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Drum Performance Support Utilizing Vibrotactile and Electrical Stimulation

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Accurate rhythm perception and coordinated four-limb control are fundamental for drum performance; however, beginners often struggle to maintain stable timing and independent limb movements. Conventional auditory or visual cues provide limited integration with bodily motion, reducing their effectiveness in supporting precise rhythm acquisition. To address this limitation, in this study, we investigated a training system that employs vibrotactile stimulation and electrical muscle stimulation (EMS) as embodied feedback. Vibrotactile cues provide clear beat timing through brief cutaneous pulses, whereas EMS induces muscle contractions that can guide limb movements that novices find difficult to execute. We developed a system that synchronizes tactile beat cues and EMS-based movement assistance with musical tempo, and conducted experiments to evaluate its training effectiveness. The results indicate that embodied feedback can enhance rhythm accuracy and motor coordination, demonstrating the potential of this approach for music training and related motor-learning applications.

1. Introduction

Goodwin *et al.* reported that applying vibration of approximately 80–100 Hz to the muscle–tendon complex induces an illusory sensation of joint movement, even in the absence of any actual physical displacement.(1) This phenomenon, known as vibration-induced movement illusion, has been applied in various rehabilitation contexts. In drum performance, it may similarly enhance rhythm acquisition by inducing the sensation of correct movement timing prior to the learner's full understanding of the rhythmic structure.

Albert *et al.* demonstrated that returning Ia afferent signals originating from ankle movements back to the participant can induce the illusion of performing the same movement.(2) Their study focused on the muscles surrounding the ankle joint, specifically the peroneus lateralis, the gastrocnemius–soleus complex, and the tibialis posterior—major muscle groups controlling left-ankle motion. Ia afferent patterns recorded from these muscles were converted

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vibration stimuli and fed back to the participant. In other words, vibration stimuli mimicking the firing patterns of muscle spindles evoked the sensation of ankle motion despite the absence of actual limb movement.

Eschelmüller *et al.* investigated elbow-extension illusions induced by tendon vibration. By applying 40–120 Hz vibration to the biceps brachii tendon, they measured the intensity and frequency of the resulting illusions and found that 40 and 60 Hz produced the strongest effects.[3] They also reported differences between right- and left-handed individuals: left-handed participants showed less frequency-dependent variability and more stable illusion perception. Furthermore, nondominant arms exhibited stronger and more consistent illusions than dominant arms. These findings suggest that proprioceptive integration and motor perception are modulated by handedness characteristics.[4]

Research on haptic feedback has been rapidly expanding. Holland *et al.* proposed the "Haptic Drum Kit," a tactile-feedback system designed to improve rhythm performance involving multiple limbs.[5] In their system, vibration devices attached to a drummer's hands, feet, and drumsticks deliver tactile cues synchronized with beats and rhythmic patterns, providing timing information that may be difficult to perceive through auditory cues alone. Experimental results showed that the tactile cues improved strike timing accuracy and enhanced multilimb coordination in complex rhythmic tasks, demonstrating the potential of tactile feedback for rhythm learning and performance support.

In addition to sensory stimulation, electrical stimulation aimed at inducing muscle contraction has also been widely studied, particularly in rehabilitation. Liberson *et al.* developed the first functional electrical stimulation (FES) system that synchronized electrical stimulation with gait.[6] Their device detected the gait cycle using a heel switch attached to the shoe and delivered rectangular pulses to the peroneal nerve during the swing phase, inducing dorsiflexion via the contraction of the tibialis anterior. This pioneering attempt demonstrated effectiveness for foot-drop correction and later became the foundation of modern FES-assisted gait systems.

Since then, electrical muscle stimulation (EMS) has been applied to not only rehabilitation but also recreating force sensations and movement experiences. Uddin *et al.* provided a systematic review of EMS-based kinesthetic feedback for AR/VR applications.[7] EMS offers the lightweight and rapid generation of force or movement sensations through induced muscle contractions, enabling applications such as collision feedback, weight sensation, and guided motion. They noted challenges including individual variability, comfort, and fine tactile reproduction, while emphasizing future potential through multichannel control, AI-based optimization, and integration with other haptic modalities.

Ebisu *et al.* proposed stimulated percussion, a method that uses EMS to directly control the human body and generate percussion performance.[8] Unlike purely illusory stimuli, their approach enables dynamic, physically executed movements through electrical stimulation. Inspired by their EMS-based system and considering the complementary benefits of vibration-induced movement illusions, we investigated both EMS and vibrotactile stimulation (VTS) as potential methods for supporting novice drummers.

