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Article

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ABSTRACT

This study presents the design, fabrication, and performance evaluation of a wearable haptic system based on electronic textiles (e-textiles) for application in advanced ensemble training, specifically within a saxophone quartet context. The core of the system is a functional textile armband engineered from a stretchable and breathable double-knit fabric (85% nylon, 15% spandex) to ensure ergonomic comfort and consistent skin contact. A series of vibrotactile actuators was directly integrated into this textile substrate. Circuitry was created using silver-coated conductive yarns, which were stitched into the fabric in a pattern designed to maintain electrical integrity under mechanical strain. This fabrication resulted in a Textile-based Haptic Metronome System (THMS) that addresses the auditory masking limitations of traditional metronomes. A crossover study involving 24 saxophone players evaluated the e-textile's performance against standard auditory metronomes (AM) and a no-metronome (NM) condition. Rhythmic accuracy and ensemble synchronization were quantified through audio analysis. Results showed that the textile-based system led to a statistically significant improvement in rhythmic accuracy, reducing mean Inter-Onset Interval (IOI) deviation by 18.5% compared to the AM ($p < 0.05$). The THMS also significantly enhanced ensemble synchronization and lowered perceived cognitive load. The findings confirm that functional fabrics incorporating haptic actuators provide an effective, non-invasive interface for complex rhythmic guidance, demonstrating significant potential for advanced textile structures as enabling platforms for wearable technology in specialized fields.

KEYWORDS

e-textiles, conductive yarns, haptic interface, wearable technology

INTRODUCTION

Rhythmic precision is a cornerstone of musical proficiency, both for solo performers and, most critically, for ensemble musicians. The ability to maintain a steady tempo and synchronize accurately with fellow musicians is fundamental to achieving a coherent and aesthetically pleasing performance [1,2]. For centuries, the primary pedagogical tool for developing this skill has been the auditory metronome (AM). By providing a consistent, audible click at a designated tempo, the AM offers a clear and objective rhythmic reference [3,4]. It is an indispensable device in practice rooms and educational settings worldwide, guiding musicians in developing an internal sense of time and mastering complex rhythmic passages [4,5]. However, reliance on the auditory channel for this rhythmic information is not without significant drawbacks, particularly in the context of ensemble playing and advanced musical interpretation [6,7].

The primary limitation of the AM is the phenomenon of auditory masking [8]. The percussive sound of the metronome can interfere with or obscure the subtle nuances of musical tone, articulation, and intonation [9]. For musicians, especially those playing instruments with rich harmonic profiles like the saxophone, listening intently to one another is paramount for achieving precise intonation and a blended ensemble sound [10,11]. An external auditory click can distract from this critical listening process, forcing musicians to split their auditory attention between the rhythmic guide and the musical performance of their peers [10,12]. This division of attention can lead to an increased cognitive load, where the mental effort required to process conflicting or competing auditory streams detracts from higher-level musical tasks such as dynamic shaping, phrasing, and emotional expression. In an ensemble setting like a saxophone quartet, where the timbres are relatively homogeneous, the ability to discern individual parts within the collective sound is crucial for tight synchronization, and an external click can disrupt this delicate balance.

In response to these limitations, researchers have explored alternative modalities for conveying rhythmic information. The tactile sense, or haptics, presents a promising alternative channel. Haptic feedback can deliver information silently and discreetly, freeing the auditory channel to focus entirely on the music itself. Early explorations into haptic metronomes involved bulky, rigid devices, but recent advancements in the field of smart textiles and flexible electronics have paved the way for more integrated and user-friendly solutions [13,14]. Smart textiles, which embed electronic components such as sensors, actuators, and conductive pathways directly into the fabric structure, allow for the creation of wearable systems that are comfortable, lightweight, and unobtrusive [15,16]. A textile-based metronome, for instance, can be worn as a simple armband or integrated into clothing, providing rhythmic pulses through small, silent vibrations directly on the

skin. This approach offers a private, non-invasive rhythmic cue that does not interfere with the auditory experience of the performer or their fellow musicians [17].

