Corresponding sound clips are added as supplementary files E1 … E4. (a) Excerpt 1 (E1); (b) Excerpt 2 (E2); (c) Excerpt 3 (E3); (d) Excerpt 4 (E4).

(e.g. ABRSM), saxophone competitions (e.g. Adolphe Sax Competition of Dinant), and technical bibliography (Ingham, 1998). The most cited pieces were analysed by two of the authors, who are specialised in Music (one PhD student in Music Science and one PhD in Music Psychology), to extract excerpts representing different technical requirements suited for this study. Illustrative fragments of the music are presented in Figure 1, and corresponding sound clips are added as supplementary material (E1 … E4). The description of the musical characteristics of the excerpts is presented in Table 2.

Table 2. Musical characteristics of the excerpts (E1 … E4) used in this study.

Musical Excerpt	Technical Difficulty	Rhythmical Density	Pulse Indication (bpm)	Articulation
E1	High	High	112–120	Legato
E2	Low	Low	52	Legato
E3	Low	Low	52–60	Legato
E4	High	High	160	Staccato, Accents

Given our goal of studying musicians' natural expressive behaviour, we chose to prioritise the use of fragments from standard saxophone repertoire rather than new fragments created for this purpose. First, this option ensured high levels of familiarity with the repertoire, allowing expert participants to employ reliable motor programmes consolidated for years of practice; second, the future applicability of our findings deemed more useful if studying emblematic pieces that are part of the learning process of most classical saxophone players. In our study, all participants confirmed they had already practiced (most even publicly presented) the pieces prior to the data collection. Participants received the scores of the musical fragments to perform one month before the recording date, ensuring everyone followed the same version.

2.4. *Experimental protocol*

Participants performed four musical excerpts, in a standing position, under two conditions (randomised order). Each condition was played once per excerpt without repetitions. In the immobile condition (IMO), participants were instructed to restrict to the minimal movements required for effective playing while still delivering a musically expressive interpretation, whereas in the expressive condition (EXP), participants were instructed to move freely, with no restrictions to expressive movement. Approximately 30 min prior to data collection, participants were allowed to warm up and practice any passages or conditions as they deemed necessary to familiarise themselves with the task demands. This dual paradigm, retrieved from previous studies in music-related movement (Broughton & Stevens, 2009; Davidson, 1993, 1994; Massie-Laberge et al., 2019; Thompson & Luck, 2012; Wanderley, 2002; Wanderley et al., 2005), allows for the identification of movements carrying expressive intentions of the performer by comparing them with the movements executed in the immobile baseline condition, which assume a technical function. For both conditions, participants were asked to remain within a 1 × 1 metre square marked on the floor, corresponding to the motion capture system calibrated volume. To facilitate score reading without interfering with the motion capture, a large screen was positioned in front of the participants but outside the calibrated area, where the musical scores were projected.

2.5. *Data processing*

Motion data was pre-processed in Qualisys Track Manager 2021.1 (QTM), including the steps of marker labelling, trajectory smoothing (10 Hz low-pass Butterworth filter) and gap-filling (polynomial interpolation). We used Visual 3D 2021.11.3 (C-Motion, USA) to calculate the CoM based on the positions of the 6 degrees-of-freedom body segments. The participants' initial positions were normalised by subtracting the CoM position mean in the first second of recording from the CoM position throughout the recordings, hence setting the initial position to zero in both the AP and ML directions. Then, we imported the CoM data into a custom MATLAB R2022a (MathWorks, USA) script to calculate the CoM's vertical projection on the ground (CoM_{proj}). This kinematic measure serves as an estimation of postural sway by capturing subtle body oscillations in the anterior-posterior (AP) and medial-lateral (ML) directions. The CoM designates the geographical central point of the body's mass and reflects whole-body movement coordination and balance control, providing us with insights into how participants regulated their posture and maintained stability during performance tasks. The CoP and CoM are interconnected: while the CoM is independent, the CoP follows the CoM's displacement by reflecting the ground reaction forces needed to maintain its balance (Duarte & Freitas, 2010).

The postural control variables were then computed following previous literature (Duarte & Freitas, 2010; Schubert et al., 2012). The CoM_{proj} variables used to analyse dynamic postural control were: anterior-posterior range (AP Range), mediolateral range (ML Range), anterior-posterior mean path velocity (AP Mean Velocity), mediolateral mean path velocity (ML Mean Velocity), total distance (Total Distance), Mean Velocity, 95% elliptical sway area (CoM_{proj} Area), anterior-posterior frequency at 95% of the power spectrum domain (AP Frequency 95) and mediolateral frequency at 95% of the power spectrum domain (ML Frequency 95). Table 3 presents a description of the postural control variables used.

