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Association Between Interoceptive Accuracy and Pain Perception: Insights From Trained Musicians and Athletes

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ABSTRACT

Background: The integration of concurrent endogenous and exogenous multisensory information throughout years of dedicated sensorimotor training is associated with enhanced interoceptive accuracy and altered pain perception in healthy individuals. However, this relationship remains inconclusive, with outcomes varying by training modality and pain stimulus. This study examines associations between distinct forms of sensorimotor training, interoception and pain perception.

Methods: Two groups of individuals performing extensive sensorimotor training, 17 musicians and 15 athletes, and 14 non-musicians/athletes were recruited. Participants completed a cardiac interoceptive accuracy (IAcc) task and quantitative sensory tests, including mechanical and electrical detection thresholds (MDTs and EDTs), pressure and heat pain thresholds (PPTs and HPTs), as well as music-related perceptual discrimination and self-reported physical activity assessments.

Results: Results revealed superior IAcc and PPTs in athletes compared to controls. Musicians exhibited increased heat pain sensitivity. While IAcc in musicians did not reach significance, training duration significantly predicted IAcc across both groups. PPTs correlated positively with both IAcc and accumulated training, but mediation analyses revealed that training effects on PPTs occurred independently of IAcc, suggesting distinct pathways for interoception and pain modulation. Additionally, physical activity levels correlated positively with both IAcc and PPTs across participants.

Conclusions: These findings support the emerging view that individuals engaging in sensorimotor training routines, which require embodied multisensory integration for optimal performance, enhance interoceptive accuracy. They also confirm that pain processing varies by training modality. Furthermore, they suggest that the type of acute pain stimulus may explain inconsistencies in the interoception–pain relationship in healthy populations.

Significance Statement: This study advances our understanding of the interoception–pain-training nexus by revealing two distinct pathways: one linking sensorimotor training, interoceptive accuracy and pressure pain perception and another showing that accumulated sensorimotor training independently elevates pain thresholds. By differentiating between pain modalities, the findings contribute to resolving previous contradictory results, refine our insights into interoception in healthy populations and inform about potential clinical interventions.

1 | Introduction

Sensorimotor training, like musical and physical activity, involves the integration of multiple exteroceptive cues (visual, tactile, acoustic) with ongoing internal bodily signals (proprioception, visceral) to optimise performance (Lee and Noppeney 2011; Petzschner et al. 2021). This multisensory experience has been associated with enhanced cardiovascular interoception (Ceunen et al. 2016; Schirmer-Mokwa et al. 2015; Wallman-Jones et al. 2021) and pain perception to pressure, thermal or electrical stimulation (Zamorano et al. 2015; Zamorano, Kleber, Arguissain, Vuust, et al. 2023). However, the relationship between sensorimotor training, interoception and pain processing remains unclear, highlighting the need to disentangle their contributions to pain modulation.

Interoception is the ability to perceive internal body conditions, like cardiovascular responses and sensations arising from connective tissue and muscles (Craig 2002). While muscle sensations contribute to proprioception, they are also considered a form of interoception (Ceunen et al. 2016; Chen et al. 2021). Pain, defined as an unpleasant sensory and emotional experience associated with actual or potential tissue damage (Raja et al. 2020), is strongly associated with interoceptive processes via shared neuroanatomical pathways (Craig 2002). Lower interoception accompanies chronic pain states (Di Lernia et al. 2016), while increased interoception correlates with decreased pain thresholds and tolerance in pain-free subjects (Pollatos et al. 2012). However, different experimental pain paradigms have yielded contradictory results, indicating a more complex relationship between interoception and pain perception in healthy populations (Di Lernia et al. 2016).

Extensive sensorimotor training in expert musicians and endurance athletes is associated with distinct adaptations in interoception and pain processing. Musicians engage in fine-motor tasks aimed at emotional expression and precision, which enhance cardiac interoceptive accuracy (IAcc) and heart-evoked brain responses (Hina et al. 2020; Schirmer-Mokwa et al. 2015). These adaptations extend to pain processing, with expert musicians showing increased perception of phasic pain (Zamorano et al. 2015; Zamorano, Kleber, Arguissain, Vuust, et al. 2023). In contrast, endurance athletes engage in cardiovascular and gross motor training, emphasising prolonged high-intensity activity and proprioceptive feedback, which research links to higher pain tolerance, lower pain ratings and distinct neural responses to noxious stimuli (Assa et al. 2019; Geisler et al. 2021; Pettersen et al. 2020; Tesarz et al. 2012). Regular high-intensity physical exercise thus improves pain tolerance, cardiac IAcc and top-down predictive processes (Wallman-Jones et al. 2021), which aids exercise-fatigue prediction (McMorris et al. 2018).

This study examines how distinct sensorimotor regimens affect interoception and pain perception in athletes and musicians versus non-trained controls, while also exploring their mediating relationships. We hypothesise that (i) trained groups will exhibit superior IAcc, reflecting heightened bodily awareness across training modalities. (ii) Musicians will have lower pain thresholds and higher pain intensity ratings, reflecting enhanced sensitivity, while athletes will show the opposite, reflecting training-induced pain tolerance. By investigating the interactions between training, IAcc and pain, we further hypothesise that (iii) longer training experience enhances IAcc and increases pain thresholds, and (iv) IAcc will correlate more strongly with PPTs than thermal pain thresholds, reflecting interoceptive pathways linked to muscular and proprioceptive signals. Lastly, we expect physical activity to enhance IAcc and pain processing beyond training-specific effects.

2 | Methods

2.1 | Participants

This study comprised three participant groups: professional classical musicians, semi-professional athletes and non-musician/non-athlete individuals. The third group, non-musicians/non-athletes, served as a control, having no regular exercise routines nor any experience playing a musical instrument (see Section 3 for details). Eligibility criteria for the musicians group required training at classical music conservatories and ongoing involvement in musical practice and performance. For the semi-professional athlete group, active endurance training in federal sports clubs and regular participation in local or national competitions were necessary. These criteria ensured the selection of individuals demonstrating a high level of commitment and engagement in their respective fields.

The exclusion criteria for all participants were any history of neurological, cardiorespiratory or mental disorders and pregnancy. A minimum sample size of 45 participants was determined based on prior research on interoceptive accuracy in specialised participants (Christensen et al. 2017; Schirmer-Mokwa et al. 2015), targeting an 80% power to detect at least a medium effect size (Cohen's $d \geq 0.6$) on IAcc with an independent t-test analysis at an alpha level of 0.05. A total of 46 participants were ultimately recruited for the study. At the time of recruitment, all participants were verbally informed about the details of the study and provided written consent, in accordance with the Declaration of Helsinki (1991). The study was performed in laboratory facilities of the Research Institute of Health Sciences (IUNICS) at the University of the Balearic Islands (UIB) and approved by the Local Ethics Committee (PSI2015-66295-R).

2.2 | Measuring Interoceptive Accuracy

We measured cardiac IAcc with a heartbeat counting task (Schandry 1981). The IAcc assessments were conducted while participants were seated in a relaxed position, with legs uncrossed and arms placed over the chair. This positioning was implemented to prevent any contact between the arms or legs with the rest of the body, while participants silently counted their own heartbeats across three intervals—25, 35 and 45 s. To avoid any order effects, the sequence of the time intervals was counterbalanced among participants, who were not informed about the exact durations.

We guided participants with the following instructions: 'Without checking your pulse manually, silently count each heartbeat you feel within your body from the moment you hear 'start' until you hear 'stop'. Focus on the heartbeats you feel without estimating your pulse from memory'. Throughout the heartbeat counting task, we captured Electrocardiogram (ECG) signals continuously via the Biopac amplifier and software (MP150; Biopac Systems Inc., Goleta, CA). Self-adhesive electrodes, arranged in a three-lead montage, were affixed to participants' thoraxes—two electrodes positioned on the left and right upper chest, and one 2 cm below the left lower rib. From the R-peaks in the ECG signal, we determined the actual number of heartbeats ($n\text{beats}_{\text{real}}$). Additionally, we calculated and compared the average heart rate across all groups using all heartbeat counting conditions (25, 35 and 45 s).

We calculated an IAcc score for each participant during each time interval using the following formula (Garfinkel et al. 2015):

$$1 - \left(n\text{beats}_{\text{real}} - n\text{beats}_{\text{reported}}\right) / \left(\left(n\text{beats}_{\text{real}} + n\text{beats}_{\text{reported}}\right) / 2\right)$$

These scores were then averaged across the three trials to obtain a single IAcc score per participant. Including the reported heartbeat counts ($n\text{beats}_{\text{reported}}$) in the denominator serves to mitigate the influence of large variations in reported counts, thereby improving the stability of the accuracy estimate. This approach helps control for over- and underestimation tendencies, reducing variability in individual accuracy scores while ensuring a more reliable measure of interoceptive ability. Alternative methods exist for calculating IAcc, but this approach is widely used in interoception research for its robustness against individual reporting biases.