This study focuses specifically on the application and evaluation of a novel Textile-based Haptic Metronome System (THMS) within the context of saxophone ensemble performance and education. The saxophone quartet is an ideal testbed for this technology due to the high degree of precision required for rhythmic and intonational synchrony among its four members. The core research problem this paper addresses is the quantifiable impact of a textile-based haptic metronome on rhythmic accuracy and ensemble synchronization compared to a traditional AM and a baseline condition with no metronomic aid. We hypothesize that by offloading the rhythm-keeping task to the tactile domain, the THMS will reduce cognitive load, minimize auditory interference, and thereby lead to measurable improvement in both individual rhythmic precision and overall ensemble cohesion. This research aims to provide empirical data to support the viability of smart textiles as an advanced pedagogical tool for musicians at the conservatory level, offering a refined solution to the challenges posed by AM in a demanding ensemble context.

METHODOLOGY

Textile-Based Haptic Metronome System (THMS) Design and Fabrication

The THMS developed for this study was designed as a lightweight, wearable device to provide reliable tactile rhythm cues during ensemble performance. The system was implemented as a flexible armband fabricated from a double-knit stretch fabric (85% nylon, 15% spandex). The textile armband was designed to provide a snug yet compliant fit, ensuring stable actuator–skin contact without introducing rigidity or localized compression.

Five evenly spaced eccentric rotating mass (ERM) vibration motors (Model 304-101, Jinlong Machinery & Electronics; 4 mm × 8 mm) were embedded along the length of the armband. The motors were arranged linearly on the upper forearm to generate a spatially distributed haptic field, enhancing perceptual salience without relying on high-intensity stimulation from a single actuator. Vibrotactile output was characterized using a miniature accelerometer, yielding a primary vibration frequency of approximately 235 Hz at the operational voltage. Based on pilot testing, a pulse-width modulation (PWM) duty cycle of 75% was selected to ensure clearly perceptible yet non-distracting tactile cues.

The electronic circuitry was integrated into the textile using silver-coated conductive yarn (220/2 dtex)

stitched in a zigzag pattern to maintain electrical integrity under fabric deformation. A compact control unit housed a LilyPad Arduino-compatible microcontroller, a Bluetooth Low Energy (BLE) module, and a 150 mAh rechargeable LiPo battery. The total mass of the armband, including the control unit, was 45 g.

During operation, the system delivered short, pulse-based haptic stimuli synchronized to the musical tempo. All five ERM motors were activated simultaneously to produce a brief, collective vibration on each beat, with a slightly stronger pulse on the first beat of each measure for metric accentuation. After initial configuration via the tablet application, timing signals were generated locally on each microcontroller using onboard timers; BLE communication was primarily used for setup and occasional resynchronization rather than continuous high-rate data transmission.

Power consumption was evaluated under experimental conditions at a tempo of 120 BPM using the pulse-based actuation scheme described above. Owing to the low effective duty cycle of the ERM motors and the predominantly local timing control, the system exhibited a modest average current draw, allowing the 150 mAh battery to support over 10 hours of continuous operation. Thermal testing conducted during a 90-minute continuous-use session showed a maximum surface temperature increase of 3.1 °C above ambient, remaining well within safety limits for body-worn electronics.

Four identical THMS armbands were fabricated and initialized via a central tablet application to establish a common start time. Inter-unit haptic output synchronization error was quantified using an oscilloscope and miniature accelerometers, revealing a deviation of less than 2.5 ms between any two units. This confirms that hardware-induced timing discrepancies were negligible relative to the musical performance measures investigated.

Participants

Twenty-four advanced saxophone students from a university-level music conservatory participated in this study (16 male, 8 female; mean age = 21.3 years, SD = 2.1 years). All participants were majoring in saxophone performance with a minimum of eight years of formal training. All participants reported normal hearing and tactile sensation. The 24 participants were pre-organized into six established saxophone quartets (comprising soprano, alto, tenor, and baritone saxophones), each having rehearsed and performed together for at least one year prior to the study. This ensured a high level of familiarity and ensemble experience within each group. The study was approved by the Institutional Review Board, and informed consent was obtained from all participants prior to the experiment.

