Maestro: testing haptics for primary feedback in a music-making multisensory interactive system

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***Abstract*—**In designing a Digital Musical Instrument (DMI), two kinds of feedback need to be considered. The so-called primary feedback is feedback that the performer gets from the control surface of the instrument itself, for example the tactile sensation of pressing a piano key, or the visual feedback of a synthesizer button that lights up when pressed. Secondary feedback instead relates to the sound produced by the instrument. [6]

Empty-handed digital musical instruments are a category of DMI where there is no physical control surface, and which therefore do not provide haptic primary feedback to the performer, as there is no physical control surface in the hands of the performer.

We would like to answer the following question: could the addition of primary haptic feedback in an empty handed gesture controller improve the instrument's playability and playing experience?

We created a DMI based on hand gestures, composed of a glove and a baton, inspired by orchestra conductors' technique. We addressed the lack of primary feedback in empty-handed musical instruments by embedding vibration motors in the physical supports necessary for gesture recognition.

We tested the system with 18 participants following a between-subjects experimental design, with haptic feedback as the independent variable. We developed a playing experience questionnaire and collected behavioral measures including Time on Task and error rate. We administered the System Usability Scale (SUS) to assess interface usability and playability. Results showed marginally improved playing experience and significantly enhanced glove interface usability with haptic feedback, while revealing interaction challenges in precise tempo control and gesture selection.

I. Introduction

Maestro is a multisensory interactive system for musical exploration through an immersive experience based on embodied interaction. The system is based on a gestural controller inspired by the techniques of orchestra conductors, with the important difference that Maestro is primarily aimed at people with little to no musical experience.

The system consists of a glove, a baton, a projected graphical interface, and a speaker. Users wear the glove on their left hand and hold the baton in their right, allowing them to control the system entirely through gestures. A graphical user interface is projected on a wall in front of the user, while music plays through a speaker, creating a multimodal interaction that combines visual, auditory, and haptic responses.

Maestro can serve as a platform for researching various aspects of musical interaction. Our focus is on determining whether the integration of haptic feedback into the controls enhances playability and the overall playing experience. This project therefore has two main goals:

1) **Prototype Development** – Creating a system that provides users of all musical backgrounds with an immersive, interactive way to explore and manipulate musical compositions through gesture-based control of pre-existing musical loops.
2) **Haptic Feedback Study** – Evaluating the impact of haptic feedback on user experience and playability to assess its effectiveness in improving interaction with the system.

This work is driven by the desire to explore the potential of embodied interaction in the design of Digital Musical Instruments (DMIs), particularly in creating immersive musical experiences that are accessible to users with little to no musical background. In this context, we investigated the impact of haptic feedback on playability and the overall user experience, expecting that its thoughtful integration would significantly enhance interaction.

Systems like Maestro can be applied in various settings, from recreational to educational contexts, offering intuitive and engaging musical exploration. Beyond its specific application, Maestro's gestural interface is particularly interesting from an interaction standpoint. Gestural interfaces are a growing trend in HCI, especially given the rising popularity of Extended Reality (XR) and the advancements in computer vision algorithms for hand tracking, which now allow for hands free interactions in VR/AR (e.g. Apple's Vision Pro).

The potential of gestural interfaces extends beyond VR and vision-based systems. Maestro's approach to the gestural interface is linked to that of emerging technologies, such as Google ATAP's Project Soli [1] and Meta's recently unveiled EMG wristband [5], which demonstrates how hand gestures could soon enable seamless interaction across a wide range of applications in everyday technology outside of VR.

II. Related work

A number of examples can be found in the literature of systems that use conductor-like gestures to control music. Notable examples that we found while researching our system include the MiMu Gloves [3], a pair of hananced gloves for expressive musical creation, Maestro VR [11], a game that uses gestures to let players "conduct" an orchestra, and MIT Media Lab's Digital Baton [7]. These systems all include aspects related to our design, but are still very different in many ways. Much work has also been done on researching the impact and the role of haptics in DMIs [12] [4] [9].

Our research aims to expand on the existing work in the field of conductor-like interfaces for musical exploration and on the use of haptics as a feedback mechanism for open air and empty handed controllers.

