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Master Degree course in Communications Engineering

Master Degree Thesis

Enhanced Haptic Feedback System for Conveying an Orchestra Conductor's Directional Cues in a Virtual Environment to Blind or Visually Impaired Musicians

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Abstract

This thesis presents the design and preliminary evaluation of a haptic feedback system intended to translate the gestures of an orchestra conductor into tactile signals for blind or visually impaired musicians. Building on previous work on remote orchestra conduction, the proposed system detects the conductor's movements by tracking the coordinates of the hand and head in a virtual environment. This information forms the basis for recognizing conducting gestures and conveying them as haptic cues. The system comprises two main components: a gesture recognition module based on these virtual-environment coordinates, and a vibration feedback module. At the current stage of development, these modules operate separately: the system attempts to recognize conducting gestures from positional data, and, independently, vibration patterns are sent from a computer for given gestures to explore translation strategies. User needs were identified through interviews with blind, visually impaired, and sighted musicians, which informed the selection of suitable body areas (arm or leg) for haptic feedback and guided the physical design of the prototype. A wearable device integrating the necessary electronic components was fabricated, and preliminary mappings between conducting gestures and vibration schemes were proposed and tested on individuals. While the resulting prototype demonstrates the feasibility of the concept, it remains a proof of concept; further integration and refinement are required to achieve real-time automatic translation of gestures into tactile feedback and to fully support remote orchestral performance.

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Chapter 1

Introduction

1.1 Addressed Scenario and Problem

Music performance is inherently a multisensory activity, relying not only on auditory perception but also on visual and tactile cues to achieve precise coordination and expressive communication. Haptic feedback is the use of tactile sensations, such as vibrations or forces, to communicate information through the sense of touch. It is increasingly applied in human-computer interaction to provide users with non-visual or non-auditory cues, enhancing perception, awareness, and coordination. One domain where haptic feedback has the potential to play a transformative role is music performance, which often relies on precise timing, gesture recognition, and multisensory communication. In orchestral conducting, musicians depend heavily on visual cues—hand gestures, baton movements, and body language—to interpret tempo, dynamics, and expressive intent. For Blind or Visually Impaired (BVI) musicians, accessing these cues is inherently challenging, making it difficult to synchronize and perform with the ensemble.

This challenge becomes even more pronounced in remote orchestra performances, where musicians cannot rely on direct line-of-sight with the conductor or fellow performers. Communication is mediated through screens or audio streams, often introducing latency, reducing spatial awareness, and limiting access to subtle visual cues that are critical for precise timing and coordination. Without an alternative channel, BVI musicians face a heightened risk of falling out of sync with the ensemble.

Recent advances in Networked Music Performance (NMP), particularly accelerated during the COVID-19 pandemic, have demonstrated the feasibility of remote orchestration. For instance, a recent study [44] showed that a conductor in Turin could successfully lead an orchestra in Poland using a Virtual Reality (VR)-based system, where musicians followed a real-time avatar of the conductor's gestures. While this represents a breakthrough for remote music collaboration, such systems rely exclusively on visual feedback, making them inaccessible to BVI musicians.

This thesis addresses this gap by developing a haptic feedback solution that translates the conductor's directional cues into tactile signals, enabling blind or visually impaired musicians to follow remote orchestral performances with improved timing and coordination.

1.2 Relevance and Practical Importance

The lack of inclusivity in digital orchestra conducting solutions presents a significant accessibility gap. BVI musicians face considerable challenges in traditional orchestral settings, relying on individually developed, often improvised alternative cues, learned through experience rather than formal training, to follow the conductor. These challenges are further amplified in virtual or remote environments, where alternative sensory cues are often missing. Developing a haptic feedback system to transmit a conductor's directional cues provides a direct solution to this accessibility issue, enabling BVI musicians to participate more in both physical and virtual orchestras. Beyond accessibility, such a system can also benefit sighted musicians in situations where their view of the conductor is obstructed, or when they must focus closely on their music sheets and cannot simultaneously watch the conductor. By providing tactile cues alongside traditional auditory and visual signals, this approach enhances ensemble coordination and opens the door to more universally adaptable and multimodal virtual conducting systems, improving the overall performance experience for all musicians.

1.3 Main Contribution

The primary contribution of this thesis is the development of a haptic feedback prototype that translates a conductor's gestures into tactile sensations. This prototype extends the existing VR-based conducting system proposed in [44] by integrating haptic feedback, enabling visually impaired musicians to perceive directional cues without relying on visual elements. The key contributions include:

- Design and implementation of a suitable haptic feedback system, based on an arduino Nano processor.
- Implementation of a gesture recognition algorithm to indentify conducting movements acquired by means of an Oculus Quest 3 Head Mounted Display(HMD).
- Definition of a gesture-to-vibration mapping and implementation of the translation of the recognized gestures into the haptic system for real-time feedback conveyance.
- Validation of the system through experiments and user testing.

1.4 Methodology

The research methodology combines multiple approaches:

- **Literature Review**: Examining existing haptic feedback technologies, gesture recognition systems, and previous VR-based conducting prototypes.
- **Prototype Development**: Designing and implementing a haptic feedback system tailored for conveying conducting cues.
- **Gesture Recognition Implementation**: Developing an algorithm to detect and interpret a conductor's gestures.
- **Experimental Validation**: Conducting usability tests to evaluate the effectiveness of the prototypal system in conveying conducting cues.

1.5 Thesis Organization

The thesis is structured as follows:

1. **Chapter 2: Related Work** – This chapter reviews previous studies on virtual orchestra conducting and the development of haptic devices.
2. **Chapter 3: Background** – This chapter outlines the technical constraints identified in previous research and highlights the role and importance of the conductor.

3. **Chapter 4: Preliminary Interviews and Problem Definition** – This chapter presents the specific needs of blind musicians, the challenges of conducting in both physical and virtual environments, and the constraints shaping the development of a haptic solution, based on conducted interviews.

4. **Chapter 5: Prototype Design and Implementation** – This chapter describes the selection of the most suitable implementation approach and the design of the wearable solution.

5. **Chapter 6: Gesture Recognition Implementation** – This chapter explains the methods used for recognizing conducting gestures and converting them into digital signals.

6. **Chapter 7: Haptic System Integration and Validation** – This chapter details the process of translating recognized gestures into haptic feedback and evaluates its effectiveness through testing.

7. **Chapter 8: Prototype Testing** – This chapter presents the final system testing under practical conditions.

8. **Chapter 9: Conclusion** – This chapter summarizes key findings, and discusses potential future improvements.

Chapter 2

Related work

Recent developments in haptic technology and virtual conducting systems have enhanced the ways musicians, conductors, and audiences interact in digital and immersive musical environments.

This section reviews previous work on virtual conducting solutions, focusing on the use of virtual reality and gesture recognition technologies to interpret conductor movements through various techniques. It also explores the application of haptic devices in musical contexts, as well as their roles in navigation, guidance, and virtual reality environments. Additionally, the use of haptic feedback in real-life scenarios will be examined.

2.1 Virtual Conducting Solutions

Virtual conducting systems are emerging as promising tools to enhance accessibility for BVI musicians in orchestral settings. These technologies aim to replicate the conductor's visual cues through digital environments and multimodal feedback.

2.1.1 VR-Based Conducting Systems

Virtual Reality (VR) has been effectively applied to orchestral conducting in remote performance settings [44]. In these systems, both the conductor and the musicians are represented as avatars within a shared virtual environment, enabling real-time visualization of gestures and interactive communication. The platforms are typically developed using the Unity game engine and incorporate features such as gesture tracking, motion capture, and latency monitoring to ensure precise synchronization among participants. To maintain musical coherence, audio latency must remain below approximately 100 ms, as higher delays can disrupt rhythm and ensemble timing. Consequently, wired network connections are generally preferred over wireless ones, as they provide more stable and lower-latency transmission essential for synchronized remote performances.

2.1.2 Gesture Recognition and Feedback Translation

To improve accessibility for BVI musicians, researchers have developed gesture recognition systems that integrate Kinect-based motion tracking with multimodal feedback systems, which combine different sensory channels such as sound and touch [5]. These systems analyze the conductor's gestures in real time by comparing the tracked movements to a predefined gesture library, using spatial zones to classify expressive commands such as "soft," "medium," or "loud." The interpreted gestures are then communicated back to musicians through auditory signals, vibrotactile vibrations, or a combination of both, allowing them to perceive the conductor's intent without relying on sight. While auditory cues can be masked in noisy rehearsal environments, vibrotactile feedback has demonstrated greater reliability and faster response times. As a result, haptic feedback, alone or in combination with audio, offers a more effective solution for enhancing communication and responsiveness in live orchestral environments.

2.2 Haptic Devices in Musical Applications

Haptic feedback plays a growing role in enhancing music performance, learning, and emotional engagement. By translating auditory cues into tactile sensations, these systems support musicians in maintaining rhythm, interpreting expressive elements, and accessing musical information through non-visual means.

2.2.1 Wearable Haptic Devices for Musicians

Wearable haptic systems provide vibrotactile cues to support tempo, articulation, dynamics, and synchronization. Common formats include belts, bands, and bracelets, each designed to convey different layers of musical information [35]:

Haptic Belt: Equipped with several actuators, it delivers rhythmic patterns and musical instructions to performers, facilitating ensemble coordination.

Elastic Haptic Band: A simplified variant with a single actuator, focused on conveying basic features such as tempo and dynamics.

Haptic Bracelets and Anklets: Wireless devices that send rhythmic signals to specific limbs, supporting coordination and aiding visually impaired musicians.

Multi-sensory Metronome: Developed at Politecnico di Torino, this system integrates visual, auditory, and tactile cues via two motors controlled by an Arduino Nano, compensating for latency and drift. [40]

Tactons—predefined vibration patterns—are often used in these systems to represent specific musical commands. For example, a slow pulsing tacton might signal a crescendo, while a sharp burst may indicate staccato. These tools have been tested in live performance contexts, such as a concert where a trombonist successfully received real-time vibrotactile cues [35].

2.2.2 Emotional Engagement and Audio-Tactile Mapping

Beyond performance, haptic feedback enhances emotional connection to music. The **FeelMusic** sleeve integrates eight vibrating motors and an inflatable cuff, translating musical elements (e.g., melody, bass) into physical sensations. High notes are positioned closer to the wrist, and vibrations (2–128 Hz) are updated every 10 ms [16]. Studies found a correlation between vibration frequency and perceived emotional intensity, suggesting tactile input can enrich music listening [39].

Similarly, the **Haptic Chair** allows users to feel music through their hands, back, and feet using embedded vibration modules and a visual display [36]. The **VibroBelt**, with eight vibrators each linked to specific notes or functions, supports interactive music making [36].

2.2.3 Assistive Technologies for Conducting and Synchronization

The **DIAMI system** helps BVI musicians follow conductors using vibrating bracelets equipped with four motors [1]. The conductor's baton, fitted with an infrared sensor, is tracked via the WiiMote. The WiiMote, short for Wii Remote, is a motion-sensing wireless controller developed by Nintendo for the Wii console, allowing players to interact with games through physical gestures and button presses. Movements are projected in a virtual 2D plane, divided into zones corresponding to different vibration patterns. For example, vertical and horizontal movements activate specific motors, while diagonal gestures combine two. Stronger gestures trigger higher-intensity vibrations. The system is wireless, Bluetooth-enabled, and built on Arduino .

Another promising approach is the use of **lightweight upper-limb exoskeletons** to provide kinesthetic feedback [30]. These devices guide the user's arm in real time, improving synchronization with a teacher or ensemble. Two scenarios—human-machine and human-human interaction—were studied. The system improved accuracy over visual-only cues and showed strong potential in educational contexts, particularly for beginners. However, current designs remain intrusive and best suited for controlled environments.

2.2.4 Haptic Feedback for Conductors

Haptic systems have also been developed for conductors to replace click tracks with continuous vibrotactile cues. One such prototype uses **Vibropixels**, modular wireless units equipped with two ERM actuators (one slow and efficient, the other fast and strong) [19]. These actuators generate programmable vibration envelopes (attack, peak, decay), synchronized with audio click tracks. Different motors or intensities emphasize downbeats and tempo changes.

Latency was measured using an oscilloscope to ensure responsiveness, with future iterations aiming to further reduce delay. This system provides a scalable and reconfigurable solution for conductors seeking more intuitive ways to follow pre-recorded playlists.

2.3 Haptic Feedback for Navigation and Guidance

Haptic technology is increasingly used to assist BVI in navigation, object detection, spatial orientation and digital accessibility. Through tactile cues, these systems offer an intuitive and non-visual alternative for perceiving the surrounding environment.

2.3.1 Wearable Haptics for Real-World Navigation

Vibrotactile and skin-stretch feedback have shown promise in guiding BVI users through real environments. Research suggests that **skin-stretch feedback** offers superior directional accuracy due to its continuous nature [26].

Wrist-mounted haptic devices have proven more reliable than pocket-worn systems, offering direct skin contact and consistent signal detection. Vibrations applied to the wrist or hand are detected nearly 100% of the time, compared to less than 75% for pocket-based systems [21]. For improved precision, two wristbands—one on each wrist—are often used, and users must be given time to adapt to the cues.

PneuFetch is a wearable system that simulates the feeling of being gently guided by another person. It uses tactile cues on the wrist and forearm, modulated in intensity and frequency based on object proximity. This technique improves object localization in unfamiliar environments [17].

2.3.2 Obstacle Detection and Spatial Awareness

Haptic systems have been developed to help BVI detect obstacles beyond the capabilities of a traditional cane. For example a wearable haptic jacket is proposed in [43], which divides the user's surroundings into five spatial zones (left/right ground, left/right torso, and head level), each linked to a corresponding motor. When an obstacle is detected in a zone, the related motor vibrates with an intensity proportional to the object's proximity. This multi-zone feedback provides comprehensive environmental awareness, including objects at head or torso level that a white cane cannot detect. Initial tests are promising, although further trials in real-world contexts are needed to refine system usability.

2.3.3 Haptic Feedback in Digital Environments

Haptic feedback has also been applied to web accessibility for BVI users. Audio screen readers, though informative, often present content in a linear and time-consuming manner. To address this, researchers developed a **force-feedback mouse** that provides tactile landmarks corresponding to interactive elements such as buttons and links [22].

Through iterative design with BVI participants, the system evolved into a more intuitive interface. Users were able to perceive the spatial layout of a webpage, locate key elements, and build a mental map of the page, thereby improving navigation efficiency and confidence.

2.3.4 Advanced Prototypes: The ARMadillo System

The **ARMadillo** is a wearable haptic device designed for the forearm [41]. It combines motion tracking and vibrotactile feedback for a wide range of applications, including musical interaction, spatial orientation, and text reading. The forearm is chosen due to its sensitivity to vibration and active mobility.

Key features include:

- A lightweight, adjustable structure using Velcro.
- Multiple vibrotactile motors arranged in a "constellation" pattern to ensure tactile distinguishability.
- Use of Unscented Kalman Filters to suppress parasitic vibrations and improve tracking precision.
- Inertial sensors (accelerometers, gyroscopes, magnetometers) to support real-time motion capture.

Compared haptic methods show that **vibrotactile feedback** is the most practical for wearables—being compact, low-cost, and effective—while electrocutaneous and thermal feedback present limitations in safety and responsiveness [41].

2.4 Haptic Feedback for Virtual Reality

Haptic feedback systems are increasingly integrated into VR environments to enhance immersion, realism, and user interaction. These technologies aim to replicate touch sensations, simulate collisions, and support training in both entertainment and professional contexts.

2.4.1 Wrist-Based and Temple-Based Feedback

Studies comparing wrist-based, temple-based, and combined haptic solutions for VR collision detection show that **wrist-mounted feedback** provides the most intuitive experience for hand-based interactions [34]. Users reported enhanced object manipulation and a more natural sensation when vibrations were applied at the wrist. While combining wrist and temple feedback offered additional confirmation for some users, the wrist remained the most effective location for consistent interaction.

2.4.2 Full-Body Haptic Vests for Immersive VR

Full-body haptic vests have been developed to simulate tactile sensations during virtual collisions. A representative prototype includes 16 vibrotactile actuators embedded in a lightweight vest made of neoprene [27]. The vest divides the torso into square zones, each associated with a specific motor. When the virtual body encounters an object, the corresponding zone vibrates to replicate contact.

To ensure precise feedback, the material minimizes vibration propagation, and the system maintains skin contact throughout use. Adjustable straps improve fit across users, while wireless Bluetooth connectivity and rechargeable batteries offer freedom of movement. Despite its effectiveness, further refinement is needed to enhance comfort and responsiveness.

2.4.3 Haptic Feedback in VR Surgical Simulators

Haptic feedback also plays a role in **medical VR simulators**, especially for laparoscopic surgery training [48]. Two instrument handles were tested—one equipped with haptic feedback and one without. While haptic sensations were valuable for simulating tissue resistance during grasping and pulling, many surgeons preferred the non-haptic prototype.

Their feedback indicated that the haptic feedback device did not yet replicate real surgical sensations accurately. Although the technology helps learners understand force interactions, fine-tuning is necessary to align the haptic response with realistic expectations. Artificial feedback, if not properly calibrated, can quickly become counterproductive.

2.5 Haptic Feedback in Daily Life

Haptic feedback is deeply integrated into everyday technology, enhancing interactions for both sighted and visually impaired (BVI) individuals. By translating digital information into tactile sensations such as vibrations, pulses, or pressure, haptic systems provide an additional communication channel that improves usability, accessibility, and situational awareness. Their applications extend from personal electronics to mobility aids and entertainment systems, illustrating their versatility and growing importance in modern life.

On smartphones, haptic feedback has become a standard feature that reinforces user actions. Vibrations confirm touch inputs, notify users of incoming messages, or simulate the sensation of pressing a physical button on virtual keyboards. This tactile response helps users interact confidently with touchscreens, even without visual attention, which is particularly valuable for BVI users. Furthermore, haptic cues integrated into accessibility settings assist in navigating interfaces by signaling the selection of menu items or confirming gestures, thereby supporting non-visual interaction.

Haptic technology is also common in wristwatches. For BVI individuals, haptic-enabled watches offer a discreet and independent way to tell time. These devices typically use distinct vibration patterns in which long pulses indicate tens and short pulses represent units to communicate both hours and minutes. Smartwatches extend this concept by combining timekeeping with health monitoring and notifications, where vibrations can alert users to heart rate changes, physical activity goals, or incoming calls. In sports contexts, haptic feedback provides real-time guidance by signaling when to adjust pace, turn, or rest, offering a non-intrusive form of communication that allows athletes to remain focused on their performance.

Another common application appears in vehicle navigation systems, where haptic feedback enhances driver awareness and safety. Vibrations integrated into steering wheels or seats can indicate lane departures, upcoming turns, or obstacles, reducing the need for drivers to constantly monitor visual displays [13]. This multisensory approach improves reaction times and decreases distraction, showing how haptic feedback supports effective real-world decision-making.

In the gaming industry, haptic feedback has become a key element of immersive design. Modern controllers, joysticks, and VR gloves reproduce sensations such as impact, resistance, or surface texture to increase realism and emotional engagement [32]. However, BVI players face additional challenges in navigating and interacting within virtual environments. To address this, adaptive systems combine audio feedback, such as spatialized sound cues, with tactile responses, allowing players to perceive object locations or in-game events [15]. Research suggests that players must construct mental maps and remember spatial layouts, but excessive information should be avoided to prevent cognitive overload, ideally limiting feedback to seven concurrent elements [8]. Complementary systems have also been developed to convert visual elements, such as color gradients or object outlines, into vibration intensities, making virtual environments more accessible to players with visual impairments [31].

Beyond entertainment, haptic feedback plays a vital role in everyday tasks. Kitchen scales equipped with tactile and auditory feedback allow BVI users to measure ingredients accurately and safely, improving independence in food preparation.[1] Similarly, accessible payment terminals use haptic or audio cues to confirm inputs, ensuring that financial transactions can be performed securely and privately without external assistance.[2]

For mobility, smart canes represent a significant innovation in assistive technology.[3] These devices detect obstacles through sensors and communicate their proximity using vibrations transmitted through the cane handle. More advanced versions incorporate adjustable vibration intensities, GPS navigation, and real-time voice guidance. Despite their potential, only about 20% of BVI individuals currently use such canes, citing high costs and excessive vibration intensity as limitations. Continued improvements in haptic sensitivity and adaptive feedback are expected to make these devices more accessible and comfortable in the future.

Tactile tablets extend haptic feedback into educational and professional contexts. These devices allow users to perceive textures, shapes, and images through touch, offering a tactile means to explore visual information. Such tools are particularly valuable in teaching geography, mathematics, and architecture, where tactile representations of maps, graphs, and spatial layouts help users develop a deeper understanding of abstract concepts [11]. Some tactile tablets use electrostatic technology to simulate surface friction, enabling users to distinguish borders, contours, and elevations. In spatial navigation research, touch-sensitive screens allow users to explore and memorize room structures or building plans through interactive tactile exploration, significantly enhancing orientation and spatial reasoning for BVI users.

[1] https://www.guidedogs.org.uk/getting-support/information-and-advice/how-can-technology-help-me/talking-kitchen-scales/

[2] https://ingenico.com/en/newsroom/blogs/making-touchscreen-terminals-accessible-people-visual-impairment

[3] https://www.ceciaa.com/deplacements-mobilite-deficience-visuelle/cannes-deplacement-aveugles/cannes-blanches.html

Chapter 3

Background

Designing effective haptic feedback systems requires a detailed understanding of both the physiological limitations of human tactile perception and the technical capabilities of actuators. Various studies provide critical insights into these constraints, as detailed in the following.

Understanding orchestral performance requires recognizing the conductor's pivotal role in coordinating musicians, shaping interpretation, and maintaining cohesion. These responsibilities have been extensively examined in the literature, as outlined in the following.

3.1 Technical Constraints

3.1.1 Perceptual Characteristics of Vibrotactile Feedback

Research has shown that temporal features play a more decisive role than spectral characteristics in vibrotactile perception. Experiments involving frequency shifts (50–100 Hz and 200–400 Hz, with durations of 80 to 320 ms) demonstrated that abrupt changes in temporal structure were more easily detected than differences in waveform or pitch [47]. Sequences modulated in frequency and amplitude were better perceived at lower frequencies, with an estimated transmission rate of 6 bits per second per channel. The wrist, in particular, offered reliable results when vibration intensity was adjusted for reduced sensitivity.

The frequency range between 200 and 390 Hz was found to activate the auditory cortex through tactile stimulation, with a peak response at 300 Hz [3]. This suggests a potential for enhancing musical perception through haptics. To ensure that the responses were purely tactile, participants wore sound-isolating headphones.

3.1.2 Actuator Technologies and Signal Design

Several types of actuators exist for haptic applications, each with specific trade-offs [39]:

- **Voice Coil Actuators (VCA)**: Directly driven by audio signals but bulky and energy-consuming.

- **Linear Resonant Actuators (LRA)**: Compact and responsive, but limited frequency range.

- **Eccentric Rotating Mass (ERM)**: Lightweight and simple, yet unable to independently modulate frequency and amplitude.

- **Piezoelectric Actuators**: Efficient across a wide frequency range with low power consumption, though requiring specific drivers.

- **Dual Mode Actuators (DMA)**: Allow simultaneous dual-frequency output for rich signals but remain experimental.

Signal amplification or dedicated driver circuitry is generally required for VCAs, LRAs, piezoelectric actuators, and most DMAs to maintain consistent intensity, whereas small ERMs can sometimes be driven directly without additional amplification.

These actuators are used in various applications. For example, a glove equipped with six haptic actuators (300–20,000 Hz), powered by Class D micro-amplifiers, effectively conveyed musical emotions through touch—demonstrating the potential of multisensory communication [45].

3.1.3 Tactons and Tactile Information Encoding

Tactons (structured tactile messages) convey information through perceptual variables such as rhythm, roughness, spatial location, and pulse duration. Research shows that amplitude-modulated vibrotactile signals (250 Hz carrier modulated at 20–50 Hz) effectively encode roughness, especially when delivered through high-performance transducers like the EAI C2 Tactor [6]. Participants could reliably distinguish three levels of roughness using this device, achieving recognition rates of approximately 80 percents. Rhythm emerged as the most easily identified parameter, with a 93 percents recognition rate, underscoring its robustness for tactile communication.

Short pulses under 0.1 seconds are interpreted by users as discrete taps, making them ideal for conveying simple, unambiguous cues [4]. While variables like rhythm and spatial location prove highly effective, differences in waveform shape are not reliably perceived, suggesting limited utility in relying on signal form alone.

Complementary findings from studies using eccentric rotating mass (ERM) actuators (140–380 Hz) further inform tactile interface design [12]. When positioned on the back, these actuators exhibited a minimum stimulus separation threshold of 200 ms for events to be perceived as distinct. Ramp-up times were rapid (under 15 ms), but ramp-down times could extend beyond 600 ms, complicating rapid successive signaling. Effective perception required duty cycle values above 0.2, with reliable discrimination only when intensity differences exceeded 0.3–0.5 in duty cycle.

Together, these studies highlight critical design parameters for tactile systems: rhythmic patterns, temporal spacing, and amplitude modulation are far more perceptible than waveform shape, reinforcing the value of temporal and spatial encoding in multisensory communication, particularly for BVI users or musicians requiring non-visual cues.

3.1.4 Sensitivity and Spatial Constraints on the Body

Human skin demonstrates peak sensitivity to vibrotactile stimulation in the 150–300 Hz range, particularly in high-density receptor areas such as the palms and soles. However, perceptual thresholds can vary significantly depending on factors such as age, skin condition, and individual sensitivity [9]. Temporal resolution is notably high; humans can distinguish pulses separated by as little as 5 milliseconds.

