MappEMG: Enhancing Music Pedagogy by Mapping Electromyography to Multimodal Feedback *

Ziyue Piao[1[0009−0007−1281−9469]], Marcelo M. Wanderley[1[0000−0002−9169−4313]], and Felipe Verdugo[1,2[0000−0003−2486−3444]]

[1] IDMIL, CIRMMT, McGill University, Montreal, Canada
[2] Faculté de musique and S2M laboratory, Université de Montreal, Montreal, Canada

Abstract. Music learning and practice may be enhanced by the use of biofeedback based on both learners' and teachers' muscle activity, an essential component of music performance typically unavailable to listeners. By incorporating haptic vibrations, MappEMG enables the audience to experience the performers' muscle effort. This paper updates the MappEMG system to make muscle effort explicit in music lessons. We integrated a low-cost EMG system (BITalino MuscleBIT) and modified processing, communication, and mobile application modules. We conducted a series of experimental teaching workshops where a piano professor guided beginner and intermediate piano students with the updated MappEMG. Four interaction scenarios with MappEMG were identified from these workshops, and we gathered feedback on the initial effectiveness of using MappEMG in music pedagogy.

Keywords: Music Pedagogy · Electromyography · STEAM · Multimodal Interaction · Digital Musical Interfaces

1 Introduction

Muscle activity plays a vital role in music performance. It allows body motion for sound-producing and expression-facilitating purposes, thereby impacting the overall quality of the performance [19]. However, the hidden or non-visible nature of muscle activity poses a significant obstacle to fully understanding its role in music performance. To address this, the MappEMG system was developed to enable individuals to experience performers' muscle activity, leading to new opportunities for understanding performance intentions and playing techniques [3], and potentially enhancing knowledge transfer among musicians, listeners, and music students.

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The MappEMG system offers interactive opportunities designed to enrich the classical concert experience by giving audiences access to musicians' bodily engagement [4, 3]. The system captures musicians' muscle activity using electromyography (EMG) and translates it into haptic vibrations on a mobile phone through the hAPPtiks application. Initial use of MappEMG during a 45-minute immersive classical piano performance yielded diverse listener responses, as perceptions of the vibrations influenced their experiences [3]. Our goal was to extend the use of the MappEMG system to music lessons to enhance the interaction between music teachers and students. Several system limitations had to be addressed for its application in pedagogical settings. First, the original MappEMG was only interfaced with the Delsys Trigno^{TM} Wireless EMG system, which, while reliable, proved less suitable for teaching due to its high cost. Second, while audiences in performances experience the performer's muscle activity, a pedagogical set-up requires interaction flexibility (e.g., recurrent changes of the person/muscle targeted, the system calibration, etc.) to allow a deep understanding, interpretation, and reproduction of the aimed muscle activity [19].

To address these limitations, we updated the MappEMG system. We incorporated the low-cost EMG system BITalino MuscleBIT; enhanced processing and communication capabilities for acquiring, processing, streaming, and transmitting EMG data to multiple phones; we also enhanced the hAPPtiks application to manage both haptic vibration and color changes on mobile phones. Our main contribution lies in applying the updated MappEMG system in exploratory piano teaching workshops and identifying four interaction scenarios for students to learn performance techniques using MappEMG. We found that different scenarios provided varying potential benefits to learners at different levels of musical proficiency.

2 Related Works

2.1 Electromyography in Music Pedagogy

In music education, biofeedback enhances tactile and auditory feedback, promoting "physiological self-regulation" for behavior adjustment. EMG stands out as a primary acquisition tool to develop biofeedback systems based on muscle activity for rehabilitation and learning purposes [23]. Its popularity is attributed to its straightforward and non-invasive nature, making it a valuable tool for directly measuring muscle activity levels and patterns [17]. Surface EMG (sEMG) has diverse applications, including medical research for diagnosing neurophysiological conditions [35] and prosthetic control [14], as well as in music biomechanics research, where it aids in investigating muscle load associated with different playing strategies (e.g., [4, 3]).