2.6. *Statistical analysis*

Statistical analyses were conducted using R Studio (RStudio Team, 2020). Outcome variables were analysed using generalised linear-mixed effects models (GLMM) with a Gamma distribution, using the lme4 package, version 1.1-35.1 (Bates, Maechler, et al., 2015). One GLMM was performed for each variable. Identity link functions were selected, with the exception of CoM_{proj} Area, in which a logarithmic link function was deemed more parsimonious (Lo & Andrews, 2015). Alpha level for all tests was set at 0.05. Models were printed using the sjPlot package, version 2.8.16 (Lüdecke, 2024).

First, we created null models by introducing the independent variables movement condition (2 levels: Immobile, Expressive), rhythmical density (2 levels: Low, High), articulation (2 levels: Low, High), and musical expertise (2 levels: University Students, Professionals) as fixed effects. Participants were regarded as a random effect to account for potential effects of individual variability. This approach resulted in the following formula: response variable $\sim$ rhythmical density $*$ articulation $*$ movement condition $*$ expertise $+ (1 \mid \text{ID})$. Second, to

Table 3. Description of the postural control variables used in this study.

Variable	Abbreviation	Units	Dimensionality	Description
Range	AP Range ML Range	cm	1D (AP & ML)	Distance between the maximum and minimum CoM_{proj} displacement for each direction
Mean Path Velocity	AP Mean Velocity ML Mean Velocity	cm/s	1D (AP & ML)	Distance travelled by the CoM_{proj} divided by trial time, reflecting the speed of postural reactions while standing for each direction
	Mean Velocity		2D	Distance travelled by the CoM_{proj} divided by trial time, reflecting the speed of postural reactions while standing for AP and ML directions together
Total Distance	Total Distance	cm	2D	Length of CoM_{proj} trajectory on the base of support
95% Elliptical Sway Area	CoM_{proj} Area	cm^2	2D	Area of the CoM_{proj} movement on the base of support containing 95% of data points
Frequency	AP Frequency 95 ML Frequency 95	Hz	1D (AP & ML)	Frequency band that contains up to 95% of the power spectrum domain of the CoM_{proj} trace for each direction, representing the modifications on the postural control system

Note: AP, anterior-posterior; ML, mediolateral; cm, centimetres; s, seconds; Hz, Hertz.

improve model fit and better control for Type I error, we developed a maximal model adding the predictors as random slopes (Barr et al., 2013; Matuschek et al., 2017): response variable $\sim$ rhythmical density $*$ articulation $*$ movement condition $*$ expertise $+$ $(1 +$ rhythmical density $+$ articulation $+$ movement condition $+$ expertise $|$ ID$)$. Finally, to avoid overparameterisation, we performed a backward-selection approach (Bates, Kliegl, et al., 2015) by gradually removing non-significant predictors and respective random slopes. Maximal and post hoc simplified models were compared to select the better fitting option for each response variable (Table A1 of the Appendix).

To explore potential differences in performance durations between conditions, paired-sample t-tests were conducted for each excerpt with the tidyverse package (Wickham et al., 2019).

3. Results

3.1. Postural sway

All maximal models revealed significantly better model fit when compared to the null models (for all, $p < 0.001$, with exception of ML Frequency 95%, in which $p = 0.01$). When comparing maximal models to *post hoc* simplified models (by removing non-significant predictors), we found either no significant differences or decreased model fit (in AP and ML Range, $p < 0.001$). Detailed results of the model comparisons are reported in Table A1 of the Appendix.

Movement condition was a significant predictor for all postural variables except for AP and ML frequencies at 95%, indicating decreased ranges, distances, and velocities in IMO conditions when compared to EXP conditions.

Rhythmical density was a significant predictor for AP and ML Mean Velocities, Total Mean Velocity, Total Distance, and AP and ML Frequencies 95%. High rhythmical density, when compared to low rhythmical density, translated into increases in AP Mean Velocity (0.69 cm/s), ML Mean Velocity (1.18 cm/s), Total Mean Velocity (1.55 cm/s), Total Distance (37.84 cm), AP Frequency 95% (0.17 Hz) and ML Frequency 95% (0.27 Hz) (Figure 2). However, interaction effects with movement conditions revealed that this positive effect of high rhythmical density was attenuated under IMO conditions, resulting in decreases in AP Mean Velocity (−0.32 cm/s), Total Mean Velocity (−0.84 cm/s), and Total Distance (−22.45 cm), compared to EXP conditions. Therefore, while high rhythmical density generally promoted increased movement, this effect was diminished when participants were limited to technical movements.