EXPERIMENTAL DESIGN AND PROCEDURE

A within-subjects, repeated-measures crossover design was employed to evaluate the effectiveness of the THMS. Each of the six saxophone quartets performed two musical excerpts under three distinct conditions:

- No Metronome (NM): A baseline condition in which the quartet performed without any external rhythmic aid, relying solely on their internal timing and visual cues from one another.
- AM: The quartet performed while listening to a standard digital metronome click through discreet in-ear monitors. The volume was set to a comfortable but clearly audible level chosen by each participant.
- THMS: Each member of the quartet wore and received rhythmic cues from the synchronized haptic armbands. No auditory click was provided.

The order of the three conditions was counterbalanced across the six quartets to minimize potential order effects.

Two musical excerpts were composed to represent distinct, ecologically valid performance scenarios encountered in saxophone pedagogy.

Excerpt A (Baseline/Stability Task): A 16-bar homophonic passage at 120 BPM. This tempo and simple rhythmic structure mimic standard technical etudes or march-style repertoire, serving as a baseline to evaluate rhythmic stability under low cognitive load.

Excerpt B (Complex/Cognitive Stress Task): A 16-bar polyrhythmic passage at 100 BPM. The tempo was deliberately set slower than Excerpt A to accommodate the increased technical demands of the syncopated and polyrhythmic figures, reflecting common practice in ensemble rehearsal where complex sections are often practiced at a moderated tempo.

Engineering Note: Although the tempi differ, the inter-beat intervals (500 ms for 120 BPM and 600 ms for 100 BPM) provide ample spacing between cues. While the utilized haptic pulses are shorter (~20 ms) than the motor's typical rise time (~45 ms) to conserve power, the simultaneous activation of five motors leverages the skin's spatial summation capabilities. This ensures that the haptic signal remains perceptually distinct and salient in both conditions, without requiring the motors to reach full steady-state amplitude. Key features included: (1) polyrhythmic elements, such as a recurring two-against-three pattern between the alto and tenor saxophones in measures 5–6; (2) frequent syncopation, especially in the soprano saxophone line, which contained off-beat eighth and sixteenth notes tied across beats; and (3) staggered entries, where each part entered sequentially a sixteenth note apart in the final two measures, requiring extremely precise timing to execute cleanly. The passage was designed to disrupt the performers' internal pulse and force them to rely

heavily on the external metronome cue.

Each quartet attended a single experimental session lasting approximately 90 minutes. The session began with a 15-minute introduction to the THMS, during which participants were fitted with the armbands and familiarized themselves with the haptic sensations. This was followed by the performance phase. For each of the three conditions, the quartets were given a 5-minute rehearsal period to practice both excerpts before performing the recorded trials. Each excerpt was performed twice under each condition. For rhythmic accuracy, metrics were calculated separately for each participant in each trial and then averaged across the two trials within each condition. This yielded one representative Inter-Onset Interval (IOI) deviation value per participant per condition, reducing transient variability associated with initial adaptation and execution noise.

DATA COLLECTION AND ANALYSIS

- Quantitative Analysis

The primary quantitative data were derived from the audio recordings. Two key metrics were analyzed: Rhythmic Accuracy and Ensemble Synchronization.

- Rhythmic Accuracy: The onset of each note was detected from the individual audio tracks using a custom MATLAB script. The process began with computing the Short-Time Fourier Transform (STFT) using a 1024-sample Hann window with 50% overlap. The spectral flux was then calculated as the sum of positive changes in the magnitude spectrum between consecutive frames. To identify note onsets, a peak-picking algorithm was applied to the spectral flux novelty curve. The detection threshold was adaptive, set as the output of a 200 ms moving median filter across the novelty curve plus a constant offset. Given the complex harmonic spectrum of the saxophone, relying solely on automated spectral flux detection can introduce micro-timing errors. Therefore, to ensure the highest degree of scientific rigor for the IOI analysis, the automated detections served as a preliminary dataset, which was then validated against a Gold Standard Ground Truth. This Ground Truth was established through a standardized visual inspection protocol: note onset was strictly defined as the point of the first zero-crossing immediately preceding a 10 dB rise in the signal's amplitude envelope. This protocol ensures that the validation process was objective, rule-based, and reproducible, eliminating subjective bias in the timing data. The IOI, which is the time duration between two consecutive note onsets, was calculated for each player. Rhythmic accuracy was quantified as the absolute deviation of the measured IOI from the ideal, notation-based

IOI. The mean absolute deviation, expressed in milliseconds (ms), was calculated for each participant for each condition. A lower value indicates higher rhythmic accuracy.