EMG has been used for music pedagogy since the 1990s, enriching instructional practices and improving musical performance [43]. Many studies focus on supplying students with feedback and using EMG as a teaching analysis tool, which involves recording and analyzing specific muscle signals within a controlled laboratory environment [43]. For instance, EMG biofeedback effectively addressed left-hand muscle tension and reduced unwanted muscle tension in violin and viola pedagogy [29]. EMG has also been used to analyze muscle activity during techniques like trills and vibrato, providing ergonomic considerations in instrument design, such as the impact of shoulder rests on muscle engagement [30, 45, 44]. Some real-time EMG analysis and biofeedback interfaces have been developed for music learning [31, 33], however, few interfaces are used in lessons to support dynamic music instruction.

2.2 Haptic Augmenting Music Pedagogy

Researchers have investigated multi-modal detection and haptic feedback as means to improve instrumental learning, highlighting haptics' benefits in rhythm and posture guidance, as well as creating immersive experiences. A study [21] on snare drum learning found that haptic feedback accelerates the learning process, making music pedagogy more effective. Haptic feedback has been applied to posture learning for string instruments like the violin [22], enhancing musical immersion due to touch and acoustic signal correlations [37]. However, there is a gap in applying and evaluating haptic feedback in music lessons [2]. Haptic devices may have varying outcomes for students of different skill levels, making it essential to explore haptic feedback's potential and impact on music instruction to benefit students of all levels.

Using Music Information Retrieval technologies, computer-aided music learning can facilitate self-practice scenarios by analyzing performance elements [11]. The Piano Tutor [9] is one of the smartest piano teaching systems with expert assessment and feedback, but most of such intelligent systems lack bodily interaction essential for sensorimotor engagement during instrumental playing [7]. This highlights the irreplaceable role of music teachers in providing physical guidance and personalized instruction.

2.3 Motion in Piano Performance

While many studies concentrate on functional aspects of music-related motion analysis, muscle activity, which is within the intrinsic level of motion, remains relatively underexplored [24, 34]. Various methods are used to capture motion data in piano performance, including optoelectronic systems and electromyography (EMG) [26]. Optoelectronic systems have been broadly employed for analyzing and visualizing pianists' movements, enabling the development of performer stimulations [27], real-time hand gesture following and learning in mixed reality [28], and analysis of performers' sound-producing [42] and ancillary whole body gestures [32]. In contrast, EMG provides data on the activity of individual muscles and muscle groups during movement, which is an essential tool for understanding muscle control and movement organization [26]. In piano performance, muscles of the upper limbs, particularly at the forearm and hand segments, have been traditionally associated with sound production and control needs [15]. However, recent research and research-creation works have shown that trunk and upper limb segments (and therefore muscles) might have interrelated functions for sound-production [41, 39], expression-facilitating [3], and ergonomic purposes [40].

3 MappEMG

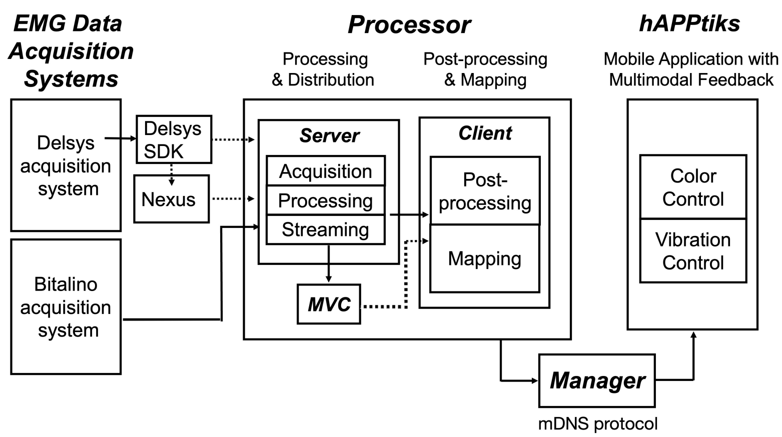

Fig. 1: The diagram framework of MappEMG. The data streaming procedure involves the following steps: a. EMG Data Acquisition Systems: EMG signals are acquired using Delsys or BITalino systems via a Bluetooth connection; b. Processor: The server receives live stream data, the MVC software collects MVC data for processing, and the client transfers the data to hAPPtiks; c. Manager: Transmits color and vibration changes to hAPPtiks; d. hAPPtiks: Provides real-time visual and haptic feedback updates.