III. Architecture Design

A. System Design

The system is designed to simulate the behavior of a conductor using a wearable interface consisting of a glove and a baton. The prototype is intended for general users, not necessarily musicians, and is used in a controlled environment where a researcher monitors the software and initiates tests. The user interacts with the system in front of a projected interface, with all hardware components connected via cables fixed to the desk to ensure stability.

Key assumptions underlying the system design include:

- Users will have a standard hand size, ensuring compatibility with the glove.
- The baton must be held in a specific orientation so that its internal accelerometer's Y-axis correctly detects the peak movements.
- Beats are detected based on downward movements of the baton.

The system architecture consists of several interconnected components:

- **Baton**: A 3D-printed device housing an accelerometer that detects conducting gestures.
- **Glove**: Equipped with an Inertial Measurement Unit (IMU) on the back of the hand for pointer control, three flex sensors on the fingers to recognize gestures for activating musical clips and a coin vibration motor on the palm for haptic feedback (Fig. 1)
- **Microcontroller (Teensy)**: Responsible for computing the Beats Per Minute (BPM), processing IMU data, and determining finger positions based on predefined threshold values.
- **Processing Software**: Communicates with the Teensy via a serial port, rendering the visual interface and interpreting user inputs.
- **Pure Data (PD)**: Receives Open Sound Control (OSC) messages from Processing and relays them as MIDI signals to a Digital Audio Workstation (DAW), such as Apple Logic Pro.

The communication flow is structured as follows:

1) The Teensy microcontroller processes sensor inputs and sends data to Processing.
2) Processing interprets the data and updates the visual interface accordingly.
3) Processing transmits OSC messages to Pure Data.

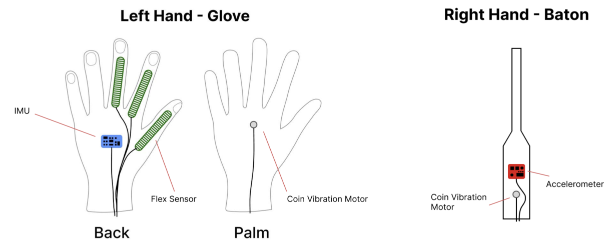

Fig. 1. Maestro Controllers

4) Pure Data converts the OSC messages into MIDI signals, which are sent to the DAW for real-time audio manipulation.

B. Usage Model

The system is designed to be easy to learn and responsive to the user's gestures. The user wears the glove on their left hand and holds the baton in their right hand. The baton includes a marked grip area to ensure proper orientation, aligning the accelerometer's Y-axis for accurate beat detection.

A large screen (e.g., a projected 180 inches screen) displays the interface, which consists of four icons representing available musical instruments. The user interacts with the system as follows:

- **Pointer Control**: With an open hand, the glove's IMU allows free movement of the on-screen pointer.
- **Instrument Selection**: Pointing with the index finger selects an instrument.
- **Instrument Complexity Adjustment**: Raising or lowering the left hand adjusts the complexity of musical execution of the selected instrument. In this context, instrument complexity refers to the richness of sound and intensity of each clip for a given instrument. Clips are chosen from the Logic Pro database, adjusting them in complexity, intensity, and more parameters.
- **Selection Confirmation**: Reopening the hand finalizes the selection.
- **Tempo Control**: The right hand, holding the baton, determines the tempo. Regular downward movements are interpreted as beats, and the system calculates the BPM, adjusting the playback speed accordingly.

This architecture and interaction model provide an immersive and easy to learn conducting experience, bridging gestural input with digital music performance.

IV. Implementation

A. System Components Implemented

The implemented system consists of a glove and a baton, both custom-built and wired to a Teensy microcontroller. The Teensy runs dedicated firmware, transmitting serial data to a Processing sketch that manages the graphical interface and communicates with a Pure Data patch for audio control (Fig. 4).