2.3 | Quantitative Sensory Testing

A set of pressure and heat pain thresholds were performed on the pad of the middle finger on the right hand to avoid the calluses on the musicians' fingertips, and to minimise variability arising from handedness and instrument-specific somatosensory adaptations, as prior studies have shown that handedness and instrument training influence tactile and pain sensitivity (Zamorano et al. 2015; Elbert et al. 1995). Additionally, to control for potential confounding factors related to enhanced tactile perception, we included assessments of mechanical and electrical detection thresholds. These assessments were performed to ensure that any observed relationships between training type, IAcc and pain were not influenced by differences in tactile sensory processing abilities across the groups.

Mechanical detection thresholds (MDT) were measured following the recommendations of the German Research Network on Neuropathic Pain (Rolke 2006). MDT were measured using a set of von Frey monofilaments (Somedic Sales AB, Hörby Sweden) featuring 17 nylon hairs of increasing diameter, equating to tactile pressures between 0.5 and 1078 mNewtons (mN). Monofilaments were applied by pressing them slowly down onto the skin until the hair buckled, holding them steady for 1.5 s (±0.5 s) and removing them in the same way they were applied (i.e. perpendicularly). To ensure precise timing, a clock was used to monitor the duration of application and removal. Following familiarisation with the procedure, participants were asked to close their eyes and respond when they perceived a touch stimulus. If a participant's response to a stimulus was delayed by more than 3 s, the trial was considered invalid and repeated. The method of limits was employed, wherein the intensity of a stimulus applied to the skin is systematically increased or decreased until the participant perceives or no longer perceives a stimulus (Backonja et al. 2013). Specifically, we started with the thickest filament in descending order; the procedure was stopped when the subject no longer perceived the touch stimulus. This procedure was repeated in ascending order, stopping the test when the subject perceived the touch stimulus.

Electrical detection thresholds (EDT) were estimated using a staircase procedure (Zamorano, Kleber, Arguissain, Vuust, et al. 2023; Zamorano, Kleber, Arguissain, Boudreau, et al. 2023). We used a stimulus current generator (DeMeTec, Langöns, Germany) and a concentric surface (WASP) electrode developed by Brainbox Ltd. (UK), consisting of an inner ring (Ø: 2 mm) with a platinum pin (height: 0.5 mm) surrounded by a cylindrical outer ring (Ø: 6.5 mm). The electrode was secured to the pad of the middle finger using tape to ensure stability during testing. Participants were instructed to close their eyes during the procedure and respond when they perceived a mild tickle or vibration stimulus. The procedure started with an initial stimulation intensity of 1 mA, which was increased incrementally by a factor of 2 until the participant reported cutaneous sensations twice. At this point, the stimulation intensity was reduced until the participant no longer perceived the stimulus. The step-factor was then changed to 1.25, and the process continued until we reached 15 reversal points. The geometric mean of the last eight reversal points was calculated. We repeated the process twice for each participant, and the mean of the two measurements was recorded as the participant's threshold.

Pressure pain thresholds (PPTs) were measured to identify the lowest intensity at which participants perceive a pressure stimulus as painful (i.e. pressure pain perception). PPTs were collected following the recommendations of the German Research Network on Neuropathic Pain (Rolke 2006). We used a digital dynamometer with a flat rubber tip (1 cm^2; Force One, Wagner Instruments, Greenwich, CT USA). Participants were instructed to have their hands in a supinated position, resting on a pad over a table. Starting with the device perpendicularly in contact with the skin, pressure was continuously increased until the participant reported feeling pain (pain threshold). The maximum allowable force was 140 N. Participants rated their perceived pain intensity at the threshold after each measurement using a 0–100 numerical rating scale (NRS), where 0 represented 'no pain' and 100 represented the 'worst pain imaginable'. We repeated this procedure twice for each participant, and the mean of the two measurements was used as the participant's threshold. Finally, we calculated the pressure pain sensitivity index (PPSI), which reflects the intensity of the pain experience relative to the applied stimulus intensity, as the ratio of the averaged perceived pain intensity (NRS) elicited by the stimulus and the averaged stimulus intensity, measured in newtons (N).

Heat pain thresholds (HPTs) were measured to identify the lowest intensity at which participants perceive a thermal stimulus as painful (i.e. thermal pain perception). HPT were also measured following the recommendations of the German Research Network on Neuropathic Pain (Rolke 2006). We utilised a contact thermal stimulator (Cold/warm plate AHP-301CPV, Teca, Schubert, IL, USA). Participants were instructed to keep their finger pad in contact with the thermal plate and to withdraw it as soon as the heat became painful. Starting from a non-painful lukewarm temperature of 37°C, the temperature was increased at an average rate of 0.2°C/s up to a maximum of 52°C. To assess the subjective perception of pain, participants were asked to rate their perceived pain intensity at the threshold, using a 0–100 numerical rating scale (NRS), where 0 represented 'no pain' and 100 signified the 'worst pain imaginable'. We repeated this procedure twice for each participant, and the mean of the two measurements was used to determine the participant's threshold. Lastly, we calculated the *heat pain sensitivity index* (HPSI), which reflects the intensity of the pain experience relative to the applied stimulus intensity, as the ratio between the perceived pain intensity (NRS) elicited by the stimulus and the stimulus intensity, expressed in Celsius degrees (°C).

2.4 | Music-Related Perceptual Discrimination Assessment

We evaluated differences in music perception skills across groups by conducting acoustic frequency discrimination and rhythmic equidistance beat discrimination tests. These assessments were performed to ensure that any observed relationships between training type, IAcc and pain were not influenced by differences in musical processing abilities across the groups.

2.4.1 | Acoustic Frequency-Discrimination Thresholds

Acoustic frequency-discrimination thresholds were determined by playing two pure tones, each lasting 250ms, with a silent gap of 600ms separating them (Kleber et al. 2013). The tones had a ramped onset and offset over 10ms. The first tone, the standard, had a frequency (f) of 500Hz, while the other, the target, had a frequency of 500Hz plus a frequency difference ($f\Delta$). The order in which the tones were played was random, and there was an equal probability of the higher-frequency tone being played in the first or second observation interval. Participants had to identify which interval contained the target tone. We adaptively varied the frequency difference ($f\Delta$) using a two-down one-up rule, which targeted a 70.7% correct threshold on the psychometric function (Levitt 1971).

At the start of each test block, we set $f\Delta$ to a large value (7%) to make the difference between the two tones easily perceptible. If the participant gave two consecutive correct responses, we decreased $f\Delta$ by a factor. We increased $f\Delta$ by the same factor after each incorrect response. The factor was equal to 2 initially; it was reduced to 1.25 following the second reversal in the direction of the change in f (from decreasing to increasing, or vice versa). We terminated the procedure after the 15th reversal in $f\Delta$ change direction, defining the threshold as the geometric mean calculated over the last eight reversals. We repeated this procedure twice for each participant, and the mean of these two measurements was considered the participant's individual threshold. Threshold values were expressed as percentages of the standard frequency.

2.4.2 | Beat Discrimination Accuracy

Auditory equidistance beat discrimination accuracy was determined using a novel task developed at the Center for Music in the Brain (Aarhus University, Denmark). The perceptual task consisted of two isochronous kick drum sounds (KD) with a steady interval of 1000ms, between which a snare drum sound (SD) was played with a variable onset relative to the first of the two KDs. Participants were to determine at which position the pulse of the SD sound was perfectly aligned, defined as an equidistance of 500ms between both KDs. Before the beginning of the task, an example of an equidistance beat was given.

The task always started with the SD at a noticeable offset of 650ms, making it easier to identify when the sound was out of equidistant beat. Participants adjusted the position of the SD sound by pressing buttons to shift it closer to either the first or second KD, based on their perception of whether it was equidistantly placed or not. The initial adjustment step was 25ms and decreased adaptively based on participant responses. After two consecutive correct responses, the adjustment step was multiplied by a factor to refine the positioning of the snare drum. Initially, this factor was set to 1.25, meaning the adjustment step was reduced by dividing it by 1.25 after two correct responses. After the second reversal in the perceived equidistance beat direction (e.g. from too early to too late, or vice versa), the factor was reduced to 1.15 to allow for finer adjustments in subsequent trials. The task concluded after the 10th reversal, with the equidistance perception threshold calculated as the mean squared error (in milliseconds) of the final eight reversals.

In the haptic version of the beat discrimination accuracy task, participants followed the same protocol as described previously. Instead of auditory cues, they felt the beats through their thumbs on the transducers of bone conduction headphones (Goldendance Co. Ltd., Korea). To eliminate auditory perception, pink masking noise was delivered through regular headphones. The masking sound volume was calibrated individually for each participant to ensure optimal effectiveness. This was achieved by incrementally increasing the intensity of the pink noise until participants indicated that they could no longer hear any air-transmitted sound from the bone conduction headphones. The order of the auditory and haptic paradigms was counterbalanced across participants.