The MappEMG system (Fig. 1) features a modular live-streaming structure that acquires EMG data from Delsys and BITalino acquisition systems, processes, streams, and emits the processed data to iPhones, offering real-time vibration feedback with multiple mobiles.

The initial version of MappEMG used in musical performance faced challenges, including costly and limited portable EMG acquisition and the need to manually insert the IP addresses of all the phones used to produce the haptic feedback in the pipeline code [3]. To address these challenges and meet the demands for using MappEMG in music lessons, subsequent designs and improvements were made. We present here the new MappEMG framework, including the acquisition interface, the Python-based Processor, and the hAPPtiks mobile application, with key goals of:

- Enabling both Delsys and Bitalino EMG devices to acquire EMG data.

- Incorporating the latest biosiglive[3] Python library to support better data acquisition, processing, and streaming [1].
- Refactoring of the communication protocol between the processor and the hAPPtiks application to allow automatic discoverability of the used phones (in the previous version, IP addresses of each phone had to be integrated manually in an emitter module coded in Max).
- Using the hAPPtiks application to control not only vibration but also the screen color of mobile phones.

3.1 Electromyography Acquisition Systems

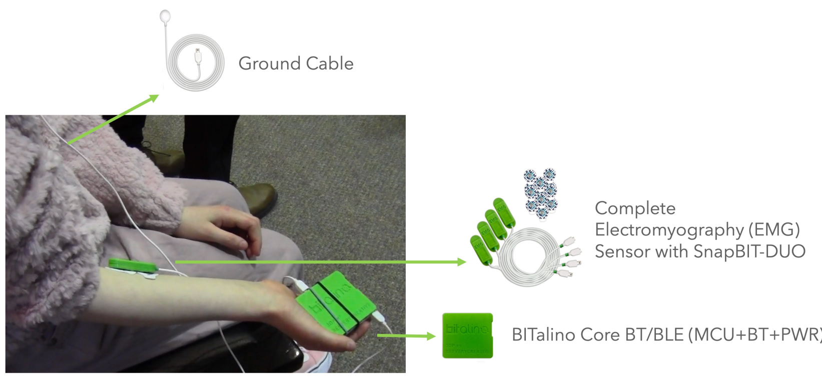

Fig. 2: The Bitalino MuscleBIT bundle, designed for EMG signal acquisition, consists of the following components: a. A ground cable: This serves as a reference for recorded electrical signals (in the photo, it's connected to the participant's clavicular notch); b. EMG Sensors: These Assembled Electromyography (EMG) Sensors with SnapBIT-DUO allow for fast and precise measurements, ensuring accuracy in repeated measurements; c. BITalino Core: The Core includes multiple connection ports, allowing for the simultaneous connection of one to four sensors.

The Delsys Trigno^{TM} System is a high-reliability commercial EMG acquisition system, serving as the primary acquisition system in the first generation of MappEMG [3]. However, low-cost alternatives with similar functionalities, such as OpenEMG, BITalino, and SparkFun Muscle Sensor, are available. We chose the BITalino MuscleBIT due to its standalone and easy-to-carry/wear design, enabling convenient use on performers and wireless data streaming via low-latency and low-energy Bluetooth (BLE) communication. The system comprises four bipolar electrodes and one reference electrode, allowing EMG data acquisition

[3] biosiglive is a Python library that aims to provide a simple and efficient way to access and process biomechanical data in real-time. https://github.com/aceglia/biosiglive

up to 1000 Hz (Fig. 2). Despite its advantages, the BITalino system faced difficulties establishing Bluetooth connections with macOS during our testing, which could potentially be linked to the absence of recent updates to its Python API. As a solution, the MappEMG Processor was operated on Windows. To connect the BITalino MucleBIT to MappEMG, we developed a BITalino Interface in biosiglive, including the BITalino device as an input data acquisition system for our Python Processor.

3.2 The Processor

The Python Processor uses the biosiglive package [1] to implement real-time data processing and sharing modules. It consists of three separate modules: the Server, the Client, and the MVC modules [4].

The Server. The Server allows users to connect to the BITalino MucleBIT system by inserting its Bluetooth address to define the EMG acquisition channels (number of electrodes used), to process and plot in real-time EMG data, and to create a TCP/IP connection for data streaming. Users can adjust the EMG acquisition sampling rate, window size for processing raw EMG data, and server acquisition rate for smoothing and downsampling purposes. The server utilizes Python's multiprocessing for concurrent data acquisition, processing, and streaming. The default EMG processing function in biosiglive involves a bandpass filter with adjustable frequencies. EMG signals are collected at 1000 Hz and rectified using a bandpass filter.