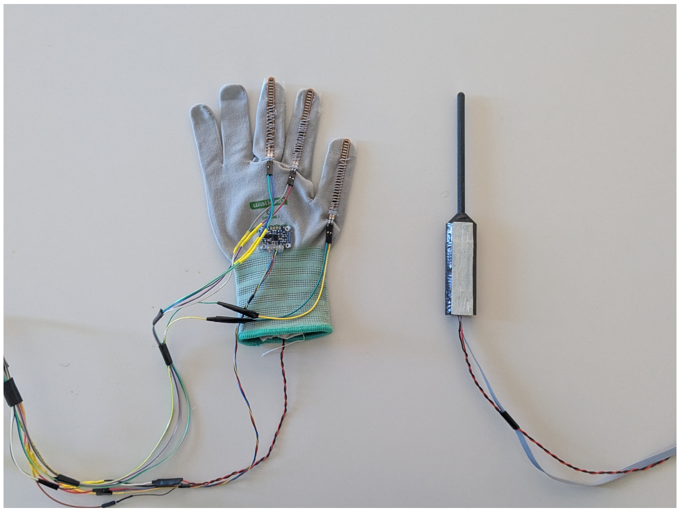

Fig. 2. Maestro Controllers. Prototype used during tests

Fig. 3. Visual Interface and Experimental Setup

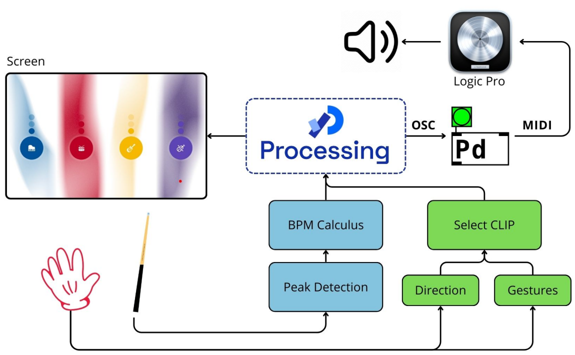

Fig. 4. System Architecture

The software implementation includes three key components:

- **Teensy firmware**: Handles sensor input and serial communication.
- **Processing sketch**: Manages the graphical user interface (GUI) and relays data to Pure Data.
- **Pure Data patch**: Processes Open Sound Control (OSC) messages and controls MIDI parameters.

The Teensy microcontroller operates at a baud rate of 9600 and a sampling frequency of 100 Hz. It initializes the BNO055 IMU sensor and the vibration motor before acquiring input from the sensors.

Glove Implementation: The glove uses Euler angles from the IMU sensor to control an on-screen pointer. The roll (Euler.x) and yaw (Euler.y) values are wrapped within a valid range and calibrated with an offset. Gesture recognition is achieved using three flex sensors placed on the fingers, with predefined threshold values. During development, three primary gestures were utilized:

- ”Open hand” for pointer movement and selection confirmation.
- ”Index pointing” for selecting the complexity level.
- “Closed fist raised” to silence all instruments.

To optimize the design, only two flex sensors (on the index and middle fingers) could be used instead of three, reducing hardware complexity. Additionally, a vibration motor was integrated into the palm of the hand. The vibration activates for 100ms everytime the user points to a different level during selection.

Baton Implementation: The accelerometer was positioned at the handle rather than the tip of the baton to reduce sensitivity while maintaining sufficient responsiveness. This design choice also allowed for a lighter, more traditional baton form factor.

- *Peak Detection Algorithm*: A z-score-based peak detection algorithm was implemented using the PeakDetection library [2]. If a new data point deviates by a defined number of standard deviations from a moving average, it is registered as a peak.
- *Tempo Calculation*: Time intervals between peaks are recorded, and the beats per minute (BPM) are computed based on the average interval. A smoothing filter stabilizes the BPM estimation, and haptic feedback is triggered for 200ms upon beat detection. The system resets if no peaks are detected within a predefined timeout, ensuring robustness against noise and irregular motion.

Data from the Teensy is transmitted via a serial port to Processing, which manages the visual interface. The GUI consists of four columns, each representing an instrument, with three selectable complexity levels arranged in ascending order. The pointer's movement is constrained along the x-axis once an instrument is selected to facilitate precise level selection. The system sends OSC messages at the same frequency as the serial port to the Pure Data patch, containing the selected clips and the current tempo.