- **Ensemble Synchronization:** To rigorously quantify the rhythmic cohesion of the quartet as a unified system, we employed a Global Pairwise Cross-Correlation method, rather than relying on a single instrument as a reference. The amplitude envelopes of all four audio tracks were extracted using the same rectification and low-pass filtering process (50 Hz cutoff). We calculated the cross-correlation for all possible unique pairs within the quartet (Soprano-Alto, Soprano-Tenor, Soprano-Baritone, Alto-Tenor, Alto-Baritone, and Tenor-Baritone), resulting in six distinct synchronization metrics for each performance. The lag time at peak correlation was determined for each pair. The Mean Synchronization Error (MSE) was then derived by averaging the absolute lag times of all six pairs. This approach eliminates the bias of assuming a fixed leader and provides a robust, decentralized measure of the ensemble's overall temporal tightness.

Immediately following the trials for each condition, participants completed a survey to assess their subjective experience.

- **Cognitive Load:** The NASA Task Load Index (NASA-TLX) was used to measure perceived cognitive workload. This is a multidimensional rating scale that assesses workload across six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration.
- **System Usability:** After the THMS condition, participants completed the System Usability Scale (SUS), a standard 10-item questionnaire for assessing the perceived usability of a system.
- **Qualitative Feedback:** Participants also provided open-ended written feedback on their experience with the THMS, focusing on its comfort, intuitiveness, and perceived effect on their performance.

Statistical analysis was performed using SPSS. Given the hierarchical nature of the data, different approaches were employed for individual and group-level metrics.

For Rhythmic Accuracy (IOI deviation), which represents individual-level data, a linear mixed-effects model (LMM) was employed to account for the non-independence of participants nested within quartets. The model included the metronome condition as a fixed effect and the quartet ID as a random effect. Degrees of freedom were estimated using the Satterthwaite approximation.

For Ensemble Synchronization (MSE), which is a group-level metric (one value per quartet per condition), a repeated-measures ANOVA was conducted with the metronome condition as the within-subjects factor.

RESULTS

The study yielded quantitative data on performance accuracy and synchronization, as well as qualitative data on user experience. The analysis reveals significant differences in performance outcomes across the three metronome conditions.

Rhythmic Accuracy

The analysis of IOI deviation revealed a significant main effect of the metronome condition on the rhythmic accuracy of the performers, $F(2, 38.4) = 15.89, p < 0.001$. This indicates that the type of rhythmic guidance provided had a substantial impact on the precision of individual players.

Post-hoc comparisons using the Bonferroni correction showed that both the AM and the THMS led to significantly higher rhythmic accuracy (lower IOI deviation) compared to the NM condition ($p < 0.001$ for both). This confirms the fundamental role of an external tempo reference in maintaining rhythmic stability.

Crucially, the comparison between the AM and THMS conditions revealed a statistically significant difference. The mean IOI deviation in the THMS condition ($M = 22.4$ ms, $SD = 4.8$ ms) was significantly lower than in the AM condition ($M = 27.5$ ms, $SD = 5.9$ ms), with $p = 0.012$. This represents an average reduction of 18.5% in rhythmic error when using the haptic system compared to the traditional auditory click. The baseline NM condition showed the highest deviation ($M = 45.1$ ms, $SD = 8.2$ ms). A summary of these results is presented in Table 1 and visualized in Figure 1.

Table 1. Mean IOI Deviation and Mean Synchronization Error Across Conditions

Condition	Mean IOI Deviation (ms)	Standard Deviation	Mean Synchronization Error (MSE) (ms)	Standard Deviation
No Metronome (NM)	45.1	8.2	38.6	7.5
Auditory Metronome (AM)	27.5	5.9	24.1	5.3
Textile Haptic (THMS)	22.4*	4.8	17.2**	4.1

Note: * $p < 0.05$; ** $p < 0.01$ (THMS vs. AM).