The MVC. The MVC module connects to the TCP/IP created by the server to receive the real-time collected data. The module is used to perform Maximum Voluntary Contraction (MVC) trials for each of the targeted muscles and to compute and store MVC values for each muscle. The saved MVC values are used for normalization purposes in an ulterior stage.

The Client. The Client can receive raw and processed EMG data from the server through the TCP/IP connection. This module applies a secondary set of processing procedures: it normalizes the EMG rectified signals using the previously stored MVC values; it determines the mapping curve from processed EMG data to vibration amplitude/frequency values and to screen brightness/color values. The Client initiates data streaming (OSC messages) with an 'emg' command message. A 'close' command message is sent to stop data streaming when the connection is closed.

3.3 hAPPtiks

We integrated the mDNS communication protocol in the hAPPtiks application to allow automatic mobile phones' discoverability and communication. A module

[4] https://github.com/IDMIL/MappEMG

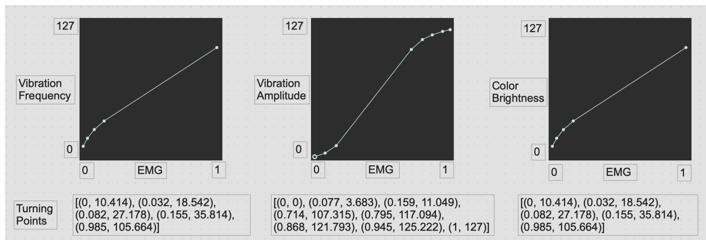

Fig. 3: The relationships between processed EMG signals and feedback (vibration frequency, vibration amplitude, and color brightness) are initially configured in the MaxMsp software [3]. These configurations are then stored as a list of points on the Processor. Parameters related to vibration are fine-tuned for tactile comfort, and brightness follows the same mapping function as frequency.

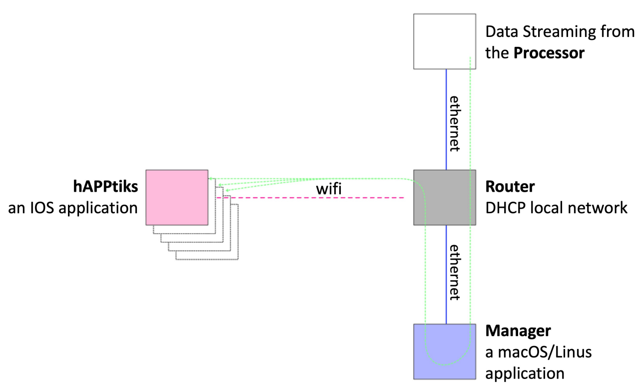

Fig. 4: The network connection between devices

named Manager was implemented (macOS and Linux) to manage the mDNS communication protocol. All computer and mobile devices must be connected to the same WIFI network to allow successful communication between the different modules. Therefore, we created a local Network (DHCP) (see Fig. 4).

hAPPtiks is an iOS application designed to receive vibration amplitude/frequency and screen brightness/color messages from the Processor, providing real-time multimodal feedback with a simple interface without additional widgets.

Fig. 5: During the MappEMG workshop and piano master class, some photos were captured: a. A comprehensive demonstration of the entire system in action. b. The teacher is providing guidance to a student, utilizing feedback from MappEMG. c. A student performing a piece while connected to MappEMG. d. Enthusiastic beginner students volunteering to experience MappEMG.

4 Piano Workshops

MappEMG aims to enhance teacher-student interaction during real piano lessons through body interaction, addressing aspects challenging to convey through language or touch. Workshops were conducted in different Quebec Conservatories (Canada) involving piano students of different levels as preliminary work for exploring MappEMG's potential use in music lessons. Led by Prof. A., a pianist and professor with a kinesiology background, the use and application of MappEMG was adapted to the level of students' and to the specific needs of each workshop. It is important to note that the workshops were exploratory lessons [36]; they were not based on a formal experimental design and evaluation, and they focused on addressing teacher A.'s pedagogical strategies and preferences.