2. Proposed Drum Performance Support System

The proposed system is designed to assist novice drummers in acquiring rhythm accuracy and multilimb coordination by integrating VTS and EMS into the practice environment. The system aims to provide both perceptual and motor-level guidance by synchronizing tactile cues and muscle activations with musical tempo and rhythmic patterns.

2.1 Rationale for effectiveness of sensory stimulation in drum performance

According to the hypothesis proposed by Ebisu *et al.*,[8] as illustrated in Fig. 1, skilled drummers generate precise muscle contractions by transmitting motor commands from the brain to the relevant muscle groups through motor nerves. These contractions produce the downward motion of the drumstick at the intended timing. The resulting movement is conveyed back to the brain via sensory afferents, enabling the accurate perception of one's own motion and facilitating stable rhythm maintenance.

In contrast, novice drummers often struggle to produce strokes at the correct timing, as their ability to generate appropriate motor commands has not yet developed sufficiently. Consequently, their strike timing becomes unstable, and coordination among the limbs is easily disrupted.

To address this limitation, external electrical or vibrotactile stimulation can be delivered at the correct timing to support or induce the required striking motion. Even when a beginner is unable to generate appropriate motor commands, the externally induced movement is fed back to the brain as sensory information, allowing the performer to experience the correct motor timing. This externally guided motion is expected to be particularly effective during the early stages of motor learning, promoting the acquisition of rhythm accuracy and enhancing sensorimotor integration.

An important consideration arises when comparing VTS delivered through vibration motors with low-intensity EMS that does not induce substantial muscle contraction. In these cases, sensory feedback—such as timing cues or vibration-induced movement illusions—can be

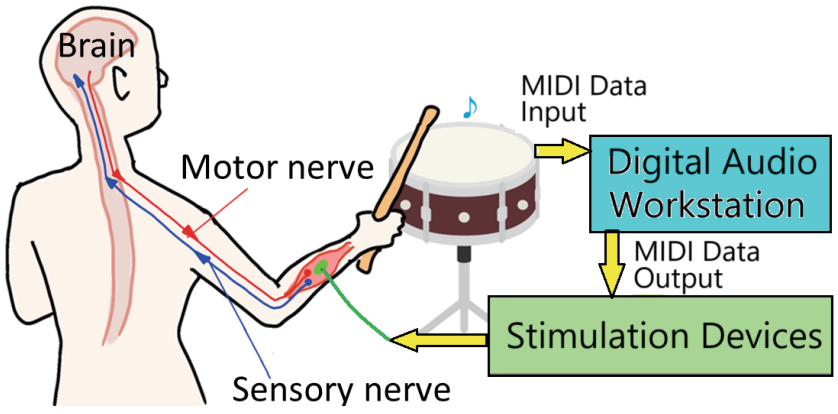


Fig. 1. (Color online) Schematic diagram of experimental system.

provided simply by presenting the stimulus at the moment when the drum should be struck. In such situations, the precise timing of the stimulus onset is not critically constrained.

However, when using EMS at voltages sufficient to elicit notable muscle contractions, as compared to voltages that are merely perceptible without causing contraction, the timing of the stimulation must be carefully controlled. After an EMS pulse is delivered, a delay occurs before the muscle begins to contract, followed by the downward motion of the drumstick and the final impact on the drum surface. Although the exact duration varies among individuals, this sequence typically requires approximately 200 ms (the detailed experimental measurements are presented in a later section).

Therefore, to ensure that the drum is struck at the correct musical timing, the EMS stimulus must be issued approximately 200 ms in advance. If this anticipatory stimulation is not correctly calibrated, the resulting strike timing will deviate from the intended beat, reducing the effectiveness of the training. This timing management is a critical aspect of the proposed support system.

2.2 System overview

The proposed drum performance support system integrates Musical Instrument Digital Interface (MIDI) analysis, stimulus presentation, and performance recording, as illustrated in Fig. 2. The system operates through the following four stages:

(1) Playback of MIDI Data Containing Drum Notation

MIDI data created in a Digital Audio Workstation (DAW) are played back and transmitted to an Arduino MEGA equipped with a MIDI shield via a USB–MIDI interface [Fig. 2(i)].

(2) MIDI Parsing and Generation of Instruction Signals

MIDI files contain information such as instrument type, note number, note-on and note-off timings, and velocity.