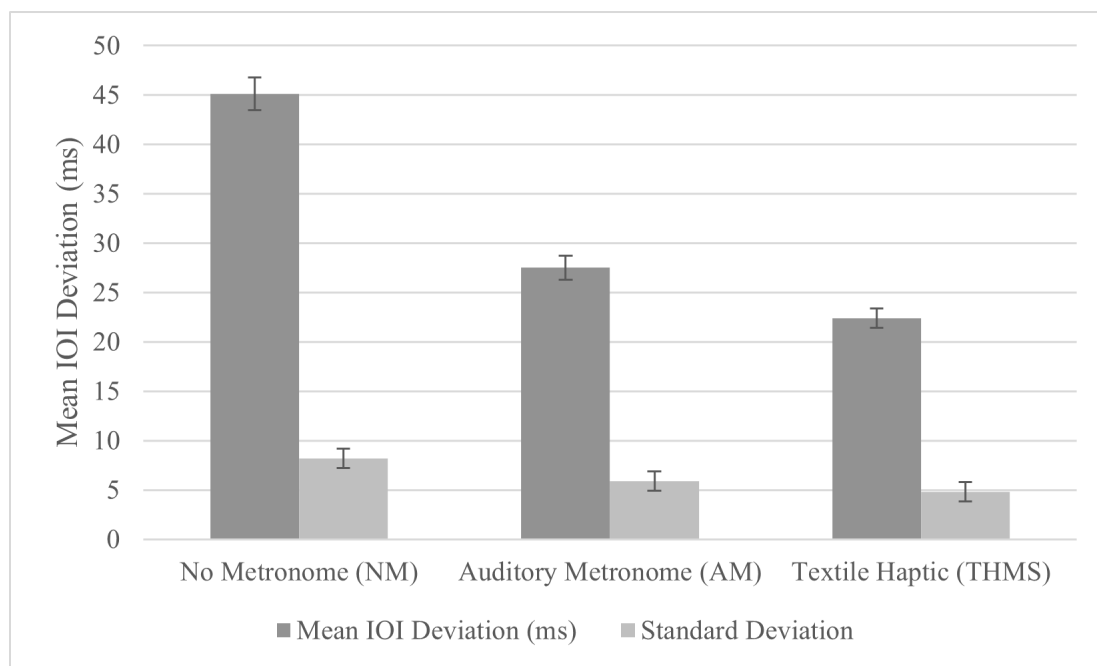


Figure 1. Mean Inter-Onset Interval Deviation Across Conditions

Ensemble Synchronization

The analysis of MSE, which measures the temporal alignment between the four quartet members, also showed a significant effect of the metronome condition, $F(2, 10) = 13.92$, $p = 0.001$. This strong effect size indicates that the choice of metronome profoundly impacted the quartet's ability to play together.

Post-hoc tests revealed that synchronization was significantly worse in the NM condition compared to both the AM and THMS conditions ($p = 0.005$ and $p = 0.001$, respectively). The most important finding was the comparison between the AM and THMS. The MSE was significantly lower in the THMS condition ($M = 17.2$ ms, $SD = 4.1$ ms) than in the AM condition ($M = 24.1$ ms, $SD = 5.3$ ms), with $p = 0.008$. This demonstrates that the haptic system enabled the quartets to achieve a tighter level of rhythmic cohesion than the AM. The results are detailed in Table 1.

Subjective User Experience

- Cognitive Load

The NASA-TLX results, summarized in Table 2, indicate that the perceived cognitive load was highest in the AM condition (Overall Workload $M = 58.1$) and lowest in the THMS condition (Overall Workload $M = 34.9$). The NM condition fell in between (Overall Workload $M = 45.5$). A repeated-measures ANOVA on the overall

workload score was significant, $F(2, 46) = 11.91, p < 0.001$. Participants reported the highest Mental Demand and Frustration levels when using the AM, often citing the challenge of separating the click from the music. In contrast, the THMS condition received the lowest scores in Mental Demand, Effort, and Frustration.