2.5 | Self-Report Data Collection

Physical activity was evaluated using the International Physical Activity Questionnaire—Short Form (IPAQ-SF), which records the participant's physical activity over the past 7days (Lee et al. 2011). The 9-item IPAQ-SF details the time spent on activities at four intensity levels: (1) vigorous-intensity activities like aerobics, (2) moderate-intensity activities such as leisure cycling, (3) walking and (4) sitting.

We also collected other self-reported data, including the Edinburgh Handedness Inventory for manual dominance (Oldfield 1971), the State–Trait Anxiety Inventory (Spielberger et al. 1971) and the NEO-Five Factor Inventory extraversion subscale (Costa and McCrae 1992), in line with prior studies on interoception in musicians (Schirmer-Mokwa et al. 2015).

To compare music aptitudes and behaviours across groups, all participants completed the Goldsmith Musical Sophistication Index (Gold-MSI; Mullensiefen et al. 2014). We used the Pain Vigilance and Awareness Questionnaire (PVAQ; McCracken 1997) as a measure of body-centred awareness, and the Pain Catastrophizing Scale (PCS; Sullivan et al. 1995) to explore if IAcc and pain might be inherently related to a more prevalent (or dispositional) attention to painful stimuli.

We collected all data in a quiet and naturally lit room with a stable temperature. The order of tasks was randomly assigned at the start of each session, with the only constant being that pain thresholds were always performed at the end of the session.

2.6 | Statistical Analysis

Behavioural responses were analysed using JASP (Version 0.19.2) for statistical computations. Normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. Where violations of homogeneity were detected, degrees of freedom corrections were applied. Non-parametric tests were used for analyses when assumptions of normality or homogeneity were not met. Statistical analyses were not pre-registered. Confirmatory analysis and exploratory analysis have been described following APA recommendations to ensure the transparency and rigour of the results.

2.6.1 | Between-Group Comparisons

Group differences were analysed using Kruskal–Wallis tests, a non-parametric method robust to deviations from normality. This test was applied to assess variations in IAcc, quantitative sensory measures (MDT, EDT, PPT, HPT, pain ratings and PSI), musically relevant sensory tasks (e.g. beatdiscrimination accuracy, acoustic frequency-discrimination thresholds, musical aptitudes) and self-reported physical activity and psychological variables (e.g. IPAQ-SF, STAI-T, STAI-S, PVQA, PCS and extraversion). When significant effects were identified, pairwise comparisons were conducted using Mann–Whitney U tests with Bonferroni corrections, setting the adjusted significance threshold to $p < 0.017$ for three comparisons.

Effect sizes were calculated to quantify the magnitude of group differences. For Kruskal–Wallis tests, eta-squared (η^2) was reported, with thresholds of 0.01, 0.06 and 0.14 indicating small, medium and large effects, respectively. For Mann–Whitney U tests, rank-biserial correlation (r) was used as the effect size, with thresholds of 0.1, 0.3 and 0.5 representing small, medium and large effects.

2.6.2 | Relationships Between Variables

To investigate the relationships between accumulated training, physical activity, IAcc and pain-related outcomes, multiple approaches were employed, including moderated hierarchical regression, mediation analyses and partial correlations.

2.6.2.1 | Moderated Hierarchical Regression Analysis. Moderated hierarchical multiple regression was used to examine the effects of accumulated training and group membership on IAcc. Training hours were mean-centred, and an interaction term (Group × Accumulated Training) was included to test whether the relationship between accumulated training and IAcc differed between musicians and athletes. The main effects of accumulated training and group were interpreted at the mean-centred level of training. Model diagnostics included checks for multicollinearity (VIFs < 10), normality of residuals (Shapiro–Wilk tests, Q–Q plots and histograms) and homoscedasticity (residuals versus predicted values plots).

2.6.2.2 | Mediation Analyses. Two mediation models were used. The first model assessed whether group membership mediated the relationship between IAcc (predictor) and PPTs (outcome). The second model evaluated whether IAcc mediated the relationship between accumulated training (predictor) and PPTs (outcome), with group membership included as a confounding variable to account for differences in training modalities, onset and intensity. Mediation analyses employed bias-corrected bootstrap confidence intervals (5000 resamples) to test the significance of indirect effects.

2.6.2.3 | Partial Correlations. Partial correlations were conducted to further evaluate the relationships between physical activity (IPAQ-SF), IAcc and pain outcomes while controlling for group membership. These analyses assessed the extent to which individual-level variations in these measures were independent of group effects.

2.6.3 | Exploratory Analyses

Exploratory analyses examined the relationship between IAcc and self-reported musical aptitude (Gold-MSI subscales), auditory and tactile perceptual discrimination, as well as psychological measures (e.g. STAI, PCS). These psychological measures also helped assess whether dispositional traits influenced IAcc or pain thresholds, ensuring that observed effects were primarily attributable to training rather than psychological confounders.

2.6.4 | Data Visualisation

Mediation path plots were created in JASP. All other visualisations were created in RStudio (Version 2014.09.1 + 394) using the ggplot2 and cowplot packages. Scatterplots displaying partial correlations between variables utilised residualised data to illustrate associations independent of group membership.

3 | Results

3.1 | Participants

Participants were assigned to three groups based on their primary training background. Seventeen professional classical musicians (five female, average age 33.1 ± 10.1 years), 15 semi-professional athletes (six female, average age 30.5 ± 6.7 years) and 14 non-musician/non-athlete individuals (seven female, average age 30.6 ± 3.1 years) completed the tasks. There were no significant group differences with respect to the sex distribution, $X^2(2) = 1.37$, $p = 0.503$ and age, $F_{(2,45)} = 0.65$, $p = 0.528$.

The musician group consisted of a variety of professionally conservatoire-trained instrumentalists, including 7 string, 4 piano, 2 brass, 1 percussion, 1 woodwind and 1 guitar player, as well as one singer. Similarly, the athletes consisted of a diverse group of 11 triathletes, 2 runners and 2 football players, who all compete in local or national tournaments. Whereas athletes and control participants had no prior musical experience, musicians and controls reported engaging in light-to-moderate physical activity. Only one musician reported experience with higher and vigorous physical activity levels. See Table 1 for detailed descriptives of physical activity and daily- and total accumulated practice time for all groups.

3.2 | Interoceptive Accuracy

A Kruskal-Wallis test revealed significant group differences in IAcc ($\chi^2_{(2)} = 7.105$, $p = 0.029$, $\eta^2 = 0.14$). Subsequent post hoc Mann–Whitney *U* tests, using a Bonferroni-corrected significance threshold (adjusted $p < 0.017$), indicated that athletes had significantly higher IAcc than control participants ($p = 0.007$, $r = 0.54$), indicating a large effect size. The comparison between musicians and control participants indicated a trend, approaching statistical significance ($p = 0.019$) with a moderate effect size ($r = 0.45$). No significant difference was observed between musicians and athletes ($p = 0.60$, $r = 0.11$; Figure 1A).

To assess participants' average resting heart rate during interoceptive task performance, beats per minute were analysed across all heartbeat counting conditions (25, 35 and 45s). A Kruskal–Wallis test indicated a significant effect of group, $\chi^2_{(2)} = 11.54$, $p = 0.003$, $\eta^2 = 0.23$, suggesting differences in resting heart rate between training groups. Subsequent post hoc Mann–Whitney *U* tests, using a Bonferroni-corrected significance threshold (adjusted $p < 0.017$), showed that athletes exhibited significantly lower resting heart rates compared to untrained controls, $p = 0.0009$, $r = 0.68$. No significant differences in heart rate were observed between musicians and athletes ($p = 0.02$, $r = 0.51$) or between musicians and untrained control participants ($p = 0.26$, $r = 0.26$).

3.3 | Quantitative Sensory Testing

No significant effects of group were found for *mechanical detection threshold* ($\chi^2_{(2)} = 2.879$, $p = 0.237$, $\eta^2 = 0.058$).

Kruskal–Wallis test yielded a significant effect of group on *electrical detection thresholds* ($\chi^2_{(2)} = 7.682$, $p = 0.021$; $\eta^2 = 0.094$). Post hoc Mann–Whitney U tests, using a Bonferroni-corrected significance threshold (adjusted $p < 0.017$), revealed that *electrical*

TABLE 1 | Socio-demographic and professional characteristics of musicians, athletes and controls.