Articulation was a significant predictor for ML Range, and AP and ML Mean Velocities, indicating decreases in *staccato* articulation conditions (respectively, −5.04 cm, −0.56 cm/s and −1.24 cm/s) when compared to *legato* articulation conditions (Figure 3). Nevertheless, in the interaction analysis, we found relative increases in ML Range (1.95 cm), AP Mean Velocity (0.36 cm/s), and Total Mean Velocity (0.86 cm/s) in combined *staccato* and IMO conditions, suggesting that *staccato* articulation promoted movement when participants were limited to technical motion.

Expertise level was a significant predictor for ML Frequency 95%, indicating increased frequency (0.1 Hz) in professional saxophone players when compared to university students. Additional interaction effects revealed that professional saxophone players decreased AP mean velocity (−0.44 cm/s) in high rhythmical density conditions.

The detailed results of all GLMM models are presented in Table 4.

Table 4. Generalised linear mixed model analyses for each postural sway variable, including fixed effects (movement condition, rhythmical density, articulation, expertise level) and random effects (ID).

Dependent Variable	Effects	Coefficient	SE	95% CI	*t*	R^2_m	R^2_c
AP Range (cm)	Intercept	**7.09*****	1.07	4.97 – 9.21	6.62	0.65	0.99
	Movement Condition: IMO	**−2.94****	1.02	−3.74 – −1.42	−2.90		
	Expertise Level: Professional	0.04	1.40	−2.72 – 2.80	0.03		
	Rhythmical Density: High	0.82	0.79	−0.73 – 2.38	1.05		
	Articulation: Staccato	−1.23	1.04	−3.29 – 0.84	−1.18		
	Random Effect: ID (variance components)^{a}	3.07	1.75	ICC = 0.98			
ML Range (cm)	Intercept	**19.42*****	1.88	15.70–23.13	10.33	0.74	1
	Movement Condition: IMO	**−8.28*****	1.09	−10.44 – −6.12	−7.58		
	Expertise Level: Professional	0.13	1.69	−3.21 – 3.46	0.08		
	Rhythmical Density: High	1.42	1.66	−5.22 – 0.38	−1.71		
	Articulation: Staccato	**−5.04****	1.91	−8.82 – −1.27	−2.64		
	Articulation: Staccato X Movement Condition: Immobile	**1.95***	0.92	0.13 – 3.77	2.11		
	Random Effect: ID (variance components)^{a}	17.58	4.19	ICC = 0.99			
AP Mean Velocity (cm/s)	Intercept	**1.24*****	0.16	0.93–1.54	7.95	0.84	0.98
	Movement Condition: IMO	**−0.60****	0.19	−0.97 – −0.23	−3.23		
	Expertise Level: Professional	0.05	0.22	−0.38–0.48	0.25		
	Rhythmical Density: High	**0.69*****	0.18	0.33–1.05	3.76		
	Articulation: Staccato	**−0.56****	0.18	−0.92 – −0.21	−3.16		
	Rhythmical Density: High X Movement Condition: Immobile	**−0.32****	0.12	−0.56 – −0.08	−2.67		
	Articulation: Staccato X Movement Condition: Immobile	**0.36****	0.13	0.11–0.61	2.83		
	Rhythmical Density: High X Expertise Level: Professional	**−0.44***	0.22	−0.88 – −0.01	−2.03		
	Random Effect: ID (variance components)^{a}	0.05	0.23	ICC = 0.87			
ML Mean Velocity (cm/s)	Intercept	**3.28*****	0.51	2.27–4.30	6.39	0.76	0.97
	Movement Condition: IMO	**−1.85*****	0.43	−2.69 – −1.00	−4.31		
	Expertise Level: Professional	0.51	0.64	−0.76–1.78	0.80		
	Rhythmical Density: High	**1.18***	0.47	0.25–2.11	2.52		
	Articulation: Staccato	**−1.24***	0.62	−2.46 – −0.02	−2.01		
	Random Effect: ID (variance components)^{a}	0.81	0.90	ICC = 0.88			
Total Distance (cm)	Intercept	**108.85*****	15.13	78.92–138.78	7.19	0.79	1
	Movement Condition: IMO	**−56.31*****	12.27	−80.58 – −32.03	−4.59		
	Expertise Level: Professional	11.88	19.09	−25.87–49.63	0.62		
	Rhythmical Density: High	**37.84****	11.77	14.55–61.12	3.22		
	Articulation: Staccato	−16.05	15.77	−47.24–15.15	−1.02		
	Rhythmical Density: High X Movement Condition: Immobile	**−22.45***	10.06	−42.35 – −2.54	−2.23		
	Random Effect: ID (variance components)^{a}	650.20	25.50	ICC = 1.00			
Total Mean Velocity (cm/s)	Intercept	**3.56*****	0.44	2.70–4.42	8.19	0.79	0.98
	Movement Condition: IMO	**−1.86*****	0.48	−2.82 – −3.86	−6.85		
	Expertise Level: Professional	0.70	0.64	−0.57–1.10	0.82		
	Rhythmical Density: High	**1.55****	0.48	0.60–2.50	3.22		
	Articulation: Staccato	−1.20	0.61	−2.42–0.01	−1.96		
	Rhythmical Density: High X Movement Condition: Immobile	−**0.84***	0.40	−1.62 – −0.05	−2.10		
	Articulation: Staccato X Movement Condition: Immobile	**0.86***	0.44	0.00–1.72	1.98		
	Random Effect: ID (variance components)^{a}	0.45	0.67	ICC = 0.91			
CoM_{proj} Area (cm^2)	Intercept	**79.47*****	0.28	45.27–139.53	15.37	0.54	0.77
	Movement Condition: IMO	**0.35*****	0.26	0.21–0.58	−4.10		
	Expertise Level: Professional	0.83	0.37	0.40–1.72	−0.51		
	Rhythmical Density: High	0.80	0.23	0.51–1.25	−1.00		
	Articulation: Staccato	0.75	0.27	0.44–1.28	−1.07		
	Random Effect: ID (variance components)^{a}	0.31	0.56	ICC = 0.50			
AP Frequency 95% (Hz)	Intercept	**0.39*****	0.03	0.33–0.45	12.76	0.10	0.21
	Movement Condition: IMO	0.01	0.02	−0.03–0.04	0.32		
	Expertise Level: Professional	0.07	0.04	−0.01–0.16	1.70		
	Rhythmical Density: High	**0.17****	0.06	0.05–0.29	2.81		
	Articulation: Staccato	−0.04	0.04	−0.12–0.04	−0.91		
	Random Effect: ID (variance components)^{a}	0.002	0.05	ICC = 0.12			