Table 2. Mean NASA-TLX Subscale Scores (0–100 scale)

NASA-TLX Subscale	No Metronome (NM)	Auditory Metronome (AM)	Textile Haptic (THMS)
Mental Demand	55.2	72.5	40.8
Physical Demand	30.1	31.5	32.0
Temporal Demand	50.8	68.0	44.5
Performance	42.5	35.0	28.8
Effort	53.0	65.5	41.5
Frustration	41.3	76.0	21.5
Overall Workload	45.5	58.1	34.9

- Usability and Qualitative Feedback

The THMS received a high mean SUS score of 88.5 (SD = 6.2), which falls in the excellent range and indicates a high degree of user acceptance.

The qualitative feedback from the open-ended questions was overwhelmingly positive. A recurring theme was the non-invasive nature of the haptic cues. One participant wrote, “With the armbands, the beat felt like it was just part of me. I could stop thinking about it and just listen to my partners.” Another commented, “The click track always feels like a battle. I’m fighting to hear the other players over it. The vibration was a quiet guide that let me focus 100% on our sound.” Several participants noted that the THMS was particularly helpful in navigating the complex rhythmic passages in Excerpt B, where auditory cues could become confusing. Some minor negative feedback related to the desire for customizable vibration patterns, but the overall sentiment was that the THMS was a more intuitive and less distracting tool for ensemble rehearsal.

DISCUSSION

The results of this study provide strong empirical support for our hypothesis that a textile-based haptic metronome can enhance rhythmic performance in a saxophone ensemble beyond the capabilities of a traditional AM. The quantitative data showed statistically significant improvements in both individual rhythmic accuracy and overall ensemble synchronization when participants used the THMS compared to the AM. This suggests that delivering rhythmic information through the tactile modality offers distinct advantages over the conventional auditory channel in a musically complex, multi-performer environment.

The observed 18.5% reduction in mean IOI deviation with the THMS is a noteworthy finding. While a deviation measured in milliseconds may seem small, this level of precision is critical in a musical context. A reduction of this magnitude (from 27.5 ms to 22.4 ms) contributes to a perceptibly tighter and more rhythmically secure performance, particularly in passages with rapid notes where even minor inconsistencies can make the music sound unclear or muddy. The NASA-TLX data provide a nuanced view of cognitive load that clarifies the advantages of the haptic system. Crucially, the NM condition should not be viewed as a zero-load baseline; it required significant mental effort for internal timekeeping and intense visual monitoring to maintain ensemble cohesion, resulting in a moderate overall workload score (45.5). The AM condition imposed the highest cognitive load (58.1), as it added the demanding task of auditory stream segregation—mentally separating the non-musical click from the rich musical information—to the existing performance demands. This context highlights why the THMS yielded the lowest overall workload (34.9). The haptic system appears to offer the most cognitively efficient strategy for rhythmic guidance. By providing an external tempo reference, it alleviates the burden of self-regulated timekeeping required in the NM condition. Simultaneously, by using a separate and unoccupied sensory channel, it avoids the high-cost auditory interference associated with the AM. This effective offloading of the timekeeping task is reflected not only in the participants' subjective workload ratings but also in their objective improvements in rhythmic accuracy and synchronization.

The improvement in ensemble synchronization is perhaps the most critical finding for music education. The primary goal of an ensemble is to perform as a single, cohesive unit. The data, which showed a significant reduction in MSE with the THMS, indicate that the haptic system facilitated a tighter rhythmic alignment among the quartet members. To place this finding in a practical context, timing discrepancies between musicians become perceivable at around 10–20 ms. The MSE in the AM condition (24.1 ms) and even the improved THMS condition (17.2 ms) fall within this perceivable range. Therefore, the reduction in error

achieved with the THMS represents a musically meaningful improvement, moving the ensemble closer to a unified sound where simultaneous notes strike as one, rather than sounding slightly staggered or flammed. This can be attributed to the private and direct nature of the haptic cue. With an auditory click delivered via in-ear monitors, each player is essentially synchronizing to an external source independently. While this is effective, the ultimate goal is for players to synchronize with each other. The THMS appears to foster this internal synchronization more effectively. By providing a subtle, internal-feeling pulse, it acts as a shared, silent reference that helps align the players' internal clocks without distracting them from listening to one another. As one participant noted, the haptic cue allowed them to "just listen" to their partners, which is the essence of high-level ensemble playing. The haptic system serves as a scaffold, supporting the rhythmic structure privately so that the players can focus their overt attention on musical interaction.