In this study, the drum track is analyzed, and note-on timings corresponding to the following three percussion instruments are extracted:

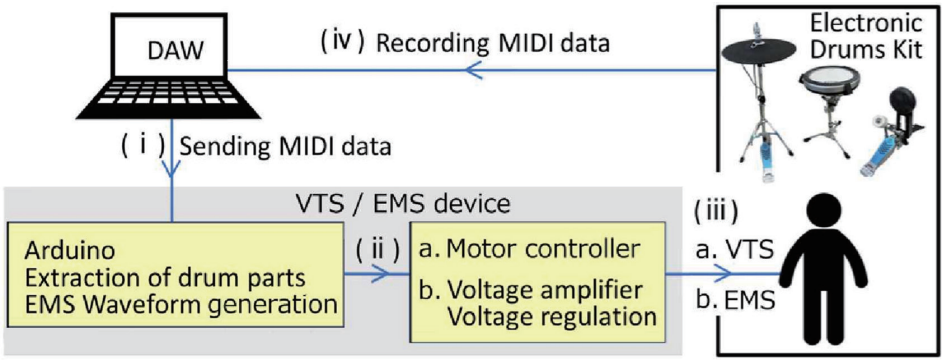


Fig. 2. (Color online) Experimental system layout showing signal flow and components.

- closed hi-hat (right hand),
- snare drum (left hand), and
- bass drum (right foot).

With these three timing channels, instruction signals for stimulation devices are generated [Fig. 2(ii)].

a. VTS
Command signals are generated for vibration motors corresponding to each channel.

b. EMS

For each channel, the system generates stimulation command signals and the EMS waveform required for electrical stimulation. Details on motor points and waveform parameters are described in later sections.

(3) Delivery of Stimulation to Muscles

On the basis of the generated commands, VTS or EMS is delivered to the muscles associated with each channel [Fig. 2(iii)].

a. VTS
Drive signals are transmitted to the vibration motors attached to each target muscle.

b. EMS
EMS waveforms are delivered to the electrode pads attached to each target muscle.

(4) Recording of Performance Data

The performer's actual closed hi-hat, snare drum, and bass drum strikes are recorded as MIDI data and transmitted to a PC [Fig. 2(iv)]. This allows the quantitative analysis of how the presented stimuli affect performance timing.

2.3 Overview of stimulation delivered to muscles

2.3.1 VTS using vibration motors

2.3.1.1 Placement of vibration motor

For VTS, the vibration motor was initially attached near the proximal region of the flexor carpi ulnaris (FCU), which spans from the medial side of the elbow to the base of the pisiform and contributes to wrist and hand movements [Fig. 3(a), cited from Ref. 9]. The attachment position is shown in Fig. 3(b).

Fujii *et al.* compared wrist muscle activity during high-speed repetitive single-hand drumming between expert drummers and non-drummers.[10] Their measurement included the FCU—responsible for wrist flexion and ulnar deviation—and an extensor muscle. They found that experts exhibited a reduced co-contraction of flexors and extensors, as well as more stable on/off activation timing, enabling efficient and accurate strikes. This indicates that optimized neuromuscular control and efficient FCU utilization are key factors for skilled drumming.

We consider that the FCU contributes to wrist palmar flexion, ulnar deviation, and the stabilization of the ulnar side of the forearm and wrist. Furthermore, prior EMS studies such as Ref. 8 also stimulated this region; thus, preliminary VTS experiments were conducted with the motor attached at this location.

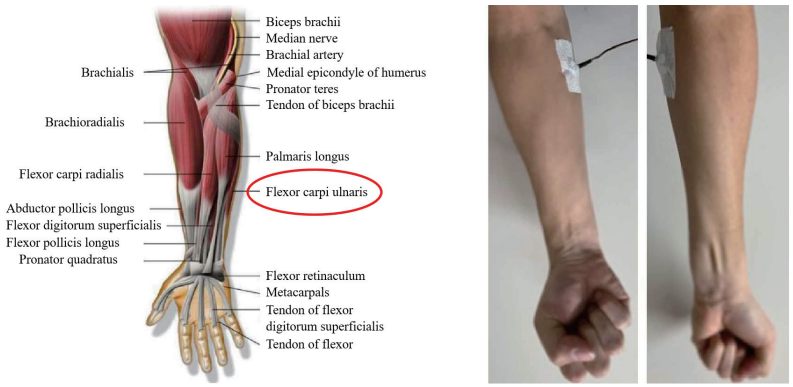


Fig. 3. (Color online) Stimulation devices attached to each muscle. (a) Flexor muscles and tendons of forearm. (b) Placement locations for vibration motors.