Pure Data filters and routes the OSC messages:

- The selected clips are triggered via MIDI.
- The BPM value is transmitted as a MIDI Control parameter to the chosen Digital Audio Workstation (DAW).

An alternative implementation using *Ableton Link* was tested but resulted in audio distortions in the given setup. Consequently, we modify the playing BPM directly with a MIDI control message, although this forces us to be limited between 50 and 177 BPM.

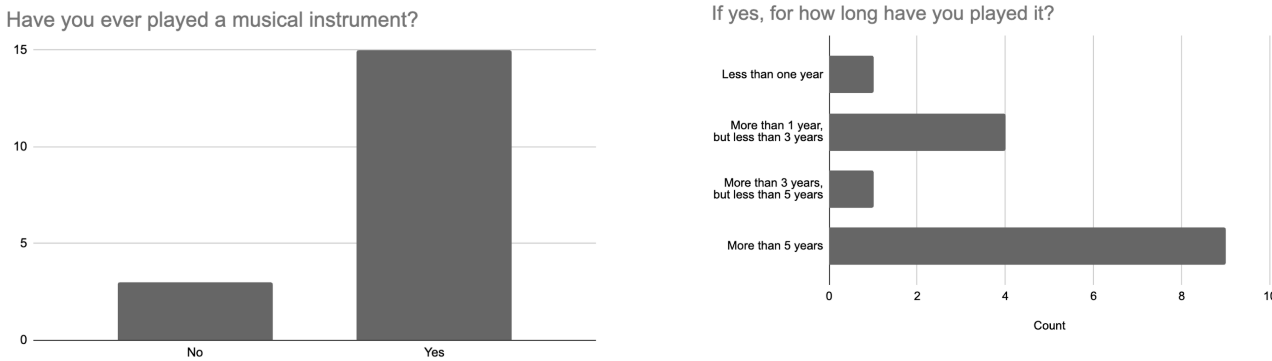

Fig. 5. Musical experience of our sample

V. Evaluation

A. Hypothesis

By grounding in Rovan and Hayward 2000's work [9], we expect that a minimized but still adequate tactile stimulation, produced in response to instrumental gestures, will provide a valuable aid to the interaction with Maestro. In this study, we consider as valuable "aid" a higher score both in users' performance *(playability)* and impressions (*playing experience*). As a matter of fact, prototypical computer music systems that use open air controllers, such as *Maestro*, don't necessarily need to provide users with tactile feedback. In this use case scenario, the performer receives feedback through the audio, visual and proprioceptive channels. However, matched with users' gestures, tactile feedback stimulates both short and long term learning and supports motor control accuracy [9], which is essential in music production. Overall, its implementation enriches *Maestro*'s feedback, and we expect to observe effects that can be expressed in the following hypotheses:

1) A significantly higher Playing Experience score;
2) A significantly lower Time on Task for the glove task (1) ;
3) A significantly higher SUS score for the glove (task 1);
4) A significantly lower BPM Root Mean Squared Error in the baton task (2);
5) A significantly higher SUS score for the baton (task 2);

B. Testing and experimental procedure

In order to test our hypothesis, we have run a between subject testing on a total of 18 participants (9 for each condition). The choice to discard a within subject design has been made in response to the structure of the test itself, which would have been extremely long and possibly annoying if each participant would have been subjected to both conditions. Participants have been recruited through a snowball sampling technique. Overall, the recruited sample emerged to be quite balanced in terms of gender (10M, 8F), while the age ranged between 20 and 28 years old. Moreover, participants' previous musical experience and proficiency have emerged as higher than expected: 83,3% of the sample has played a musical instrument, with 9 out of 15 having played it for more than five years (Fig. 5).

The test was conducted on the 4th February of 2025 in the projector room of block F of the SanBa student dormitory of the University of Trento.

For what concerns the roles division among researchers, four main tasks were established, with a rotation during the testing day. The roles consisted in:

- Welcoming and resting
- Facilitation (introduction, familiarization, tasks explanation)
- Qualitative observations and interview
- Technical management of the system

The experimental procedure consisted in:

1) Welcoming and consent form submmission: Each participant has been welcomed by one of us in the room adjacent to the one where the testing was taking place. There, participants were free to enjoy refreshments while reading and signing the consent form.