(*continued*).

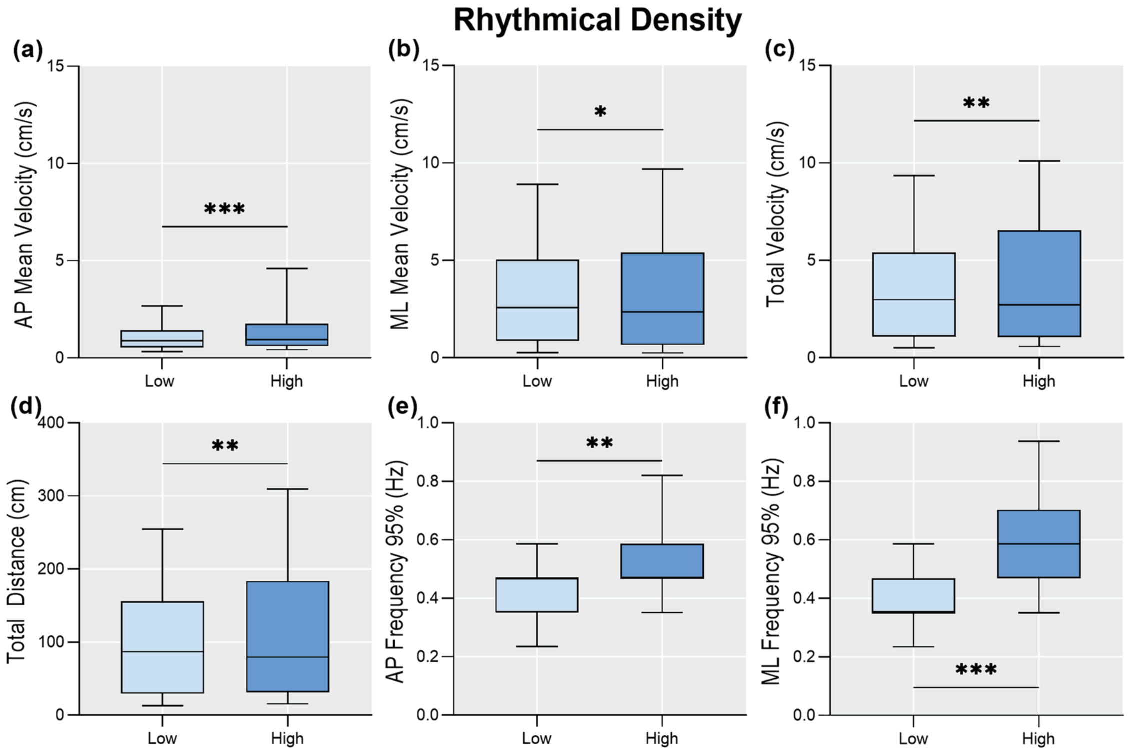

Figure 2. Boxplots representing significant predictors related to rhythmical density (median with 95% confidence interval). (a) AP Mean Velocity, (b) ML Mean Velocity, (c) Total Mean Velocity, (d) Total Distance, (e) AP Mean Frequency at 95%, and (f) ML Mean Frequency at 95%.