However, participants reported that vibration intensity was insufficient at this site. Therefore, the motor was shifted slightly medially toward the medial antebrachial cutaneous nerve—responsible for sensitive cutaneous perception—and attached at each participant's most perceptible location.

Regarding the right leg, priority was similarly placed on cutaneous sensitivity. The motor was attached near the common fibular nerve, which innervates the tibialis anterior and fibularis muscles and provides sensory input to the dorsum of the foot [Fig. 4(a), cited from Ref. 11; Fig. 4(b)].

2.3.1.2 Vibration motor specifications

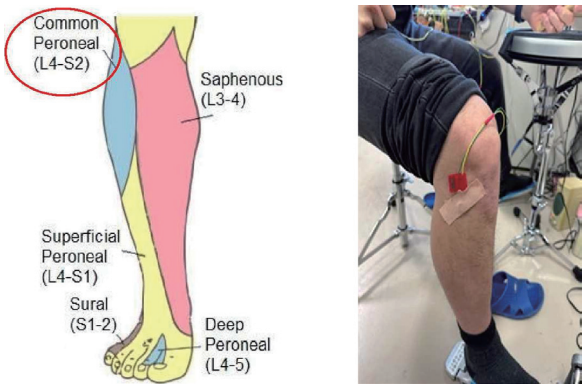
A flat-type vibration motor (FM34F, T.P.C. Co.) was used. Its specifications are as follows: 12 mm diameter, 3.4 mm thickness, 3 V rated voltage, 13000 rpm rotational speed, and approximately 1.8 G vibration amplitude. This model is commonly used in mobile phones and generates vibrations at roughly 2167 Hz.

Measurements using a microphone detected a 106 Hz peak in the motor's acoustic vibration. When the motor was attached to the arm and recorded with a bone-conduction microphone positioned 5 cm away, a dominant peak appeared at 56 Hz.

Since inducing movement illusions via vibration typically requires 40–60 Hz, this frequency range is considered appropriate. Manual testing confirmed that the vibration was able to evoke a kinesthetic illusion. A wider propagation of vibration through the musculature is desirable; however, in this study, stimulation intensity was prioritized to maximize cutaneous sensation.

Regarding the motor activation duration, at a tempo of 80 BPM, one beat corresponds to 750 ms and an eighth note to 375 ms. Using such long durations caused overlap with adjacent notes, leading to ambiguous rhythmic perception, and a prolonged vibration made it difficult to detect the onset timing.

Therefore, on the basis of empirical observations, the duration was set to 120 ms.



(a) (b)

Fig. 4. (Color online) Stimulation devices attached to each muscle. (a) Bifurcation of the common fibular nerve. (b) Placement locations for vibration motors.

2.3.2 EMS

2.3.2.1 Placement of EMS pads

The EMS electrodes were attached along the FCU of both arms [Fig. 5(a), cited from Ref. 9], as shown in Fig. 5(b). The position was slightly adjusted for each participant to ensure optimal muscle contraction. For the right leg, electrodes were placed along the gastrocnemius muscle [Fig. 6(a), cited from Ref. 12; Fig. 6(b)].

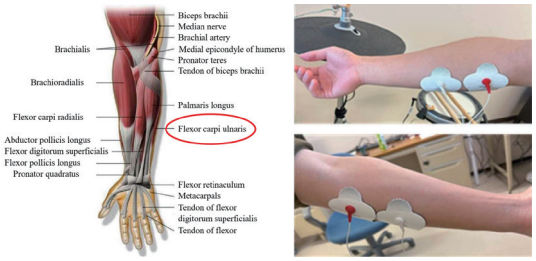
2.3.2.2 EMS device

As shown in Fig. 7, the EMS device was built with reference to the multi-channel EMS toolkit proposed by Kono *et al.*[13,14] and its publicly available schematics. The circuit consists of a voltage regulation stage and a signal amplification stage. The voltage regulation circuit is powered from the 5 V terminal of an Arduino, whereas the signal amplification circuit uses an external power supply; the power and ground lines of these circuits are electrically isolated. The key specifications are as follows.

- The terminal enclosed by a red oval in Fig. 8 is connected to pin 22 of the Arduino Mega. Unless this pin outputs HIGH, electrical stimulation is inhibited, even if pulse signals are generated by the Arduino.
- The terminal in the green box receives pulse-signal input from the Arduino.
- The terminal in the blue box is connected to pin 23 of the Arduino Mega. When this pin outputs HIGH, the boosted-voltage circuit is discharged.