2) Introduction and familiarization: Once entered in the testing room, participants were introduced to the system and asked to wear the glove. All the system functionalities and the related gestures were introduced by guiding the participant to perform and actively experience gesture by gesture. In the meanwhile, participants were free to ask questions and only when everything was clear to them they were let free to explore the system by themselves for more or less two minutes. Once the participants were satisfied with their exploration, they were asked to fill the first part of the questionnaire, which was aimed at collecting the demographic and playing experience data.

3) Musical tasks: The second part of the testing consisted in two tasks, which aimed at measuring the playability of *Maestro* as a complex system made of two control modalities (glove and baton). Both the tasks were explained by the facilitator and supported by the technical manager.

The first task asked the participants to set each instrument at a specific complexity level, which was shown on the interface as a number from 0 (instrument turned off) to 3 (maximum level of complexity). This task was repeated three times with different configurations of complexity levels per instrument: combination 1 (1,3,1,3), combination 2 (0,2,1,3), combination 3 (0,0,0,0).

Since it dealt specifically with *Maestro*'s features controllability, users only needed the glove to perform the task and were free to hold or not the baton in the meanwhile. Before moving on the second task, participants were asked to fill a SUS questionnaire referring to their experience with the glove while performing the task.

The second task consisted in keeping the same tempo of a metronome at 100 BPM for 45 seconds. This task was performed with the sound of two instruments playing and with the usage of the baton. In the end, a second SUS was submitted to the participants, who needed this time to refer to their experience with the baton.

4) Final Interview: A final interview was carried out by the one of us who was in charge of the observations. In general, the following guideline questions were adjusted and expanded accordingly to each participants and what we have observed:

1) First of all we ask you: what do you think? What is your overall impression about the system?
2) Is there something that has struck you positively, that you think works particularly well?
3) And instead, is there something that has struck you negatively, that you think doesn't work well?

C. Pilot test

On the 28th January 2025, we conducted a pilot test in order to better define the experimental procedure. Overall, the experimental procedure has been confirmed, but we refined some aspects. First of all, we have noticed something relevant regarding the second task: by using a visual target that flashed at a certain tempo, the pilot user seemed to be struggling with the "conversion" from visual input to motor output. Thanks to this observation, we have realised that an audio stimulus, such as a metronome, would have been more effective as a reference target BPM thanks to the higher temporal resolution of the auditory channel.

Secondly, we have realised that Maestro is more complex that we have thought: baton and glove are two controllers that work synchronously but have different patterns of interactions. For this reason, we have decided to use two SUS questionnaires to measure playability (one for each control modality) instead of only one.

D. Independent and dependent variables

In order to test our hypothesis, we have set the presence or absence of haptic feedback as an independent variable. Each participant has been assigned to one of these two levels, which have been compared according to playability and playing experience metrics.

Since Maestro deals with music, we have considered that its evaluation has to measure both users' performance and subjective impressions [8].

1) Playability: Users' tasks performances and SUS questionnaire results have been used as dependent variables to measure Maestro's playability in both conditions (with and without haptic feedback). More specifically, users' tasks performance measures consisted in:

TABLE I
PLAYING EXPERIENCE SCORES

PEQ	All	SD	With	SD	Without	SD
Overall Score (0-100)	82.54	9.34	83.49	11.93	81.59	6.40

- Time on task needed to set each instrument at the correct level;
- Error rate in keeping the tempo, so how the tempo set by the baton compared to the given target tempo of the metronome (100 BPM for all participants) over time.

2) Playing experience: On the other hand, since there is no standardized measure to assess playing experience in DMI's, we have adapted the game flow model by Sweetser and Wyeth (2005) [10] for evaluating the enjoyment in learning and playing with Maestro. This model suggests 8 elements of interest: concentration, challenge, skills, control, clear goals, feedback, immersion and social interaction. Each element has been translated into a statement, which had to be evaluated by each participant according to a Likert scale from 1 (strongly disagree) to 5 (strongly agree):

1) While I was interacting with the system, I felt **in control**.
2) While I was interacting with the system, I felt **challenged**.
3) While I was interacting with the system, I felt **concentrated**.
4) While I was interacting with the system, I felt **skilled enough**.
5) While I was interacting with the system, the **feedback was satisfying**.
6) While I was interacting with the system, I felt **immersed**.
7) I think the system can be successfully implemented in **social contexts**.