	Musicians ($n = 17$)	Athletes ($n = 15$)	Controls ($n = 14$)
Age of training onset (years)	8.0 (1.0)	18.5 (17.7)	—
Weekly practice (h)	18.0 (12)	12 (5.2)	—
Accumulated training (h)	21,632 (20,436)	9230 (7059)	—
IPAQ (min)	525 (607)	1095 (822)	285 (452)
Heartrate across trials	69 (14)	56 (14.5)	71.5 (16.5)
Gold-MSI			
Active engagement	112 (198)	69 (25)	68 (105)
Perceptual abilities	54.5 (5.5)	40 (14.5)	37 (7.7)
Musical training	45.5 (2.6)	8 (9)	3.7 (5.5)
Emotional responses to music	38 (4.5)	27 (10.5)	26 (6.2)
Singing abilities	30.5 (5.2)	27 (6.5)	25.5 (7.5)
State Anxiety	6 (10)	9 (9)	9 (4.5)
Trait Anxiety	13 (10)	14 (14.5)	10.5 (11.25)
Extraversion (NEO-V)	32 (7.5)	32 (8)	37.5 (6.7)
PVAQ	38 (9)	37.5 (14.7)	35.0 (8)
Pain catastrophizing			
Rumination	3 (4)	1 (3)	2.5 (2.7)
Magnification	2 (4)	0 (2)	2 (1.7)
Helplessness	3 (4)	2 (3.5)	2.5 (4.2)

Note: All values represent median and interquartile range (IRQ, in brackets).

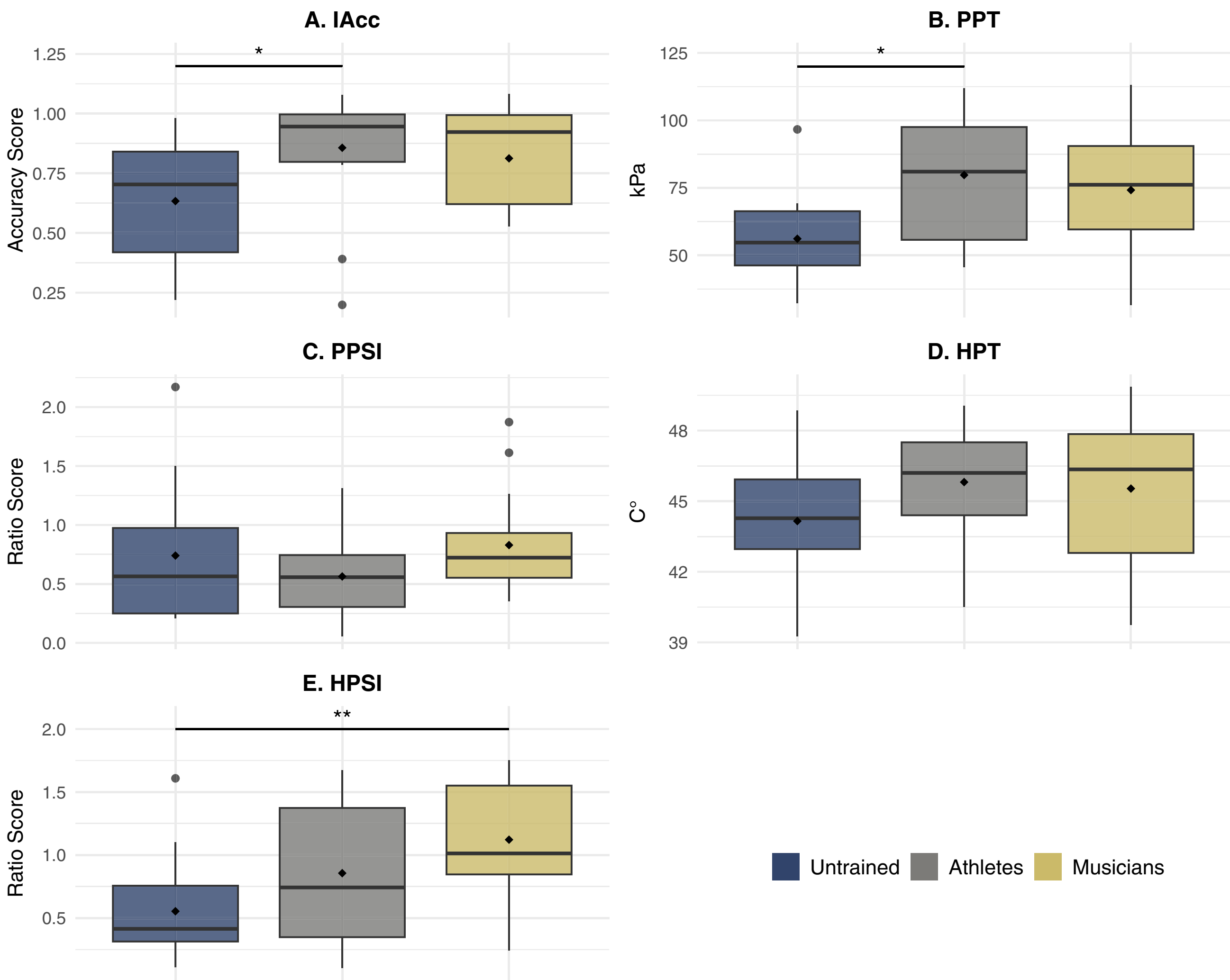

FIGURE 1 | Box plots representing median, interquartile range and mean (represented as a rhombus) of group scores. (A) Athletes display enhanced interoceptive accuracy (IAcc) compared to controls. (B) Athletes also demonstrate increased pressure pain thresholds (PPT) compared to controls. (C) Pressure pain sensitivity index (PPSI) and (D) Heat pain thresholds (HPT) across groups showed no significant differences. (E) Heat pain sensitivity index (HPSI) was significantly greater in musicians compared to controls. Between-group differences were analysed using Kruskal–Wallis tests, followed by post hoc Mann–Whitney *U* tests. Significance was determined using a Bonferroni-corrected threshold ($p<0.017$): *$p<0.017$; **$p<0.001$.

detection thresholds were higher in athletes than in musicians ($p=0.017$, $r=0.51$). The comparison between athletes and musicians did not achieve statistical significance ($p=0.021$) but showed a large effect size ($r=0.505$). No differences were found between musicians and controls ($p=0.676$, $r=0.09$).

Kruskal–Wallis test yielded a significant effect of group on *pressure pain thresholds* ($\chi^2_{(2)}=7.440$, $p=0.024$, $\eta^2=0.174$; Figure 1B). Post hoc Mann–Whitney *U* tests revealed that PPTs were significantly higher in athletes ($p=0.003$, $r=0.59$) than in controls. The comparison between musicians and control participants did not achieve statistical significance ($p=0.029$) but showed a moderate effect size ($r=0.40$). No differences were found between musicians and athletes ($p=0.526$, $r=0.14$). No significant effects were found for the *pressure pain sensitivity index* ($\chi^2_{(2)}=2.650$, $p=0.266$, $\eta^2=0.059$; PPSI, Figure 1C).

No significant effects were found for *heat pain thresholds* ($\chi^2_{(2)}=2.640$, $p=0.267$, $\eta^2=0.061$; HPTs, Figure 1D). However, the Kruskal–Wallis test revealed a significant effect of group for the *heat pain sensitivity index* ($\chi^2_{(2)}=8.881$, $p=0.012$, $\eta^2=0.199$; HPSI). Post hoc tests (Figure 1E) revealed that HPSI was higher in musicians than in controls ($p<0.001$, $r=0.64$). No differences were found between musicians and athletes ($p=0.146$, $r=0.30$) and between athletes and controls ($p=0.093$, $r=0.29$).

3.4 | Music-Related Perceptual Discrimination Results

3.4.1 | Acoustic Frequency-Discrimination Thresholds

Kruskal–Wallis test showed a significant effect of group ($\chi^2_{(2)}=13.741$, $p=0.001$, $\eta^2=0.21$). Post hoc Mann–Whitney *U* tests, using a Bonferroni-corrected significance threshold (adjusted $p<0.017$), revealed enhanced frequency discrimination in musicians compared to both athletes ($p<0.001$, $r=0.67$) and control subjects ($p=0.001$, $r=0.69$), whereas no significant difference was detected between athletes and controls ($p=0.981$, $r=0.011$; Figure 2A).