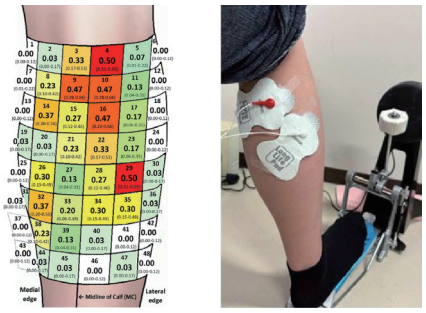
2.3.2.3 EMS electrodes

Omron's Long Life Pads (HV-LLPADs), typically used in household low-frequency therapy devices, were used. The specifications are as follows.



(a) (b)

Fig. 5. (Color online) Stimulation devices attached to each muscle. (a) Flexor muscles and tendons of forearm. (b) Placement locations for EMS pads.



(a) (b)

Fig. 6. (Color online) Stimulation devices attached to each muscle. (a) Motor point distribution map of gastrocnemius. (b) Placement locations for EMS pads.

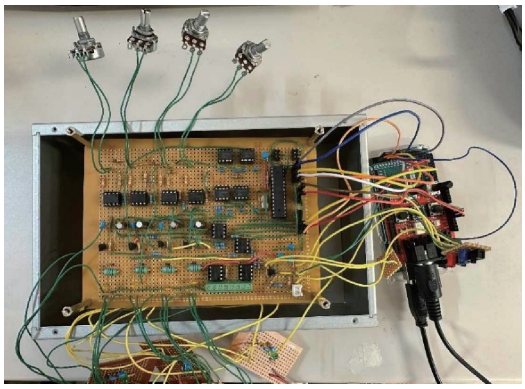


Fig. 7. (Color online) External view of EMS device fabricated on the basis of circuit diagram.

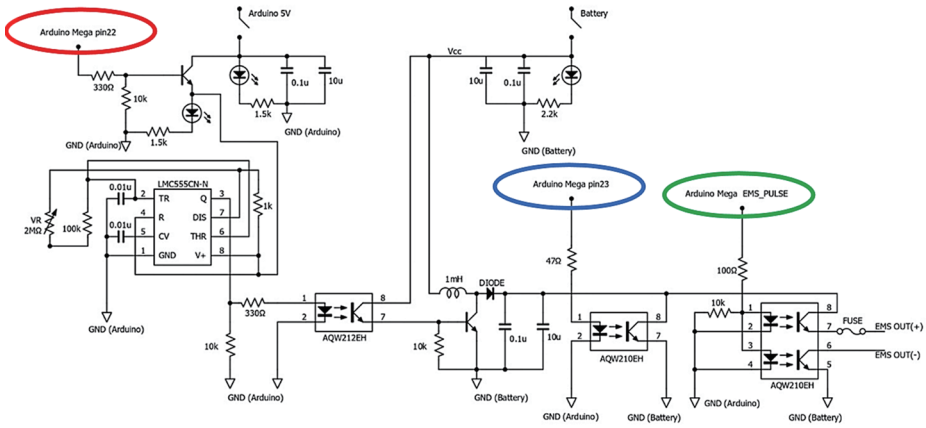


Fig. 8. (Color online) Circuit diagram for signal amplification and voltage regulation (Channel 1 only), reproduced from Ref. 14.

- Size ($H \times W \times D$): 3.9 × 2.5 × 0.06 in^3 (98 × 62 × 1.6 mm^3)
- Weight: 0.2 oz (6.5 g)
- Material: PMMA (cross-linked acrylic resin)

2.3.2.4 Output EMS pulse waveform

As shown in Fig. 9, the pulse waveform had a pulse width w = 200 μs and a frequency f = 70 Hz, corresponding to a period $T = 1/f \approx 14.3$ ms. Two cycles of this pulse were delivered for each EMS stimulation event.

The maximum output voltage was approximately 114 V, and the current under a 500 Ω load was 0.227 mA. The pulse energy was approximately 0.37 mJ, well below the limits specified by JIS standards and the Japan Home-Health Apparatus Industrial Association.[15] Although biphasic pulses are generally preferable, monophasic pulses were used in this study.

Regarding safety, the multi-channel EMS device employs an isolated architecture in which each channel is independently controlled. This design prevents unintended current flow or malfunction across channels, ensuring safe and precise operation even when multiple channels are activated simultaneously.