While the hands and face offer the highest tactile resolution, the back and legs provide a larger surface area but with significantly lower sensitivity. These differences present distinct opportunities and constraints that must be considered when designing tactile systems. However, delivering more than two or three simultaneous tactile cues can lead to perceptual overload, as the brain struggles to process multiple stimuli at once [14]. For optimal perception, vibrations must be clearly distinguishable, both spatially and temporally, and should not occur in rapid or erratic sequences. Simple, well-separated patterns with no more than two concurrent signals are significantly easier for users to interpret. Importantly, the ability to decode complex tactile information improves with practice and training, underscoring the critical role of learning in enhancing the effectiveness of body-based communication systems.

3.1.5 Multimodal and Advanced Feedback Techniques

Haptic feedback includes not only vibration but also pressure, temperature, and kinesthetic inputs. It is generally divided into two main categories: tactile feedback, which stimulates the skin's surface, and kinesthetic feedback, which engages muscles, joints, and tendons to convey force or motion [18]. A wide variety of actuation technologies support these feedback types, including hydraulic and pneumatic systems, as well as piezoelectric and electromagnetic actuators. Each technology involves trade-offs in terms of size, response time, power consumption, and integration complexity.

Thermal feedback is typically too slow for dynamic interactions, limiting its effectiveness in real-time applications. In contrast, direct neural stimulation using low-intensity electrical currents can activate nerves beneath the skin with speed and precision, offering fast and localized sensory feedback. However, this approach demands careful calibration to prevent discomfort or unintended sensations.

Each technique presents its own limitations, but when thoughtfully combined, they can contribute to more immersive and nuanced multisensory experiences.

In our project, haptic feedback must be efficient, safe, and compact, ensuring that it integrates seamlessly into the system without compromising usability or comfort.

3.1.6 Summary of Technical Considerations

Designing effective haptic systems involves balancing perceptual, technical, and application-specific factors. Key considerations from the literature can be summarized as follows:

- Prioritize temporal features over waveform shape.
- Use frequencies between 200–390 Hz for optimal perceptual and cortical activation.
- Select actuators based on trade-offs in size, frequency range, and energy efficiency.
- Limit the number of simultaneous tactile cues to prevent perceptual overload.
- Choose body locations with high sensitivity or large surface area depending on the application.
- Incorporate multimodal stimuli when appropriate to enrich user experience.

3.2 Role and Functions of an Orchestra Conductor

The orchestra conductor plays a central role in shaping the musical interpretation and ensuring the cohesion of an ensemble. Their fundamental responsibility is to interpret the musical score, coordinate performers, and convey artistic direction. While the specifics of their role have evolved, their function remains rooted in unifying the performance both technically and expressively.

Figure 3.1: Photograph of an Orchestra Conductor[1]

Conductors establish and maintain the pulse of a piece, serving as a rhythmic reference throughout the performance. They prepare musicians for precise entrances and manage tempo changes with clarity. Traditionally, the right hand defines tempo and pulse, while the left hand communicates expressive elements such as phrasing, dynamics, and articulation. Through coordinated gestures, conductors balance individual voices, shape the ensemble's sound, and unify its artistic vision.

Beyond rhythmic control, conductors guide emotional expression and stylistic nuances, transforming written scores into dynamic interpretations. Their leadership extends to all moments of performance, including the start and end of phrases, climaxes, transitions, and even silences. In doing so, they ensure that each element of the music is intentional, expressive, and coherent [46].

3.3 Gesture Detection Methodology

3.3.1 Random Forests

Random Forests (RFs) are ensemble classifiers that aggregate the predictions of multiple decision trees, each trained on bootstrapped samples and random feature subsets. This structure makes them both robust to noise and capable of generalizing well to unseen data. In gesture recognition, this robustness is particularly important because conducting gestures are prone to tracking errors, background motion, and variability across different conductors. By including non-gesture samples during training and applying iterative bootstrapping to correct misclassified examples, RFs achieve strong discrimination between intentional gestures and incidental movements [20].

Another advantage of RFs lies in their computational efficiency. During inference, each frame or temporal window is simply passed through a fixed set of trees, and the final decision is obtained by majority voting. This process is lightweight compared to deep learning models and

[1]Source : https://www.scienceabc.com/eyeopeners/use-conductor-orchestra-baton-music-baton-podium-opera.html

thus supports real-time deployment — an essential property for interactive musical environments [49].

RFs also integrate naturally with the multi-scale sliding window technique, which is widely used for gesture localization in continuous video streams. By classifying overlapping temporal segments of different lengths (e.g., 20–60 frames), RFs can capture both short and extended conducting gestures. Non-Maxima Suppression can then be applied to eliminate redundant detections, yielding precise gesture boundaries. This makes them particularly suitable for conductor-gesture analysis, where gestures vary in duration and overlap with non-gestural motion [20].

Additionally, RFs provide flexibility in feature representation. They can be trained on skeletal joint data, image patches, or motion trajectories without requiring domain-specific feature engineering. This is crucial in the conducting scenario, where both fine-grained hand movements (e.g., indicating beat accents) and large-scale arm trajectories (e.g., shaping musical phrases) carry meaning [7].

3.3.2 Alternative Approaches

While Random Forests offer a balanced trade-off between speed and accuracy, other supervised and unsupervised models are also applicable to gesture recognition:

Hidden Markov Models (HMMs): Well-suited for modeling sequential data, as they explicitly represent gestures as transitions between hidden states. They have been successfully used for continuous gesture recognition with the Viterbi algorithm for inference. However, they require careful design and filtering to avoid false positives in real-time applications [25].

Support Vector Machines (SVMs): Highly effective for classifying static gestures from structured visual features such as LBP, SURF, or PCA-reduced descriptors. They can achieve very high accuracy on well-defined pose classes, but lack the temporal modeling ability required for dynamic conducting gestures [23].

Recurrent Neural Networks (RNNs) and LSTMs: These networks model long-term dependencies in sequential data, allowing them to capture how gestures evolve over time. LSTMs in particular can distinguish gestures with similar appearances but different temporal dynamics [24]. Their main drawback is high computational cost and the need for large annotated datasets.

Convolutional Neural Networks (CNNs) and Hybrid CNN-LSTM Architectures: CNNs excel at extracting spatial features from visual input, while LSTMs add temporal modeling. Hybrid CNN-LSTM systems achieve state-of-the-art performance in many gesture recognition tasks, but at the expense of real-time efficiency and hardware requirements [33].

k-Nearest Neighbors (k-NN): Effective in smaller-scale settings, especially when combined with dimensionality reduction techniques like PCA. Weighted or dynamic k-NN variants can work in real time, but scalability is limited and ambiguity in complex gesture classes reduces robustness [38].

Unsupervised clustering methods (K-Means, DBSCAN): These approaches are useful for segmenting gestures or discovering recurring conductor motion patterns without labeled data. They are less suited for real-time recognition tasks but can be integrated into offline analysis pipelines [42].

3.3.3 Choice

In the specific context of orchestral conducting in a virtual environment, Random Forests stand out as a technically sound choice. Their noise resilience, low-latency inference, and compatibility with multi-scale sliding windows make them ideal for capturing the fluid yet structured nature of conducting gestures. Other methods, such as HMMs or LSTM-based architectures, provide stronger temporal modeling but at the cost of complexity and computational overhead. As such, Random Forests strike an effective balance between accuracy, efficiency, and robustness, making them a strong baseline for real-time virtual conductor gesture recognition [7] [20].

Chapter 4

Preliminary interviews and problem definition

Learning music as a BVI presents unique challenges, particularly in accessing sheet music, perceiving rhythm, and coordinating instrumental performance. In the absence of visual cues, touch becomes a primary means of understanding music, but this reliance introduces several constraints that require adapted solutions. The following section presents the interview findings, covering the challenges faced by BVI musicians, their reliance on touch for learning music, the selection of body locations for the prototype, additional requirements to be implemented in the prototype, and the perceived role of conductors. These insights are compared with existing literature to enable a more comprehensive analysis.

4.1 Interviews

To better understand the situation, interviews where conducted with 12 BVI subjects, aged 38 to 79. Participants responded to a predefined set of open-ended questions, and supplementary questions were asked when the participant identified as a musician. They explained their specific visual impairments and described how they imagine solutions to various challenges they face, such as accidentally bumping into someone on the street, understanding a professor's gestures in class, or maintaining synchronization in a group performance.

They shared insights into the haptic feedback they rely on in their daily lives and the haptic solutions they would like to use. Additionally, they described their bodily sensations in detail and identified the most and least sensitive parts of their bodies. Some of them (10) were also musicians, which allowed them to explain how they adapt to musical practice. They provided valuable perspectives on their experiences in orchestras and how they follow the conductor's cues. They also compared their most sensitive body parts to their use in playing their instruments.

In parallel, interviews were conducted with 16 sighted musicians from various orchestras, aged 20 to 28. They were asked to respond to a similar set of predefined questions, excluding those related to visual impairment, but including additional questions on their perception of the orchestra conductor. They described their use of haptic feedback in daily life, the freedom of movement required for each body part while playing their instruments, and the reasons and frequency with which they look at the conductor. These insights will help identify the key information that needs to be transmitted to BVI musicians through haptic feedback.

By synthesizing these findings, we can outline the constraints that our prototype must adhere to. These constraints will be combined with those identified in the existing literature.

A brief summary of the interviews is presented in Figure 4.1.

Age	Sex	Visual aptitude	Haptic feedback knowledgement	Instrument (years of experien	Suitable body part	Unsuitable body part
23	w	Sighted	None	Harp (13)	Hands, wrists, arms	Thighs
21	m	Sighted	Video games	Side flute (10)	Wrists, belt	Torso, legs
28	m	Sighted	Video games	Trombone (8)	Torso, left arm, left hand	Right arm
21	w	Sighted	Video games	Violin (14)	Chest	Arm and leg
21	m	Sighted	Phone	Trombone (12)	Fingers, face	Back
21	m	Sighted	Phone and video games	Trombone (13)	Hand, belt, temples	Right hand, shoulders, neck
25	w	Sighted	Connected watch	Side flute (12)	Arms, legs	Hands, thighs, head
24	m	Sighted	Connected watch and video games	Cello (18)	Ankles, head	Arms, wrists, torso, hands
23	w	Sighted	None	Harp (10)	Ankles, feet, arms	Belly, neck, head, back,hands
23	m	Sighted	Connected watch and phone	Guitar (13)	Arm, ribbs, hipps, legs	Hands, right arm
24	w	Sighted	Phone	Piano (7)	Feet, wrists	Head
24	w	Sighted	Phone	Piano (10)	Arms, legs	Head
22	w	Sighted	None	Side flute (10)	Legs, torso, back	Hands, arms
23	m	Sighted	Watch	Trumpet (15)	Wrists, torso, ankles, neck	
23	m	Sighted	Smartphone, video games	Violin (15)	Bottom parts	
20	w	Sighted	None	Cello (14)	Legs, shoulders	Bellly, back
65	m	Shadow, after age 45	Phone	Trumpet (before)	Ears	
38	w	Shadow since birth	Known in theory	Sing (5), Accordion, Piano(1)	Hands, belt	Knees
54	m	Light and contrast perception only, after age 5	Braille	Guitar	Hands, arms	Belt, ankles
63	m	Blind, after age 21	Phone	Accordion	Hands, back	
54	m	Blind since birth	None	Piano(50)	Arms, shoulders	Back, belly, hands
56	m	Blind, after age 18	Watch to give hour with vibration	None	Wrists, ankles, belt	Elbows, knees
57	m	Blind, after age 8	Phone, balance, connected watch, connected cane	Accordion, Piano (50)	Wrists, ankles	Ears, head
60	w	Shadow since birth	None	None	Arms, wrists	Legs
59	w	Blind, after age 44	None	Sing, tom tom	Arms, wrists, feet, head	
51	m	Light and contrast perception only, since birth	Phone, connected watch, connected cane, connected jacket	Guitar	Torso,belt	Limbs (except small)
79	w	Light and contrast perception only, since birth	None	Piano		
76	w	Lightand contrast perception only, after age 62	None	Percussion	Left forearm, neck	Fingers

Figure 4.1: Table of Interview Responses

4.2 Problems Faced by BVI Musicians

According to the interviewees, BVI musicians primarily learn by listening to audio recordings and relying heavily on memorization. As they cannot use visual cues, posture and gesture corrections are often provided through physical guidance, helping them internalize movement via tactile memory. To fully understand instructions, they depend on attentive listening to verbal explanations. Some, particularly beginners, use Braille music scores, although these are more time-consuming to read and less common for advanced repertoire.

BVI musicians must rely on compensatory strategies to access and learn musical content. Repetition and in-depth explanations, especially during music analysis, are essential for reinforcing memory and comprehension. Musical illustrations that link auditory and tactile information can help form a clearer understanding of music. Collaborative learning methods also foster shared understanding and inclusion. Additionally, developing tactile-motor skills supports the mastering of gestures and techniques through physical memory.

One of the main obstacles faced by BVI musicians is the inability to read standard sheet music. Without direct visual access, they must either rely on Braille scores or learn through repeated listening. This significantly increases the time and effort required for preparation.

As a result, they often perform entirely from memory, guided by recorded lessons and verbal instructions instead of visual references. Tactile musical illustrations, combining touch with auditory cues, can support interpretation and learning [29].

According to the interviewees, in ensemble and orchestral settings, BVI musicians rely on predefined setups and structured routines to support both practice and performance. Verbal cues often replace visual gestures, serving as crucial tools for orientation and coordination. As a result, BVI musicians primarily depend on their auditory perception and ingrained habits.

We can imagine the challenges BVI musicians face while performing or playing their instruments. Unfortunately, the difficulties extend beyond performance. Standard tuning devices, which rely heavily on visual feedback, are not accessible to them. Instead, BVI musicians interviewed use adapted tuning tools that provide auditory cues or, for those with some residual vision, high-contrast LED indicators. Additionally, some modern tuning apps now offer spoken instructions, eliminating the need for visual interfaces altogether. Some interviewees also mentioned the difficulty of navigating the stage due to obstacles such as chairs, music stands, and cables. Unfortunately, no specific solutions have yet been developed to assist them with this issue.

Interestingly, participants suggested that the loss of vision may enhance other perceptual abilities. Several reported an increased sense of spatial awareness, which enabled them to perceive the presence of nearby objects or detect variations in air displacement. They can often feel objects such as large trees, vehicles, or other massive structures around them. One striking example emerged during a choir rehearsal:

"I was singing in a choir, and the director used a violin bow instead of a traditional conductor's baton. This helped me feel the air movement on my skin since I was in the first row. I could also hear the slight sound it made as it moved through the air. This allowed me to follow her."

This anecdote illustrates how BVI musicians develop alternative strategies to compensate for the absence of visual cues, underscoring the importance of sensory adaptation in musical performance.

Additionally the adaptability of educators plays a key role in the success of BVI students. Teaching methods must be tailored to individual abilities, often requiring professors to redesign their approach. However, this integration remains inconsistent across institutions, depending on each teacher's experience and willingness to adapt [2].

A widely held belief is that the loss of one sense enhances the others. This belief is deeply rooted in the collective mindset. Although this assumption is largely anecdotal [37], the experiences shared by the interviewees tend to support it.

Overall, the findings from the interviews align closely with existing literature. Despite the challenges posed by vision loss, BVI musicians demonstrate remarkable adaptability, using personalized strategies and perceptual compensation to fully engage in musical practice and performance.

4.3 Constraints of Touch in Music Learning

While touch is an essential mode of learning for BVI musicians, it also presents specific limitations. Spatial awareness of instruments, such as the location of keys or strings, can be challenging without visual input. Recognizing notes and rhythms through touch alone requires prolonged training, and haptic feedback systems must be highly precise to prevent misinterpretation of tactile signals. Yet, current technologies remain limited in terms of accessibility and adaptability to the nuanced needs of musicians.

The interview findings support these observations. Participants explained that although Braille music sheets offer a tactile method to read music, they are significantly more time-consuming than traditional notation. Consequently, Braille scores are often used during the early stages of musical training but tend to be abandoned in favor of audio recordings as musicians advance. Audio resources are perceived as more efficient tools for memorization and learning.

To acquire and refine musical techniques, BVI musicians benefit from direct tactile guidance. Physical correction of posture and gestures enhances muscle memory and supports the development of accurate motor skills. The sensation of touch while playing is also fundamental to note recognition and performance consistency. For any haptic prototype to be effective, it must align with the fixed reference points that BVI musicians rely on, preserving the consistency of their tactile interaction with the instrument.

In addition to instrument-specific applications, the role of touch extends to broader communication and digital accessibility. Notably, BVI individuals are already accustomed to using haptic technologies in everyday life. Participants reported frequent use of vibrating smartphone interfaces, enhanced white canes for object detection and GPS navigation, smartwatches, kitchen scales with auditory signals, and video game controllers with force feedback. This familiarity suggests that integrating haptic feedback into musical learning tools could feel intuitive and facilitate adoption.

4.4 Considerations for Haptic Feedback Placement on the Body

Figure 4.2: Somatosensory homunculus representation.

The somatosensory homunculus reported in 4.2 visually maps the regions of the body with the greatest tactile sensitivity. Enlarged features such as the hands and lips indicate the brain's heightened sensory processing in those areas [10]. This insight is crucial when determining optimal placement for haptic feedback for BVI musicians. While the homunculus highlights areas of maximum sensitivity, it must be considered alongside the physical feasibility of accessing these areas during the performance of each instrument.

Based on interview data and the somatosensory homunculus, a classification table was developed to assess possible placement areas for a haptic feedback prototype. These placements are categorized as follows:

- **Possible**: Unrestricted placement.
- **Conditional**: Placement feasible with specific limitations.
- **Discomfortable**: Placement may cause discomfort.
- **Impossible**: Placement interferes with instrument use.

Table 4.1: Instrumental Compatibility with Haptic Feedback (Part 1)

Body Part	**Sensitivity**	**Size**	**Harp**	**Piano**	**Trumpet**	**Trombone**	**Side Flute**
Feet	Medium	Medium	Conditioned	Conditioned	Discomfortable	Possible	Conditioned
Ankles	Low	Small	Possible	Possible	Possible	Possible	Possible
Calf	Low	Big	Possible	Possible	Possible	Possible	Possible
Knees	Low	Small	Possible	Possible	Discomfortable	Discomfortable	Conditioned
Thighs	Low	Big	Discomfortable	Possible	Discomfortable	Discomfortable	Impossible
Belt	Low	Medium	Discomfortable	Discomfortable	Possible	Possible	Possible
Belly	Low	Big	Discomfortable	Possible	Discomfortable	Possible	Conditioned
Chest	Medium	Big	Impossible	Possible	Possible	Possible	Conditioned
Back	Medium	Big	Discomfortable	Discomfortable	Possible	Impossible	Conditioned
Hands	High	Medium	Conditioned	Impossible	Conditioned	Conditioned	Impossible
Wrists	High	Small	Conditioned	Conditioned	Possible	Conditioned	Conditioned
Forearm	Medium	Big	Possible	Possible	Possible	Conditioned	Conditioned
Elbow	Low	Small	Discomfortable	Possible	Possible	Conditioned	Conditioned
Biceps	Medium	Big	Possible	Possible	Possible	Conditioned	Conditioned
Shoulders	Medium	Small	Conditioned	Possible	Possible	Discomfortable	Conditioned
Neck	High	Medium	Discomfortable	Discomfortable	Conditioned	Impossible	Discomfortable
Face	High	Medium	Discomfortable	Discomfortable	Impossible	Impossible	Impossible
Scalp	Medium	Medium	Discomfortable	Discomfortable	Conditioned	Possible	Impossible

Table 4.2: Instrumental Compatibility with Haptic Feedback (Part 2)

Body Part	**Sensitivity**	**Size**	**Accordion**	**Violin**	**Cello**	**Percussion**	**Guitar**	**Singing**
Feet	Medium	Medium	Discomfortable	Conditioned	Possible	Possible	Conditioned	Possible
Ankles	Low	Small	Possible	Conditioned	Possible	Possible	Conditioned	Possible
Calf	Low	Big	Possible	Conditioned	Possible	Possible	Conditioned	Possible
Knees	Low	Small	Discomfortable	Conditioned	Possible	Possible	Conditioned	Impossible
Thighs	Low	Big	Possible	Conditioned	Impossible	Possible	Conditioned	Possible
Belt	Low	Medium	Possible	Conditioned	Discomfortable	Possible	Possible	Conditioned
Belly	Low	Big	Possible	Conditioned	Impossible	Possible	Possible	Conditioned
Chest	Medium	Big	Possible	Possible	Discomfortable	Possible	Possible	Conditioned
Back	Medium	Big	Possible	Discomfortable	Impossible	Conditioned	Possible	Conditioned
Hands	High	Medium	Conditioned	Discomfortable	Discomfortable	Discomfortable	Discomfortable	Possible
Wrists	High	Small	Conditioned	Discomfortable	Discomfortable	Conditioned	Conditioned	Possible
Forearm	Medium	Big	Conditioned	Discomfortable	Discomfortable	Conditioned	Conditioned	Possible
Elbow	Low	Small	Conditioned	Discomfortable	Discomfortable	Discomfortable	Conditioned	Possible
Biceps	Medium	Big	Possible	Discomfortable	Discomfortable	Conditioned	Conditioned	Possible
Shoulders	Medium	Small	Impossible	Impossible	Discomfortable	Conditioned	Conditioned	Possible
Neck	High	Medium	Possible	Impossible	Discomfortable	Possible	Possible	Conditioned
Face	High	Medium	Discomfortable	Discomfortable	Discomfortable	Impossible	Impossible	Impossible
Scalp	Medium	Medium	Discomfortable	Discomfortable	Conditioned	Impossible	Impossible	Discomfortable

4.4.1 Instrument-Specific Constraints

The following findings are derived directly from the interviews with musicians and summarize the instrumental compatibility and comfort constraints detailed in Tables 4.1 and 4.2. Each instrument involves specific body movements and presents unique comfort considerations, which are crucial for determining optimal placement and design of haptic feedback.

Figure 4.3: Illustration of an harpist

Harp: Playing the harp requires full freedom of the hands and fingers, especially for techniques such as hand closure and harmonics. Therefore, any haptic device must not impede fine motor skills or interfere with upper limb dexterity. Suitable placements include the wrists, forearms, upper arms, and ankles. The wrists and the back of the hands may be acceptable as long as they do not restrict movement. The forearms and upper arms are also viable locations, provided the device remains stable and does not shift during play. Ankles are compatible with harp performance, as they do not interfere with the instrument or posture. However, certain areas (such as the thighs, back, or skull) are unsuitable. The thighs are intrusive due to their proximity to the instrument, and the skull and back can become uncomfortable during extended seated sessions. Additionally, because harpists play seated with the instrument resting between the knees and leaning against the shoulder, any device on the torso can be problematic due to contact points and the range of motion required while playing.

Figure 4.4: Illustration of a violinist

Violin: For violin players, the central chest area is seen as a potential location for haptic feedback, provided the device remains subtle and does not restrict movement or breathing. This zone offers a relatively stable surface without interfering directly with performance. While hands, arms, and shoulders are deeply involved in the instrument's precise and coordinated actions, these areas are generally less favorable for feedback, as any restriction could affect playability. Similarly, the legs may introduce issues related to balance or comfort, especially during longer performances.

Figure 4.5: Illustration of a pianist

Piano: The wrists and feet are considered optimal for haptic device placement, as they avoid interfering with the fine hand movements essential to performance. The forearms, upper arms, and shoulders may also be viable, provided the feedback remains subtle and non-distracting. Pianists consistently emphasized the need to keep the hands completely free, making it crucial that any nearby device does not restrict mobility. The torso was generally viewed as less suitable due to potential discomfort when seated. However, unlike harpists (who found both the front and back problematic) pianists mainly identified the back as unsuitable. The front of the torso (e.g., chest or abdomen) may be acceptable in certain cases, depending on the device's design and placement.

Figure 4.6: Illustration of a trumpetist

Trumpet: Trumpet performance involves relatively limited body movement, which makes many areas technically viable for haptic placement. However, comfort and non-interference with breathing and embouchure are the primary constraints. The wrist stands out as a suitable location, as it avoids disrupting posture or playing mechanics. In contrast, the hands and fingers are actively engaged in operating the valves and are generally unsuitable, though minimal placement may be possible if it doesn't hinder finger mobility. Foot placement is also problematic due to the variability between seated and standing positions, which affects comfort and consistency. Similarly, the knees and thighs may cause discomfort, particularly in a seated posture. The abdomen is sensitive due to its role in breath support, while facial areas are entirely unsuitable because they interfere with the precise muscle control required for tone production. Placement on the skull or neck may be acceptable if it does not affect airflow or embouchure stability.

Figure 4.7: Illustration of a trombonist

Trombone:Haptic placement for trombone players must account for the instrument's asymmetrical handling. The right arm, which controls the slide and is in constant motion, is unsuitable for device placement. In contrast, the left arm (particularly the hand or forearm) remains more stationary and can be considered a viable option. The trombone rests on the left shoulder, leaving the right shoulder free, though this area is typically not used for support. Placement on the back or legs is discouraged due to discomfort and limited feasibility in seated positions. Additionally, heavier devices are not recommended on the upper limbs, as these are involved in supporting or manipulating the instrument.

Figure 4.8: Illustration of a side flutist

Side Flute: For side flute players, the wrist is considered a natural location for haptic feedback, provided it does not interfere with the precise finger positioning required for performance. The forearm and biceps are also seen as viable options, as they are near the hands but generally less involved in fine motor control. Opinions on the arms varied slightly among players. While some viewed areas like the forearm and upper arm as acceptable for subtle feedback, others were concerned about overstimulating regions already engaged in performance. As a result, placements on the hands or lower arms should be approached cautiously and designed to avoid distraction. The thighs are excluded due to the seated posture common in orchestral contexts. The head is considered uncomfortable, and the chest and back are only potentially suitable if vibrations are extremely subtle and do not affect posture or breath control.