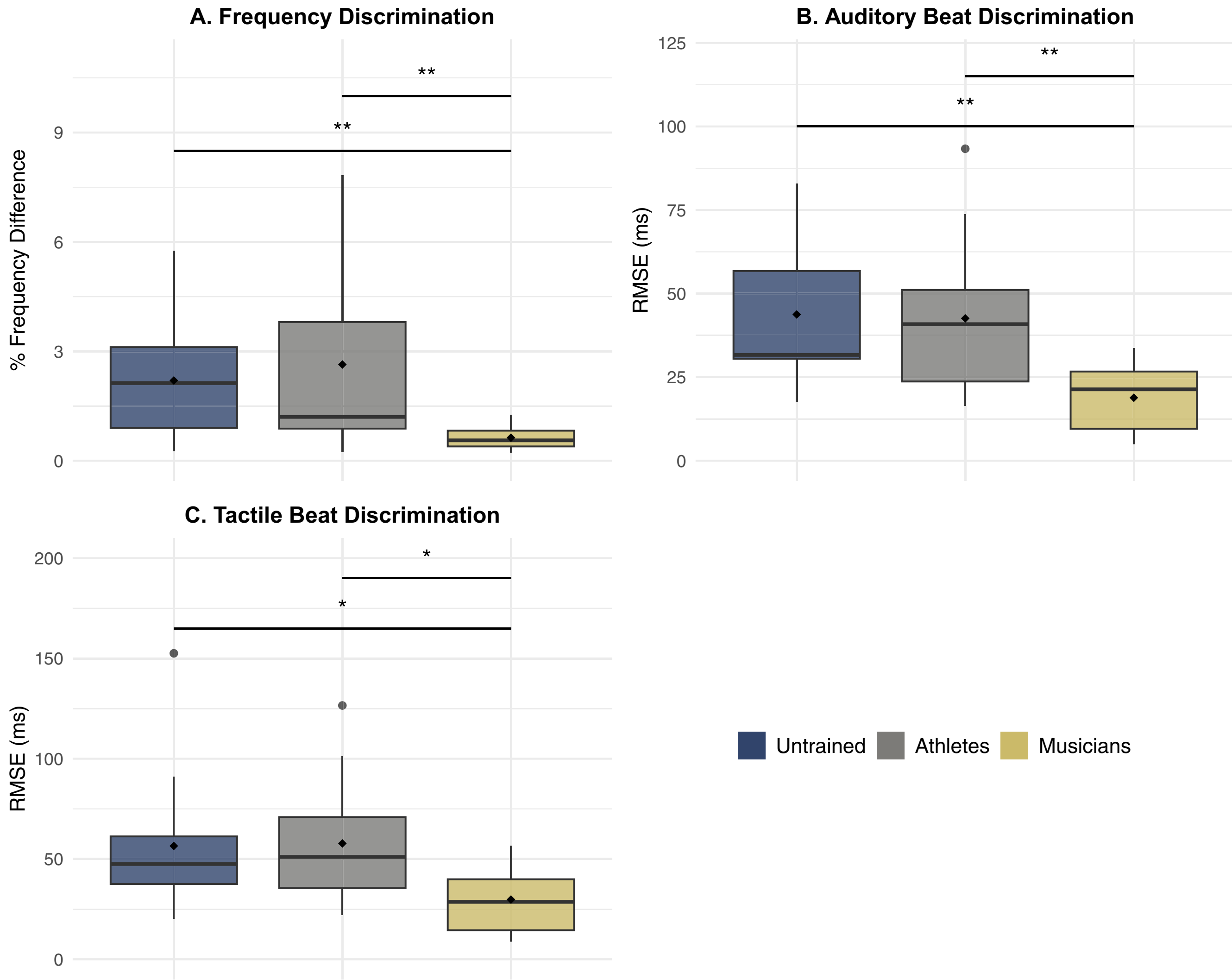

FIGURE 2 | Box plots representing median, interquartile range and mean (represented as a rhombus) of group scores. (A) Lower scores indicate enhanced auditory frequency discrimination in musicians relative to athletes and controls. The box plot indicates the average frequency difference ($f\Delta$)—expressed as a percentage from a standard tone (500 Hz)—participants were able to hear. On a cent scale (100 cent = 1 semitone in musical notation), a $f\Delta$ of 1 translates to 17.4 cent and a $f\Delta$ of 3 to 52.7 cent. (B) Musicians also demonstrate superior auditory beat discrimination accuracy (lower RMSE) compared to athletes and controls. (C) Similarly, tactile beat discrimination accuracy (lower RMSE) is better in musicians than in athletes and controls. RMSE refers to the root mean square error, representing deviation (in ms) from isochrony at which participants rated a beat as isochronous, with lower numbers indicating better rhythmic perception. Between-group differences were analysed using Kruskal–Wallis tests, followed by post hoc Mann–Whitney *U* tests. Significance was determined using a Bonferroni-corrected threshold ($p < 0.017$): *$p < 0.017$; **$p < 0.001$.

3.4.2 | Auditory Beat Discrimination Accuracy

Kruskal–Wallis test revealed a significant effect of group ($\chi^2_{(2)} = 15.593$, $p < 0.001$, $\eta^2 = 0.31$). Mann–Whitney *U* tests revealed that acoustic beat discrimination was overall better (i.e. lower thresholds) in musicians than in athletes ($p < 0.001$, $r = 0.71$) and control subjects ($p < 0.001$, $r = 0.697$). Differences between athletes and control subjects were not significant ($p = 0.91$, $r = 0.029$; Figure 2B).

3.4.3 | Tactile Beat Discrimination Accuracy

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 10.240$, $p = 0.006$, $\eta^2 = 0.19$). Mann–Whitney *U* tests revealed that tactile beat discrimination was overall better (i.e. lower temporal thresholds) in musicians than in athletes ($p = 0.002$, $r = 0.59$) and control subjects ($p = 0.004$, $r = 0.58$). Differences between athletes and controls were not significant ($p = 0.856$, $r = 0.04$; Figure 2C).

3.5 | Self-Report Data

3.5.1 | Physical Activity

As shown in Table 1, a Kruskal–Wallis test based on the average amount of unweighted (i.e. combined low, moderate and vigorous) weekly physical activity as self-reported by IPAQ-SF, showed significant group differences ($\chi^2_{(2)} = 14.664$, $p < 0.001$, $\eta^2 = 0.30$). Post hoc Mann–Whitney *U* test, using a Bonferroni-corrected significance threshold (adjusted $p < 0.017$), revealed that accumulated physical activity per week was higher in athletes compared to both musicians ($p = 0.006$, $r = 0.53$) and controls ($p < 0.001$, $r = 0.81$). No significant differences were detected between musicians and controls ($p = 0.183$, $r = 0.29$).

3.5.2 | Extraversion

A Kruskal–Wallis test yielded a significant effect of group with respect to extraversion ($\chi^2_{(2)} = 6.207$, $p = 0.045$, $\eta^2 = 0.13$; Table 1). Post hoc Mann–Whitney *U* tests revealed that musicians had lower extraversion scores compared to controls ($p > 0.017$, $r = 0.52$). No significant differences were detected between musicians and athletes ($p = 0.628$, $r = 0.11$) and between athletes and controls ($p = 0.084$, $r = 0.39$).

3.5.3 | Anxiety

A Kruskal–Wallis test yielded no significant group differences with respect to state anxiety ($\chi^2_{(2)} = 1.352$, $p = 0.509$, $\eta^2 = 0.03$) and dispositional trait anxiety ($\chi^2_{(2)} = 0.338$, $p = 0.845$, $\eta^2 = 0.12$). All state and trait anxiety scores were within the normal range.

3.5.4 | Pain Vigilance and Catastrophizing

Pain vigilance ($\chi^2_{(2)} = 2.309$, $p = 0.315$, $\eta^2 = 0.05$) and pain catastrophizing subscales did not show significant differences across groups either (rumination: $\chi^2_{(2)} = 3.754$, $p = 0.153$, $\eta^2 = 0.05$; magnification: $\chi^2_{(2)} = 4.047$, $p = 0.132$, $\eta^2 = 0.05$; and helplessness: $\chi^2_{(2)} = 1.733$, $p = 0.421$, $\eta^2 = 0.03$).

3.5.5 | Musical Aptitude

Across all Gold-MSI subscales, musicians showed higher levels of self-reported musical aptitude compared to both athletes and controls (see also Table 1).

3.5.6 | Gold-MSI Active Engagement

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 9.085$, $p = 0.011$, $\eta^2 = 0.21$). Post hoc Mann–Whitney *U* test revealed that active engagement was higher in musicians compared to athletes ($p = 0.001$, $r = 0.63$). Post hoc test comparing musicians vs non-musicians approached statistical significance ($p = 0.024$, $r = 0.43$), whereas no significant difference was detected between athletes vs controls ($p = 0.631$, $r = 0.11$).

3.5.7 | Gold-MSI Perceptual Abilities

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 24.932$, 2, $p < 0.001$, $\eta^2 = 0.56$). Post hoc test revealed that perceptual abilities were higher in musicians compared to athletes ($p < 0.001$, $r = 0.81$) and controls ($p < 0.001$, $r = 0.95$) whereas no significant difference was detected between athletes and controls ($p = 0.155$, $r = 0.31$).

3.5.8 | Gold-MSI Musical Training

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 31.010$, $p < 0.001$, $\eta^2 = 0.94$). Post hoc test revealed that musical training was significantly higher in musicians compared to both athletes ($p < 0.001$, $r = 1.00$) and controls ($p < 0.001$, $r = 1.00$), whereas no significant difference was detected between athletes and controls ($p = 0.269$, $r = 0.25$).

3.5.9 | Gold-MSI Emotional Responses to Music

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 26.274$, $p < 0.001$, $\eta^2 = 0.54$). Post hoc test revealed that musicians showed stronger emotional responses to music compared to both athletes ($p < 0.001$, $r = 0.84$) and controls ($p < 0.001$, $r = 0.99$), whereas no significant difference was detected between athletes and controls ($p = 0.315$, $r = 0.22$).