Solid-state photo-MOS relays, rather than mechanical relays, and a boost converter are used to improve control accuracy and safety. The rise and fall times of the relays were explicitly considered to prevent excessive current spikes or unintended pulses.

Pulse-timing control was implemented using the delayMicroseconds() function provided by the Arduino framework (a built-in delay function with microsecond resolution). The Arduino Mega was selected for its improved timing stability. The firmware was carefully designed to avoid unstable timing or incorrect pulse widths that could lead to overstimulation.

2.3.2.5 Safety considerations and determination of stimulation intensity

EMS intensity was carefully adjusted following the standard three-step threshold protocol:

1. sensation threshold — the lowest intensity at which the participant perceives a tingling sensation,
2. comfortable threshold — a non-painful and non-irritating level, which was the intensity used in the experiment, and
3. motor threshold — the lowest intensity at which slight muscle movement occurs.

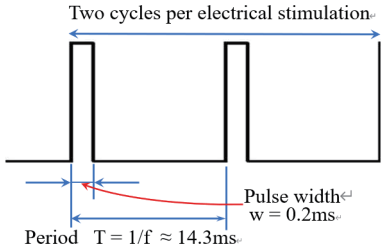


Fig. 9. (Color online) Pulse waveform generated per electrical stimulation.

During a session, intensity was gradually increased, beginning at 60–70% of the target level. To avoid fatigue-induced reductions in sensory thresholds and ensure safety, continuous stimulation longer than 15 min was prohibited.

This experiment was approved by the Ethics Committee of the Faculty of Engineering, University of Fukui (Approval ID: H2023002). All participants were informed of the experimental procedures and provided written consent. They were allowed to stop the experiment at any time at their own discretion.

3. Experimental Methods

As shown previously in Fig. 2, the instructional MIDI data—serving as the reference performance— were played back on a PC. During playback, the reference audio was output through speakers while the drum-pattern commands embedded in the MIDI data were transmitted to the VTS/EMS device via a USB–MIDI interface.

Participants performed by imitating the reference under one of three conditions: no assistance, VTS assistance, or EMS assistance. Their performance data were recorded on the PC.

A YAMAHA DTX-PRO electronic drum set[16] was used for the experiment. Performance data were recorded using DAW software. By comparing the stimulation data and the recorded performance data, the quality of the performance could be quantitatively evaluated.

3.1 Evaluation method for drum performance

The onset times of the notated musical events in the score and the participant's performance were compared for each note (Fig. 10).

The synchronization error for each note was defined as

$$TL_i = \left| a_i - b_i \right|, \tag{1}$$

where a_i denotes the onset timing specified in the score (reference data) and b_i denotes the onset timing of the participant's performance.

The mean synchronization error across N notes was then calculated as

$$\overline{TL} = \frac{1}{N} \sum_{i=1}^{N} TL_i. \tag{2}$$

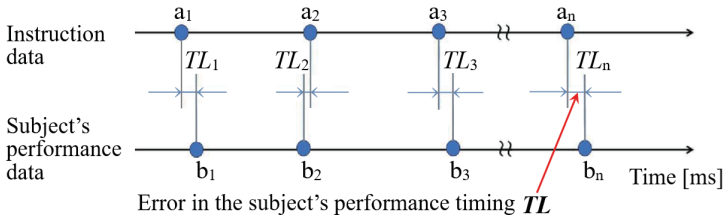


Fig. 10. (Color online) Evaluation methods for subjects' performance data.

The rhythm pattern used in this study was an eight-beat pattern at 80 BPM; therefore, one beat (i.e., a quarter note) corresponded to 750 ms. Notes occurring within ±1/4 beat (±187.5 ms) relative to the reference timing were classified as valid hits and included in the evaluation. Hits falling outside this window, as well as additional unintended hits, were treated as errors.

Although this temporal window is perceptually lenient compared with the precision expected of skilled drummers, it remains sufficiently demanding for novice participants. Accordingly, it was adopted as a practical criterion for evaluating beginner-level performance.

3.2 Analysis and compensation of system latency

3.2.1 Baseline latency of electronic drum set

The monitor speaker for the electronic drum set and the PC audio output were placed approximately 2 m from the participant's ears.

Given an experimental temperature of approximately 20 °C, the speed of sound was calculated as

$$331.5 + 0.6 \times 20 = 343.5 \text{ m/s}. \tag{3}$$

Thus, the reference sound reached the participant with a delay of approximately 5.8 ms.