Figure 4.9: Illustration of an accordionist

Accordion: For accordion players, the right hand is a potential location for haptic placement, as it primarily uses finger movements and remains relatively stable. In contrast, the left hand, which actively controls the bellows, must remain fully unrestricted, making it unsuitable for feedback devices. The right leg is also considered viable, as it does not interfere with bellows operation. However, the knees are generally discouraged, particularly when playing while standing, due to muscular tension in that area, which may reduce tactile sensitivity. The waist (belt) is seen as a stable and unobtrusive location that does not obstruct the instrument. The shoulder is unsuitable, as the accordion's strap typically rests on it and could interfere with both comfort and device placement.

Figure 4.10: Illustration of a cellist

Cello: For cello players, the lower body (the ankles, legs, and knees) is well suited for haptic feedback, as these areas remain stable and do not interfere with playing technique or posture. In contrast, vibrations applied to the upper body, especially the wrists, hands, arms, and chest, are often disruptive due to their active involvement in performance. Participants noted that even wearing a wristwatch can be distracting, underscoring the importance of keeping the upper limbs entirely unencumbered. The chest and back were also seen as unsuitable, as they may interfere with posture and breathing. Shoulders are generally considered uncomfortable for placement, given their role in supporting and balancing the instrument.

Figure 4.11: Illustration of a percussionist

Percussion: For percussionists, both hands are actively involved in performance, often with differing movement amplitudes and speeds. This makes it challenging to place haptic devices on the arms, especially near the joints. In some cases, areas such as the inner side of the left forearm may be viable, provided the placement does not impede movement—but this depends heavily on the playing style and specific instrument. The stomach area is generally considered uncomfortable, as it may interfere with breathing or posture during performance.

Figure 4.12: Illustration of a guitarist

Guitar: For guitar players, the forearm of the fretting arm (typically the left arm for right-handed players) is considered a suitable location for haptic feedback, as it remains relatively stationary and does not interfere with technique. In contrast, the strumming arm is in constant contact with the instrument body, making it less appropriate due to potential vibration transfer. The hands and fingers are essential for precision and tactile sensitivity, and are generally viewed as uncomfortable locations for feedback. The thorax may be viable depending on placement and device subtlety, though its proximity to the instrument poses some challenges. The waist or hips are also mentioned as potentially suitable, especially when seated. The thighs are considered conditional areas. They may be usable depending on the seated posture and player preference. It's worth noting that the guitar is usually supported by the leg opposite the fretting arm, which may influence placement feasibility on the lower body.

Figure 4.13: Illustration of a singer[1]

Singing: For singers, the belt area (particularly at the sides) is seen as an effective and minimally intrusive location for haptic feedback, as it avoids interfering with posture or vocal technique. Feedback, however, should be carefully timed to prevent disruption during phonation. Depending on the device's design and feedback intensity, the arms and feet may also be viable. In contrast, the knees are generally unsuitable when standing due to muscle tension and lower sensitivity. The belly is a conditioned area; its acceptability varies with personal comfort and the subtlety of the device. The head, especially the skull, is typically avoided due to its sensitivity and potential to affect concentration or vocal resonance.

To effectively design the prototype, all of these constraints must be taken into account.

4.4.2 Body Part Sensitivity and Practical Considerations

These findings combine outcomes from the interviews with notions reported in Figure 4.2. Each body part has different sensitivity levels and practical conditions that must be taken into account.

Hands: Extremely sensitive and essential for fine motor control. Placement may be acceptable for singing or in the case of the right hand in accordion, but is generally avoided for instruments requiring precision.

Feet: Moderately sensitive but affected by footwear and standing posture. Practical for seated musicians.

Wrists and Ankles: Offer sensitivity and minimal interference. Ideal for compact feedback devices but must avoid restricting movement.

[1] All images of instrument playing were generated by ChatGPT to give readers an idea of the playing posture.

Arms (Forearms and Biceps): Adaptable across several instruments, particularly on the non-dominant arm. Provide a good balance between sensitivity and freedom.

Shoulders: Limited sensitivity and generally unsuitable for instruments using shoulder support.

Legs (Calves and Knees): Less sensitive and can impact posture. Occasionally viable when seated.

Thighs: Often intrusive and uncomfortable during seated play.

Belt Area (Waist/Pelvis): Discreet and generally compatible but may interfere with breathing in wind instruments.

Back: Lacks sensitivity and is unsuitable for prolonged sitting.

Torso (Chest and Abdomen): Offers a broad surface for feedback but may interfere with breathing or instrument contact.

Elbows and Knees: Joint areas should be avoided to preserve mobility.

Head (Skull, Face, Neck): Highly sensitive but often intrusive or uncomfortable, potentially disrupting auditory perception.

Overall, haptic feedback placement must balance sensitivity, comfort, and instrument compatibility. Each instrument imposes unique biomechanical and perceptual constraints that must guide prototype design.

4.5 Key Design Requirements for Haptic Feedback Systems

To be both effective and musician-friendly, a haptic feedback system must fulfill several essential criteria. These requirements ensure that the device supports musical performance without interfering with technique or comfort. As discussed in [28], the design of wearable musical garments for BVI musicians must prioritize both functionality and comfort. Materials should be quiet, durable, and suitable for various learning contexts, such as conveying musical gestures or supporting tactile reading of musical notation. The textures used must enhance tactile perception without causing discomfort or distraction. Additionally, garments should be adjustable or tunable to accommodate individual user needs and adapt to different musical tasks, ensuring versatility and ease of integration into the learning process. The following outcomes were reported in the interviews:

- **Comfort and Safety:** The device must be safe and comfortable for prolonged use, avoiding pain, irritation, or restricted movement.
- **Vibration Parameters:** Vibrations should be perceptible but not disruptive, delivered in a way that prevents sensory overload or fatigue.
- **Ergonomics and Usability:** The system should be intuitive, discreet, and flexible, allowing independent use and full freedom of movement without interfering with instrument handling.
- **Technical Specifications:** The device must withstand repeated use and sweat, use practical wireless technology, and remain easy to operate with minimal learning required.

4.6 The Importance of a Conductor

4.6.1 Conductor Cues and Visual Communication

Interviews with sighted musicians highlight the indispensable role of visual communication with the conductor. Key conductor cues identified by musicians include:

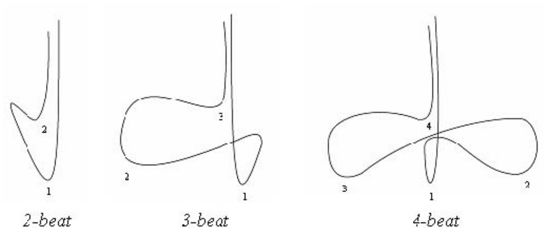

Figure 4.14: Pulse scheme[2]

- **Pulse Establishment and Maintenance**: The conductor's gestures define the initial tempo and maintain it throughout the piece, reported in Figure 4.14 depending on the time signature. A haptic system could replicate this pulse for BVI musicians.
- **Tempo Changes**: Sudden shifts in pulse are visually indicated. Haptic feedback could provide real-time adjustment cues.
- **Phrase Beginnings**: The start of musical phrases is marked visually. A gentle haptic signal could help structure the BVI musician's interpretation.
- **Entrances**: Visual cues signal when different instruments or sections should begin playing. Haptic feedback could offer precise entrance timing.
- **Nuance and Dynamics**: Conductors use hand movements to signal changes in intensity, such as crescendos or decrescendos. Subtle vibrations could convey these expressive changes.
- **Transitions Between Sections**: Conductors guide performers smoothly from one section to the next. A transition cue could help BVI musicians anticipate changes.
- **Climaxes**: Larger, more expressive gestures signal musical peaks. Stronger or distinct haptic cues could mirror this intensity.
- **Silence and Pauses**: Stillness or subtle motion cues moments of rest. Haptic feedback could synchronize musicians during silence.
- **Repetitions and Restarts**: Conductors often cue the return to earlier sections of a piece, particularly during repetitions. While haptic signals could be used to notify BVI musicians when a repetition begins, these cues may be harder to interpret in real time. In such cases, a brief auditory description indicating the section to be repeated may offer greater clarity and effectiveness.
- **Expressive Intentions**: Articulation and style are conveyed through motion. While tactile feedback can offer limited support, it quickly reaches its limits when attempting to convey the subtlety and fluidity required for expressive musical interpretation.

4.6.2 Implications for Haptic Feedback Systems

These insights confirm that visual communication with the conductor is essential for real-time synchronization, expression, and ensemble cohesion. Translating these cues into haptic signals offers BVI musicians an alternative channel for receiving musical direction. Such a system must replicate the conductor's communicative gestures through well-timed, nuanced, and unobtrusive tactile feedback. This approach holds promise for enhancing inclusive participation in ensemble performances.

[2]Source: https://journals.openedition.org/signata/1126

Chapter 5

Prototype design and implementation

To address the various constraints imposed by different instruments, two prototype designs were developed and compared. The first prototype consists of a sleeve intended to be worn on the arm, while the second is designed to be worn on the leg. The following section describes the selection of all components, including both electronic and textile elements, and explains the design choices that guided the development of each prototype.

5.1 Selection of the Components

In this section, the selection of both the electronic and fabric components of the sleeves is detailed, including the rationale behind each choice in terms of functionality, comfort, and integration.

5.1.1 Electric Components

Each electronic component was selected to satisfy the design requirements, with a focus on maintaining unrestricted user mobility, delivering precise and perceptible vibrations, and ensuring that the system remains fully autonomous, compact, and non-bulky for comfortable wearability. This subsection provides a detailed explanation of each component.

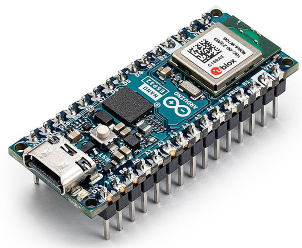

Figure 5.1: Picture of Arduino Nano ESP32

The Arduino Nano ESP32 was chosen as the central microcontroller for controlling the vibrational motors due to its integrated Bluetooth Low Energy (BLE) functionality, which enables seamless wireless communication and allows users unrestricted movement without the limitations of cables or bulky devices.

Figure 5.2: Picture of ERM DC vibration motors

We selected DC vibration motors of the ERM (Eccentric Rotating Mass) type — model 12,000 rpm, 3 V DC. These motors provide strong, localized tactile stimulation while remaining compact and comfortable for direct skin contact. The sleeve integrates five of these low-profile pancake actuators, arranged in a constellation pattern as shown in Figure 5.7 to deliver distributed and precise haptic cues.

Each actuator is equipped with a 1N4007 diode to safely dissipate residual current and protect the circuit when the motors are switched off. The actuators are driven via 2N3904 transistors operating as Arduino-controlled switches, with base resistors included to prevent overcurrent and ensure reliable operation.

Figure 5.3: Picture of Li-Ion battery

To ensure full autonomy and portability, the system is powered by a compact rechargeable Li-ion polymer battery (LP502030-PCM-LD, 3.7 V, 250 mAh). This battery provides high energy density while maintaining a very low weight, making it well-suited for wearable applications. A manual power switch is included to give users direct control over activation and to enhance operational safety. In addition, a TP4056 charging module is integrated into the circuit, allowing safe and efficient recharging via the Arduino's USB-C port without the need to remove the battery. Weighing only 5 grams, the battery meets the design requirements for a lightweight and unobtrusive prototype.

To enhance maintainability, both the battery and the Arduino Nano ESP32 are connected via terminals rather than being soldered directly to the board. This approach allows for quick disconnection, easy replacement, and safer handling without risking damage to the components or requiring resoldering.

5.1.2 Components for the Sleeves

The components of the sleeves must accommodate the constraints of movement freedom while ensuring effective vibration attenuation.

Figure 5.4: Picture of Neoprene

For the wearable component, the sleeves are constructed from 2 mm-thick neoprene fabric. Neoprene was selected for its flexibility and excellent vibration-damping properties, which help confine tactile feedback to individual actuators and prevent unwanted signal bleed. By contrast, tests with a more vibration-conductive fabric resulted in overlapping sensations, making it difficult for users to distinguish motor locations. Effective vibration isolation is therefore essential to deliver clear and interpretable haptic patterns.

To ensure precise positioning of the neoprene sleeve, the prototype incorporates Velcro fasteners and elastic bands. These elements not only secure the sleeve in place during use but also allow users to adjust the fit for improved comfort and personalized ergonomics.

5.2 Designing of the prototype

5.2.1 Electric device

Initial testing was conducted on a breadboard to validate the circuit. Upon successful validation, the final design was soldered onto a custom PCB, developed using KiCad. This tool allowed us to create both the schematic and the PCB layout.

The electronic schematic is shown in Figure 5.5:

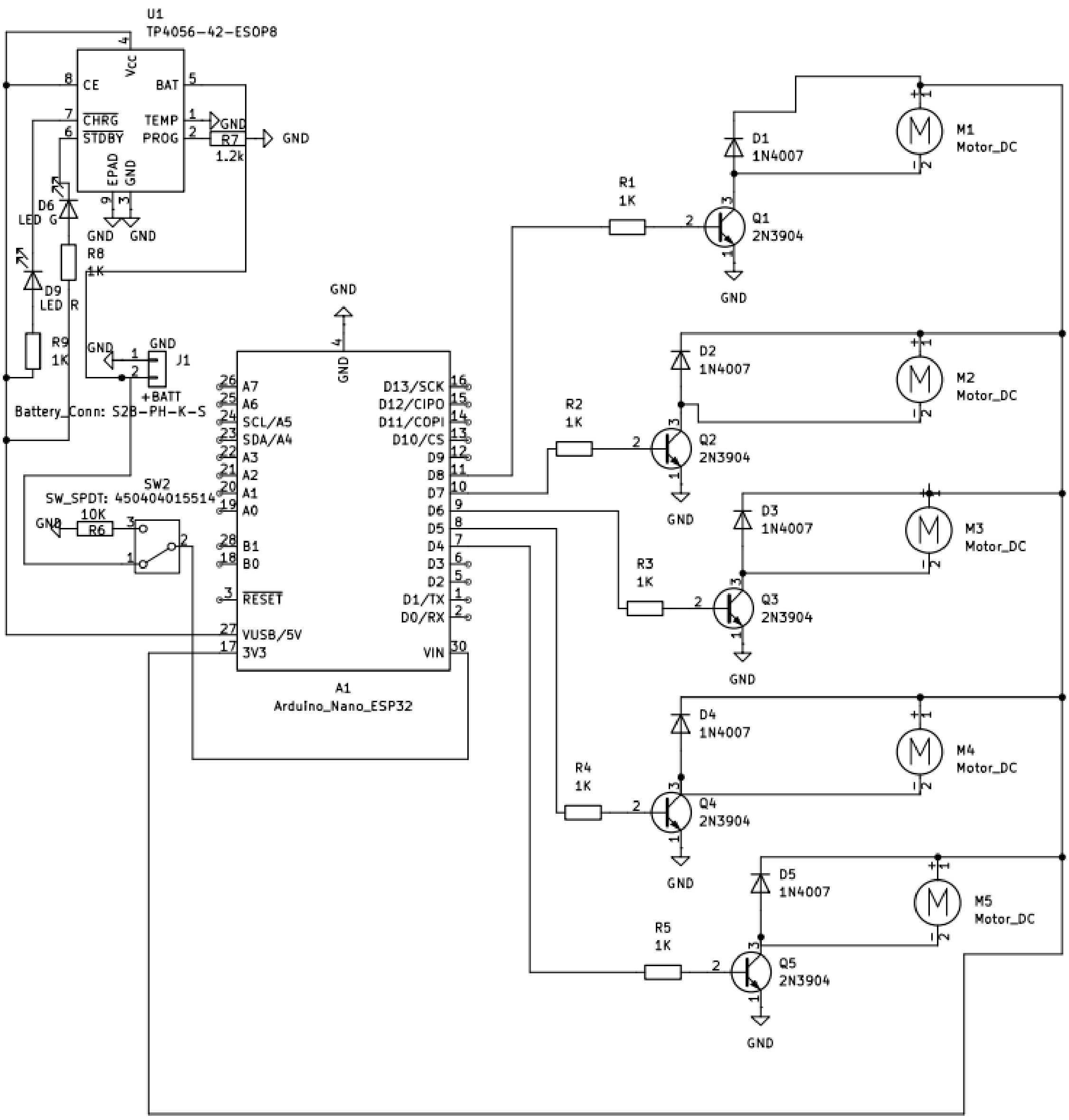

Figure 5.5: Electronic Schematic of the Designed System

This schematic illustrates the control system architecture. The Arduino manages motor activation through five transistor switches, each equipped with a current-limiting resistor. When a signal is sent from an Arduino pin to a transistor, the transistor allows current to flow through the corresponding motor by providing a path to ground via its emitter. Diodes connected in parallel with the motors protect the circuit from voltage spikes caused by motor back-EMF. On the power management side, the TP4056 module handles safe battery charging, while a physical switch controls overall power. When the switch is in the OFF position, the battery can be safely charged; when in the ON position, the battery powers the rest of the circuit.

The corresponding PCB layout is presented in Figure 5.6:

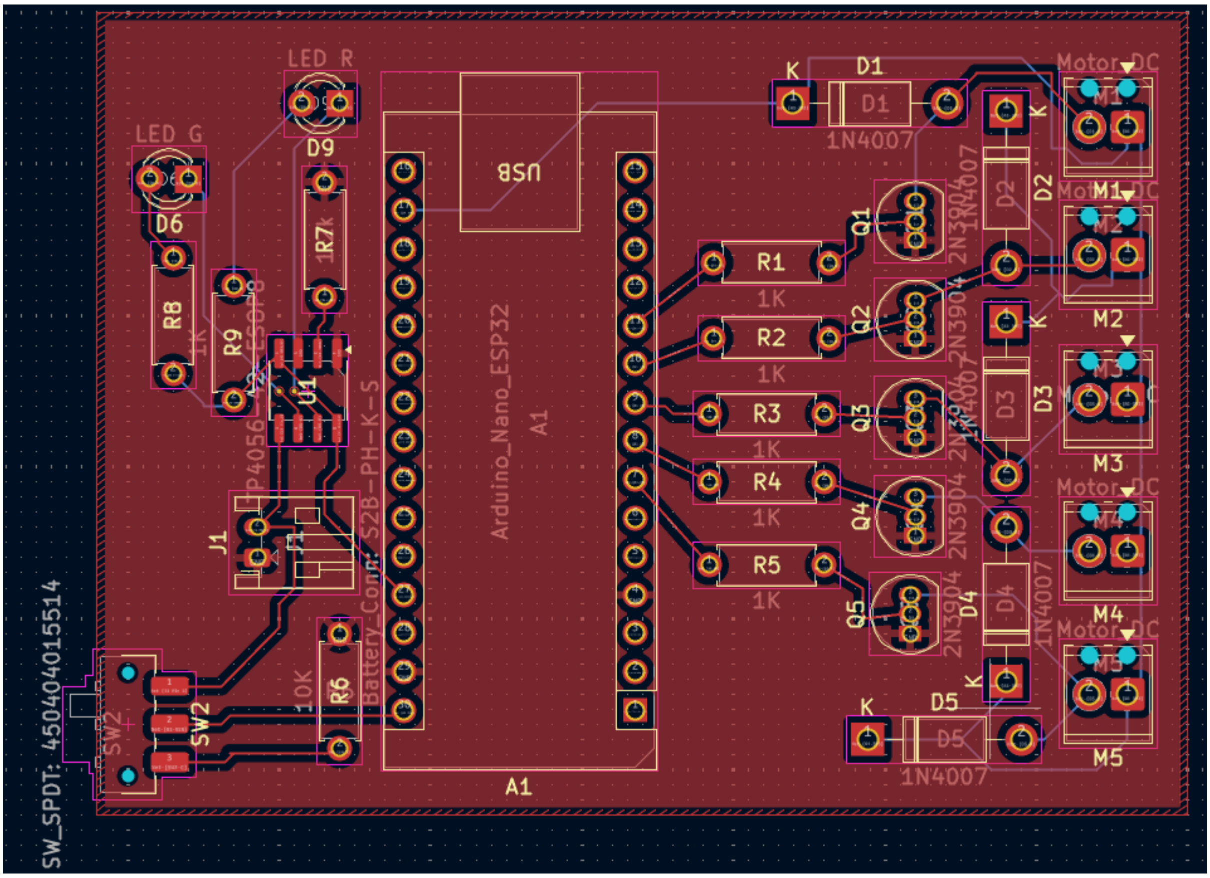

Figure 5.6: PCB Layout of the Designed System

This layout reflects the schematic, with the Arduino Nano ESP32 positioned centrally. The right side of the board accommodates the motor control section, including transistors, resistors, and screw terminals for motor connections. Each motor line includes a diode placed near its terminal to minimize voltage spikes.

The left side houses the power management components: the TP4056 charging circuit, battery connector, and a manual switch. Charging status is indicated by two LEDs (red and green) controlled by the TP4056. Careful routing separates power and control traces to reduce interference and enhance performance. The compact design also supports ease of testing and maintenance.

5.2.2 Wearable sleeves

Due to the significant size difference between the forearm and the leg, two distinct versions of the prototype were developed, one for each limb. Initial testing using small pieces of neoprene aimed to determine the minimum distance at which users could reliably perceive individual vibrations. With actuators spaced 4 cm apart, participants generally struggled to identify which motor was active, whereas increasing the spacing to 8 cm significantly improved perceptibility. Preliminary tests indicated that a minimum spacing of 6 cm between vibromotors ensures high detection accuracy, with larger spacing further enhancing the user's ability to distinguish between vibration sources. Based on these results and the average forearm size, the textile pattern layout 5.7 for the sleeve was designed.

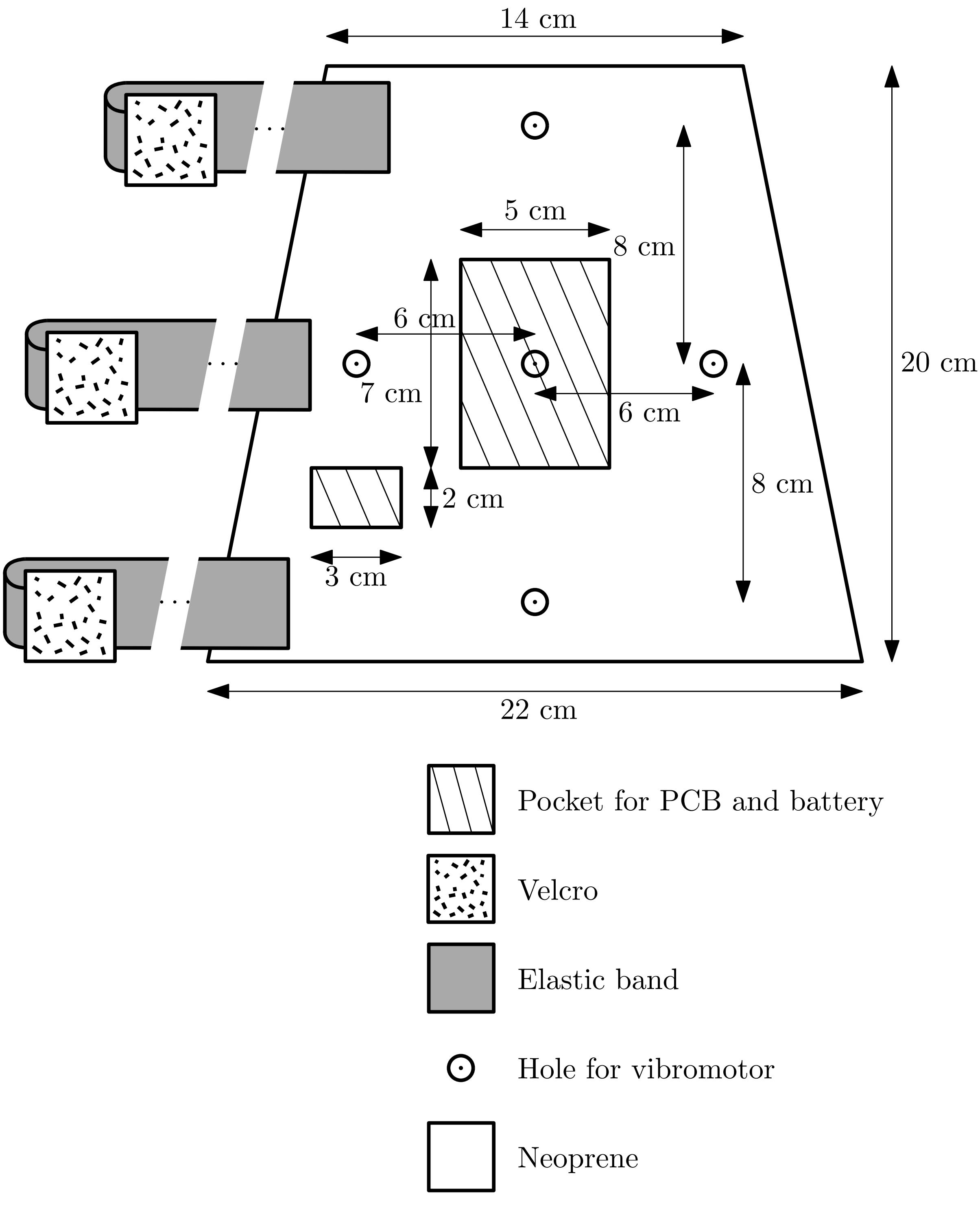

Figure 5.7: Sewing Pattern of the Arm Device

On the layout, we can see a piece of neoprene cut into a trapezoidal shape. The wrist should be positioned at the narrower, upper end, and the elbow at the wider, lower end. This ensures that the smaller section wraps snugly around the wrist while the larger section accommodates the elbow.

The neoprene piece contains five holes arranged in a cross pattern for the motors. The vertical spacing between holes is 8 cm, and the horizontal spacing is 6 cm.

On top of the neoprene, two additional pockets made of another fabric are attached. The larger pocket is designed to hold the PCB and includes openings to allow cable routing. The smaller pocket is intended to house the battery.