Quantitative measures have been enriched by qualitative data, which have been collected through observations and interviews.

E. Results

In this section, quantitative results will be discussed both from a descriptive and an inferential standpoint. Hypotheses have been all tested by a One-tailed Welch Two Sample t-test with 95 percent confidence interval between conditions.

1) Playing experience:

H1: A significantly higher Playing Experience score;

In order to test our first hypothesis, the Playing Experience Questionnaire scores have been compared between the two conditions. From the descriptive analysis, the overall score appears higher in the haptic feedback condition (Table I, Fig. 6). However, the one-tailed Welch Two Sample t-test highlights no significant difference between the scores of the two conditions ($t = 0.42184$, $df = 12.256$, p-value $= 0.3402$).

2) Playability: Playability has been measured by both behavioral and self-reported measures (SUS). The related

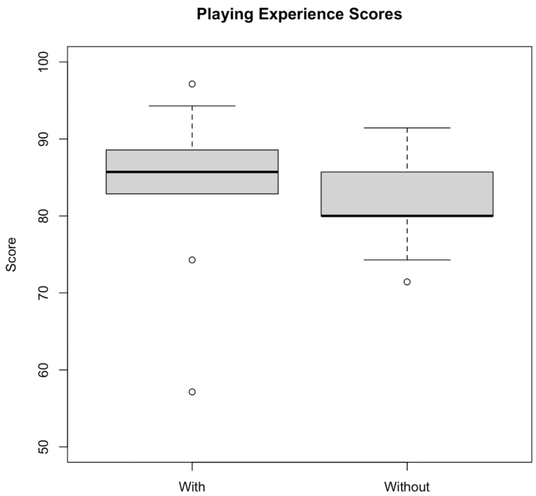

Fig. 6. Playing Experience scores distribution

hypotheses and results will be organised here according to which controller they refer to.

3) Glove Playability:

H2: A significantly lower Time on Task for the glove task (1);

In order to test our second hypothesis, Time on Task (ToT) for each of the three combinations has been compared between the two conditions. The inferential analysis has been conducted with a one-tailed Welch Two Sample t-test, which highlights no significant differences in all the three conditions:

- Combination 1 (t = 1.4105, df = 11.74, p-value = 0.9078)
- Combination 2 (t = -0.6939, df = 12.644, p-value = 0.2501)
- Combination 3 (t = -0.71175, df = 9.5764, p-value = 0.2468)

However, we have noticed a general decrease of ToT through the three combinations (Fig II), regardless of haptic feedback. This can be explained both by the instrument level combination chosen, which could be increasingly easier to set, and by participants learning to use the system better with practice.

TABLE II
COMPARISON IN TOT AMONG TASK 1 COMBINATIONS

ToT Averages (s)	All	SD	With	SD	Without	SD
Combination 1	28.22	15.47	32.22	19.04	23.22	9.48
Combination 2	16.83	6.36	15.78	4.49	17.89	7.94
Combination 3	9.28	7.5	8	3.24	10.56	10.27

H3: A significantly higher SUS score for the glove (task 1);

The third hypothesis has been tested by a One-tailed Welch Two Sample t-test with 95 percent confidence interval between conditions. The SUS scores for the haptic condition are higher (Table V-E3 and Fig. 8), and the difference emerged as