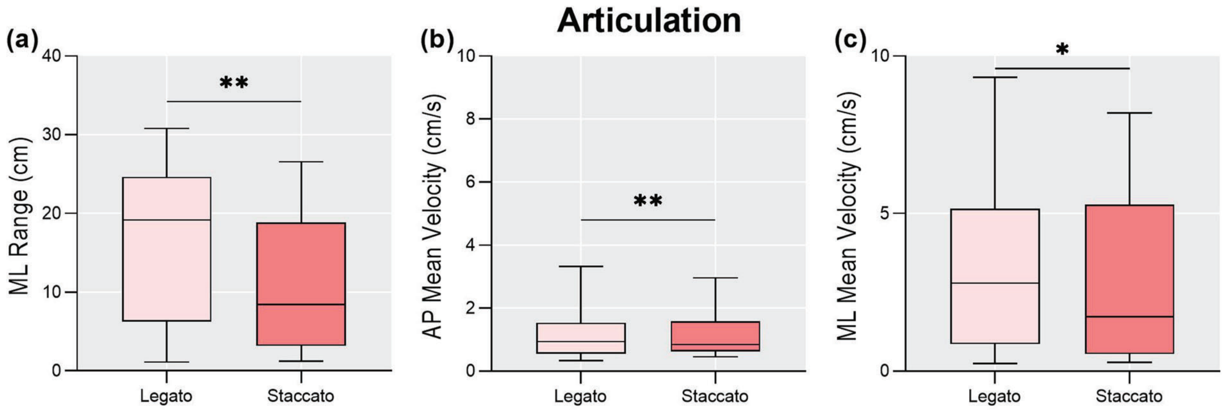

Figure 3. Boxplots representing significant predictors related to articulation (median with 95% confidence interval). (a) ML Range, (b) AP Mean Velocity, and (c) Total Mean Velocity.

Table 4. Continued

Dependent Variable	Effects	Coefficient	SE	95% CI	t	$R^2{}_m$	$R^2{}_c$
ML Frequency 95% (Hz)	Intercept	**0.34*****	0.03	0.29–0.39	12.955	0.18	0.26
	Movement Condition: IMO	0.00	0.02	−0.04–0.03	−0.19		
	Expertise Level: Professional	**0.10***	0.04	0.01–0.19	2.28		
	Rhythmical Density: High	**0.27*****	0.06	0.14–0.39	4.21		
	Articulation: Staccato	0.02	0.05	−0.07–0.11	0.44		
	Random Effect: ID (variance components)[a]	0.001	0.04	ICC = 0.09			

Notes: CoM_{proj}, vertical projection of the Centre of Mass on the ground; AP, antero-posterior; ML, mediolateral; cm, centimetres; s, seconds; Hz, Hertz; SE, standard error; CI, confidence interval; ICC, intraclass correlation coefficient; $R^2{}_m$, marginal R squared; $R^2{}_c$, conditional R squared. Coefficients, standard errors, and 95% confidence intervals are reported in the variables' units. Significance levels are reported as follows: $p < 0.001$***, $p < 0.001$**, $p < 0.01$*.

3.2. Performance duration

When comparing performance durations between movement conditions, we found that IMO was longer than EXP, with significant differences for three out of the four excerpts. Respectively: for E1, M = 27.77 s, M = 27.31 s, $t(19) = 2.73, p = 0.013$; for E2, M = 28.69 s, M = 27.90 s, $t(19) = 4.70$, $p < 0.001$; for E3, M = 29.77 s, M = 29.07 s, $t(19) = 2.67$, $p = 0.015$; and for E4, no significant difference emerged, $t(19) = 1.48$, $p = 0.157$, though durations were still slightly longer in IMO (M = 31.94 s) than in EXP (M = 31.65 s).

4. Discussion

This study investigated the effects of musical features on the dynamic postural sway of experienced saxophone players during performance. To better understand the potential functions underlying postural patterns, performances were compared in two conditions: an expressive condition in which participants moved freely, and a baseline immobile condition in which participants were limited to essential technical movements.