From a textile engineering perspective, the study validates the use of smart textiles as a viable platform for creating functional and user-accepted wearable technology for musicians. The choice of a stretchable, breathable fabric combined with flexible conductive thread circuitry resulted in a device that was deemed highly usable and comfortable, as reflected in the excellent SUS score. This is a crucial factor for adoption; if a wearable device is cumbersome or uncomfortable, it will not be used, regardless of its technical benefits. The successful implementation of the THMS demonstrates that it is possible to create sophisticated electronic systems that feel less like external gadgets and more like an integrated piece of apparel—a key principle in the design of truly wearable technology. The integration of electronics within the textile itself, rather than attaching a rigid box to a strap, is a significant step forward for devices in this domain.

Despite the promising results, this study has several limitations. First and foremost, the study's findings are specific to the population of advanced, university-level saxophone players. The homogeneity of this participant pool means that the results may not be generalizable to musicians of other skill levels, such as beginners, or those who play different instruments with distinct pedagogical needs. Furthermore, while all participants were categorized as advanced, the study did not attempt to stratify skill levels within this cohort. It is plausible that even among advanced musicians, there is significant variation in innate rhythmic precision. This could mean that the benefits of the THMS are not uniform; for instance, a performer with an exceptionally stable internal metronome might gain less from the haptic cue than an equally talented peer for whom rhythmic synchronization remains a greater challenge. Future studies could incorporate a pre-screening assessment of rhythmic acuity to explore how the efficacy of a haptic system correlates with a musician's baseline skill. The research was conducted in a controlled laboratory setting with short, specifically

designed musical excerpts that maintained a steady tempo. While this approach was necessary to isolate rhythmic variables, it does not capture the full spectrum of challenges encountered in authentic musical performance. For example, the excerpts did not include gradual tempo changes (*accelerando/ritardando*), expressive timing variations (*rubato*), or the physical and cognitive demands of an extended performance. Consequently, the current findings on the THMS's efficacy are most applicable to rhythmically stable contexts. The long-term effects of using the THMS in regular, extended rehearsals and its efficacy across a broader range of musical styles and dynamic temporal conditions remain to be explored. Furthermore, the participants were all advanced, university-level musicians. The benefits and potential challenges of using such a system with novice players, who are still developing a foundational internal sense of rhythm, would be a valuable area for future research. It is possible that for beginners, the explicit and ever-present nature of an auditory click is a more necessary pedagogical tool. Future iterations of the THMS could also incorporate more sophisticated feedback mechanisms, such as adaptive haptic patterns that respond to a player's rhythmic deviations, moving from a metronomic tool to a more interactive coaching system.

CONCLUSION

This study investigated the application of a THMS in saxophone ensemble performance, directly comparing its effects on rhythmic accuracy and synchronization with a traditional AM and a no-metronome condition. The findings demonstrate that the THMS yielded statistically significant improvements in both individual rhythmic precision and ensemble cohesion. Performers using the haptic system exhibited fewer timing errors and tighter synchronization than when using the AM. Furthermore, subjective assessments revealed that the THMS induced a significantly lower cognitive load and was perceived as a highly usable and intuitive tool. The results strongly suggest that by transferring rhythmic guidance from the overloaded auditory channel to the tactile channel, smart-textile-based systems can offer a more effective and less intrusive method for rhythm-keeping in a demanding ensemble context. This research contributes to the fields of music pedagogy and textile engineering by demonstrating the potential for wearable, haptic technology to address long-standing challenges in advanced instrumental ensemble training, providing a clear direction for developing next-generation pedagogical tools for highly skilled musicians. Future work should explore the longitudinal effects of THMS integration in regular practice and its applicability to different musical genres and skill levels.

Author Contributions

Jiaqi Zhao designed, collected and analyzed the data, and drafted the manuscript. Jiaqi Zhao conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Jiaqi Zhao participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of Interest

The author declares no conflict of interest.

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Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Ethics Approval and Consent to Participate

This survey was conducted in compliance with Ethics Committee of China Conservatory of Music. Participants were informed of the study's purpose and data usage prior to participation, and responses were collected anonymously. No personally identifiable information was stored.

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Not applicable.

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