Table 1: MappEMG Workshops

No.	Age	Number	Piano Level	Interaction with MappEMG
1	5-15	13	Beginner	Scales + struck/pressed touch
2	12-18	11	Intermediate	Whole pieces
3	6-13	12	Beginner	Scales + struck/pressed touch
4	16-21	8	Intermediate	Whole pieces

4.1 Participants

Table 1 overviews the participants' number and level of four workshops, including beginner and intermediate-level piano students. The piano teachers from the hosting conservatories invited their students to participate in the workshop. The students were grouped according to their piano level (assessed by their respective teachers) and participated in the workshop corresponding to their piano level. The beginner group comprised participants with less than three years of piano experience, while the intermediate group included those with around 4 to 7 years of practice. Workshop attendees voluntarily joined the sessions to receive guidance from Prof. A. The analysis excludes other workshop attendees, such as piano teachers, parents, and students of different levels.

4.2 Procedure

Each workshop included four sessions to enhance piano technique and understanding of basic body and mechanic principles of piano playing. Sessions 1 and 2 focused on fundamental piano techniques and essential body movements in piano playing. Session 3 was the core MappEMG session, exploring the potential of MappEMG benefits for students and teachers. Session 4 involved a master class where 2-3 piano students received guidance from Prof. A.

Session 1 and 2: Fundamental Technique and Body Movement. Session 1 differentiated "pressed touch" and "struck touch" using key velocity, hammer velocity, force, and position data from research papers [18, 25]. Session 2 covered vital body movements in the trunk, shoulders, elbows, wrists, and fingers when playing the piano [5]. These sessions provided beginners (40 minutes) and intermediate-level (20 minutes) piano students with fundamental insights into body movement in piano playing.

Session 3: MappEMG. Session 3 introduced biofeedback, EMG, and the MappEMG system. Participants used iPhones with the hAPPtips application to connect to a testing interface for personalized feedback. A selected group of 5-10 piano students wore MappEMG consecutively while playing the piano or receiving instructions from both Prof. A. and a researcher from our team.

Session 4: Master Class. Session 4 featured 2-3 piano students performing prepared pieces for a master class, receiving guidance from Prof. A. Beginner-level and intermediate-level students wore MappEMG for corresponding guidance using hAPPtiks. The master class lasted about 30 minutes, focusing on refining piano-playing skills and technique.

4.3 Feedback

We gathered anonymous feedback from student participants by submitting notes at the end of the MappEMG session, and Prof. A. provided his feedback after each workshop.

Teacher's Feedback. Prof. A. explained, "In this workshop series, I aimed to explore the use of MappEMG while adapting to each student level. I dynamically adjusted and refined teaching methods, especially after the first two workshops." Then Prof. A. gave feedback on different levels of students (in Table 2).

Students' Feedback. The most commonly mentioned word for beginner-level students was "interesting". One beginner student stated, "I think this helps us understand our gestures when playing and prevents bad postures."

Other three intermediate students commented: "A very useful educational tool that benefits students at all levels and is not limited to just piano players." "It helps learn from mistakes, optimize techniques, and eliminate unnecessary and inefficient movements." "I appreciated the connection between music and physics; it adds an interesting and more scientific dimension to learning."

Some intermediate students provided valuable suggestions to improve MappEMG. Another two students mentioned that the system could benefit from more visual interaction and pre-recorded performances. Additionally, they suggested that it would be more helpful for their self-practice using hAPPtiks to recognize and evaluate muscle gestures for specific techniques.

5 Discussion

During the workshops, Prof. A. focused on guiding and improving students' piano techniques. Developing from the ecological dynamics theory of motor learning [10], which emphasizes the interaction between the individual and the environment, we specified interaction scenarios in music pedagogy with MappEMG. Moreover, we garnered insights from feedback provided by both Prof. A. and the participating students. These insights shed light on the potential efficacy of MappEMG in improving the teaching and learning processes, further contributing to our understanding of motor skill acquisition in the domain of music.