Participants listened to a metronome sound to establish a timing reference and practiced striking the snare drum until the perceived timing felt synchronized. Their performance sound was mixed into the same speaker output. No participant reported perceiving latency at this stage.

3.2.2 Latency from MIDI playback to VTS/EMS command output

Next, the MIDI commands received by the Arduino Mega + MIDI shield [Fig. 2(ii)] were used to trigger a buzzer placed near the speaker. Participants compared the buzzer sound with the reference sound from the speaker. None reported perceivable latency. In general, the delay from USB–MIDI reception to digital output on an Arduino Mega is approximately 0.1–0.5 ms, and even with more complex processing, the delay typically remains within 0.2–1 ms, and in the worst case does not exceed approximately 5 ms.

3.2.3 Latency from EMS stimulation to drum strike completion

The latency from EMS activation to the completion of the striking motion (i.e., EMS output + muscle response + stick movement + snare impact) was measured.

For a participant with moderate drumming experience, 25 measurements yielded the following:

- mean latency: 220.6 ms and
- standard deviation: SD = 25.6ms.

Thus, approximately 220 ms is required from EMS onset to sound production. This latency is non-negligible.

Note that when the snare drum was struck manually, the YAMAHA DTX-PRO module exhibited no perceptible latency in direct monitoring output. When recording via USB–MIDI, latency can be reduced to a few to a few tens of milliseconds using proper settings (low buffer size, ASIO drivers in Windows).

3.2.4 Compensation of latency during EMS Assistance

On the basis of the above findings, mechanical/electronic latency was estimated at several to ~15 ms, whereas motor execution delay was approximately 220 ms. Therefore, a 250 ms advance shift was applied to the EMS timing for safety margin and synchronization. This value was validated in additional trials with the same participant, resulting in nearly perfect alignment. Although individuals with slower motion initiation (e.g., beginners or participants with less muscular strength) may require personalized adjustment, a fixed 250 ms advance was adopted for this study. Concretely, at 80 BPM, 250 ms corresponds to approximately 1/3 of a beat. A dedicated EMS command track was created in the MIDI score, offset by this amount, and used to generate the EMS timing signals.

4. Experiments

4.1 Performance data

The 8-beat rhythm pattern shown in Fig. 11 was used as the instructional sequence. The performance tempo was set to 80 bpm. While the right- and left-hand parts consisted of repetitive basic rhythm patterns, the bass drum followed an irregular sequence that formed a two-measure beat pattern. This irregularity tends to induce errors, particularly among beginners.

4.2 Participants

Ten healthy university students (fourth-year undergraduates to second-year master's students; mean age = 23.3 ± 0.94 years) participated in this study. All participants had little to no prior experience in playing musical instruments. To balance age distribution, participants were divided into two groups: five in the VTS group and five in the EMS group.

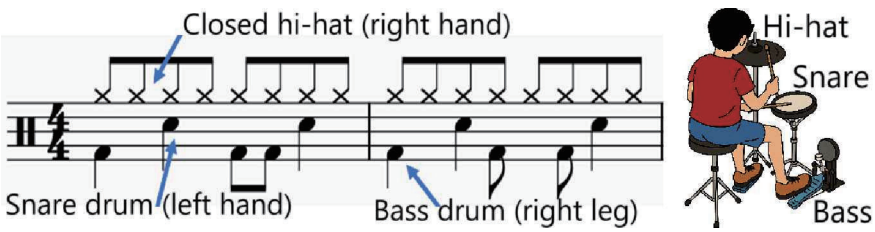


Fig. 11. (Color online) Instruction data (8-beat rhythm pattern).

4.3 Practice

Prior to the experiment, participants practiced to familiarize themselves with the relationship between musical notes, body movements, and performed actions. While viewing the musical score, participants practiced the following combinations, performing ten beat patterns for each of the following:

(1) hi-hat + snare drum,
(2) hi-hat + bass drum,
(3) snare drum + bass drum, and
(4) hi-hat + snare drum + bass drum.

At this practice stage, Pattern (1) is fundamental and therefore relatively easy to perform, whereas Patterns (2)–(4) are more difficult, leading to sudden increases in errors. In particular, during the practice stage without assistance, the errors exceeded the allowable tolerance; therefore, the mean synchronization error for Patterns (2)–(4) was not calculated. For reference, Fig. 12 shows the mean synchronization error for Pattern (1) for participants in the EMS and VTS groups. The error bars indicate the standard error.

Statistical testing revealed no significant difference between the two groups, suggesting that there was no difference in skill level between the EMS and VTS groups.