Elastic bands are positioned along the sides to secure the prototype to the arm. Velcro fasteners at the ends attach to the elastic bands, keeping the entire assembly in place. This arrangement ensures that the neoprene fits closely enough to the arm to minimize vibration transmission.

The leg version is larger but still includes only five motors, based on the assumption that the leg has lower tactile sensitivity than the forearm.

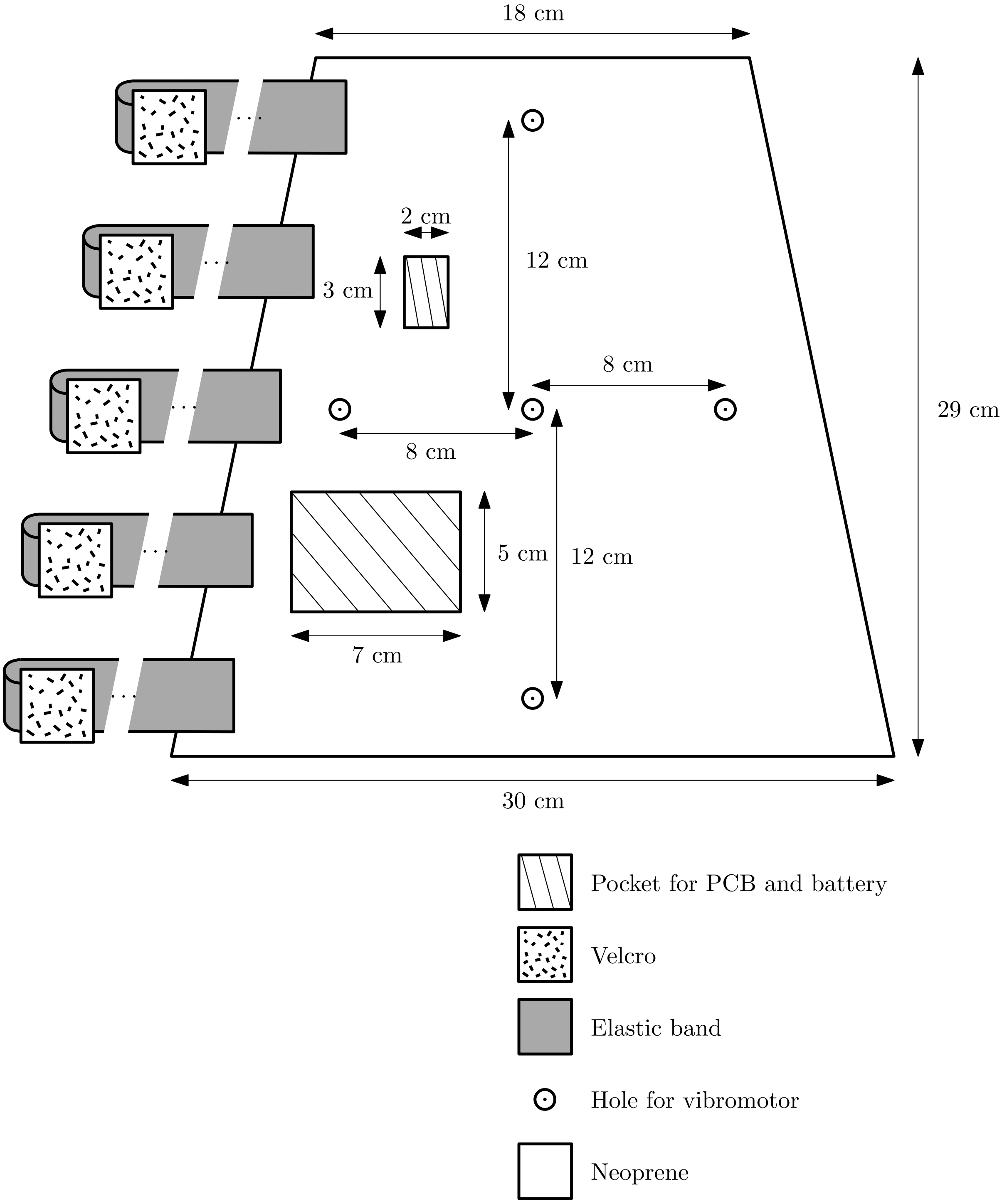

Figure 5.8: Sewing Patten of the leg device

This layout expands upon the previous design concept. The overall dimensions have been increased to fit the leg, which is larger than the arm. The narrower end is positioned at the ankle, while the wider end aligns with the knee for a secure and ergonomic fit.

The design retains five motor holes. The vertical spacing between holes has been increased to 12 cm, and the horizontal spacing to 8 cm, utilizing the additional surface area available on the leg.

The equipment pocket has been repositioned for improved ergonomics, and additional elastic bands have been incorporated to ensure the neoprene remains securely in place during use.

5.3 Prototype Operation

5.3.1 Electric device

All the electronic components previously presented have been soldered onto the PCB. The electrical circuit is now fully functional (Figure 5.9).

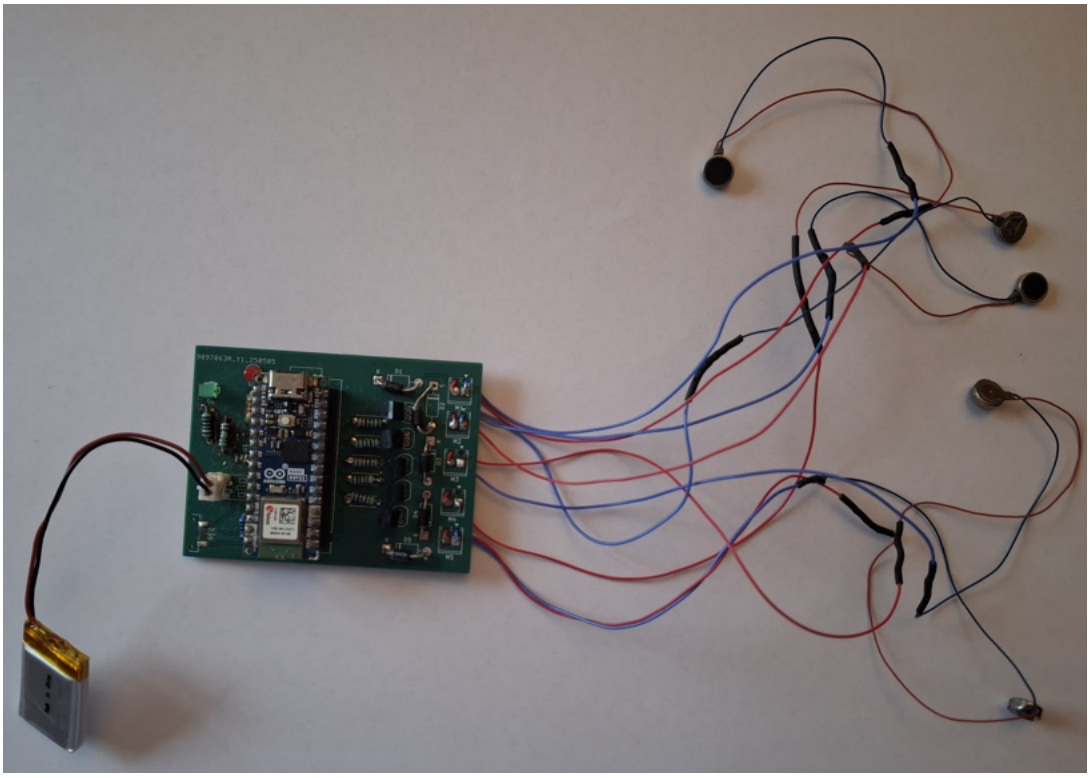

Figure 5.9: Photograph of the Assembled PCB with Electronic Components

Switching the circuit to the "ON" position powers the system.

The Arduino receives BLE (Bluetooth Low Energy) commands transmitted by an external device (such as a laptop, smartphone, or Raspberry Pi) and converts them into corresponding motor activation sequences, enabling responsive and wireless operation.

Vibration intensity is regulated via the Arduino's analog output pins. The vibration strength is directly proportional to the current supplied to the motors up to the transistor threshold. Beyond this point, the transistors enter saturation mode, where both the output current and the resulting vibration intensity stabilize.

5.3.2 Usage

Two neoprene sleeves have been fabricated according to the previously presented layouts.

Figure 5.10: Photograph of the Arm device

Figure 5.11: Photograph of the Leg device

An elastic band has been routed beneath the PCB pocket to ensure that no direct pressure is applied to the PCB itself.

Testing has shown that the neoprene must be firmly secured to the forearm or leg. When the material maintains proper contact with the skin between the vibrating motors, vibrations are more effectively transmitted and differentiated, resulting in clearer tactile feedback. The added elastic bands ensure consistent contact of the neoprene with the skin and enhance the device's performance.

Chapter 6

Gesture Recognition Implementation

6.1 Training Environment

To translate a conductor's movements into meaningful haptic feedback for blind musicians, the system must first detect and interpret those gestures accurately. A gesture recognition algorithm enables this by analyzing motion data to identify distinct conducting patterns and mapping them to their corresponding haptic translations, making it a crucial step in converting visual cues into tactile communication within the virtual environment.

6.1.1 Virtual Environment

This thesis builds upon a recent study [44] in which a conductor could remotely interact with an orchestra through virtual reality (VR). The virtual environment primarily addressed issues of data transmission rate and latency. In this setup, the conductor's movements were tracked by means of a VR head-mounted device, allowing the system to capture precise hand and head gestures. The conductor was able to view the positions of the musicians' instruments—each represented by a head-shaped marker corresponding to a musician—while the musicians could see the conductor's hands and head in real time.

Figure 6.1: Picture of the conductor in the virtual environment

Only the conductor's head and hand positions were tracked and replicated in the virtual environment, mirroring their real-life movements. The system captured the three-dimensional coordinates of key points on the conductor's hands and head. By analyzing these coordinates and their changes over time, it was possible to reconstruct the conductor's gestures.

6.1.2 Data Collection

To detect and classify movements within the virtual environment, machine learning techniques were employed. This required a suitable training dataset. A conductor from an orchestra in Milan agreed to record his gestures using VR headsets while explaining the meaning of each gesture. These recordings produced labeled data suitable for supervised learning. The recorded coordinates were then aligned with the corresponding gestures to ensure accurate training of the AI model.

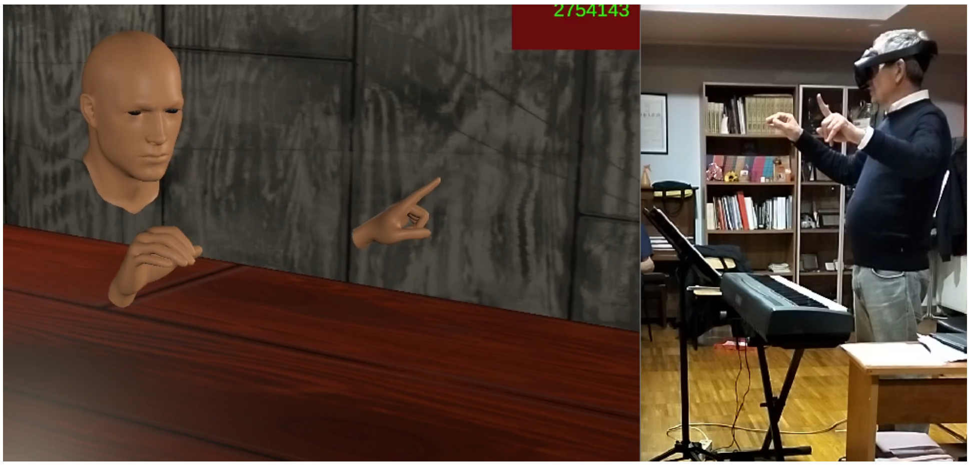

Figure 6.2: Picture Comparing the Virtual Environment and Reality

6.2 Gesture Recognition Pipeline

6.2.1 Python Libraries Used

To work with and make sense of the conductor's motion data, we relied on a small set of well-known Python libraries. We used `pandas` to keep the recorded 3D coordinates and their gesture labels neatly organised in tables, which made it easier to sort, filter and align the information. `NumPy` handled the heavy lifting for the numerical side, such as calculating distances, velocities or normalising values before training our models. For a quick look at the data, `matplotlib.pyplot` let us draw clear two-dimensional plots to check and validate what we had collected. When it was necessary to visualize gestures in three-dimensional space rather than on a flat plane, the `Axes3D` module from `mpl_toolkits.mplot3d` extended Matplotlib into 3D, allowing us to plot the trajectories of the conductor's hands and head directly. Together, these libraries gave us a flexible toolkit for organising, transforming and visualising the motion-capture data.

6.2.2 Data Alignment and Labeling

The raw VR recording of the conductor's movements contained a very high sampling rate of 29.4 Hz, so we first loaded only every third row from the file to reduce its size while preserving temporal resolution. In parallel, we imported a separate file containing the annotated gestures. Because the annotation times were expressed differently from the sampling times of the raw file, we defined a function to convert each start and end time into milliseconds, add the required offset between recordings, and round to the nearest multiple of 34 ms, which matches the sampling period of the raw data. This produced aligned start and end times for each gesture. We then iterated over the annotated gestures and, for each one, extracted the corresponding rows from the raw data that fell within the same time interval. These subsets were combined into a single data frame and merged back with the original annotation table so that every recorded sample now carries its gesture label and timing information. This procedure ensures that the motion-capture data and the gesture annotations are synchronised and formatted consistently for subsequent analysis and supervised learning. After merging the raw motion-capture data with the annotated gestures, we obtained a single data frame in which each row represents one time sample of the recording (approximately 34 ms). The first group of columns stores the temporal information and sensor measurements recorded by the VR system (e.g., start and stop time stamps, three-dimensional head and hand positions, rotation angles, and presence flags). The second group of columns carries the annotation metadata imported from the label file, including the index of the gesture in the label table, its original start and end times, and the gesture labels for different instrumental sections. Finally, the data frame also contains the aligned start and end times in milliseconds that link the annotation back to the raw data. This structure places all motion features and their corresponding gesture labels side by side, making it straightforward to select intervals, extract features, and train supervised learning models on well-synchronised data.

6.2.3 Feature Extraction and Labeling

To prepare the motion-capture data for machine learning, the continuous time series was divided into short overlapping windows of approximately 400 ms. For each window, a set of statistical features was computed for all relevant signals, including the head and hand positions, rotations, and other sensor measurements. These features included basic statistics (mean, standard deviation, minimum, maximum) as well as first and second differences to estimate velocity and acceleration within the window. Columns containing only zeros or non-informative data were ignored. Once features were extracted, each window was assigned a gesture label by taking the most frequent label of the corresponding instrument in the raw data for that time interval. Finally, the dataset was filtered to remove classes with less than 5 examples, producing a feature matrix and a corresponding label vector suitable for supervised learning. This procedure transforms high-frequency, multi-dimensional motion data into a structured set of numerical descriptors with aligned labels, enabling reliable training of classification models.

The dataset prepared for supervised learning consists of a feature matrix X and a corresponding label vector y. Each row in X represents a short, fixed-length time window of the motion-capture recording, in this case approximately 400 ms. The columns of X are numerical features extracted from the raw signals, including basic statistics (mean, standard deviation, minimum, maximum) of positions, rotations, and other tracked points, as well as derived features such as velocity and acceleration statistics computed from first and second differences. Some features may contain missing values when a signal was not present in a given window. The label vector y contains the gesture label corresponding to each window, aligned row-by-row with X. This structure allows each window of motion data to be represented by a compact set of descriptive features while providing a clear target for training classification models.

Table 6.1: Number of samples per class in y_{filtered}

#	Class	Samples
1	tempo	8549
2	mild attack	636
3	tempo (dx)	622
4	sustain intonation (sx)+tempo (dx)	492

Continued on next page

#	Class	Samples
5	mild close	274
6	diminuendo (sx)+tempo (dx)	237
7	close and start again	201
8	sustained intonation+tempo	167
9	tempo (sx)	167
10	crescendo (sx)+tempo (dx)	153
11	keep steady+tempo	130
12	diminuendo+tempo	119
13	keep steady (dx)+tempo (sx)	111
14	break	98
15	rallentando	95
16	sharp attack	79
17	sustain intonation (sx)	74
18	crescendo+tempo	72
19	mild attack (dx)	67
20	crescendo	65
21	sustained intonation(sx)+tempo(dx)	63
22	sharp close	41
23	keep steady (sx)+mild attack (dx)	40
24	mild attack (sx)	33
25	keep steady (sx)+mild close (dx)	30
26	crescendo(sx)+tempo (dx)	25
27	sharp attack (dx)	24
28	keep steady (sx)+tempo (dx)	24
29	diminuendo	17
30	close and start again (sx)	16
31	sustain intonation (dx)	16
32	sustain intonation (with threatening gesture shooting)	16
33	diminuendo+mild attack	10
34	legato (dx)+mild attack (dx)	9
35	crescendo+sharp attack	9
36	crescendo+mild attack	9
37	diminuendo (dx)	8
38	legato+tempo	8
39	mild attack (dx)+sustain intonation (sx)	8
40	legato	8
41	crescendo (dx)	8
42	mild attack (sx)+tempo (dx)	8
43	sharp attack (dx)+tempo (sx)	8
44	sustain intonation (sx)+tempo (sx)	8
45	crescendo (sx)+sharp attack (dx)	7
46	sharp close (dx)	7
47	sustain intonation (dx)+tempo (sx)	7
48	**Total**	**12875**

The dataset exhibits a strongly imbalanced distribution of gesture labels. The label *tempo* is by far the most frequent, appearing 8,549 times, while most other gestures occur much less frequently. For example, *mild attack* appears 636 times, *tempo (dx)* 622 times, and *sustain intonation (sx) + tempo (dx)* 492 times. Many other labels, such as *mild close* (274 occurrences), appear only a few hundred times, and complex combinations like *sustain intonation (sx)+tempo* *(sx)* , *mild attack (sx)+tempo (dx)*, *crescendo (sx)+sharp attack (dx)*, and *sharp close (dx)* occur fewer than 10 times each. In total, there are 47 distinct labels. This distribution highlights a strong class imbalance, with a few dominant labels and many rare ones, which should be taken into account when training supervised learning models to avoid bias toward the most frequent classes.

6.2.4 Model Training and Evaluation

To classify the conductor's gestures based on the extracted features, the dataset was first divided into training and testing sets, with 80% of the data used for training and 20% for testing. Stratification was applied to ensure that each gesture class was proportionally represented in both sets, which is important given the imbalance in the labels. A Random Forest classifier, consisting of 200 decision trees, was then trained on the feature matrix and corresponding labels. Also 400, 100, 300 decision trees where tested but 200 decision trees gives the best results. This ensemble method is robust to high-dimensional data and reduces the risk of overfitting. Once trained, the model was used to predict labels on the test set, and its performance was assessed using precision, recall, F1-score, and support for each class. This process provides a clear evaluation of the classifier's ability to recognize different gestures from the motion-capture features.

6.2.5 Interpretation of Classification Results

The evaluation of the Random Forest classifier indicates overall good performance but with substantial variation across gesture classes.

Table 6.2: Performance metrics of gesture classification using a Random Forest model

Class	Precision	Recall	F1-score	Support
break	1.00	0.68	0.81	19
close and start again	0.94	0.82	0.88	40
close and start again (sx)	1.00	0.33	0.50	3
crescendo	1.00	0.77	0.87	13
crescendo (dx)	1.00	1.00	1.00	2
crescendo (sx)+sharp attack (dx)	1.00	1.00	1.00	1
crescendo (sx)+tempo (dx)	1.00	0.48	0.65	31
crescendo(sx)+tempo (dx)	1.00	0.60	0.75	5
crescendo+mild attack	1.00	0.50	0.67	2
crescendo+sharp attack	1.00	1.00	1.00	2
crescendo+tempo	1.00	0.86	0.92	14
diminuendo	0.00	0.00	0.00	3
diminuendo (dx)	1.00	0.50	0.67	2
diminuendo (sx)+tempo (dx)	0.93	0.87	0.90	47
diminuendo+mild attack	1.00	1.00	1.00	2
diminuendo+tempo	1.00	0.71	0.83	24
keep steady (dx)+tempo (sx)	1.00	0.86	0.93	22
keep steady (sx)+mild attack (dx)	1.00	0.38	0.55	8
keep steady (sx)+mild close (dx)	1.00	0.83	0.91	6
keep steady (sx)+tempo (dx)	0.80	0.80	0.80	5
keep steady+tempo	0.96	1.00	0.98	26
legato	1.00	1.00	1.00	2
legato (dx)+mild attack (dx)	1.00	0.50	0.67	2
legato+tempo	0.00	0.00	0.00	2

Continued on next page

Class	Precision	Recall	F1-score	Support
mild attack	0.94	0.61	0.74	127
mild attack (dx)	1.00	0.62	0.76	13
mild attack (dx)+sustain intonation (sx)	1.00	1.00	1.00	2
mild attack (sx)	1.00	0.71	0.83	7
mild attack (sx)+tempo (dx)	0.00	0.00	0.00	2
mild close	0.97	0.69	0.81	55
rallentando	0.95	0.95	0.95	19
sharp attack	1.00	0.56	0.72	16
sharp attack (dx)	1.00	0.80	0.89	5
sharp attack (dx)+tempo (sx)	1.00	0.50	0.67	2
sharp close	0.50	0.25	0.33	8
sharp close (dx)	1.00	1.00	1.00	1
sustain intonation (dx)	1.00	0.33	0.50	3
sustain intonation (dx)+tempo (sx)	1.00	1.00	1.00	1
sustain intonation (sx)	1.00	0.93	0.97	15
sustain intonation (sx)+tempo (dx)	1.00	0.65	0.79	98
sustain intonation (sx)+tempo (sx)	1.00	0.50	0.67	2
sustain intonation (with threatening gesture shooting)	1.00	1.00	1.00	3
sustained intonation(sx)+tempo(dx)	1.00	0.15	0.27	13
sustained intonation+tempo	0.89	1.00	0.94	33
tempo	0.89	1.00	0.94	1710
tempo (dx)	0.98	0.85	0.91	124
tempo (sx)	1.00	0.91	0.95	33
accuracy		0.91		
macro avg	0.91	0.69	0.76	2575
weighted avg	0.91	0.91	0.90	2575

The most frequent label, *tempo*, achieves high recall (1.00) and a strong F1-score (0.94), showing that the model correctly identifies nearly all instances of this gesture. Many other common gestures, such as *mild attack* (F1-score 0.74), *mild close* (F1-score 0.81), and *rallentando* (F1-score 0.95), also reach high precision and reasonably high recall.

Several less frequent or composite gestures likewise achieve strong scores — for example, *crescendo+tempo* (F1-score 0.92), *diminuendo+tempo* (F1-score 0.83), or *sustain intonation (sx)+tempo (dx)* (F1-score 0.79). However, a few very small classes remain problematic: labels such as *diminuendo* (F1-score 0.00), *legato+tempo* (F1-score 0.00), and *mild attack (sx)+tempo (dx)* (F1-score 0.00) are never correctly predicted. This pattern shows that the model still fails completely on some rare classes.

Nevertheless, its poor performance concerns only these very rare cases, which were tested on very few instances, and should therefore be interpreted with caution.

Overall accuracy reaches 0.91, largely driven by the dominant *tempo* class. The macro-average metrics (precision 0.91, recall 0.69, F1-score 0.76) reveal much poorer average performance across all classes, whereas the weighted averages (precision 0.91, recall 0.91, F1-score 0.90) are higher because they give more weight to prevalent classes. These results show that the classifier performs well on frequent and moderately represented gestures but continues to struggle with very rare or complex gestures, underlining the impact of class imbalance on model performance.

Chapter 7

Haptic System Integration and Validation

7.1 Definition of Recognizable Patterns

To explore how the system could be used most effectively, we carried out a series of structured variations designed to better understand how vibration-based cues could be perceived and distinguished. The goal was not simply to check whether participants could recognize vibrations in isolation, but to examine how factors such as motor location, vibration intensity, and the complexity of patterns might influence clarity and usability.

These explorations covered different placements of motors along the arm, variations in vibration strength, and combinations of discrete and sequential activations. Together, these trials revealed how spatial positioning, temporal structure, and intensity changes interact to shape the perception of haptic signals. Importantly, the results highlighted the conditions under which cues became clearer, easier to identify, and less prone to confusion.

From this process, several consistent trends emerged. Dynamic patterns—such as those created by sequential motor activation that gave the impression of movement across the arm—were easier to interpret than static signals at a single location. Changes in vibration intensity were also reliably distinguished, suggesting that amplitude can serve as an effective channel for layered information. At the same time, it became evident that individual sensitivity and factors such as hair distribution on the arm influenced perception, indicating that placement and design choices matter significantly for accessibility.

Taken together, these findings provided a solid foundation for developing a practical and expressive mapping between conducting gestures and haptic feedback. They informed the design principles used to construct the gesture-to-vibration translation system presented in the following section.

7.2 Decision on Gesture Mapping

To translate conducting gestures into meaningful haptic feedback, we rely on a simplified set of gestures from the ones that were identified and refined in the previous chapter. These gestures serve as the foundation for bridging the gap between traditional visual conducting techniques and their tactile equivalents, making the interaction accessible and intuitive for blind and visually impaired (BVI) musicians. Each gesture must be carefully mapped to a corresponding haptic signal in a way that preserves its musical and expressive intent. Therefore, the design process emphasizes clarity, recognizability, and efficiency of communication.

To achieve this, we employed a cross-shaped arrangement of five vibration motors. The motors are positioned so that they can deliver spatially distinct vibrations across different parts of the body. The cross layout provides a logical structure that can be intuitively associated with directional or dynamic gestures: vibrations on the top motor can represent upward movements, while those on the bottom motor can correspond to downward gestures. Similarly, left and right placements can signal lateral motion, and the central motor serves as a neutral or focal point. This arrangement ensures that the system has enough flexibility to encode a range of conducting gestures without becoming overly complex or difficult to interpret.