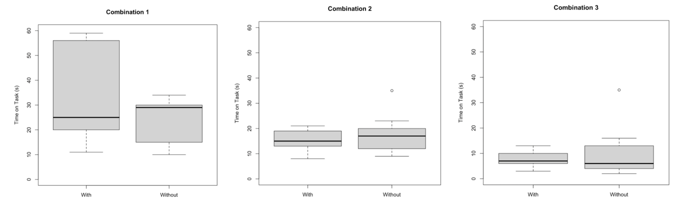

Fig. 7. Comparison in ToT among Task 1 combinations

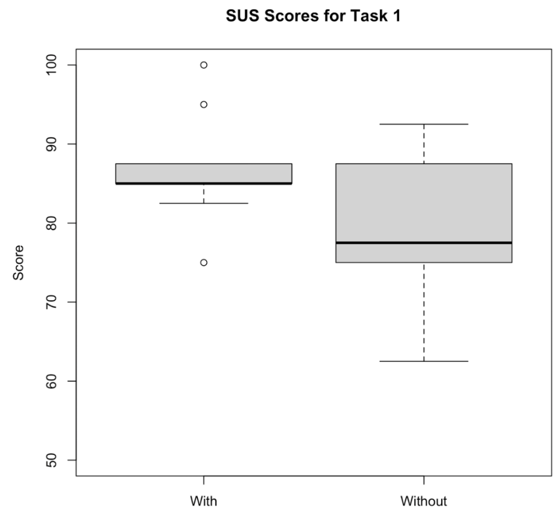

Fig. 8. SUS Scores for Task 1

statistically significant (t = 1.7623, df = 14.971, p-value = 0.04921). We can therefore reject the null hypothesis and go for the alternative one.

TABLE III
SUS SCORE RESULTS.

	All	SD	With	SD	Without	SD
SUS Score	83.19	8.86	86.67	7.18	79.72	9.39

4) Baton Playability:

H4: A significantly lower BPM Root Mean Squared Error in the baton task (2);

In the second task, the BPM Root Mean Squared Error has been compared between the two conditions. To do so, we have conducted a One-tailed Welch Two Sample t-test, which has emerged as not statistically significant (t = -1.1946, df = 9.3338, p-value = 0.1308). However, descriptive analysis still highlights a lower error for the condition with haptic feedback. (Fig.

TABLE IV
TASK 2 RESULTS.

	All	SD	With	SD	Without	SD
RMSE (BPM)	10	8.22	7.72	3.19	12.29	11.02

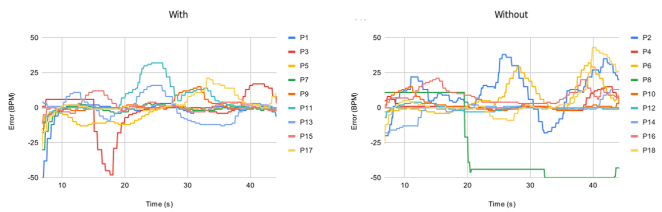

Fig. 9. Error for Task 2, with and without conditions

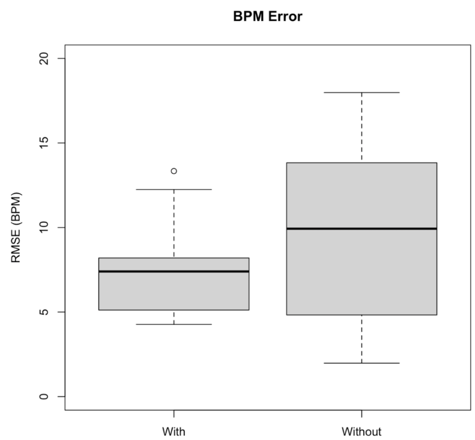

Fig. 10. RMSE (BPM) boxplots comparison between conditions.

H5: A significant higher SUS score for the baton (task 2);

The SUS scores for the baton have been measured and then analysed with a One-tailed Welch Two Sample t-test with 95 percent confidence interval between conditions (t = 1.5517, df = 13.165, p-value = 0.07222). The scores, even if higher in the condition with haptic feedback, are not significant, and we can't reject the null hypothesis (Table V-E4; Fig. 11)

TABLE V
SUS RESULTS FOR THE BATON.