3.5.10 | Gold-MSI Singing Abilities

Kruskal–Wallis test yielded a significant effect of group ($\chi^2_{(2)} = 9.144$, $p < 0.010$, $\eta^2 = 0.21$). The post hoc test revealed that singing abilities were higher in musicians compared to athletes ($p = 0.007$, $r = 0.52$) and controls ($p = 0.007$, $r = 0.58$) whereas no significant difference was detected between athletes and controls ($p = 0.798$, $r = 0.62$).

3.6 | Relationships Between Variables

3.6.1 | Effects of Accumulated Training and Group on IAcc

A hierarchical multiple regression was conducted to examine the effects of accumulated training and group (musicians vs. athletes) on IAcc, as well as the potential moderating role of group in the relationship between training and IAcc. Accumulated training was mean-centred, and the interaction term (Group × Accumulated Training) was computed using the centred training variable. The overall regression model (Figure 3A) significantly predicted IAcc, F (3, 28) = 3.21, $p = 0.04$, explaining 26% of the variance ($R^2 = 0.26$). This represented a significant improvement over the intercept-only model ($\Delta R^2 = 0.26$, $p = 0.04$).

Accumulated training significantly predicted IAcc, $b = 6.69 \times 10^{-6}$, SE = 2.73 $\times 10^{-6}$, t (28) = 2.45, $p = 0.02$, 95% CI [1.09 $\times 10^{-6}$, 1.23 $\times 10^{-5}$], with a moderate effect size ($\beta = 0.49$). Greater accumulated training hours were associated with higher IAcc scores. The main effect of group was also significant, $b = 0.25$, SE = 0.11, t (28) = 2.20, $p = 0.04$, 95% CI [0.02, 0.48], indicating that athletes had higher IAcc scores than musicians at the average level of accumulated training. However, the interaction term was not significant, $b = 9.88 \times 10^{-6}$, SE = 9.56×10^{-6}, t (28) = 1.03, $p = 0.31$, 95% CI [-9.71×10^{-6}, 2.95×10^{-5}], suggesting that the

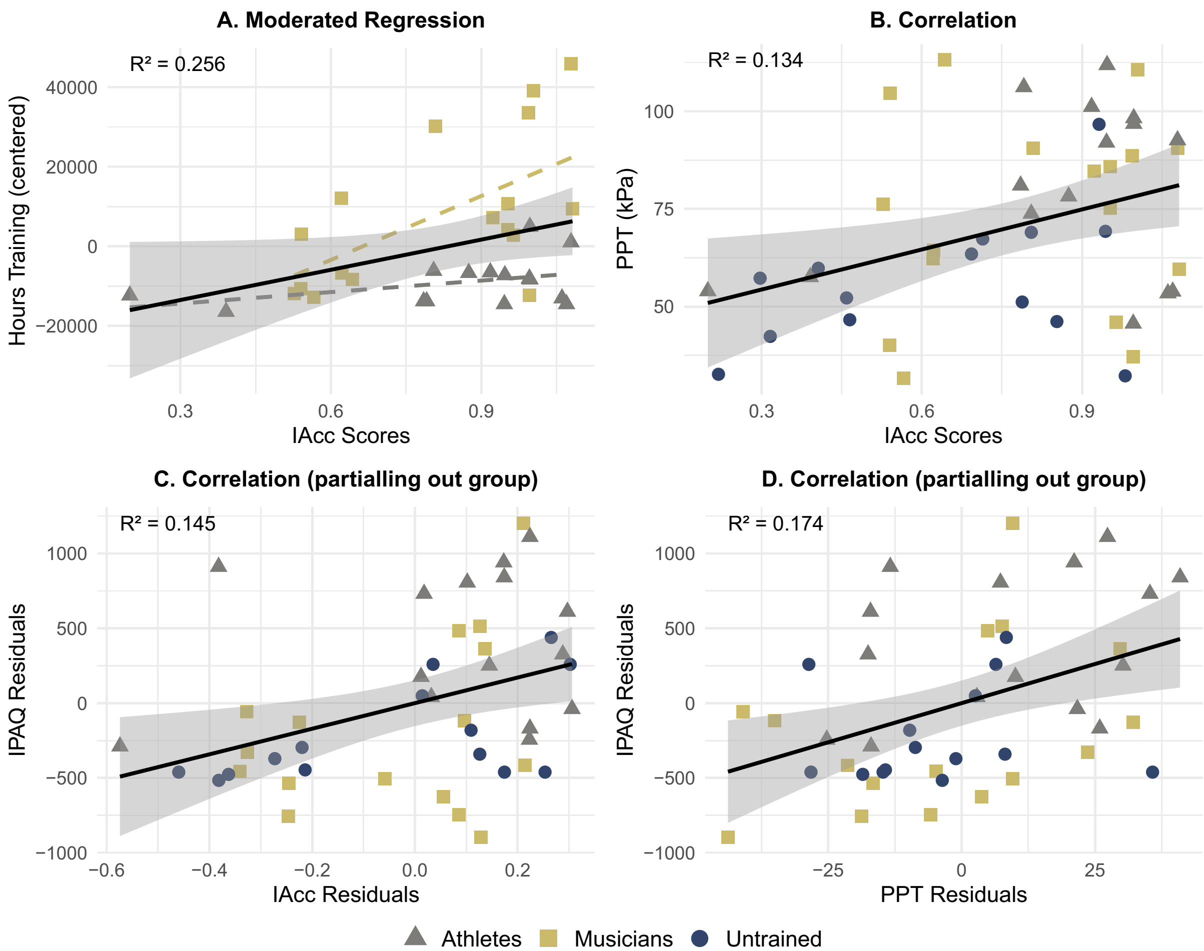

FIGURE 3 | (A) Hierarchical regression analysis examining the relationship between interoceptive accuracy (IAcc) and accumulated training hours (centred), moderated by group (musicians and athletes). The significant main effects of accumulated training and group are reflected in the overall model ($R^2=0.256$, $p=0.04$). Accumulated training was positively associated with IAcc across both groups, as shown by the solid black regression line (aggregate effect), while the dashed regression lines represent the separate group-specific effects (musicians and athletes). The interaction term (Group × Accumulated Training) was not significant, indicating that the relationship between training and IAcc did not differ significantly between groups. (B) Correlation analysis revealed a significant positive relationship between IAcc and pressure pain thresholds (PPTs) across all participants ($r=0.36$, $p=0.012$), accounting for approximately 13% of the variance ($R^2=0.134$). No significant correlations were found between IAcc and other pain processing outcomes (heat pain thresholds, pain intensity and pain sensitivity index; all $p>0.05$). (C) Partial correlation analysis revealed a significant positive relationship between physical activity (IPAQ-SF minutes residuals) and IAcc residuals, after controlling for group membership ($r=0.42$, $p=0.005$), accounting for approximately 18% of the variance ($R^2=0.18$). (D) Partial correlation analysis revealed a significant positive relationship between IPAQ-SF minutes residuals and PPT residuals, after controlling for group membership ($r=0.37$, $p=0.02$), accounting for approximately 14% of the variance ($R^2=0.14$). Colours represent group membership: Untrained controls (blue), athletes (grey) and musicians (yellow).

relationship between accumulated training and IAcc did not differ significantly between musicians and athletes.

Model diagnostics indicated no issues with multicollinearity (all VIFs < 10), and the residuals were approximately normally distributed, as confirmed by Q–Q plots and histograms. Homoscedasticity was also supported based on residuals versus predicted values plots. Marginal effects plots showed a positive relationship between accumulated training and IAcc, with no substantial differences in the slopes between musicians and athletes.

3.6.2 | Relationship Between IAcc, Pain Processing and Accumulated Training

To investigate the relationship between IAcc, pain processing, and accumulated training, correlation analyses between IAcc and PPTs, HPTs, pain intensity and PSI were performed as a preliminary step to ensure that subsequent analyses are focused on meaningful relationships. After identifying significant IAcc–pain relationships, we tested whether differences in group membership may explain the link between IAcc and pain processing, providing insights into whether IAcc effects are universal or group-specific. Subsequently, a second mediation analysis examined whether IAcc mediates the relationship between accumulated training and pain processing.

Correlation results revealed that *IAcc* was only positively correlated with *pressure pain thresholds* ($r=0.36$, $p=0.012$; Figure 3B) across all participants. No significant correlation was found between IAcc and other pain processing outcomes (HPTs, pain intensity, HPSI, PPSI; all $p>0.05$). Accordingly, the first mediation analysis examined whether group membership mediated the relationship between IAcc (predictor) and PPTs (outcome). Bias-corrected bootstrap confidence intervals were computed using 5000 resamples.

The direct effect of IAcc on PPTs was significant, $b = 1.21$, $SE = 0.55$, $z = 2.20$, $p = 0.03$, 95% CI [0.13, 2.31], indicating that higher IAcc significantly predicted higher PPTs. The indirect effect of IAcc on PPTs through group membership was not significant, $b = 0.23$, $SE = 0.19$, $z = 1.21$, $p = 0.23$, 95% CI [−0.03, 0.83], suggesting that group differences did not mediate the relationship between IAcc and PPTs. The total effect of IAcc on PPTs was significant, $b = 1.44$, $SE = 0.54$, $z = 2.67$, $p = 0.007$, 95% CI [0.43, 2.38].