A critical step in the design of the haptic language was to ensure the distinctiveness of each vibration pattern. To enhance recognizability and avoid confusion between signals, we apply the Kraft condition, a principle drawn from information theory. The Kraft condition guarantees that no code is a prefix of another, meaning that once a haptic pattern begins, it cannot be mistaken for the start of a different pattern. This ensures unambiguous decoding by the user, preventing overlap or misinterpretation. In other words, each haptic gesture has a unique "signature" that immediately sets it apart from the others, reducing the likelihood of perceptual errors. This strategy reflects the use of prefix-free binary codes in coding theory, where distinct and non-overlapping sequences form the basis of reliable communication. In adapting this principle to haptics, we create a system in which every gesture is recognizable from its very first cue.

We selected a set of six fundamental gestures to encode:

- **Start:** Represented by a static hand position at the center, followed by an upward preparatory motion and then a sharp downward impulse, this gesture signals the initiation of playing. In haptic form, the corresponding vibration must capture the sense of readiness leading into decisiveness, ensuring that performers experience both anticipation and commitment.

- **Stop:** Typically conveyed by a curved inward gesture toward the torso and followed by stillness, this cue communicates closure and silence. The haptic equivalent must contrast strongly with the "start" gesture, producing a sensation that feels definitive and conclusive.

- **Beat Pattern:** Perhaps the most fundamental of all conducting gestures, the beat pattern encodes the time signature (such as 4/4, 3/4, or 6/8). The rhythmic, periodic trajectories provide performers with a sense of temporal stability. When translated into haptics, this pattern must feel cyclical and predictable, aligning the ensemble with the conductor's pulse.

- **Increase:** This gesture is conveyed through an upward or outward sweeping motion with expanding amplitude. In musical terms, it signals a crescendo, or a general rise in energy and intensity. The corresponding vibration pattern must grow in strength or spread spatially to reflect this sense of expansion.

- **Decrease:** The opposite of increase, this gesture involves a downward or inward motion accompanied by smooth deceleration. It communicates diminuendo or reduction in intensity. The haptic cue should therefore taper off gradually, reinforcing the sensation of fading or contraction.

- **Attack Cues:** These are directed, brief impulses aimed at specific performers or instrumental sections, typically used to mark important entrances. In the haptic system, this must be encoded as short, localized bursts that immediately draw attention without ambiguity.

Together, these six gestures form a minimal but highly functional vocabulary for haptic conducting. They strike a balance between being simple enough to learn quickly and being expressive enough to support the nuances of ensemble communication. By leveraging spatial separation, intensity variation, and temporal structuring—combined with the prefix-free encoding strategy—we create a feedback system that allows BVI musicians to interpret conducting gestures with confidence and precision.

Ultimately, the translation of conducting into haptics represents more than a technical exercise; it embodies a reimagining of musical communication. Just as spoken language can be rendered in braille or sign language, the rich visual language of conducting can be transformed into tactile form. In doing so, we not only expand accessibility but also open new possibilities for multimodal performance environments, where musicians can engage with musical leadership through the sense of touch as directly as they do through sight or sound.

7.3 Translating Gestures into Haptic Feedback

The corresponding haptic feedback translation is detailed below.

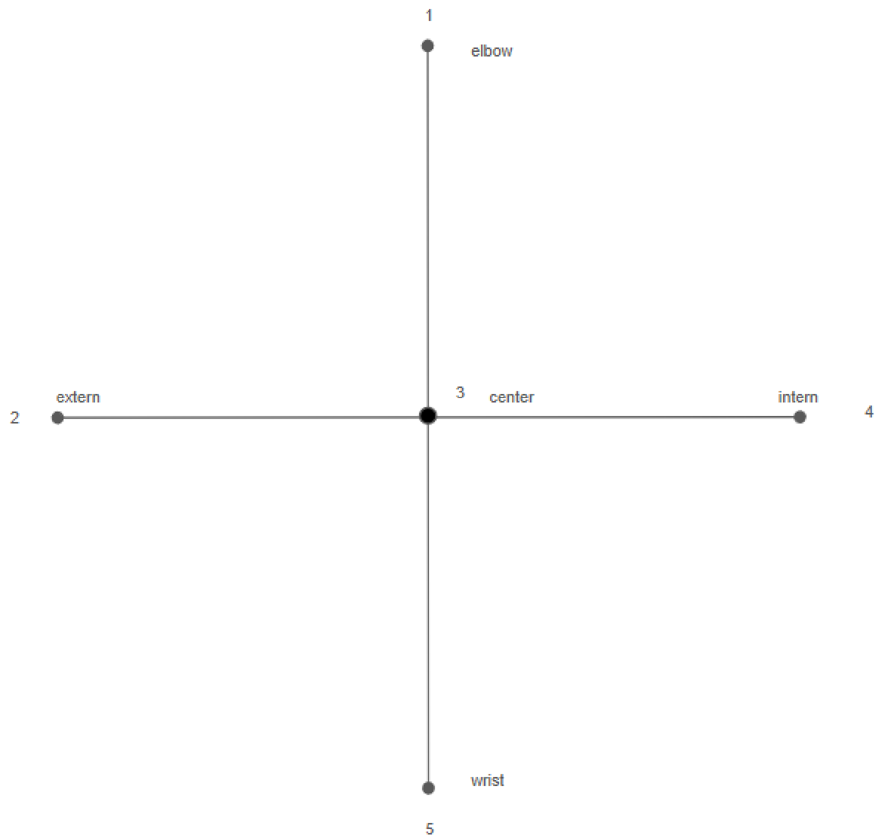

Figure 7.1: Schematic of the motor configuration

Table 7.1: Gesture Translation into Haptic Feedback Pattern

Hand	Gesture Meaning	Physical Gestures	Motor(s)	Intensity
Both	Start of piece	Hands still	2, 3, 4	Medium
		Upward motion	1	Medium
		Downward motion	5	Strong
Both	End of piece	Arms open	1, 2, 4, 5	Medium
		Arms close to torso	3	Strong
Right	Beat pattern / Tempo	Hand down	5	Strong

Table 7.1: Gesture Translation into Haptic Feedback Pattern

Hand	**Gesture Meaning**	**Physical Gestures**	**Motor(s)**	**Intensity**
		Hand inward	4	Strong
		Hand outward	2	Strong
		Hand up	1	Strong
Right	Attack cue	Pointing at a performer	3	Strong
Left	Crescendo	Hand down	5	Light–Medium
		Hand at middle height	3	Medium–Strong
		Hand up	1	Medium–Strong
Left	Decrescendo	Hand up	1	Strong–Medium
		Hand at middle height	3	Medium–Light
		Hand down	5	Medium–Light

In the proposed system, each conducting gesture is carefully designed to correspond to a distinct sequence of vibrations, ensuring that performers can recognize and differentiate them reliably. The mapping strategy draws upon both the number of steps in a sequence and the qualitative character of each vibration, such as whether it is discrete or continuous. This dual encoding method—combining quantitative and qualitative features—creates a haptic vocabulary that is both simple and unambiguous.

Among the gestures, several stand out because of their unique step structures. For example, the attack cue 7.2 is represented by a single, short-step vibration. Its brevity and isolation make it immediately recognizable; there is no other gesture with only one vibration, so participants can identify it almost instantly.

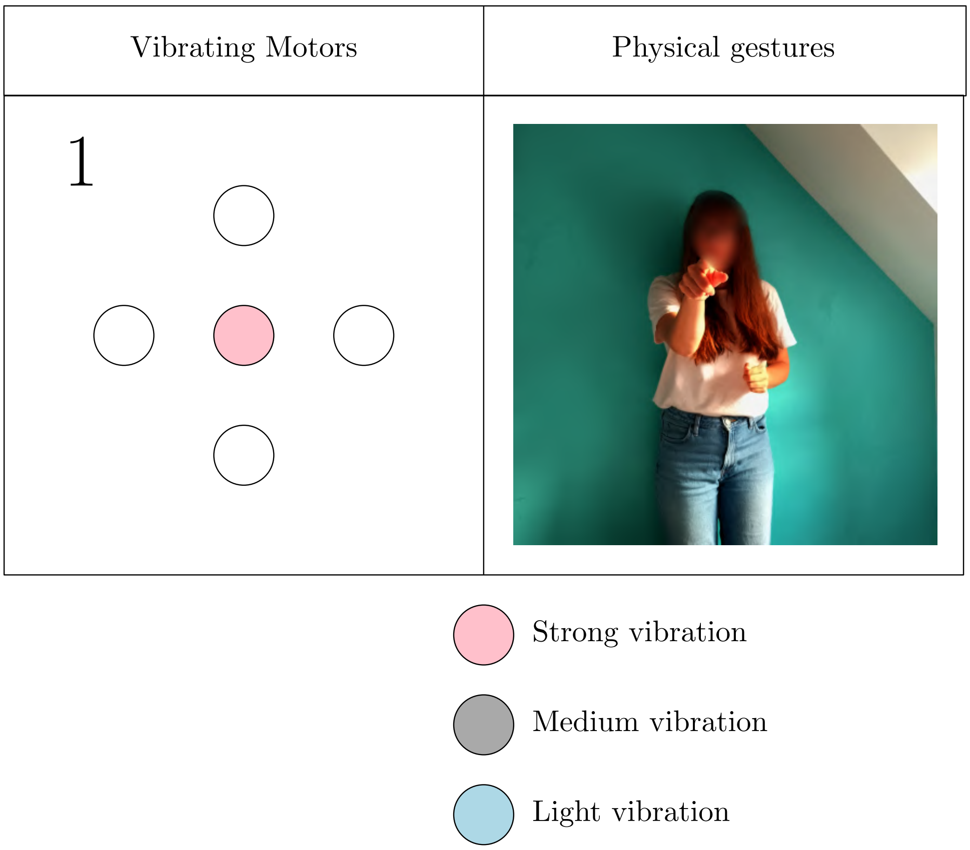

Figure 7.2: Schematic of the Attack cue Gesture Translation

Similarly, the stop gesture 7.3 consists of exactly two distinct steps, again setting it apart from the others through its minimal but unambiguous pattern.

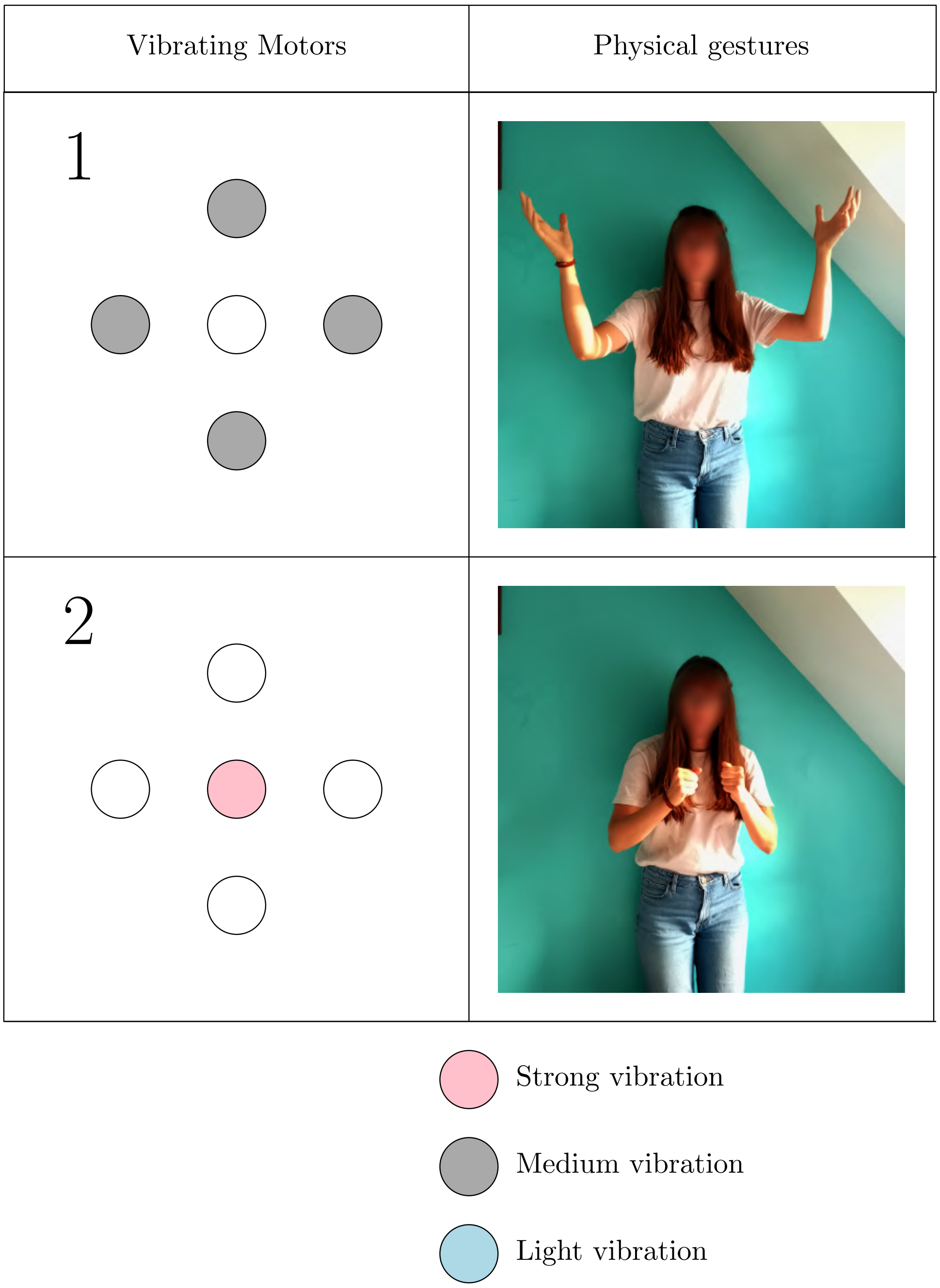

Figure 7.3: Schematic of the End Gesture Translation

By contrast, the tempo (4/4) gesture 7.4 is represented by four discrete steps, which participants can easily identify by simply counting the number of pulses.

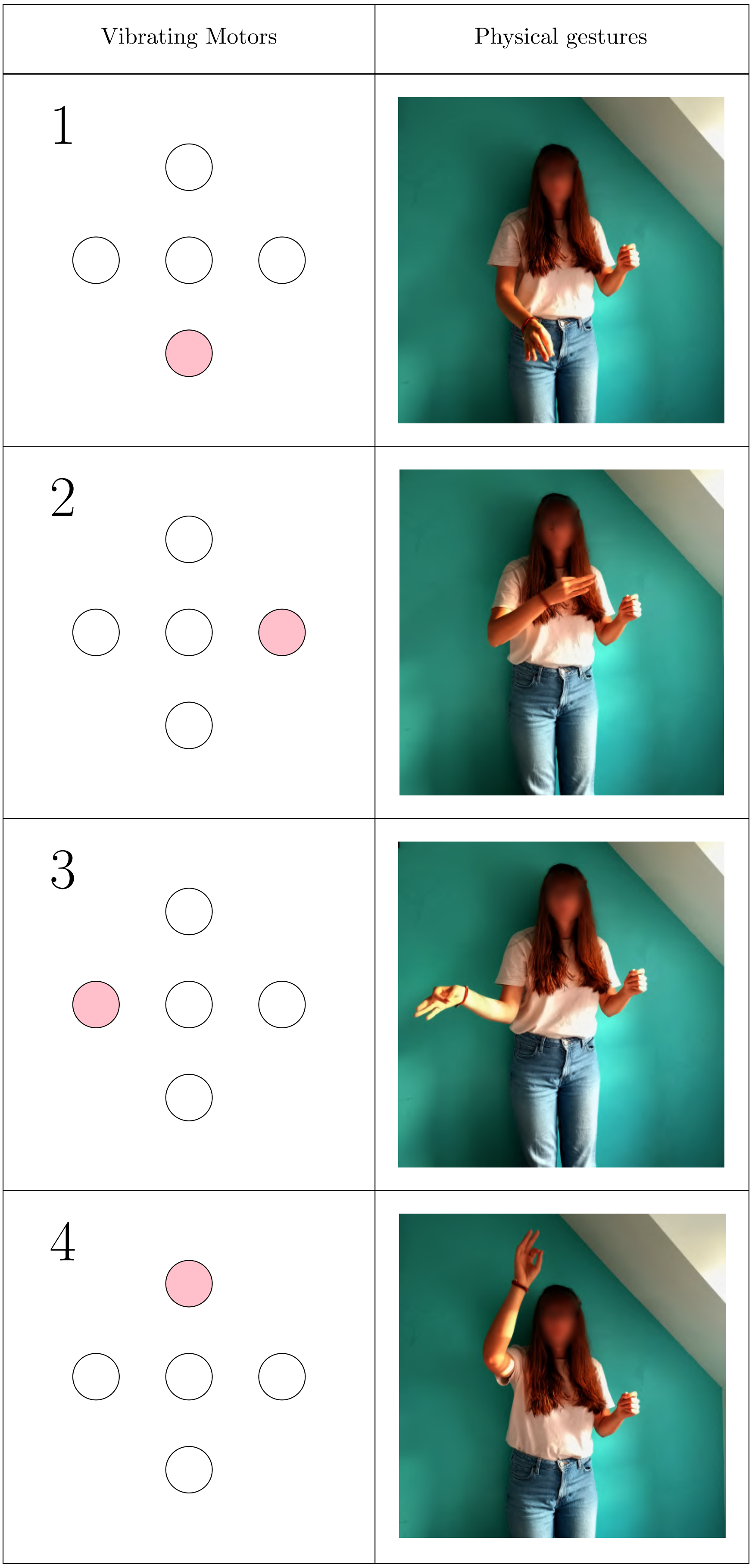

Figure 7.4: Schematic of the Tempo Gesture Translation

The reliance on step count provides an intuitive recognition mechanism, particularly when gestures are performed in quick succession or under conditions of limited concentration.

The remaining three gestures; start 7.5, crescendo 7.6, and decrescendo 7.7, each involve three-step sequences, but they are carefully differentiated through the nature of the vibrations. The start gesture uses three discrete pulses, separated clearly in time. This provides a sense of buildup and anticipation, matching the preparatory nature of the conductor's gesture. In contrast, crescendo and decrescendo are represented by three continuous steps, meaning that the vibration does not pause between phases but flows seamlessly from one to the next. This continuous quality conveys the sense of gradual change in intensity, a defining characteristic of dynamic gestures. In practice, participants described these continuous patterns as "feeling longer" than discrete ones, despite having the same number of steps—a perceptual distinction that greatly aids recognition.

A further layer of differentiation lies in the starting location of each vibration sequence. Every gesture begins with a distinct motor activation, giving each pattern a unique "opening note" that sets it apart. The only exception to this rule is the pair of gestures tempo and crescendo, both of which begin at the wrist. However, even in this case, the distinction is preserved: tempo is composed of short, discrete pulses that feel brief and segmented, while crescendo is continuous and sustained, producing a tactile impression of gradual lengthening. Moreover, their second steps diverge entirely, ensuring that confusion is minimal once the sequence progresses.

Taken together, these design decisions create a haptic lexicon that is both efficient and robust. Users can identify gestures either by counting the number of steps, by recognizing the discrete versus continuous quality of the vibration, or by noting the initial motor location. This redundancy increases reliability: if one feature is misperceived, others still provide enough information for correct recognition.

According to the preliminary tests conducted and discussed in the following chapter, this mapping of gestures proved to be highly promising. Participants demonstrated strong recognition accuracy and consistently reported that the patterns felt natural and easy to interpret. What makes this proposition especially interesting is that it achieves clarity without requiring overly complex signals; instead, it relies on carefully crafted variations in length, continuity, and motor placement. By balancing simplicity with expressive richness, the system shows strong potential for application in real-world musical contexts, where quick, reliable, and intuitive communication is essential.