	All	SD	With	SD	Without	SD
SUS Score	86.39	14.23	91.39	10.01	81.39	16.54

5) Qualitative results: The qualitative analysis has revealed several interesting insights. The most frequently observed patterns include:

- Participants' spontaneous enjoyment and appreciation of the system (9 participants);
- Challenges with setting BPM/tempo with the baton (8 participants);
- Difficulties entering selection mode using the glove (13 participants);

This last trend could be due either to hardware issues or the fact that people performed the gestures less naturally due to the stiffness of the glove mounting the flex sensors. Moreover, the glove was generally preferred over the baton, with 8 participants highlighting the glove's features positively compared

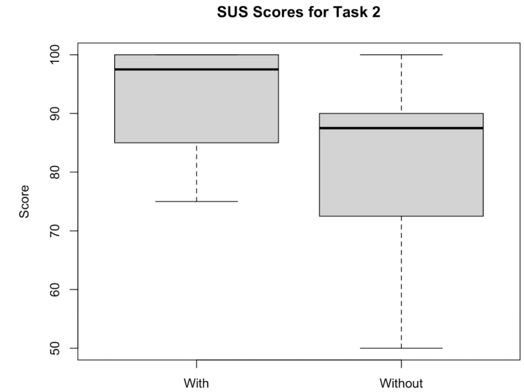

Fig. 11. SUS scores for task 2

to only 2 who favored the baton. Common criticisms focused on the baton's slow responsiveness for tempo control, with 10 participants expressing dissatisfaction with these aspects.

However, this finding doesn't mirror the quantitative results: overall SUS scores are slightly higher for the baton than the glove (Table VI).

	All	SD
Overall Baton SUS Score	86.39	14.23
Overall Glove SUS Score	83.19	8.86

TABLE VI
SUS SCORES COMPARISONS

The mismatch between the SUS's scores and the qualitative results for users' preferred controller highlights the value of Orio, Nicola Schnell, Norbert Wanderley, Marcelo (2001) [8] suggestion of evaluating both usability and personal aesthetic considerations to assess DMIs. In this case, usability measured by SUS scores falls short in understanding users' preferences. Overall, the perception of the system has emerged positively, particularly for the "silence all" gesture, which has been explicitly appreciated by 8 participants. Several potential applications, specifically in music education, have been identified by the participants.

VI. DISCUSSION AND CONCLUSIONS

This study examined how primary haptic feedback affects the playability and playing experience of Maestro, a gesture-based Digital Musical Instrument (DMI). Using a between-subjects design, we compared user performance and impressions with and without haptic feedback. The findings highlight the role of haptics in empty-handed DMIs and suggest directions for future research.

While haptic feedback only marginally improved the playing experience, it significantly enhanced glove usability, as measured by the System Usability Scale (SUS). This suggests even minimal haptic cues (100ms vibration on selection) improve the interaction.

Testing revealed key limitations: the BPM algorithm lagged, making synchronization difficult; pre-selected musical clips restricted creativity; and the rigid glove design hindered natural gestures. The distracting pointer system also demanded excessive user attention.

Key takeaways include the need for more time between pilot and final tests to refine usability and the value of combining quantitative metrics with qualitative feedback. Future work should improve BPM responsiveness, allow orchestral MIDI scores for greater creative control, explore flexible glove designs or alternative recognition methods, and redesign the pointer for reduced distraction.

In conclusion, while haptics improved glove usability, addressing these limitations is crucial. Enhancing algorithm performance, gesture recognition, and musical flexibility will make Maestro a more immersive and accessible tool for all users.

Group Members contributions

A. Andrea De Carlo

- Project idea
- BPM algorithm with fine tuning parameters
- General code management
- Observations and interviews during testing
- Architecture design and implementation sections in report

B. Gabriele Tangerini

- Literature review
- Circuit
- Teensy firmware (sensors data and actuators control)
- Processing sketch and shader for the visual interface
- Facilitation during testing
- Technical management of the system during testing
- Quantitative analysis of collected data (in collaboration)
- Qualitative analysis of collected data
- Photography

C. Lucrezia Di Bari

- Glove
- Icons for the visual interface
- Experimental design (questionnaires choice)
- Playing Experience Questionnaire construction
- Participant recruitment
- Qualitative data collection during testing
- Facilitation during testing
- Photography for the final video
- Evaluation section in report

D. Pietro Cau

- Initial research on Digital Musical Instruments
- Design of gestural interface
- Creation of music pipeline (Processing to Pure Data to Logic Pro)
- Supportive role in the design and implementation of user interface
- 3D modeling and 3D printing of baton
- User Testing
- Video Editing

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