Path coefficients (Figure 4) confirmed that IAcc significantly predicted group membership ($b = 1.09$, $SE = 0.56$, $z = 1.96$, $p = 0.05$, 95% CI [0.03, 2.00]), with trained participants (musicians and athletes) exhibiting higher IAcc compared to controls. However, group membership did not significantly predict PPTs ($b = 0.21$, $SE = 0.14$, $z = 1.53$, $p = 0.13$, 95% CI [−0.08, 0.51]).

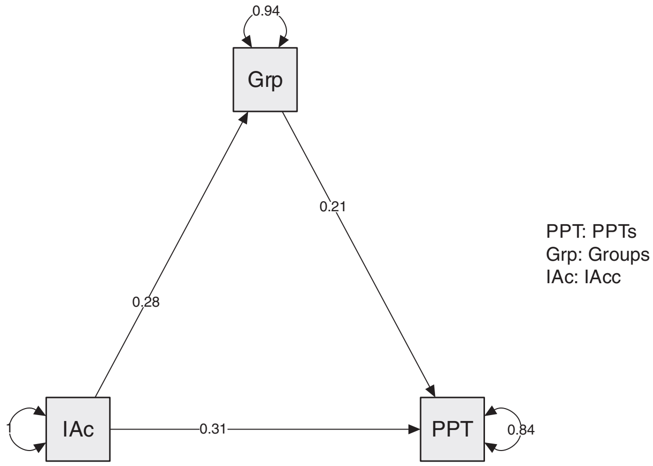

FIGURE 4 | Path diagram examining whether group membership (Grp: Untrained, athletes, musicians) mediated the relationship between interoceptive accuracy (IAcc: Predictor) and pressure pain thresholds (PPTs: Outcome). Standardised path coefficients indicate a significant direct effect of IAcc on PPTs ($p < 0.05$) but a non-significant indirect effect through group. These findings suggest that the relationship between IAcc and PPTs is primarily direct and not mediated by group membership.

The second mediation analysis was conducted to examine whether IAcc mediated the relationship between accumulated training (hours of practice) and PPTs. Group membership (musicians vs. athletes) was included as a confounder to account for potential differences in training onset, intensity and duration. Bias-corrected bootstrap confidence intervals were computed using 5000 resamples.

The direct effect of accumulated training on PPTs was significant, $b = 0.73$, $SE = 0.36$, $z = 2.01$, $p = 0.04$, 95% CI [0.06, 1.45], indicating that greater accumulated practice was associated with higher pressure pain thresholds. The indirect effect of accumulated training on PPTs via IAcc was not significant, $b = 0.06$, $SE = 0.21$, $z = 0.28$, $p = 0.78$, 95% CI [−0.43, 0.38], suggesting that IAcc does not mediate this relationship.

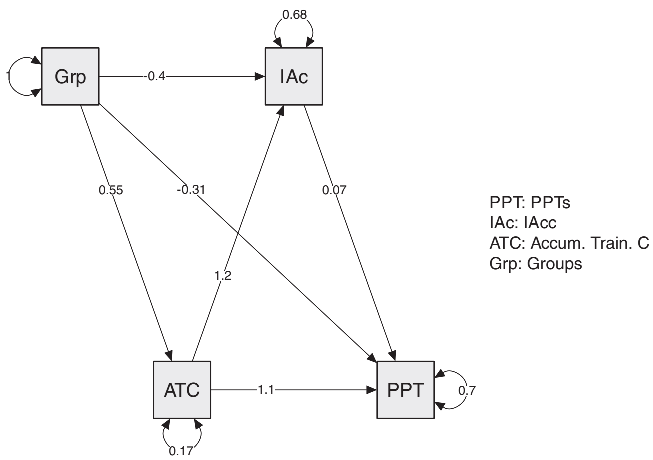

FIGURE 5 | Path diagram illustrating interoceptive accuracy (IAcc) as a mediator in the relationship between the amount of sensorimotor training (ATC: Accumulated training, mean-centred) and pressure pain thresholds (PPTs). Group membership (Grp: Musicians, athletes) was included as a confounding variable to account for potential differences in training onset, intensity and duration. The diagram shows standardised path coefficients, with the direct effect of accumulated training on both PPTs and IAcc being significant ($p < 0.05$). However, the indirect effect through IAcc was non-significant, suggesting that the effect of accumulated training on PPTs is not mediated by IAcc.

Path coefficients (Figure 5) revealed that accumulated training significantly predicted IAcc ($b = 0.84$, $SE = 0.25$, $z = 3.37$, $p < 0.001$, 95% CI [0.43, 1.39]), confirming the strong positive relationship between training hours and IAcc and PPTs ($b = 0.73$, $SE = 0.36$, $z = 2.01$, $p = 0.04$, 95% CI [0.06, 1.45]). However, IAcc did not significantly predict PPTs once the effect of accumulated training was considered, $b = 0.07$, $SE = 0.20$, $z = 0.35$, $p = 0.73$. These results suggest that accumulated training directly influences PPTs, independent of interoceptive accuracy.

Model diagnostics indicated that accumulated training accounted for 30% of the variance in PPTs ($R^2 = 0.30$) and 32% of the variance in IAcc ($R^2 = 0.32$).

3.6.3 | Relationship Between Physical Activity With IAcc and Pain Processing

Two partial correlations were conducted, controlling for group differences. The first partial correlation examined the relationship between IPAQ-SF and IAcc scores. Normality of the residuals was assessed using the Shapiro–Wilk test, revealing slight deviations from normality for IPAQ-SF residuals ($W = 0.94$, $p = 0.010$) and IAcc residuals ($W = 0.95$, $p = 0.020$). Despite these deviations, partial correlation analysis was conducted using Pearson's r, as the test is robust to moderate deviations from normality. The analysis revealed a significant positive partial correlation between physical activity and interoceptive accuracy, $r(41) = 0.42$, $p = 0.005$ (Figure 3C). The squared correlation coefficient ($R^2 = 0.18$) indicates that approximately 18% of the variance in IAcc is accounted for by physical activity, independent of group classification.

The second partial correlation examined the relationship between physical activity and pain responses (PPTs and HPTs).

The Shapiro–Wilk test indicated slight deviations from normality for IPAQ-SF residuals ($W = 0.94$, $p = 0.010$), PPT residuals ($W = 0.95$, $p = 0.020$) and HPT residuals ($W = 0.95$, $p = 0.020$). Despite these minor deviations, partial correlation analysis was conducted using Pearson's r. After controlling for group membership, a significant positive partial correlation was found between physical activity and PPTs, $r(41) = 0.37$, $p = 0.02$ (Figure 3C). The squared correlation coefficient ($R^2 = 0.14$) indicates that approximately 14% of the variance in PPTs is accounted for by physical activity, independent of group classification. For HPTs, the partial correlation was not statistically significant, $r(41) = 0.21$, $p = 0.17$.

3.7 | Exploratory Analyses

3.7.1 | IAcc With Musical Aptitudes

Across all participants and within subgroups, no significant correlations were found between IAcc and self-reported musical aptitudes (Gold-MSI subscales), or performance in musical tasks (frequency discrimination and auditory-tactile rhythm perception; all $p > 0.05$). However, among musicians, IAcc was positively correlated with accumulated hours of music training ($r = 0.59$, $p = 0.011$; see corresponding regression slope in Figure 3A).

3.7.2 | IAcc With Psychological and Pain-Related Self-Report Measures

Exploratory analyses revealed no significant correlations between IAcc and trait anxiety (STAI-T), state anxiety (STAI-S) or extraversion (NEO-F; all $p > 0.05$). Similarly, no significant associations were observed between IAcc and pain-related cognitive-emotional constructs, including pain rumination, pain magnification and pain helplessness (all $p > 0.05$; see Table 1). These findings indicate that differences in IAcc were not strongly influenced by psychological dispositions or self-reported pain-related thought patterns.

3.7.3 | IAcc and Average Heart Rate

No significant correlations were observed between IAcc and the average heart rate during the heartbeat detection task, neither across all participants nor within specific subgroups (athletes, musicians and controls; all $p > 0.05$). This suggests that task-related IAcc was independent of resting heart rate during the task.

4 | Discussion

This study reveals that, relative to controls, athletes exhibit heightened interoceptive accuracy, demonstrated by their enhanced ability to precisely perceive their own heartbeats within various time frames (Garfinkel et al. 2015). Heightened IAcc with moderate effect sizes in musicians compared to controls did not achieve statistical significance. However, accumulated training positively predicted IAcc in both musicians and athletes, with no significant differences between training modalities, aligning with our hypothesis that longer sensorimotor experience would be associated with increased IAcc.