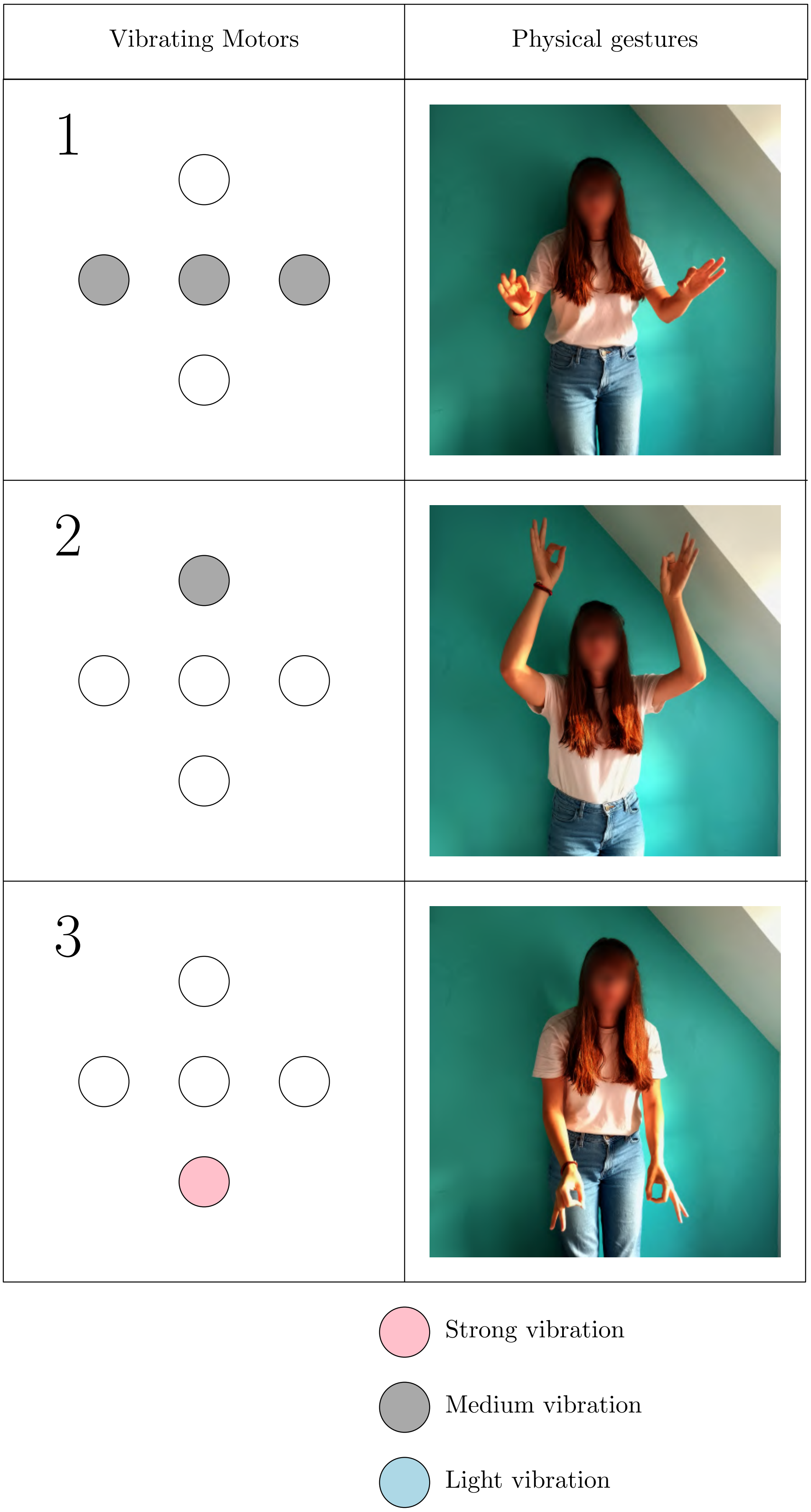

Figure 7.5: Schematic of the Start Gesture Translation

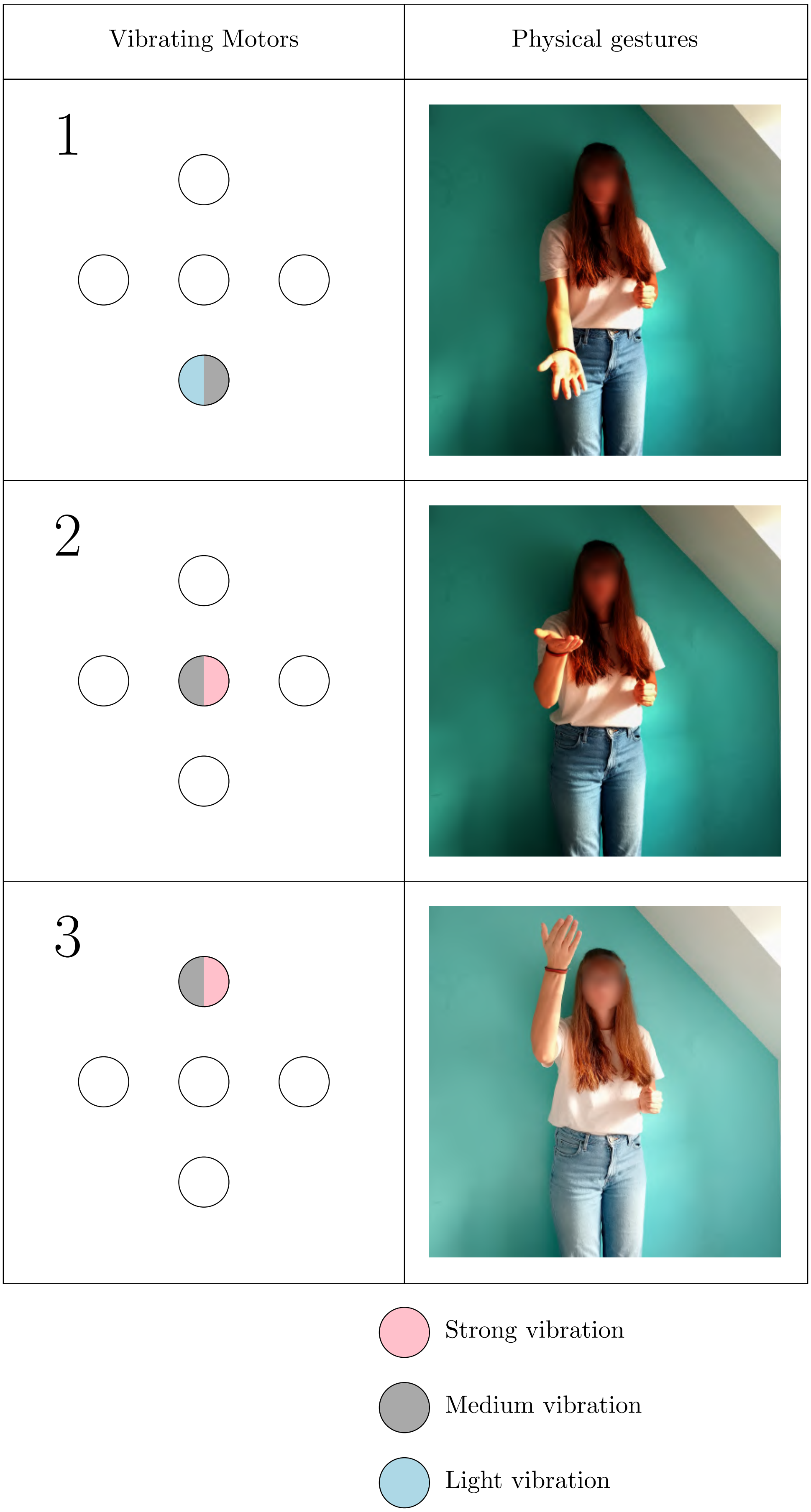

Figure 7.6: Schematic of the Crescendo Gesture Translation

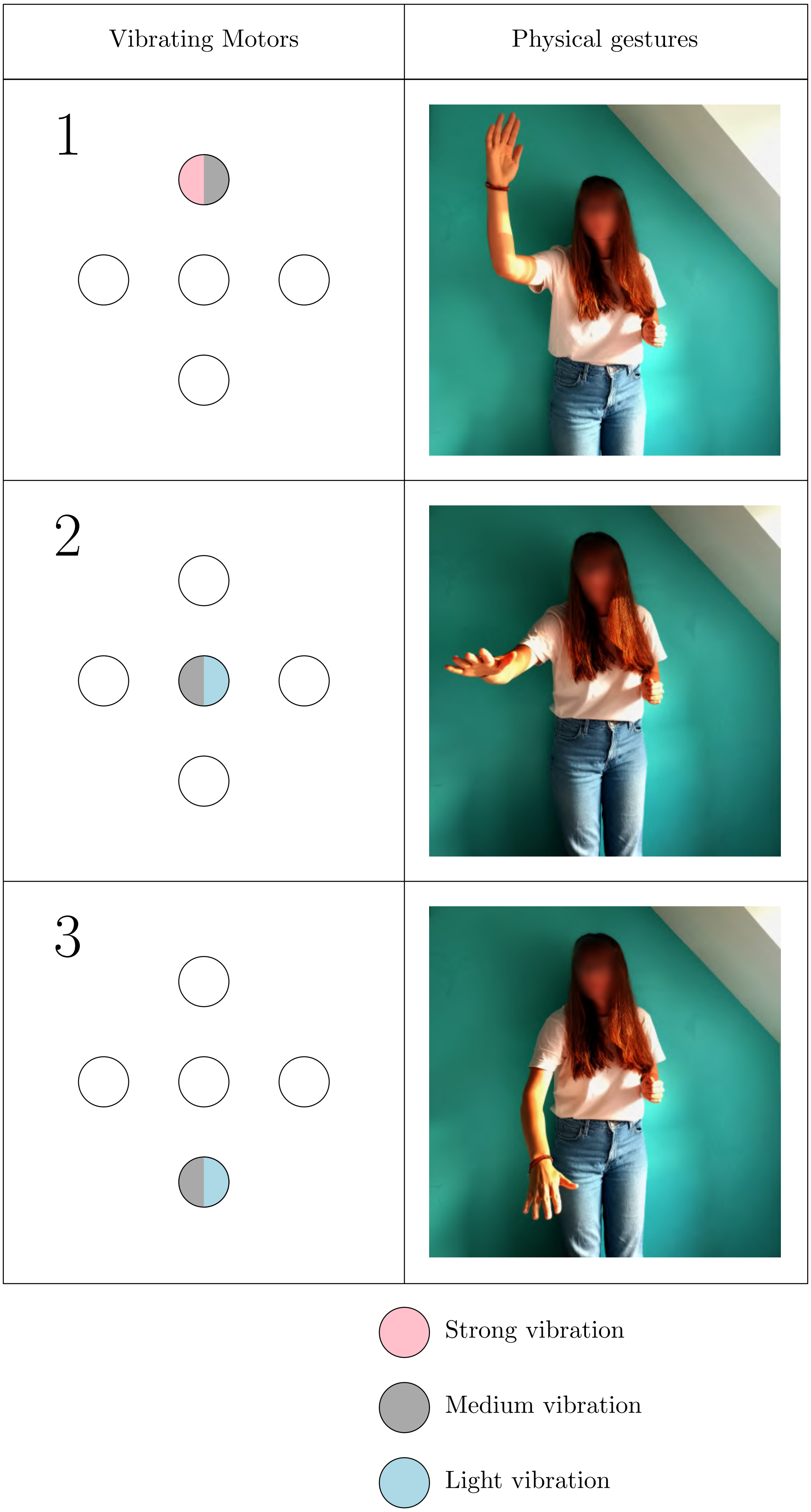

Figure 7.7: Schematic of the Decrescendo Gesture Translation

Chapter 8

Prototype Testing

To evaluate the performance and user experience of the prototype, a series of tests were conducted covering both technical and human-centered aspects. A technical assessment measured the prototype's power consumption and analyzed the reaction delay between commands sent via Bluetooth and the corresponding motor responses. In parallel, user tests were carried out to assess participants' ability to distinguish between different vibration locations and intensities. Additionally, comfort tests were performed to gauge the ease of wearing the prototype while actively playing an instrument, ensuring that both functionality and ergonomics were considered in the evaluation.

8.1 Technical Test

8.1.1 Power Consumption Analysis

In order to evaluate the autonomy of the system, measurements of the electrical consumption were carried out. The prototype consists of two main components:

- An **ESP32 Nano** microcontroller, responsible for communication via Bluetooth Low Energy (BLE) and motor control.
- Several **ERM DC vibration motors** (Eccentric Rotating Mass, 12,000 rpm, 3 V DC), used for haptic feedback.

Measurements

Experimental measurements show that the ESP32 Nano consumes approximately **60 mA** in idle mode with BLE active. When a single vibration motor is activated, the total current consumption increases to around **140 mA**. This corresponds to an additional consumption of approximately **80 mA per motor**.

Thus, the total current consumption can be expressed as:

$$I_{total} = I_{ESP32} + N \cdot I_{motor} \tag{8.1}$$

where:

- $I_{ESP32} \approx 60$ mA (baseline ESP32 consumption with BLE active),
- $I_{motor} \approx 80$ mA (per motor),
- N = number of motors simultaneously activated.

Calculation Examples

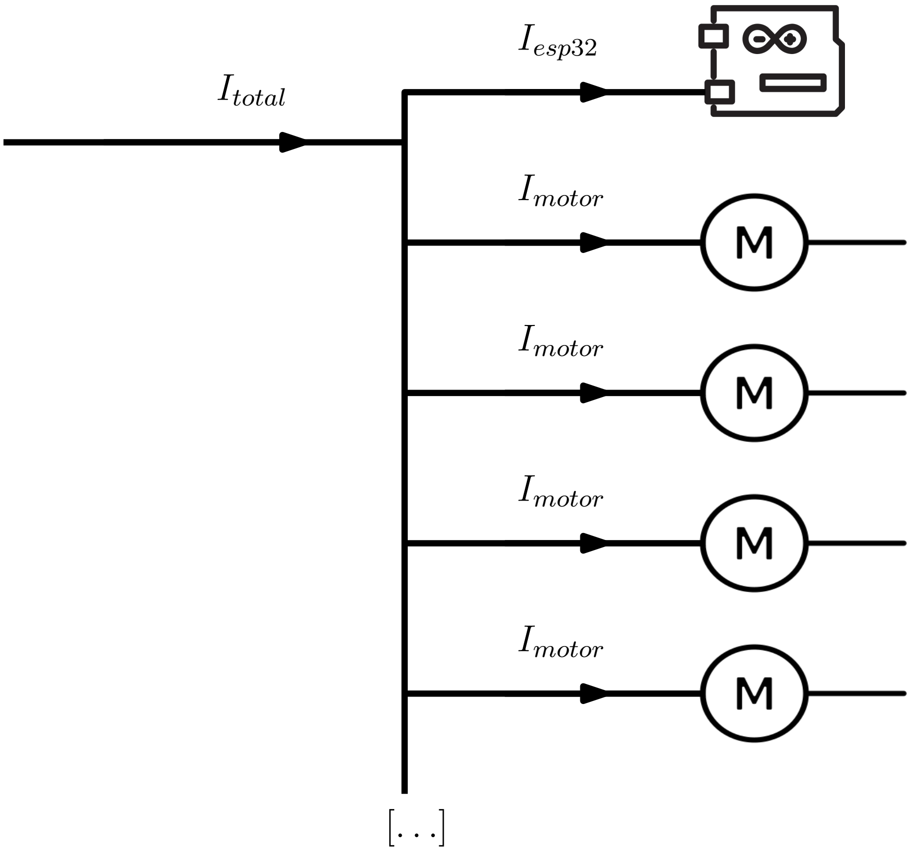

Figure 8.1: Simplified electrical schematic of the system

Using the model described in 8.1, the total current consumption for different numbers of active motors can be calculated as follows:

$$\begin{aligned}
N = 1 \quad &\Rightarrow \quad I_{\text{total}} = 60 + 1 \times 80 = 140 \text{ mA} \\
N = 2 \quad &\Rightarrow \quad I_{\text{total}} = 60 + 2 \times 80 = 220 \text{ mA} \\
N = 3 \quad &\Rightarrow \quad I_{\text{total}} = 60 + 3 \times 80 = 300 \text{ mA} \\
N = 4 \quad &\Rightarrow \quad I_{\text{total}} = 60 + 4 \times 80 = 380 \text{ mA}
\end{aligned}$$

Power Consumption

Assuming a nominal supply voltage of $U = 3.7$ V (typical for a Li-ion battery), the power consumption is given by:

$$P = U \cdot I \tag{8.2}$$

For example:

$$\begin{aligned}
N = 1 \quad &\Rightarrow \quad P = 3.7 \times 0.14 = 0.52 \text{ W} \\
N = 4 \quad &\Rightarrow \quad P = 3.7 \times 0.38 = 1.40 \text{ W}
\end{aligned}$$

Battery Life Estimation

With a battery capacity $C = 500$ mAh, the autonomy can be estimated by:

$$t = \frac{C}{I_{\text{total}}} \tag{8.3}$$

Figure 8.2 illustrates how the battery lifetime depends on the number of motors activated simultaneously.

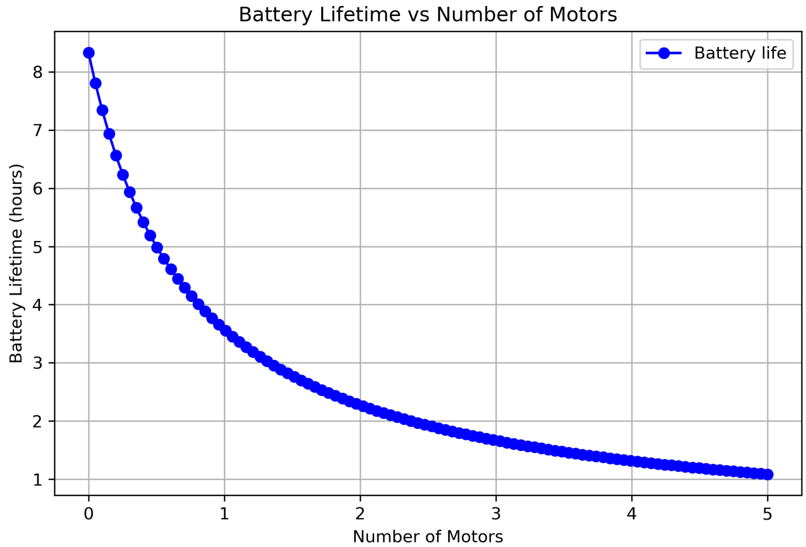

Figure 8.2: Graph of Battery Lifetime versus Number of Motors

For specific cases:

$$N = 1 \quad \Rightarrow \quad t = \frac{500}{140} \approx 3.5 \text{ h}$$
$$N = 4 \quad \Rightarrow \quad t = \frac{500}{380} \approx 1.3 \text{ h}$$

These results show that the system autonomy strongly depends on the number of motors activated simultaneously. While a single motor allows for several hours of operation, activating multiple motors in parallel significantly reduces battery life.

8.1.2 Reaction Delay

To account for the delay introduced by the prototype in the overall system response, a careful measurement setup was designed to capture the motor reaction time accurately. A microphone was positioned next to the mouse, while the motors were held in place by a finger to prevent them from jumping, ensuring that the recorded sound reflected the vibration itself rather than impact noise from hitting a hard surface. During the test, the microphone recorded the sound of the mouse click that triggered the command, followed by the sound of the corresponding motor vibration. The time interval between these two events was then measured, providing a precise estimate of the motor response delay within the system.

Measurements were carried out for each motor at the three previously defined intensity levels: Low, Medium, and Strong. For each motor–intensity combination, 10 trials were recorded, resulting in a total of 150 recordings. The results are presented in Figure 8.3.

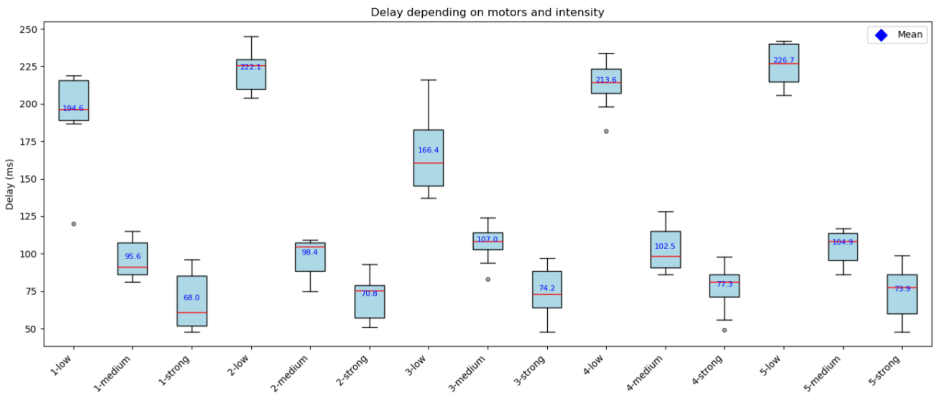

Figure 8.3: Graph of Motor response delays across different motors and intensity levels.

Figure 8.3 illustrates the distribution of delays for each motor and intensity level. The boxplots display the quartiles, with the median highlighted in red, while the mean is indicated in blue. Overall, the results reveal that delays are substantially longer at lower intensity levels. This trend is consistently observed across all motors.

Specifically, the mean delay ranges from 166.4 ms to 226.7 ms at low intensity, from 95.6 ms to 107 ms at medium intensity, and from 68 ms to 77.3 ms at high intensity. This behavior can be explained by the fact that lower intensity commands correspond to lower current supplied to the motor. Consequently, the motor accelerates more slowly and requires more time to reach the vibration threshold compared to stronger intensity commands.

8.2 User testing

To better evaluate the performance that the proposed solution can provide, a series of user tests were conducted. Fifteen individuals participated in this evaluation, where they had to choose between two different prototype configurations: one using the legs and one using the arms. Out of the 15 participants, only individual number 15 selected the leg-based prototype, while all the others preferred the arm-based version.

The experiment was structured in a progressive way to assess several levels of interaction and signal understanding. Participants were asked to complete tasks in the following order:

1. **Localization recognition** – identifying where the stimulus was applied.
2. **Intensity differentiation** – recognizing the strength of the stimulus.
3. **Complex signal interpretation** – combining different stimuli in sequence.
4. **Gesture translation** – understanding and reproducing intended gestures through the system.

The order of the questions was kept identical for all participants to reduce the risk of confusion and ensure consistency in the evaluation.

The results of these tests are presented in Figure 8.4.

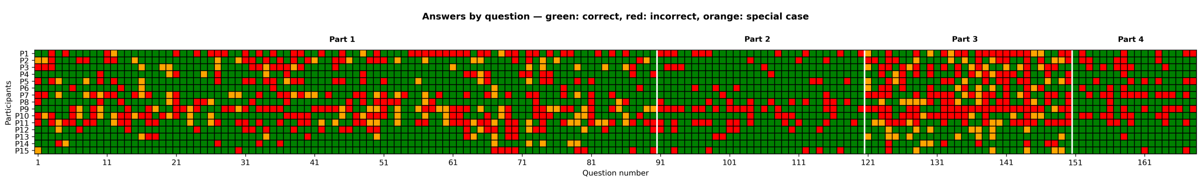

Figure 8.4: Graph of Individual Results for the Evaluation Tasks

In this figure, the **y-axis (ordinate)** represents the different participants, while the **x-axis (abscissa)** corresponds to the task/question number. The details of the questions and answers can be found in the appendix. The color coding is as follows:

- **Green** indicates a correct answer.
- **Red** indicates an incorrect answer.
- **Orange** represents an incorrect answer that nevertheless shows a reasonable interpretation within the context, meaning that the error could still be considered understandable given the environment. For example, in question 1, participant 15 answered "Both" instead of "One." However, since motor one was vibrating more strongly than the other, it was difficult to distinguish between only motor one vibrating and both motors vibrating.

From these results, it is clear that the system demonstrates promising usability. More than half of the answers provided by the participants were correct, which highlights the overall feasibility of the approach. Additionally, the presence of orange points suggests that even when mistakes occur, they often remain within an interpretable range, which is a valuable property for practical applications where some degree of tolerance is acceptable.

It is important to note that motor placement had a significant impact on performance. For some participants, the motors were positioned closer to the skin, which substantially improved the perception of vibrations and consequently increased their overall success rate. This was particularly evident for participants 6, 12, 13, 14, and 15, who consistently achieved higher scores across the different conditions.

8.2.1 Localisation detection test

The first part of the evaluation focused on the detection of the localisation of the vibrating motors. The vibration could occur in two different locations, or in both locations simultaneously. Three pairs of locations were tested, each under three intensity levels. The test conditions were therefore as follows:

- Wrist / Middle – tested at *Light*, *Medium*, and *Strong* intensity.
- Outside of the arm / Middle – tested at *Light*, *Medium*, and *Strong* intensity.
- Elbow / Middle – tested at *Light*, *Medium*, and *Strong* intensity.

For each condition, 10 signals were sent, leading to a total of 90 signals transmitted in this part of the test. The detailed results are presented in the subset of the previous figure in Figure 8.5.

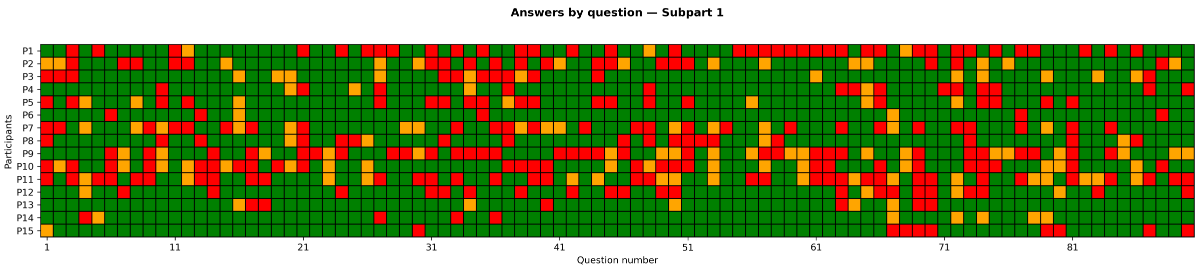

Figure 8.5: Graph of Individual Results for the localisation detection test

In this part, the orange points correspond to cases where the error involved the detection of both vibrations, either in the participant's answer or in the reference signal. This phenomenon can be explained by the fact that, in practice, one of the motors often vibrates more strongly than the other, making it particularly difficult for participants to distinguish whether one or two motors were actually activated simultaneously.

The localisation detection test revealed several insightful trends regarding participant performance across the different vibration pairings and intensity levels. In the **Middle/Wrist** condition, participants showed strong recognition rates, with average success increasing from *Low* (68%) to *Medium* (72.7%) and reaching its highest at *Strong* intensity (76%). This suggests that higher intensity vibrations improved the discriminability of signals at the wrist, consistent with the higher sensitivity of this area to haptic feedback.

The **In/Out** condition followed a similar pattern, starting with the lowest recognition rate at *Low* intensity (60.7%) but improving sharply to (76%) at *Strong*. This indicates that the In/Out pairing is more challenging for participants, though sufficient intensity helps overcome this difficulty.

For the **Elbow/Middle** condition, the pattern was less pronounced: performance was lower at *Low* (60.7%) but rose steadily through *Medium* (65.3%) and *Strong* (75.3%), showing that although the elbow is a more difficult area for precise localisation, participants were still able to achieve robust detection under stronger stimulation.

A clear trend emerges across all three location pairs: **increasing intensity systematically improves recognition rates**, confirming that stronger tactile stimulation enhances perceptual clarity. This effect was most visible for the Middle/Wrist and In/Out conditions, where performance at *Strong* intensity exceeded (75%), compared to just above (60%) at *Low*. Even the more challenging Elbow/Middle condition followed this improvement pattern, demonstrating that difficult areas also benefit significantly from stronger vibrations.

Looking across individuals, clear differences in performance are evident. For instance, Participant 6 consistently achieved near-perfect recognition (90–100%) across all conditions, whereas Participant 9 struggled in several cases, dropping to as low (20–30%) as in some trials. This variability highlights the strong influence of individual perceptual differences, such as skin sensitivity or attentional focus, on task performance. Importantly, despite these inter-individual variations, the overall trend remains consistent: higher intensity levels systematically improve recognition across all tested pairs.

For the signals **22, 52, 54, 55, and 71**, only one participant made an error during the test. These signals correspond respectively to: *Wrist strong, Extern strong, Both Middle/Extern strong, Extern strong, and Middle in Middle/Elbow Medium.*

In Figure 8.6, we can see the percentage of correct answers depending on the signal sent in each test described above. For Subparts 1 to 3, the number 1 refers to the Middle and 2 to the Wrist. For Subparts 4 to 6, the number 1 refers to the Middle and 2 to the Extern. For Subparts 7 to 9, the number 1 refers to the Elbow and 2 to the Middle.

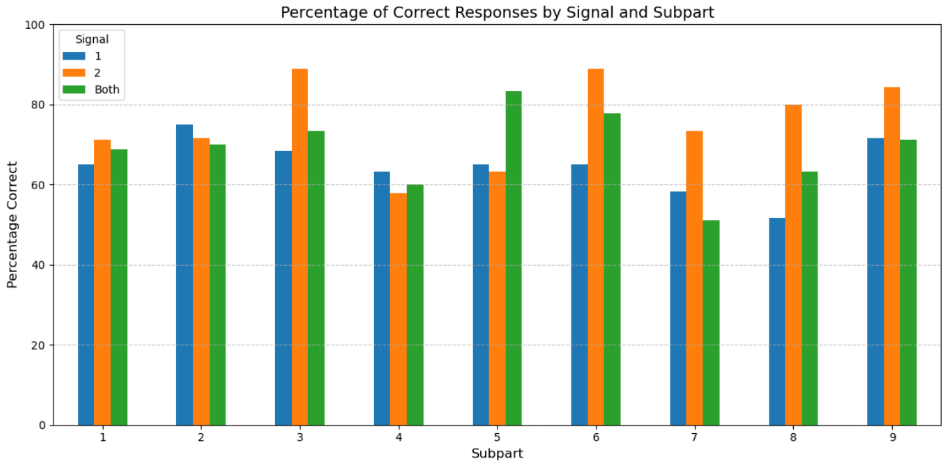

Figure 8.6: Graph of Percentage of Correct Responses by Signal and Test

The signals that consistently achieved **over 80% correct guesses** when presented were:

- *Wrist strong* in the Middle/Wrist Strong test
- *Both medium* in the Middle/Extern Medium test
- *Extern strong* in the Middle/Extern Strong test
- *Middle medium* in the Elbow/Middle Medium test
- *Middle strong* in the Elbow/Middle Strong test

The signals with the lowest accuracy, achieving only **50–60% correct guesses**, were:

- *Extern light* in the Middle/Extern Light test
- *Elbow light* in the Middle/Elbow Light test
- *Both* in the Middle/Elbow Light test
- *Elbow medium* in the Middle/Elbow Medium test

All other signals achieved **60–80% correct guesses**.

Certain configurations were recognised with over 80% accuracy, indicating that strong, well-localised vibrations are highly reliable cues for the users. By contrast, signals involving light intensities, particularly on the elbow or when multiple motors were activated simultaneously, often fell below 60% accuracy. These results confirm that **light and multi-source signals are the most error-prone**, largely due to the natural variability of vibration intensity across motors and the difficulty of perceiving subtle or overlapping stimuli.

In practical haptic communication systems, designers should **favour strong and clearly localised vibrations** when critical information must be transmitted. Lighter signals may still be useful for secondary or non-urgent cues, but they should not be relied upon in isolation. Furthermore, the observed inter-individual variability suggests that **personal calibration could substantially improve reliability**, adapting intensity levels to each user's sensitivity.