Rhythmical density and tempo were significant predictors of sway velocity, total distance, and frequency, revealing a positive effect on these postural measures, as we predicted in our Hypothesis 1 (H1). Musicians move according to rhythmical structures, e.g. consistently repeating similar gestures when playing identical rhythmical material (Buck et al., 2013; MacRitchie et al., 2013; Wanderley et al., 2005). Our findings are consistent with those of Moura et al. (2023), who found that saxophone players exhibited more frequent knee flexion, albeit with reduced amplitude, in sections of increased rhythmical density. Regarding how tempo changes influence performers' movements, Coorevits et al. (2019) found that piano and violin players' head and wrist movements showed lower periodicities at faster tempos (84–114 bpm) and higher periodicities at slower tempos (24–50 bpm). Although the fundamental metrical levels were present in the movements of both tempos, the slower tempo led participants to further subdivide these macrometrical structures into smaller units, hence the observed higher periodicities. In contrast to the latter, our results showed that the sway periodicity increased as the tempo did. This can be attributed to the fact that we analysed the postural sway, whereas the authors focused on local, technical gestures. Wrist and head movements have a direct impact on sound production and should be regulated to ensure proficient playing, particularly in contexts of fast tempo requiring fast movements. Swaying, on the other hand, is a common natural ancillary behaviour among musicians associated with entrainment, communication, and expressiveness (Broughton & Davidson, 2016; Chang et al., 2019; Demos & Chaffin, 2018; Grady & Gilliam, 2020). In research investigating listeners' natural motor responses, easily perceivable pulses and rhythmical structures tend to generate increased movement patterns. Beat clarity and percussive rhythms encourage participants to engage in whole-body movement, perform a wider range of gestures (Burger et al., 2013), and increase acceleration in multiple body parts (Burger & Toiviainen, 2018, 2020). Moreover, music with high event density (e.g. energetic rhythm) significantly affects head sway (González Sánchez et al., 2020) and facilitates beat synchronisation, particularly in low frequency ranges (Burger et al., 2010). These results align with ours, especially considering that the musicians' sway, carrying an expressive, often involuntary nature, is indeed closer to listeners' free movement than to the focal movements studied by Coorevits et al. (2019). Additionally, because humans share an innate habit of moving to the beat (Buhmann et al., 2016, 2018; Repp & Su, 2013; Rose et al., 2021; Spiech et al., 2023), it is logical that our participants adapted their movement frequencies to the tempo of the music.

Articulation was a significant predictor of sway ML range and velocity, showing a negative effect in *staccato* conditions when compared to *legato* conditions. On the one hand, this finding aligns with our H2, as we predicted decreased motion amplitude in *staccato* conditions. We also expected, however, faster swaying in this condition, which was not confirmed. While *legato* technique involves playing multiple notes within the same air flow without interruptions, *staccato* technique involves separating each note with tongue movements within the same air flow, manipulating mouth pressure and the vocal tract (Hofmann & Goebl, 2014; Pàmies-Vilà et al., 2017, 2018; Slis et al., 2021). Therefore, tonguing, as a fine motor action demanding increased attentional processing and balance control, may lead to constraints in sway velocity and range. Humans minimise sway amplitude while performing secondary tasks to improve supra-postural task performance and maintain postural control (Shumway-Cook & Woollacott, 2012). On the other hand, motor activity in the stomatognathic motor system, such as chewing or tongue activity, can influence balance and posture (Alghadir et al., 2015; Hellmann et al., 2011, 2015; Julià-Sánchez et al., 2020). Specifically, Hellmann et al. (2011) reported a reduction in AP sway in controlled biting tasks in upright stance, which is congruent with our findings.

Regarding the functional nature of swaying patterns, in our H3, we predicted that as technical difficulty increased (high rhythmical density and/or *staccato* articulation), sway amplitude, velocity, and frequency would decrease. Two novel results emerged from our analysis in this regard. First, in IMO conditions, *staccato* resulted in relative increases in ML range, AP and total mean velocity, indicating that even when participants were focusing on technical movements, they increased their sway amplitude and velocity to perform tonguing tasks. This likely reflects the essential subtle postural adjustments required to support tonguing, suggesting that certain technical demands can elicit compensatory whole-body movement, even in constrained performance contexts. Furthermore, from a musical expression perspective, this is consistent with research demonstrating that musicians perform jerky movements when playing accents (Dahl, 2004; Dahl et al., 2010; Rasamimanana & Bevilacqua, 2008). Second, AP and ML Frequency 95% were the only postural variables not predicted by movement condition, suggesting that the performers' expressive intentions have no significant impact on the rate of change in posture over time. Both results can be interpreted in two ways: either they represent core technical behaviours, essential for effective technical playing, or they are so ingrained in the performative habits of skilled musicians that they are unable to constrain them, even when instructed to. Experienced musicians develop motor programmes that become automatised after years of repetitive practice (Davidson & Broughton, 2022; Ericsson et al., 1993; Jäncke, 2006; Rosenbaum, 2009). These motor programmes are replicated across performances by the same musician and accommodate both technical and expressive movements (Davidson & Correia, 2002; Jäncke, 2006; Lehmann et al., 2007; Rosenbaum, 2009; Wanderley et al., 2005). Supporting the idea of unintentional music-related movement, Moura et al. (2023) found that saxophone players micro-flexed their knees more frequently when playing statically than when playing expressively. Other studies have found that music can induce micromotion patterns in listeners trying to standstill (González Sánchez et al., 2018; Jensenius et al., 2017; Ross et al., 2016). Listening to certain music types can even improve postural balance (Carrick et al., 2007; De Bartolo et al., 2020; Forti et al., 2010; Waer et al., 2023, 2024). Based on our data, it is difficult to determine whether the relative increases in *staccato* IMO conditions and steady frequency rates between movement conditions relate to postural control, musical feel, or both.