Pain processing also differed in athletes and musicians compared to non-trained controls. Athletes displayed significantly increased PPTs, while musicians showed an increased pain sensitivity index to heat stimulation (HPSI), consistent with our hypothesis. A subsequent mediation analysis showed that accumulated training was positively associated with both IAcc and PPTs; however, the effects of training on PPTs were not mediated by IAcc. This suggests two distinct pathways: a direct pathway where training enhances PPTs and a parallel pathway where training improves IAcc without significantly influencing PPTs. These results also supported our hypothesis that interoceptive pathways would be linked to mechanical pressure over the muscle. Specifically, PPTs—but not HPTs—were robustly linked to IAcc, underscoring the importance of pain stimulus type in understanding the interoception-pain relationship in healthy populations.

4.1 | Experience-Dependent Modulation of IAcc and PPTs

We observed heightened cardiac IAcc and increased PPTs in athletes compared to controls, suggesting a relationship between long-term, intensive sensorimotor training, interoception and pain. Musicians also displayed heightened IAcc compared to controls, with moderate effect sizes; however, these differences did not reach statistical significance, warranting cautious interpretation and further exploration in larger cohorts. Notably, moderated regression analysis supported our hypothesis by revealing a positive relationship between accumulated training and IAcc in both musicians and athletes. These findings align with the idea that longer sensorimotor experience enhances interoceptive abilities. Athletes, however, displayed higher IAcc at comparable training levels, likely reflecting the rapid interoceptive benefits of cardiovascular training. In contrast, musical training may require a more gradual and sustained trajectory to achieve comparable interoceptive improvements.

Empirical research indicates that the embodied multisensory integration of coherent endogenous and personally relevant exogenous cues may serve as a powerful mechanism for enhancing the perception of internal bodily sensations (Ceunen et al. 2016). Physical activity, a key driver of such integration, has been linked to increased afferent signalling to the interoceptive system (Caspersen et al. 1985; Craig 2006; Durlik et al. 2014; Jones and Hollandsworth 1981) and modifications in pain processing mechanisms, including higher pain tolerance and exercise-induced hypoalgesia (Law and Sluka 2017; Song et al. 2022, 2023). Consistent with this mechanistic framework, our findings reveal higher PPTs in endurance athletes. Partial correlation analyses confirmed these links, demonstrating that self-reported physical activity was significantly associated with both enhanced IAcc and elevated PPTs, independent of group effects. This highlights the benefits of physical activity on pain and body perception (Assa et al. 2019; Geisler et al. 2021; Pettersen et al. 2020; Tesarz et al. 2012; Zeller et al. 2019) and further supports a positive relationship between IAcc and physical activity (Wallman-Jones et al. 2021).

Although not traditionally emphasised in interoception research (Weng et al. 2021), musical training has been shown to modulate IAcc (Hina et al. 2020; Schirmer-Mokwa et al. 2015) and has been associated with heightened pain perception and pain sensitivity (Zamorano et al. 2015; Zamorano, Kleber, Arguissain, Vuust, et al. 2023). In this study, musicians exhibited significantly higher heat pain sensitivity index compared to controls, consistent with previous research. While IAcc post hoc comparisons between musicians and non-trained controls did not achieve statistical significance, the pattern of results highlights a potential trend that warrants further investigation in larger cohorts. Moreover, the regression findings describing the positive relationship between accumulated practice and IAcc reinforce the hypothesis that accumulated sensorimotor experience, whether through athletic or musical training, is associated with increased IAcc.

Through repetitive engagement with fine-motor tasks and multisensory feedback, musical practice enhances motor precision (Koelsch et al. 2019) while integrating acoustic, visual, tactile and interoceptive information (e.g. muscle tension, cardiovascular and respiratory patterns) to execute accurately timed and highly complex motor sequences (Bernardi et al. 2015; Wolpert et al. 2011). Similar to athletes, musicians optimise performance by intensifying their training (Brattico et al. 2021; Gembris et al. 2020), a process requiring continuous monitoring of muscle contractile states and related metabolic conditions (Craig 2006), along with cardiorespiratory adjustments (Chanwimalueang et al. 2017; Zamorano, Zatorre, et al. 2023). Beyond these physical demands, musical training engages reward, emotional and cognitive circuits (Seth et al. 2011; Zamorano et al. 2017). Similarly, both competitive sports and musical performance require effective top-down control over emotional and physiological states to optimise performance under pressure (Niering et al. 2023). Furthermore, music perception itself consistently induces physiological variations in cardiovascular and respiratory responses (Bernardi et al. 2006), contributing to this dynamic interplay between interoception and sensorimotor performance.

We suggest that prolonged experience and training in the concurrent multimodal integration of internal bodily signals with exteroceptive information, which informs perceptual representations and action selection (Khalsa et al. 2018), might not only precede expert performance (Ladda et al. 2020) but may also enhance sensitivity to perceiving unisensory cardiac interoceptive (Ceunen et al. 2016; Schirmer-Mokwa et al. 2015; Wallman-Jones et al. 2021) and pain signals (Geisler et al. 2021; McMorris et al. 2018; Zamorano et al. 2015; Zamorano, Kleber, Arguissain, Vuust, et al. 2023).

4.2 | Interoception and Pain Sensitivity

One aspect of this study addressed the ongoing scientific discourse on the correlation between interoception and acute pain processing. Chronic pain disorders often show reduced cardiac IAcc among patients (Bonaz et al. 2021; Di Lernia et al. 2016, 2020), attributed to long-term brain alterations undermining the saliency of internal bodily signals (Di Lernia et al. 2016). However, the relationship with acute pain perception appears more nuanced, with conflicting empirical evidence.

Research conducted with non-clinical populations revealed no associations between IAcc and HPTs (Werner et al. 2009) or ischemic pain (Ferentzi et al. 2018). However, a positive association has been found with electrical pain thresholds in males (Ferentzi et al. 2021) and a negative association with PPTs (Pollatos et al. 2012; Weiss et al. 2014). Contrary to these findings, our current investigation identified a positive correlation between PPTs and IAcc across groups. A mediation analysis further clarified this relationship, highlighting a direct link between IAcc and PPTs that was not mediated by group differences. Notably, no significant effects were found for mechanical detection thresholds or heat pain thresholds, underscoring the specificity of IAcc's relationship with PPTs.

A second mediation analysis examined whether accumulated training was a mediator in the relationship between IAcc and PPTs, with group membership (athletes vs. musicians) included as a confounder to account for differential training contributions. The analysis confirmed that accumulated training robustly predicted increases in both IAcc and PPTs. However, the effect of training on PPTs was not mediated by IAcc. This finding suggests that shared mechanisms across both training modalities impact interoception and pressure pain through two distinct pathways: one in which training intensity enhances pain thresholds, and a parallel one where training improves IAcc without significantly influencing PPTs, representing complementary but independent outcomes of long-term sensorimotor training.

Altogether, these findings reinforce the relationship between interoceptive pathways and muscular pain signals. Moreover, they highlight the importance of distinguishing between superficial and deep somatic pain processes (Henderson et al. 2006; Lewin and Moshourab 2004) in exploring the relationship between interoception and acute pain, as originally proposed by Sherrington (1906). Future studies should consider such subclassifications to advance our understanding of how different pain modalities interact with interoceptive processes.

4.3 | Limitations

The interpretation of our findings should consider several limitations. First, the modest sample size may limit generalizability. Second, while the heartbeat counting task (Schandry 1981) remains widely used (Ainley et al. 2020; Critchley and Garfinkel 2017), its psychometric validity has been questioned (Brener and Ring 2016; Desmedt et al. 2018; Ring et al. 2015; Schulz and Vögele 2021; Zamariola et al. 2018). To address these concerns, we provided explicit instructions to count only perceived heartbeats, yielding scores consistent with similar studies (Hina et al. 2020; Ring et al. 2015). Third, variability in sensory integration demands between endurance and team athletes (Sheffield et al. 2020) was not controlled, and future studies should account for specific training characteristics and physiological adaptations such as 'athlete's heart syndrome'. However, the absence of a negative correlation between resting heart rate and IAcc suggests this did not bias our results. Fourth, while BMI was not assessed, none of our participants were obese, minimising this as a likely confounder (Robinson et al. 2021). Lastly, longitudinal studies are required to clarify the causal relationships between sensorimotor training, IAcc and pain processing and to explore other influencing factors such as health, socioeconomic and cognitive conditions (Wiech et al. 2008).

5 | Conclusions

These findings highlight the distinct associations between sensorimotor training, interoceptive ability and pressure pain perception, emphasising the role of integrated interoceptive and exteroceptive mechanisms in shaping bodily awareness (Chen et al. 2021; Khalsa et al. 2018). They also underscore that the links between training, interoception and pain perception are independent rather than sequential, while illustrating the broader benefits of physical activity beyond the specific effects of musical and athletic training.

Author Contributions

B.K., C.S., E.B. and A.M.Z. contributed to the conceptualisation and design of the study. B.K., C.S. and A.M.Z. contributed to the experiment setup, participants recruitment, data collection, and conducted the data analysis. B.K. and A.M.Z. drafted the article. All authors discussed the results, contributed to the interpretation and commented on the manuscript.

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