Table 2: Teacher's Feedback for Different Levels of Piano Students

For Beginners	"I focused on using MappEMG to teach and let them experience the biomechanical differences between 'pressed touch' and 'struck touch', introduced in the previous session. After connecting them to MappEMG, I let them repeatedly play a note or a scale with a different touch and feel the vibrotactile feedback. Feeling their muscle activity through MappEMG helped them establish a connection between the playing goal and its corresponding muscle effort. They were pleasantly surprised to feel their muscle contractions and they were willing to play with MappEMG... Beginner students, especially younger ones, were more attracted to MappEMG. They gathered closer to me during the MappEMG session, displaying excitement to participate, possibly because the system can be seen as a game interface. They also engaged in warm discussions with their classmates."
For Intermediate Students	"With MappEMG, I could address more complex playing contexts. For example, during workshop No. 4, an intermediate student, M., performed a piano etude which included fast scale and arpeggio passages at the right hand. Although M. displayed playing proficiency, there was room for refining the technique, particularly in terms of minimizing unnecessary finger-lifting movements (i.e., overuse of extension movement at the metacarpophalangeal joints). I placed an EMG electrode on the corresponding extensor muscle, situated at the forearm, to address M.'s issue. I first guided M. to adjust the playing gesture until I could feel slight variations of the vibration based on the targeted muscle. Then, I handed my iPhone to M.'s left hand. Firstly, I asked M. to feel the vibrations with the left hand while playing the excerpt of the etude with the right hand using the playing technique she normally used. Secondly, I asked M. to adapt the playing technique to reduce as much as possible the vibrations while maintaining the same musical goal. After a few attempts, M. was able to introduce greater hand pronation/supination movements, which helped reduce finger extension movements to release the keys. This is a playing technique called 'rotation' in the piano community, and it is widely taught to reduce both finger muscle activity and exposure to risk factors of injuries, as finger extensors can be more affected by muscle fatigue than finger flexor muscles (e.g., [20]). ... Surprisingly, several intermediate students demonstrated a similar phenomenon. When they held the iPhone with one hand, and I asked them to play with the other hand, they could generally make gestural adjustments based on their previous knowledge or the content taught in previous sessions".

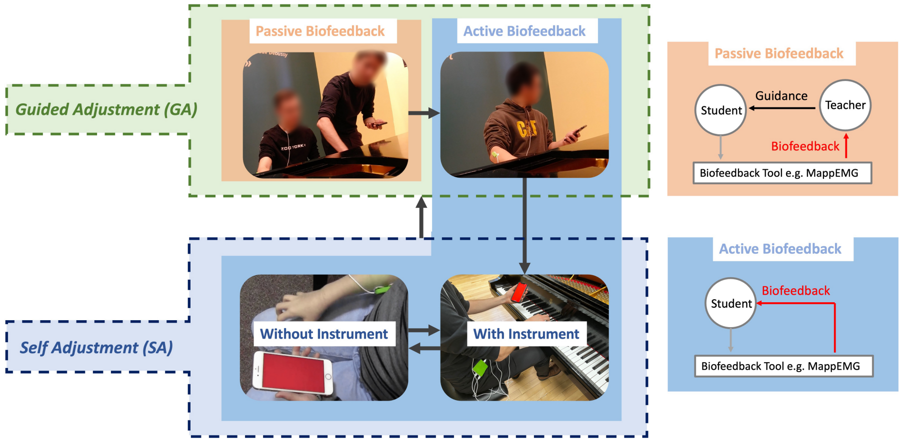

Fig. 6: Interaction scenarios for teacher-student interaction in music lessons with feedback tools

5.1 Interaction Scenarios

After conducting the workshops, we identified four types of interactions based on Prof. A.'s exploration of teaching using MappEMG:

- Guided Adjustment (GA): student adjustments with teacher guidance based on passive (1) and active (2) biofeedback during the lesson.
- Self Adjustment (SA): student self-made adjustments based on biofeedback during practice with the instrument (3) and without the instrument (4) between lessons.

As shown in Fig. 6, we categorize feedback from the student's perspective into passive and active biofeedback. Passive biofeedback refers to the case where the teacher feels the MappEMG feedback based on the student's muscle activity and provides guidance based on the teacher's perceived feedback. Conversely, active biofeedback entails students actively feeling their biofeedback and adjusting their gestures according to the student's perceived feedback. The two scenarios were used as organized pedagogical steps. In the initial step (passive GA), students' learning of new techniques was purely based on guidance from the teacher. Moving to the active GA scenario, students could practice the acquired techniques by actively feeling their muscle activity through biofeedback. They could make real-time adjustments based predominantly on their own biofeedback perception and gestural proprioception while benefiting from reduced guidance from the teacher. The next two scenarios could be introduced during practice between lessons. In the SA scenarios (both with and without an instrument), students could fine-tune their gestures by interpreting haptic feedback themselves (active biofeedback). During our workshop, we used the SA with and without instrument scenarios as a demo session, allowing students to sense their motion with MappEMG.