8.2.2 Intensity detection test

The second phase of the evaluation focused on assessing participants' ability to perceive and correctly identify the **intensity of vibration produced by the motors**. Each vibration could occur at **three distinct intensity levels**—Light, Medium, and Strong—across **three anatomical locations**. The test conditions were therefore as follows:

- **Middle** — tested at *Light*, *Medium*, and *Strong* intensities
- **Wrist** — tested at *Light*, *Medium*, and *Strong* intensities
- **Elbow** — tested at *Light*, *Medium*, and *Strong* intensities

For each condition, **10 signals were transmitted**, resulting in a total of **30 signals** for this part of the test. The detailed outcomes are shown in the subset of the previous figure 8.4 in Figure 8.7.

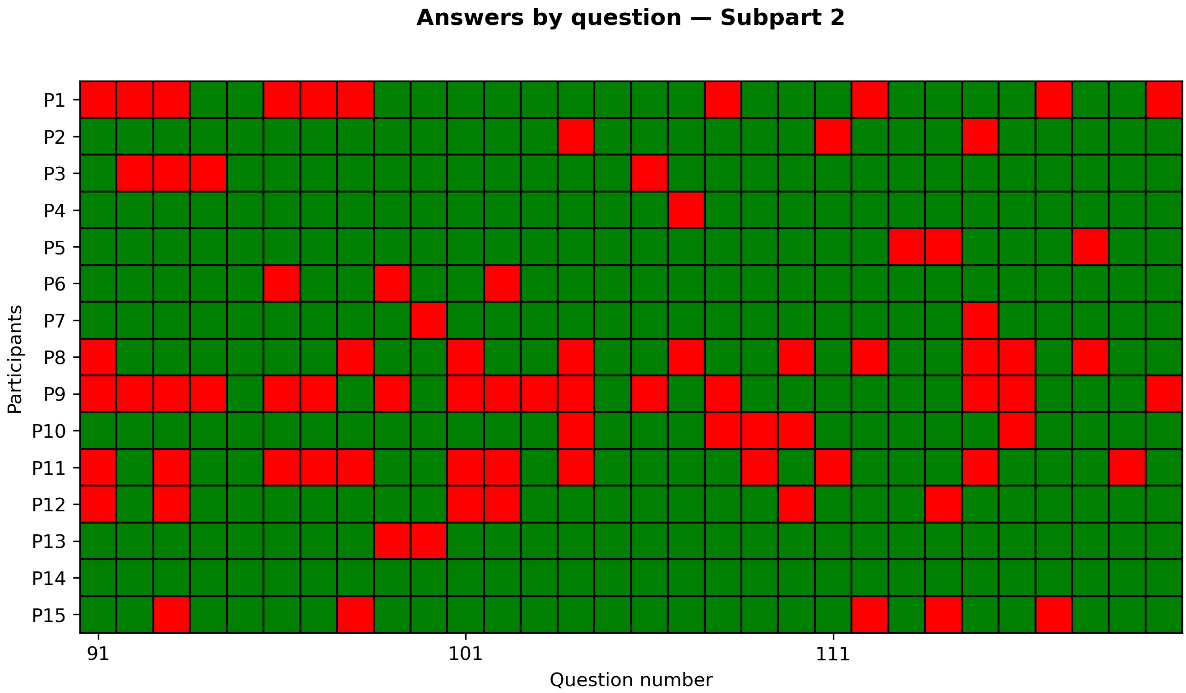

Figure 8.7: Graph of Individual Results for the intensity detection test

Overall, the intensity detection test yielded **strong performance**:

- **Middle:** average recognition rate of **78.7%**
- **Wrist:** average recognition rate of **82.7%**
- **Elbow:** average recognition rate of **84.0%**

These results indicate that participants could generally **discriminate between light, medium, and strong vibrations**, with slightly higher recognition rates at the Wrist and Elbow compared to the Middle. Notably, several participants achieved **near-perfect accuracy across all three locations**, demonstrating that vibration intensity can be reliably distinguished when sufficiently pronounced.

However, the data also revealed **inter-individual variability**: some participants experienced greater difficulty differentiating intensity levels at the Middle position. Despite this variability, the overall trend confirms the **robustness of intensity-based encoding**, particularly at the Wrist and Elbow, where users were most consistent.

Certain signals were identified with exceptional accuracy:

- **Signals 95 and 105** were **correctly identified by all participants**.

- **Signals 103, 113, and 119** resulted in only a single error across all participants.

These correspond to **Middle–Light, Wrist–Light, Wrist–Strong, Elbow–Light, and Elbow–Medium** conditions, respectively. Figure 8.8 illustrates the percentage of correct responses for each signal tested.

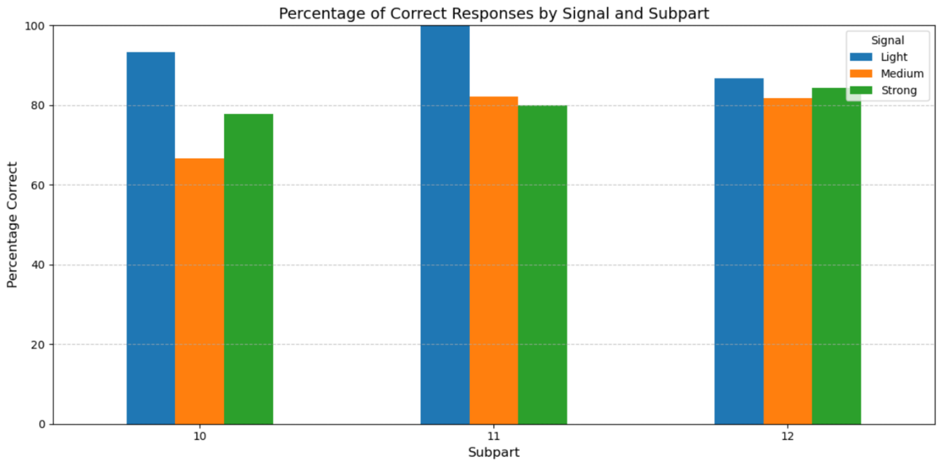

Figure 8.8: Graph of the Percentage of Correct Responses by Signal and Test

All signals achieved at least **60% correct identification**, and many exceeded **80%**, notably:

- **Light–Middle**
- **All Wrist intensities**
- **All Elbow intensities**

These findings reinforce the conclusion that **vibration intensity can be reliably detected and distinguished**, especially at the Wrist and Elbow positions.

8.2.3 Complex Signal test

The third phase of the evaluation focused on assessing participants' ability to perceive and correctly identify both the *intensity* of vibration produced by the motors and the *location* of the vibrating motors at the same time. Two pairs of locations were tested, each under three intensity levels. The vibration could occur in two different locations, in both locations simultaneously, or as a movement from one location to the other. The test conditions were therefore as follows:

- Wrist / Middle — tested at *Light*, *Medium*, and *Strong* intensity.
- Outside of the arm / Middle — tested at *Light*, *Medium*, and *Strong* intensity.

For each condition, 15 signals were sent, leading to a total of 30 signals transmitted in this part of the test. The detailed outcomes are shown in the subset of the previous figure 8.4 in Figure 8.9.

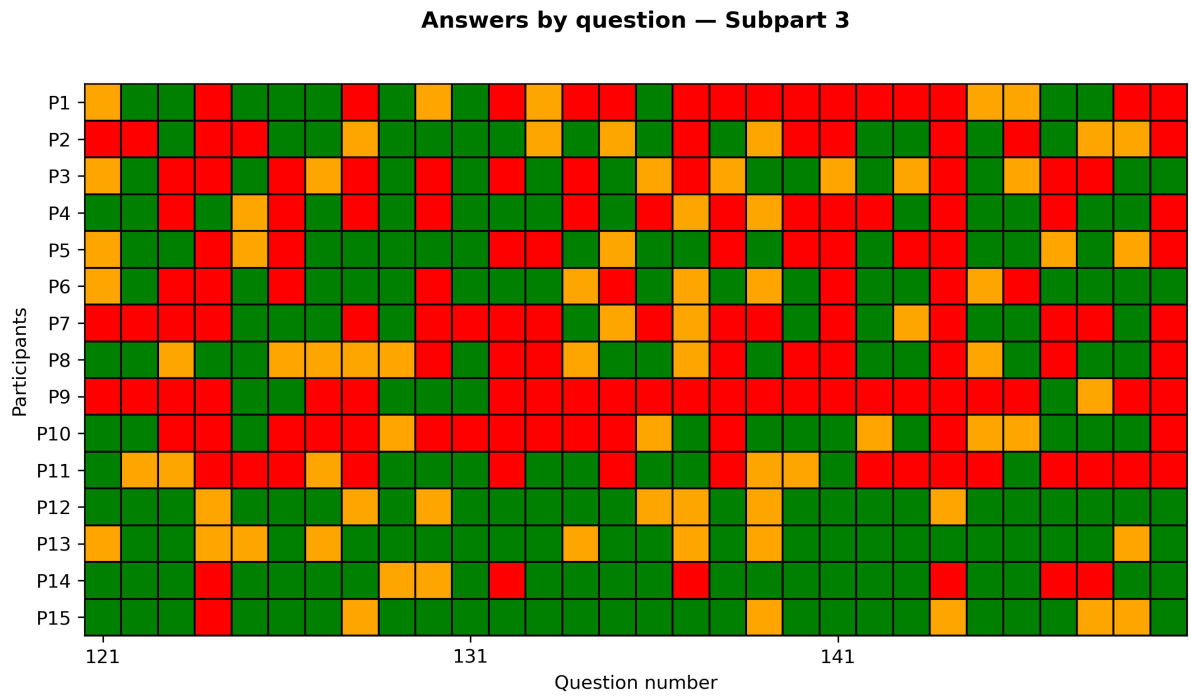

Figure 8.9: Graph of Individual Results for the complex signal detection test

In this part, the orange points correspond to cases where the error was solely due to a mistake in *intensity*, or to cases where the error involved the detection of both vibrations—either in the participant's answer or in the reference signal. This phenomenon can be explained by the fact that, in practice, one of the motors often vibrates more strongly than the other, making it particularly difficult for participants to distinguish the correct intensity.

Across all 15 participants, performance on the two complex tasks showed moderate but distinct success rates. For the **Wrist/Middle Complex** task, the mean accuracy was approximately 52%, with individual scores ranging from 20% to 86.7%. Notably, participants 12–15 achieved markedly higher accuracies (greater than or equal to 66.7%), indicating that some individuals could reliably solve this task at a high level. The **In/Out Complex** task yielded a slightly lower mean accuracy of about 47%, but again a subset of participants (12–15) performed exceptionally well, with scores between 73.3% and 80%, suggesting strong ability to distinguish the more challenging in/out patterns. While several participants showed limited success—particularly participant 9 with only 6.7% on the In/Out task—the overall trend highlights that nearly half of the signals were correctly identified even under complex conditions, and that a group of users consistently achieved high recognition rates, demonstrating the feasibility of reliably decoding these patterns.

In Figure 8.10, the percentage of correct responses is shown for each signal tested as described above. In Subpart 13, the number 1 refers to the *Middle* location and number 2 to the *Wrist*. In Subpart 14, the number 1 refers to the *Middle* location and number 2 to the *External* location.

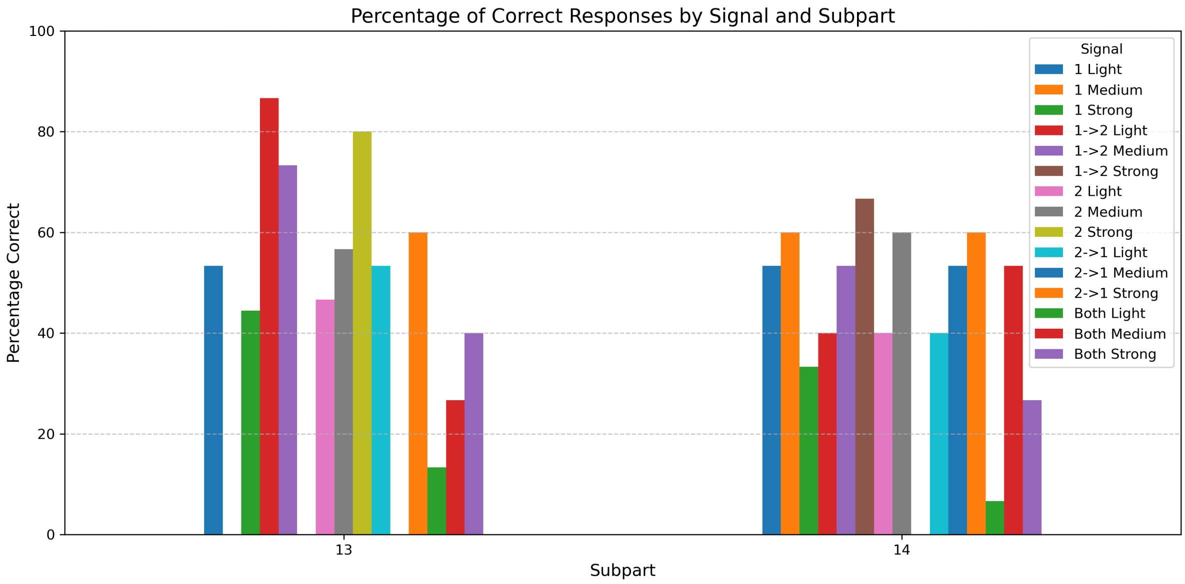

Figure 8.10: Graph of Percentage of Correct Responses by Signal and Test

Some signals showed a **0% success rate** not because participants failed to recognize them, but because those particular signals were never actually transmitted during the test. The set of signals presented to participants was randomly chosen, and by chance, these specific signals were never selected. This highlights that when signal transmission is random and uncontrolled, certain stimuli may be completely omitted, leading to misleadingly low success rates.

In **Subpart 13**, wrist and middle movements (such as 1→2 Light, 1→2 Medium, and 2→1 Strong) achieved at least **60% success**. Every time a movement was sent, it was correctly recognized as a movement, demonstrating robust detection of occurrence. Direction detection was generally accurate, with correct identification more than 12 times out of 15. However, intensity detection remained the main challenge. For example, **Wrist Strong (2 Strong)** achieved a relatively good success rate of **80%**, demonstrating better performance at higher intensities.

In **Subpart 14**, the movement 1→2 improved from **40% success at Light intensity** to **65–67% at Strong intensity**. The opposite movement (2→1) showed a similar improvement with increased intensity. As in Subpart 13, every movement sent was correctly identified as a movement, and direction detection remained accurate (≥12/15 times). Again, the intensity of movement was the main limiting factor for accuracy.

The results from Subparts 13 and 14 reveal consistent patterns regarding movement detection, direction detection, and intensity detection. Across both subparts, every time a movement was sent, it was correctly identified as a movement. This indicates a robust detection mechanism for the occurrence of movement itself, independent of direction or intensity, and suggests that the system could reliably be used to confirm whether a movement has occurred, making it suitable for applications where the presence or absence of movement is the primary concern.

In both subparts, the direction of movement was accurately detected more than 12 times out of 15, corresponding to a success rate of at least **80%**. This level of consistency demonstrates that directional information is generally well captured. With minor calibration, it is plausible that direction detection could reach success rates above **90%** across all intensities, enabling the system to serve in contexts where both presence and direction of movement are critical, such as gesture-based control.

The main source of error lies in the detection of movement **intensity**. Success rates vary considerably depending on the strength of the movement. In Subpart 13, wrist strong movements reached up to **80% success**, whereas light movements and combined movements performed substantially worse. In Subpart 14, the movement from 1→2 improved from approximately **40% success at Light intensity** to over **65% at Strong intensity**. The reverse movement (2→1) showed a similar improvement. This trend suggests that increasing movement intensity improves detection accuracy. With targeted adjustments to signal processing, intensity recognition could approach the reliability currently seen in direction detection. Furthermore, combining features from both strong and light movement profiles may help train a more intensity-robust detection model.

The highest success rates were found in **wrist strong movements in Subpart 13 (up to 80% success)** and in **strong-intensity movements in Subpart 14 (above 60% success)**. This indicates that prioritizing strong or medium-intensity movements may yield more reliable detection in real-world scenarios, and also suggests that system performance could be optimized by encouraging users to perform movements at higher intensities.

Overall, movement (one motor vibrating sequentially after another) and direction (the order in which the motors vibrate) detection are reliable, whereas intensity detection remains a limitation. The data clearly show that increasing intensity leads to improved success rates. Future system iterations should focus on enhancing sensitivity to low-intensity signals, incorporating adaptive thresholds to maintain accuracy across varying intensities, and leveraging machine learning approaches to better classify intensity levels based on existing high-quality directional data. Extrapolating these findings suggests that, with further optimization, the system could achieve uniformly high performance across all three dimensions: **movement presence, direction, and intensity**.

8.2.4 Gesture translation test

The final part of the evaluation focused on the detection of gesture translations introduced in the previous chapter. Participants were asked to identify each gesture from a library of six predefined gestures:

- **Point**: a single short vibration in the *Middle*.
- **Stop**: a two-step signal starting at the *Wrist/Elbow (internal and external)* and ending at the *Middle*.
- **Start**: a three-step signal that begins with *internal and external* vibrations together, proceeds to the *Elbow*, and finishes at the *Wrist*.
- **Increase**: a three-step continuous signal that *increases in intensity*, starting from the *Wrist* and progressing through the *Middle* to the *Elbow*.
- **Decrease**: a three-step continuous signal that *decreases in intensity*, starting from the *Elbow* and moving through the *Middle* to the *Wrist*.
- **Pulse**: a four-step signal starting from the *Wrist* and moving to the *Internal*, then the *External*, and finally the *Elbow*.

For this test, **18 signals** were sent. The detailed outcomes are shown in the subset of the previous figure 8.4 in Figure 8.11.

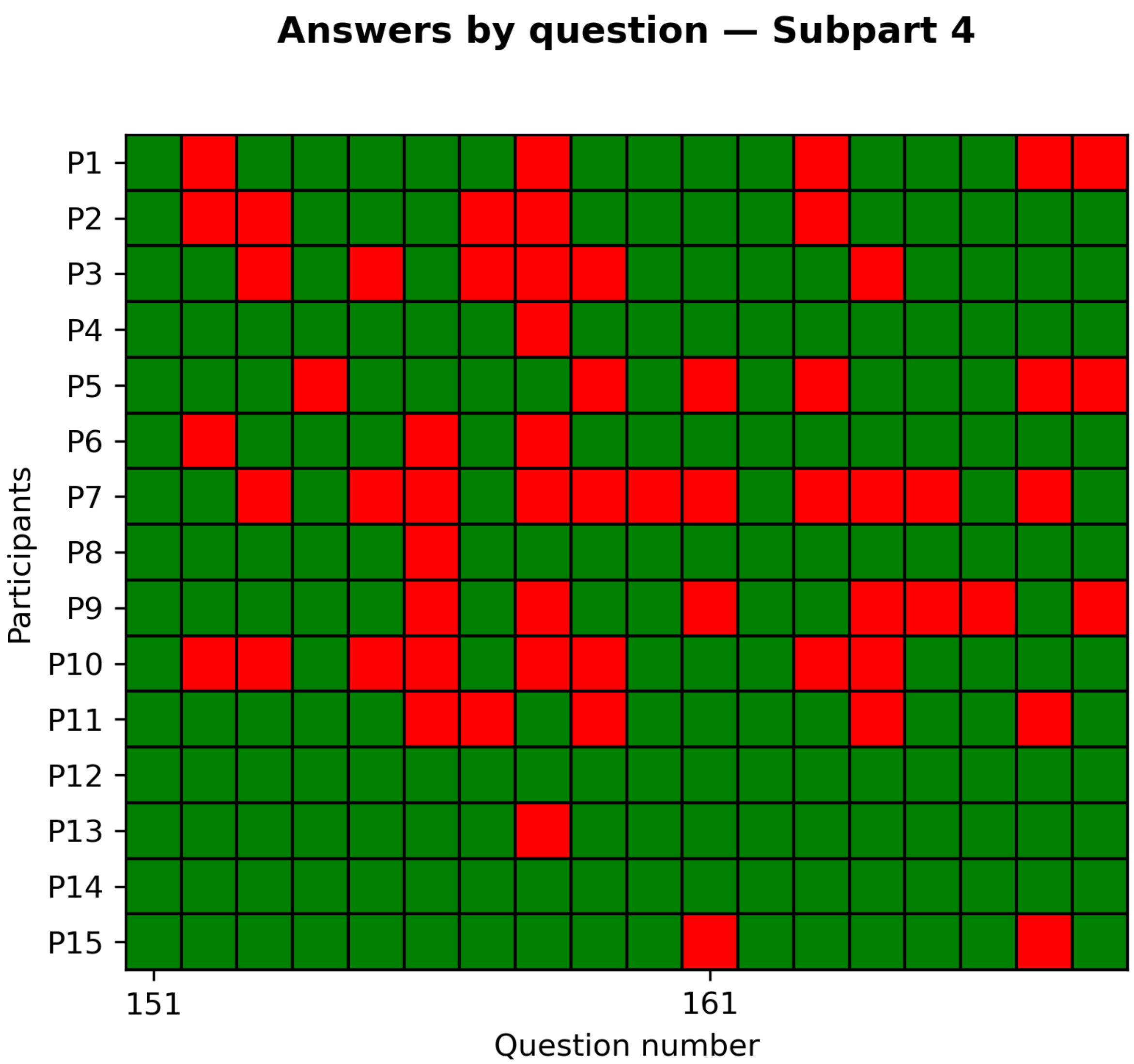

Figure 8.11: Graph of Individual Results for the gesture translation detection test

All fifteen participants were introduced to the gesture library and completed a short training session. The level of visual support differed between groups. Participants 1–8 received only a brief explanation and a simple schematic hint, achieving an average success rate of **73.6%**. Participants 9–15 received the same explanation and training, but also a detailed schematic reminder, which increased their mean success rate to **81.7%**. This highlights the benefit of richer visual cues for complex gesture translation.

Individual backgrounds also influenced performance. Participants 4, 5, 6, 8, and 13, all with musical or orchestral experience, achieved a mean success rate of **86.7%**. Participants 12 and 14, with extensive experience in haptic feedback systems, reached a perfect **100%** success rate. Participants without specific backgrounds averaged **65.9%** correct responses. These findings indicate that familiarity with structured sensory patterns—whether musical or haptic—substantially improves performance.

Overall, the results show that most participants could correctly translate the gestures at reasonably high rates, even without specialized training. Clear instructions, supportive visual aids, and relevant prior experience consistently enhanced performance, suggesting that future system deployments should incorporate richer guidance and consider users' backgrounds to maximize recognition accuracy.

Signals 151 and 162 were always correctly identified; these correspond to the **Point** gesture, which appears to be the easiest to detect due to its very short duration compared to other gestures. The last time it was sent was for signal 166, where only one participant made a mistake.

In Figure 8.12, the percentage of correct responses is shown for each signal.

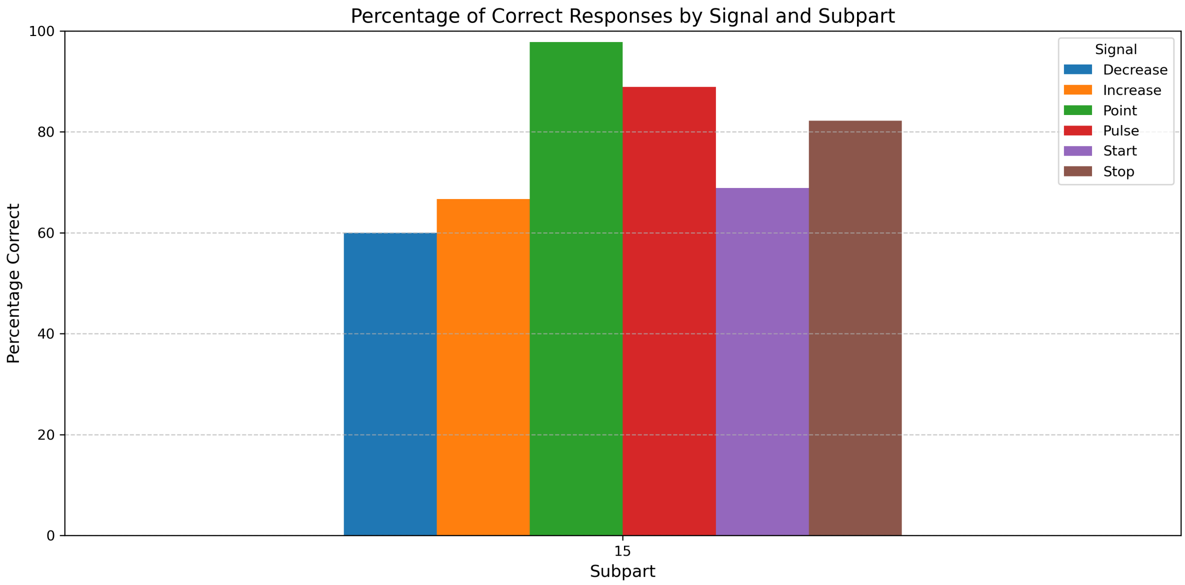

Figure 8.12: Graph of Percentage of correct responses by signal.

All gestures in the translation test achieved more than 60% correct identification. Notably, the **Point**, **Pulse**, and **Stop** gestures exceeded 80% correct guesses. This can be explained by the number of steps in each gesture: **Point** consists of a single step, **Stop** of two steps, and **Pulse** of four steps. Their unique number of steps made them easier to distinguish from the other gestures.

The results of the gesture translation test suggest promising potential for using the prototype in an orchestral setting. Even participants without specialized backgrounds achieved reasonably high success rates, with all gestures correctly identified more than 60% of the time. Participants with musical or haptic experience consistently performed better, achieving success rates above 85% and, in some cases, perfect scores. This indicates that prior experience with structured sensory patterns—such as reading musical scores, coordinating complex movements, or interacting with haptic feedback systems—enhances the ability to interpret translated gestures accurately.

In an orchestra, performers are already trained to perceive and execute precise timing and spatial patterns, often under complex sensory conditions. Based on the experimental findings, it is reasonable to extrapolate that musicians would be highly capable of detecting the prototype's gesture translations, particularly for gestures that are short, distinctive, or involve unique sequences of steps (e.g., **Point**, **Stop**, and **Pulse**). Furthermore, gestures that involve multiple steps with gradual intensity changes (**Increase** and **Decrease**) were reliably identified by participants who received detailed guidance, suggesting that with minimal training or visual support, the system could effectively convey more nuanced gestural instructions in real-time performance contexts.