4.4 Experimental results

First, each participant in both the VTS and EMS groups performed 20 measures while receiving stimulation cues synchronized with the drum audio playback. Next, participants performed ten beat patterns using only the drum audio playback, without any stimulation. The mean synchronization error for each group is shown in Fig. 13(a), and the mean number of mistakes per beat pattern is shown in Fig. 13(b). Error bars indicate standard errors.

In the practice (4) pattern described in Sect. 4.3—coordinated movement involving the hi-hat (right hand), snare drum (left hand), and bass drum (right foot)—performance could not be evaluated prior to assisted stimulation because the errors exceeded the allowable tolerance. However, after training with assistance, participants were able to perform the pattern to some extent even without assistance, as shown in Fig. 13(a), indicating that the performance pattern had been partially acquired.

4.5 Discussion

As shown in Fig. 13(a), the EMS group exhibited smaller synchronization errors than the VTS group. Significant differences between the two groups were observed in the synchronization errors for both arms and the right leg (Mann-Whitney U test, $p < 0.05$).

Similarly, Fig. 13(b) demonstrates that the EMS group made fewer errors per beat pattern than the VTS group, with significant differences also confirmed (Mann-Whitney U test, $p < 0.05$). All participants in both groups reported that the presence of stimulation cues made it easier to understand the rhythm.

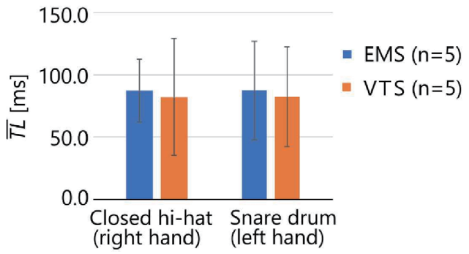


Fig. 12. (Color online) Performance comparison between VTS and EMS groups during practice session (1) without assistance.

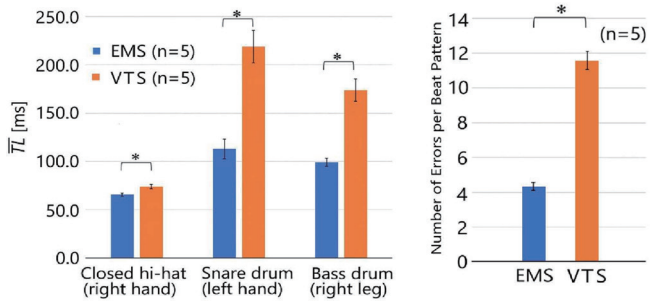


Fig. 13. (Color online) Performance comparison between VTS and EMS groups. (a) Average synchronization error. (b) Error frequency.

Figure 13 shows that the EMS group tended to show a higher learning effect than the VTS group. This tendency may not be attributable solely to differences in stimulation modality. Under the VTS condition, the stimulation provided guidance only on the timing of striking, whereas under the EMS condition, the commands were issued earlier by taking into account the time lag between the delivery of electrical stimulation to the muscle and the completion of the striking motion. As a result, participants in the EMS group may have been able to learn not only the timing of striking but also the appropriate timing for initiating the movement.

5. Conclusions

In this study, we developed a drum performance support system using EMS and investigated the effectiveness of instructional cues delivered through EMS and VTS. In particular, these stimuli were effective in facilitating the understanding of rhythm patterns during the practice phase, and EMS-based stimulus presentation may further enhance this understanding.

The present work focused on supporting beginner drummers, emphasizing rhythm comprehension and coordinated limb movements. In contrast, expert drummers typically produce strokes using flexible wrist snap movements, involving the coordinated activation of multiple muscles even for a single right-hand stroke, and are capable of expressing subtle variations in tone and dynamics.

Although the EMS system accounts for the time lag between muscle stimulation and the completion of the striking motion, striking speed varies across individuals. In addition, when

engaging with high-tempo or complex pieces involving frequent strikes, careful tuning according to individual characteristics and performance patterns may be necessary.

Because EMS can induce fear or discomfort in some users, and excessive or prolonged electrical stimulation may pose physiological risks, VTS remains a promising alternative. Although VTS cannot activate muscles as directly as EMS, vibration-induced movement illusions may still serve as an effective and user-friendly instructional modality.

In future work, we plan to analyze muscle activity using electromyography (EMG) sensors and motion using image sensors, motion sensors, and other related devices, in order to evaluate participants' drumming performance not only in terms of timing accuracy but also with respect to whether they can perform more natural drumming movements.

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