Following Gallahue's motor skill learning model [16], which was derived from the Fitts and Posner as well as Gentile models [13], the GA scenarios fall within the beginning/novice level learning stage, and the SA scenarios target the intermediate/practice level learning stage. Despite the learning processes outlined in advanced/fine-tuning music piece acquisition [8], our interactions aim to help students explore diverse approaches to gain a basic awareness of gestural and playing concepts and skills. The scenarios will serve as the basis for our following analysis.

5.2 Analysis based on the Feedback

Teaching Beginner Level Piano Students. During our workshops, based on the subjective feedback from learners, MappEMG seemed to enhance beginners' learning interest and attention more than intermediate students. For beginners, the active biofeedback interaction proved most effective in establishing the relationship between sound and body control through playful engagement. Due probably to their young age, these students demonstrated a greater interest in the system and capacity to adapt their playing while actively feeling the biofeedback [6].

Teaching Intermediate Level Piano Students. Intermediate students benefited the most from optimizing their playing techniques using MappEMG in passive biofeedback interaction (passive GA), which aligns with Gallahue's motor learning model, emphasizing skill enhancement and effective feedback at the intermediate level [38]. The teacher's ability to dynamically switch teaching methods with MappEMG maximized efficiency in the intermediate students' groups compared to the beginner group. Intermediate students showed a better capacity to move from passive GA to active GA to understand and experience the gestural modifications demanded by Prof. A. This outcome of our preliminary work should, however, be confirmed by a formal evaluation of intermediate-level students' use of MappEMG in teaching and learning contexts.

For Both Levels of Piano Students. During and after the use of MappEMG, students demonstrated improved body awareness and the ability to adjust their gestures according to the perceived biofeedback, which suggests that muscle biofeedback might be a promising complementary tool to traditional teaching methods. Students' focus shifted from imitating the teacher's demonstration to actually experiencing the link between sound production and muscle effort, particularly evident in the active GA scenario, as noted in the teacher's feedback. Based on our workshop experience, we speculate that a combination of passive and active biofeedback scenarios can effectively help teach new techniques and reinforce playing adjustments related to body posture or movements. The active feedback scenarios show significant potential in music learning as they could complement students' proprioception and self-inform required adjustments [23, 12].

5.3 Limitation and Future Work

We are currently developing the Android version of hAPPtiks to improve system accessibility. Our current partnership project, "Science at the Service of Music Performance" (three university music departments and four music conservatories around Quebec), will help refine the workshop procedure, with biannual workshops planned in the next two years. To further evaluate the results, we intend to conduct formal user experiments, assessing students' improvement and learning efficiency in controlled passive and active learning scenarios. Additionally, we plan to explore whether beginner students sustain their learning interest beyond the initial novelty, potentially requiring a longitudinal experiment with MappEMG. Ultimately, we aim to broaden MappEMG's music lessons and performance application through other learning, performance, or artistic activities.

6 Conclusion

This paper introduced the updated MappEMG system and its initial application in music pedagogy through exploratory piano workshops. The updated MappEMG system enables the acquisition, processing, and low-latency streaming of muscle data with a low-cost EMG system. It maps and emits processed EMG data to the hAPPtiks iOS application, allowing multi-users to feel the performer's muscle activity through color and vibration changes. We conducted four workshops with beginner and intermediate piano learners, exploring various interactions between teacher and students using MappEMG. We identified four interaction scenarios: Guided Adjustment with Passive and Active Biofeedback, and Self Adjustment with and without Instrument. The user feedback showed that MappEMG could be used to teach playing techniques to beginner and intermediate piano students, increasing interest and attention in beginners and optimizing playing techniques in intermediate students. Moreover, MappEMG enhanced students' focus on gesture-sound relations and might be used to prevent poor ergonomic movements and postures. The four interaction scenarios have great potential for music learning, augmenting traditional teaching and practice contexts.

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