Additionally, we found that the increase in sway associated with high rhythmical density was smaller in IMO conditions, suggesting that even under movement constraints, rhythmical density continued to encourage movement, though to a lesser extent than in EXP conditions (as predicted in H1). In this sense, we were unable to associate the increased technical difficulty introduced by high rhythmical density with reductions in postural sway variables (H3). However, this also highlights a limitation of our design: because participants were explicitly instructed to minimise movement in the IMO condition, the scope for detecting further decreases in sway was inherently limited.

Regarding expertise effects, we observed limited but noteworthy differences between professional and university students. Professionals exhibited slightly higher ML sway frequency overall, and, in high rhythmical density contexts, a smaller increase in AP mean velocity, corresponding to a more restrained sway response. Although these effects may point to subtle expertise-related differences in postural control, they may have been mitigated by the relatively comparable and advanced expertise levels of the two groups. Future research could benefit from examining a broader range of learning stages to better elucidate how postural control evolves with expertise.

One additional finding was that music mostly had a significant effect on time-related measures of postural sway (AP and ML Frequency 95%, AP Mean Velocity, and Mean Velocity) rather than space-related ones (e.g. AP Range, CoM_{proj} Area). This finding is particularly interesting considering that music is inherently an art of time: a musical work unfolds in time, requires time for presentation, and designates a temporal frame (Alperson, 1980; Morgan, 1980). The same cannot be said for, say, a painting. Furthermore, time is a major formal element of music, establishing a metrical framework with units of time (e.g. tempo, signatures), on top of which more complex rhythmical structures develop (e.g. tones with differing durations building a melody) (Parncutt, 1994). In fact, these considerations have led researchers to focus mostly on velocity and acceleration as descriptors of musicians' and listeners' music-related movements (Bishop et al., 2021; González Sánchez et al., 2018; Kozak, 2019; Ley-Flores et al., 2022). In this sense, it is plausible that time-related postural measures, such as velocity and frequency, are better predicted by the music being played than by the spatial ones, given that they relate to events with an analogous meaning in the sound domain. Supporting this interpretation, we also found that performance durations were longer in the IMO condition, suggesting that movement constraints may have interacted with musicians' internal timing mechanisms. This aligns with the view that body movement supports timing through sensorimotor coupling, allowing performers to align actions with auditory feedback and to reduce reliance on cognitive time estimation (Maes, 2016; Ross & Balasubramaniam, 2022). Music embodiment facilitates multisensory integration by linking motor programmes with predicted sensory outcomes, effectively grounding musical timing in dynamic body-based processes (Dell'Anna et al., 2021; Lee & Noppeney, 2011).

In contrast, limiting movement may disrupt this embodied scaffolding, leading to reduced timing fluency and expressive control. Recent research on the neural underpinnings of musical embodiment shows that multisensory integration can enhance both emotional engagement and motor control during music performance tasks, as reflected in more streamlined brain dynamics (Moura et al., 2023; Vidal et al., 2023, 2025).

The present study is, to our knowledge, the first to analyse how diverse musical features influence musicians' postural sway during performance using CoM_{proj}-derived variables commonly applied in traditional static postural assessments. As an emergent field of study, music performance biomechanics lacks homogenisation of analytical routines. Adopting methods that have been widely validated in biomechanics can help systematise music research and bring it closer to other fields studying human motor behaviour. Furthermore, considering the critical stabilisation role of gross motor control in performing (Shan et al., 2018) and the coupling of technical and expressive intentions in the full-body task of music playing (Turner et al., 2021, 2022), a thorough understanding of musicians' postural sway can have great implications for music performance enhancement. Our study provides novel insights regarding the potential technique-facilitating role of sway behaviours associated with specific musical contexts. Nevertheless, one limitation of this study is that, because it was designed to identify and analyse sway patterns, we did not anticipate the need to implement additional methods to assess the nature of our results. We encourage further research to pursue this question. For example, by testing the impact of such behaviours on instrumental performance, or by comparing instrumentalists at different learning and/or professional stages, researchers can further explain if these patterns improve saxophone performance at a technical level. We also acknowledge that, while the order of musical excerpts was randomised to reduce fatigue and expectation effects, a full counterbalancing design was not implemented. Given the sample size, this may have introduced residual order effects, which should be addressed in future work. Furthermore, we encourage future studies to incorporate more extensive audio analyses to deepen the understanding of how expressive sound qualities interact with motor behaviours.

Research demonstrates that the effects of instrument-specific playing techniques can explain postural differences between instrumentalists (Nusseck & Spahn, 2020). Here, we focused on characterising the postural behaviour of saxophone players. Nevertheless, this research should also be expanded to include other instruments as well as a variety of musical excerpts and genres. We highlight the significance of including characteristic repertoire that is familiar to the musicians to encourage natural expressive behaviour, to the extent possible within a laboratory context. In this sense, although challenging, future directions include implementing data collection setups that allow for in-stage recording in the presence of an audience.

5. Conclusions

This study investigated the effects of musical features and movement expression on the postural sway of elite saxophone players during performance. Rhythm and articulation features significantly influenced postural measurements. Sway distance, frequency, and velocity presented a positive relationship with musical tempo and rhythmical density. Sway mediolateral range and velocity presented a negative relationship with repetitive tonguing technique. Furthermore, when focusing on technical motion, musicians showed relative increases in mediolateral range and velocity in *staccato* passages, suggesting compensatory postural adjustments even when movement was constrained. Sway frequency, unlike other measurements, was not predicted by movement condition, suggesting that it is not influenced by performers' expressive intentions, and possibly constitutes an unconscious, potentially facilitative motor response. Additionally, performance durations were longer when movement was restricted, indicating that body movement related to temporal regulation during musical execution.

The resulting knowledge provides a foundational contribution to the understudied field of motor control in instrumental performance and pedagogy. The postural sway patterns observed offer valuable directions for future research aimed at enhancing body awareness and movement efficiency in musicians, with the ultimate goal of improving performance quality. Such insights may eventually inform pedagogical strategies and the development of monitoring tools to support distance learning and self-regulation across different levels of expertise. Second, these results help understand the processes underpinning multisensory integration and how musical content is translated into an embodied manifestation. If music can regulate swaying characteristics and induce involuntary movement, it is certainly a powerful resource in clinical, rehabilitative, and educational contexts.

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Appendix

Table A1. Summary of comparisons between GLMMs, showing whether the maximal and post hoc simplified approaches changed the fit of the model compared to the previous model.

	Model Comparison	AIC	Log-likelihood	Deviance	χ^2	D*f*	*p*
AP Range (cm)	Null	791.24	−381.62	763.24			
	Maximal(VS Null)	724.30	−334.15	668.30	94.93	14	< **0.001**
	Simplified(VS Maximal)	776.26	−384.13	768.26	99.96	24	< **0.001**
ML Range (cm)	Null	1056.43	−519.21	1038.43			
	Maximal(VS Null)	977.75	−470.88	941.75	96.68	9	< **0.001**
	Simplified(VS Maximal)	1061.58	−524.79	1049.58	107.83	12	< **0.001**
AP Mean Velocity (cm/s)	Null	214.68	−93.34	186.68			
	Maximal(VS Null)	126.62	−35.31	70.63	116.05	14	< **0.001**
	Simplified	Not applicable: all predictors were significant in maximal.					
ML Mean Velocity (cm/s)	Null	533.15	−252.58	505.15			
	Maximal(VS Null)	487.55	−220.77	441.55	63.61	9	< **0.001**
	Simplified(VS Maximal)	479.30	−222.65	445.30	3.75	1	0.71
Total Distance (cm)	Null	1623.4	−797.71	1595.4			
	Maximal(VS Null)	1577.7	−760.83	1521.7	73.62	14	< **0.001**
	Simplified(VS Maximal)	1571.5	−768.75	1537.5	15.85	11	0.14
Total Mean Velocity (cm/s)	Null	550.30	−261.15	522.30			
	Maximal(VS Null)	501.25	−222.62	445.25	77.05	14	< **0.001**
	Simplified(VS Maximal)	487.94	−226.97	453.94	8.69	11	0.65
CoM_{proj} Area (cm^2)	Null	1725.0	−848.50	1697.0			
	Maximal(VS Null)	1686.0	−826.97	1654.0	43.04	2	< **0.001**
	Simplified(VS Maximal)	1723.4	−857.70	1715.4	61.46	12	< **0.001**
AP Frequency 95% (Hz)	Null	−231.99	130.00	−259.99			
	Maximal(VS Null)	−257.19	156.59	−313.19	53.19	14	< **0.001**
	Simplified(VS Maximal)	−270.51	141.25	−282.51	30.68	22	0.1
ML Frequency 95% (Hz)	Null	−180.67	104.33	−208.67			
	Maximal(VS Null)	−185.57	115.78	−231.57	22.9	9	**0.01**
	Simplified(VS Maximal)	−204.60	110.30	−220.60	10.96	15	0.75