Overall, the combination of robust detection of gesture occurrence, accurate translation of direction and intensity patterns, and the structured sensory training typical of musicians suggests that the prototype could achieve high success rates when used to communicate gestures within an orchestra. With targeted calibration and practice, it is likely that nearly all gestures could be consistently recognized, enabling the system to serve as a practical tool for conducting, rehearsal, or remote coordination in complex musical environments.

8.2.5 Overall results

The user evaluation of the proposed prototype demonstrated generally strong performance across multiple dimensions, with clear trends in participant responses. Localization detection improved consistently with vibration intensity: for the Middle/Wrist pair, recognition increased from 68% at Low to 76% at Strong intensity; In/Out (Middle/Extern) started at 60.7% and rose to 76%; Elbow/Middle was more challenging, with Low at 60.7% and Strong at 75.3%, indicating that stronger vibrations substantially enhance detectability even in less sensitive areas. Intensity detection was similarly robust, with average recognition of 78.7% at the Middle, 82.7% at the Wrist, and 84% at the Elbow, though inter-individual variability suggests that user-specific calibration could further improve accuracy. Complex signal detection revealed moderate success: Wrist/Middle complex signals averaged 52%, and In/Out complex signals averaged 47%, with direction generally recognized correctly ($\geq$ 80%), but intensity remaining the main source of errors; participants 12–15 consistently achieved higher scores, showing that training and sensitivity influence performance. Gesture translation achieved an overall mean of 77.4%, with short or distinctive gestures (Point, Stop, Pulse) exceeding 80% success due to their unique step patterns, while longer or intensity-varying gestures (Increase, Decrease) benefited from visual guidance. Participants with musical or haptic experience performed markedly better (86.7–100%), whereas those without relevant backgrounds averaged 65.9%, highlighting the role of structured sensory experience. Overall, the prototype is particularly strong in detecting well-localized, high-intensity signals and translating clear gestures, while challenges remain for low-intensity, multi-source, or complex sequences. Potential improvements include increasing vibration strength for difficult locations, incorporating adaptive user calibration, optimizing signal design for critical gestures, and providing visual guidance or brief training sessions, which collectively suggest that the system could reliably convey both simple and complex gestures in practical applications such as orchestral communication.

8.3 Confort test

Tests were conducted on different instruments using both shapes with musicians. The musicians were asked to play their instruments while wearing the sleeves on their legs or arms. They then provided feedback on the sensations they experienced while playing with the prototype on their limbs.

8.3.1 Guitar

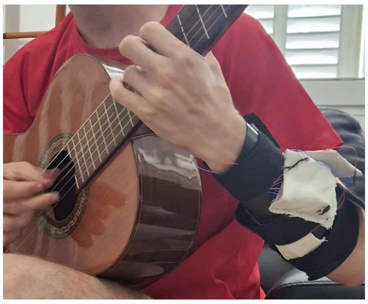

Figure 8.13: Picture of Guitar playing while wearing arm sleeves

This photo shows a musician playing the guitar while wearing the arm sleeves. The players emphasized that it is entirely feasible to play with the sleeves on. However, the arm sleeves slightly restrict the movement of the right hand and should be positioned as high as possible on the arm. The more the wrist is left free — depending on the size of the forearm — the greater the freedom of movement. Nonetheless, having something tightly fitted to the arm remains somewhat distracting and can still limit the player's motion.

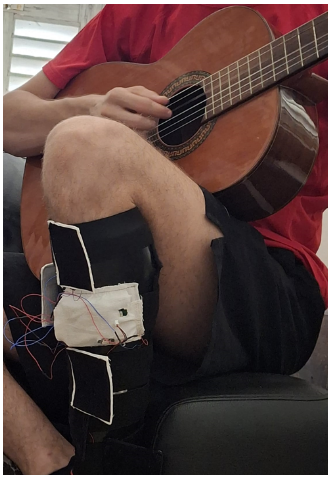

Figure 8.14: Picture of Guitar playing while wearing leg sleeves

This photo shows the musician playing the guitar while wearing the leg sleeves. In contrast to the arm sleeves, the leg sleeves caused no disturbance or restriction of movement. They were so comfortable that musicians reported it was easy to forget they were even wearing them while playing. Overall, no significant disadvantages were noted.

8.3.2 Saxophone

Figure 8.15: Picture of Saxophone playing while wearing arm sleeves

This photo shows a musician playing the saxophone while wearing the arm sleeves. The players confirmed that it is entirely possible to perform with the sleeves on without hindering their playing. They did caution, however, that the sleeves should not be overly tight and should not be worn for long periods, as excessive snugness or extended use can lead to discomfort and minor restrictions in movement.

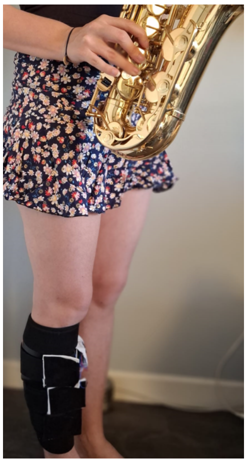

Figure 8.16: Picture of Saxophone playing while wearing leg sleeves

This photo shows the musician playing the saxophone while wearing the leg sleeves. Unlike the arm sleeves, the leg sleeves caused virtually no disturbance or restriction of movement, allowing the musician to perform comfortably and freely.

8.3.3 Piano

Figure 8.17: Picture of Piano playing while wearing arm sleeves

This photo captures a musician playing the piano while wearing the arm sleeves. The players stressed that performing with the sleeves on is completely feasible and does not disturb playing. However, they noted that the sleeves should not be too tight and should not be worn for extended periods, as excessive tightness or prolonged use can cause discomfort and slightly limit movement.

Figure 8.18: Picture of Piano playing while wearing leg sleeves

This photo shows the musician playing the piano while wearing the leg sleeves. In contrast to the arm sleeves, the leg sleeves caused almost no disturbance or restriction of movement. The only minor drawback noted was a slight limitation of ankle movement when operating the pedals for alterations; however, since this action is not constant during performance, the disturbance was much less significant than with the arm sleeves. Additionally, musicians can use the other leg to operate the pedals when needed, further reducing any impact on performance.

8.3.4 Trumpet

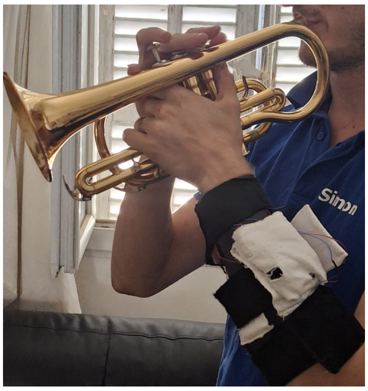

Figure 8.19: Picture of Trumpet playing while wearing arm sleeves

This photo captures a musician playing the trumpet while wearing the arm sleeves. The players emphasized that performing with the sleeves on is entirely feasible and does not interfere with playing. As long as the sleeves are not too tight, the fingers can move freely, allowing full control and dexterity while performing.

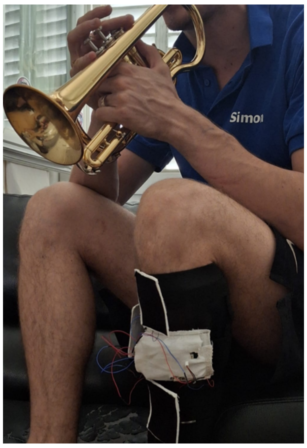

Figure 8.20: Picture of Trumpet playing while wearing leg sleeves

This photo shows a musician playing the trumpet while wearing the leg sleeves. Like the arm sleeves, the leg sleeves caused virtually no disruption or limitation of movement, allowing the musician to perform comfortably and with ease. The sleeve fit snugly without restricting mobility, and its presence was barely noticeable during playing.

8.3.5 Harp

Figure 8.21: Picture of Harp playing while wearing arm sleeves

This photo captures a musician playing the harp while wearing the arm sleeves. The players stressed that performing with the sleeves on is completely feasible and does not prevent playing. However, the snug fit around the arm remains noticeably distracting and can still impose a slight limitation on the player's range of motion — particularly at the elbow joint, where freedom of movement is most affected.

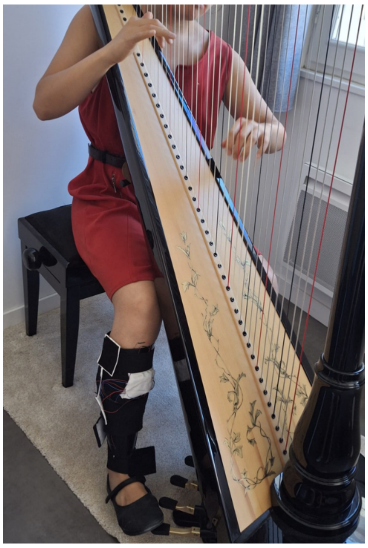

Figure 8.22: Picture of Harp playing while wearing leg sleeves

This photo shows the musician playing the harp while wearing the leg sleeves. In contrast to the arm sleeves, the leg sleeves caused almost no disturbance or restriction of movement. The only minor drawback noted was a slight limitation of ankle movement when operating the pedals for alterations; however, since this action is not constant during performance, the disturbance was much less significant than with the arm sleeves.

8.3.6 Trombone

Figure 8.23: Picture of Trombone playing while wearing arm sleeves

This photo captures a musician playing the trombone while wearing the arm sleeves. The players emphasized that performing with the sleeves on is entirely feasible and does not interfere with playing. Since the sleeve is worn on the arm, which remains relatively stationary during performance, any minor restriction is generally not problematic.

Figure 8.24: Picture of Trombone playing while wearing leg sleeves

This photo shows the musician playing the trombone while wearing the leg sleeves. Similar to the arm sleeves, the leg sleeves caused almost no disruption or limitation of movement, enabling the musician to perform with ease and comfort.

8.3.7 Overall result

Across all tested instruments, musicians confirmed that playing with the arm sleeves is feasible. However, the sleeves generally introduce some degree of restriction or distraction, particularly around joints such as the wrist or elbow, and may cause discomfort if worn too tightly or for extended periods. In contrast, the leg sleeves caused almost no disturbance during performance. Since the legs are less involved in playing most instruments, the leg sleeves were reported as comfortable and often barely noticeable, with only minor limitations when using pedals (e.g., on piano or harp). Overall, leg sleeves proved significantly less intrusive than arm sleeves.

Chapter 9

Conclusion

9.1 Recap of the result

This thesis presented the design, development, and preliminary evaluation of an enhanced haptic feedback system intended to convey the gestures of an orchestra conductor to blind and visually impaired musicians. At its core, the project demonstrated the feasibility of translating conductor cues (traditionally conveyed visually) into tactile signals that can be felt directly on the body.

Two wearable prototypes were developed in the form of sleeves: one designed for the arm and the other for the leg. These two form factors were deliberately chosen to respect the specific ergonomic requirements of musicians and the diverse body postures demanded by different instruments. By offering this flexibility in placement, the system demonstrated adaptability to a wide range of orchestral contexts without compromising freedom of movement or introducing excessive bulk.

Technical evaluation revealed that the system achieves a low average latency of approximately 150 ms between the transmission of a command and the corresponding vibration response. Importantly, this delay represents only a fraction of the overall latency, the majority of which originates from the gesture detection process rather than from signal transmission itself. This level of performance is sufficient for maintaining synchronization in live or virtual orchestral settings, making the prototype a promising starting point for real-world application. Autonomy was achieved by integrating a rechargeable battery, and wireless Bluetooth communication eliminated the need for disruptive cables, granting performers greater mobility on stage.

User testing confirmed that the concept is both usable and understandable: musicians were able to correctly interpret the haptic cues and associate them with conductor gestures. Although results varied depending on motor positioning and sleeve tightness, these experiments validated the effectiveness of haptic feedback as a medium for musical communication.

Importantly, the Random Forest–based gesture recognition system reached an accuracy of 91%, proving to be a robust solution for classifying a set of conducting movements.

In short, the project successfully demonstrated a proof of concept that unites virtual reality, machine learning, and wearable haptics to address an urgent accessibility gap in orchestral practice.

9.2 Future work

While the outcomes of this thesis are encouraging, they represent the first step in a much broader journey. Several areas for improvement and expansion were identified:

- **Gesture Recognition and Real-Time Operation**: Current approaches rely on sliding-window analysis of prerecorded datasets, but future systems should support real-time gesture detection with predictive anticipation of gesture completion, minimizing perceived latency and enabling seamless interaction.

- **Wearable Design and Comfort**: The neoprene-based prototypes, though functional, revealed limitations in durability and comfort. Future iterations should adopt more resilient multi-layer materials, possibly combining neoprene with softer linings to reduce skin irritation. Integrating the motors directly under the fabric, or exploring segmented sleeve designs, would improve stability, adaptability to different body types, and tactile clarity. Exploring alternative actuation methods, such as signals shaped to minimize propagation across the skin, could further enhance the precision of feedback.

- **Haptic Language of Conducting**: This thesis established only a foundational vibration-to-gesture mapping. The ultimate goal should be to develop a rich, standardized "haptic language" capable of translating the full spectrum of conducting gestures—including pulse, tempo changes, dynamics, entrances, phrasing, and expressive intent. Such a comprehensive library would enable blind and visually impaired musicians to experience the complete communicative power of conducting.

- **Broader Validation**: While the system was tested on a small group of users, larger-scale evaluations with professional musicians and diverse orchestral ensembles would provide more representative insights into usability, performance, and acceptance.

By addressing these challenges, the prototype can evolve from a promising concept into a fully integrated tool that enhances accessibility in both live and virtual orchestras.

9.3 Final remarks

Conducting can be understood as a gesture-driven form of musical communication that coordinates and connects an ensemble. Yet, for blind and visually impaired musicians, this essential channel of communication has long remained inaccessible. This thesis showed that with creativity, interdisciplinary methods, and the thoughtful application of technology, it is possible to reimagine this tradition and make it more inclusive.

What began as a modest proof of concept (two sleeves powered by simple vibration motors) has the potential to grow into a transformative tool for orchestral culture. Beyond its immediate application in music, this research highlights the broader possibilities of haptic technology: translating visual communication into tactile language, bridging accessibility gaps, and creating new forms of multimodal interaction in virtual environments.

In conclusion, this work demonstrates not only the technical feasibility of conveying conductor gestures through haptic feedback but also the cultural and social importance of doing so. It opens the door to orchestras where blind and sighted musicians can stand side by side, following the same gestures, sharing the same pulse, and contributing equally to the creation of music.

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Appendix

Participant	Age	Musical Background	Part 1-1	Part 1-2	Part 1-3	Part 1-4	Part 1-5	Part 1-6	Part 1-7	Part 1-8	Part 1-9	Part 1-10
P1	63.0	No	1	2	2	2	2	Both	1	2	Both	1
P2	28.0	No	Both	Both	1	2	1	Both	2	1	Both	1
P3	17.0	No	2	1	2	2	1	Both	1	2	Both	1
P4	28.0	Yes	1	2	Both	2	1	Both	1	2	Both	2
P5	39.0	Yes	2	2	2	Both	1	Both	1	Both	Both	2
P6	28.0	Yes	1	2	Both	2	1	2	1	2	Both	1
P7	26.0	No	2	1	Both	Both	1	Both	1	Both	2	Both
P8	27.0	Yes	2	2	Both	2	1	Both	1	2	Both	2
P9	82.0	No	1	2	Both	2	1	2	Both	2	1	Both
P10	84.0	No	2	Both	1	2	1	2	Both	2	2	Both
P11	58.0	No	2	2	1	Both	2	1	1	1	2	1
P12	23.0	No	1	2	Both	Both	1	Both	2	2	Both	1
P13	23.0	Yes	1	2	Both	2	1	Both	1	2	Both	1
P14	23.0	No	1	2	Both	1	Both	Both	1	2	Both	1
P15	53.0	No	Both	2	Both	2	1	Both	1	2	Both	1
Good answer	nan	nan	1	2	Both	2	1	Both	1	2	Both	1

Participant	Age	Msical Background	Part 1-11	Part 1-12	Part 1-13	Part 1-14	Part 1-15	Part 1-16	Part 1-17	Part 1-18	Part 1-19	Part 1-20
P1	63.0	No	1	Both	Both	1	2	2	Both	1	1	2
P2	28.0	No	1	2	Both	1	Both	2	Both	1	1	2
P3	17.0	No	2	1	Both	1	2	Both	Both	1	Both	Both
P4	28.0	Yes	2	1	Both	1	2	2	Both	1	1	Both
P5	39.0	Yes	2	2	Both	1	2	Both	Both	1	1	2
P6	28.0	Yes	2	1	2	1	2	Both	Both	1	1	2
P7	26.0	No	1	2	Both	1	1	Both	1	1	1	Both
P8	27.0	Yes	2	1	2	1	2	2	Both	1	1	Both
P9	82.0	No	2	1	Both	2	2	2	2	Both	1	2
P10	84.0	No	2	Both	1	2	Both	1	1	1	2	Both
P11	58.0	No	2	Both	2	2	2	2	2	2	1	2
P12	23.0	No	2	1	Both	2	2	2	Both	1	1	2
P13	23.0	Yes	2	1	Both	1	2	Both	2	2	1	2
P14	23.0	No	2	1	Both	1	2	2	Both	1	1	2
P15	53.0	No	2	1	Both	1	2	2	Both	1	1	2
Good answer	nan	nan	2	1	Both	1	2	2	Both	1	1	2

Participant	Age	Msical Background	Part 1-21	Part 1-22	Part 1-23	Part 1-24	Part 1-25	Part 1-26	Part 1-27	Part 1-28	Part 1-29	Part 1-30
P1	63.0	No	2	2	1	2	2	2	2	2	2	1
P2	28.0	No	Both	2	1	Both	2	1	Both	Both	2	Both
P3	17.0	No	Both	2	1	Both	2	1	Both	Both	2	1
P4	28.0	Yes	2	2	1	Both	Both	1	2	Both	2	1
P5	39.0	Yes	Both	2	1	Both	2	1	2	Both	2	1
P6	28.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P7	26.0	No	2	2	1	Both	2	1	1	Both	Both	Both
P8	27.0	Yes	2	2	1	1	1	Both	1	Both	2	1
P9	82.0	No	2	1	Both	1	2	1	1	2	1	Both
P10	84.0	No	2	2	Both	Both	2	Both	1	Both	2	1
P11	58.0	No	Both	2	Both	Both	2	Both	2	Both	2	2
P12	23.0	No	Both	2	1	1	2	1	1	Both	2	1
P13	23.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P14	23.0	No	Both	2	1	Both	2	1	2	Both	2	1
P15	53.0	No	Both	2	1	Both	2	1	1	Both	2	2
Good answer	nan	nan	Both	2	1	Both	2	1	1	Both	2	1

Participant	Age	Msical Background	Part 1-31	Part 1-32	Part 1-33	Part 1-34	Part 1-35	Part 1-36	Part 1-37	Part 1-38	Part 1-39	Part 1-40
P1	63.0	No	2	2	1	2	2.0	Both	1	1	2	1
P2	28.0	No	2	1	Both	1	1.0	2	1	1	Both	2
P3	17.0	No	1	1	2	Both	2.0	1	2	Both	2	1
P4	28.0	Yes	1	2	Both	Both	1.0	Both	2	2	Both	1
P5	39.0	Yes	2	1	Both	1	2.0	Both	Both	1	2	1
P6	28.0	Yes	1	2	Both	2	2.0	Both	1	2	Both	1
P7	26.0	No	1	2	2	2	1.0	2	2	Both	2	Both
P8	27.0	Yes	1	1	Both	2	1.0	Both	2	2	Both	1
P9	82.0	No	2	2	2	1	nan	1	1	2	Both	1
P10	84.0	No	1	2	Both	2	1.0	Both	2	1	2	2
P11	58.0	No	2	2	2	2	1.0	2	1	2	2	2
P12	23.0	No	2	1	Both	1	1.0	Both	1	1	Both	1
P13	23.0	Yes	1	2	Both	Both	1.0	Both	1	2	Both	2
P14	23.0	No	1	2	2	2	1.0	2	1	2	Both	1
P15	53.0	No	1	2	Both	2	1.0	Both	1	2	Both	1
Good answer	nan	nan	1	2	Both	2	1.0	Both	1	2	Both	1

Participant	Age	Msical Background	Part 1-41	Part 1-42	Part 1-43	Part 1-44	Part 1-45	Part 1-46	Part 1-47	Part 1-48	Part 1-49	Part 1-50
P1	63.0	No	2	2	Both	1	1	2	Both	Both	1	1
P2	28.0	No	Both	1	Both	2	1	Both	Both	1	2	1
P3	17.0	No	2	1	Both	2	2	2	Both	1	1	2
P4	28.0	Yes	2	1	Both	1	2	2	Both	2	1	2
P5	39.0	Yes	2	1	Both	2	1	2	Both	2	1	2
P6	28.0	Yes	2	1	Both	1	2	2	Both	1	1	2
P7	26.0	No	Both	1	1	1	2	2	2	2	1	Both
P8	27.0	Yes	2	1	Both	1	2	1	Both	2	1	1
P9	82.0	No	1	2	2	2	Both	1	Both	1	Both	Both
P10	84.0	No	2	1	Both	1	Both	2	1	Both	2	1
P11	58.0	No	2	Both	Both	Both	2	2	2	2	Both	Both
P12	23.0	No	2	2	Both	1	1	1	Both	1	2	1
P13	23.0	Yes	2	1	Both	1	2	2	Both	1	1	Both
P14	23.0	No	2	1	Both	1	2	2	Both	1	1	2
P15	53.0	No	2	1	Both	1	2	2	Both	1	1	2
Good answer	nan	nan	2	1	Both	1	2	2	Both	1	1	2

Participant	Age	Msical Background	Part 1-51	Part 1-52	Part 1-53	Part 1-54	Part 1-55	Part 1-56	Part 1-57	Part 1-58	Part 1-59	Part 1-60
P1	63.0	No	Both	2	1	Both	1	2	2	2	1	2
P2	28.0	No	2	2	Both	Both	2	1	Both	Both	2	1
P3	17.0	No	Both	2	1	Both	2	1	1	Both	2	1
P4	28.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P5	39.0	Yes	1	2	1	Both	2	Both	1	Both	2	1
P6	28.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P7	26.0	No	1	2	Both	2	2	1	Both	Both	1	1
P8	27.0	Yes	2	1	2	Both	2	1	Both	2	2	1
P9	82.0	No	2	2	Both	Both	2	Both	2	2	Both	Both
P10	84.0	No	1	2	Both	Both	2	1	Both	Both	2	Both
P11	58.0	No	Both	2	Both	Both	2	2	2	Both	2	Both
P12	23.0	No	Both	2	1	Both	2	1	1	Both	2	1
P13	23.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P14	23.0	No	Both	2	1	Both	2	1	1	Both	2	1
P15	53.0	No	Both	2	1	Both	2	1	1	Both	2	1
Good answer	nan	nan	Both	2	1	Both	2	1	1	Both	2	1

Participant	Age	Msical Background	Part 1-61	Part 1-62	Part 1-63	Part 1-64	Part 1-65	Part 1-66	Part 1-67	Part 1-68	Part 1-69	Part 1-70
P1	63.0	No	2	1	2	2	2	2	1	Both	2	2
P2	28.0	No	1	2	Both	Both	Both	Both	1	2	Both	2
P3	17.0	No	Both	2	Both	2	1	Both	1	2	Both	1
P4	28.0	Yes	1	2	2	1	Both	2	1	2	Both	1
P5	39.0	Yes	1	2	Both	2	Both	2	1	2	Both	1
P6	28.0	Yes	1	2	Both	2	1	Both	Both	2	Both	1
P7	26.0	No	1	2	1	2	1	2	Both	2	2	1
P8	27.0	Yes	1	2	Both	2	1	Both	1	2	Both	1
P9	82.0	No	2	1	2	2	Both	Both	1	Both	2	1
P10	84.0	No	2	1	Both	2	1	2	1	Both	2	1
P11	58.0	No	2	1	2	Both	2	2	Both	2	2	2
P12	23.0	No	1	2	1	2	Both	1	2	2	2	2
P13	23.0	Yes	1	2	1	Both	1	Both	Both	2	1	2
P14	23.0	No	1	2	Both	2	1	Both	Both	2	Both	1
P15	53.0	No	1	2	Both	2	1	Both	2	1	2	2
Good answer	nan	nan	1	2	Both	2	1	Both	1	2	Both	1

Participant	Age	Msical Background	Part 1-71	Part 1-72	Part 1-73	Part 1-74	Part 1-75	Part 1-76	Part 1-77	Part 1-78	Part 1-79	Part 1-80
P1	63.0	No	2	2	1	1	1	2	2	2	1	2
P2	28.0	No	2	2	Both	Both	2	Both	Both	1	1	2
P3	17.0	No	2	Both	Both	Both	2	2	Both	1	Both	2
P4	28.0	Yes	1	2	Both	2	1	2	Both	1	1	2
P5	39.0	Yes	2	Both	Both	2	1	2	Both	1	2	2
P6	28.0	Yes	2	1	Both	1	2	2	1	1	1	2
P7	26.0	No	2	2	2	1	2	2	1	1	Both	2
P8	27.0	Yes	2	1	2	1	2	2	Both	1	1	2
P9	82.0	No	2	1	2	2	Both	Both	2	2	1	Both
P10	84.0	No	2	1	1	2	1	2	Both	1	Both	Both
P11	58.0	No	2	Both	Both	2	2	2	1	Both	Both	2
P12	23.0	No	2	Both	1	2	2	2	Both	1	1	Both
P13	23.0	Yes	2	1	Both	1	2	2	Both	1	1	2
P14	23.0	No	2	Both	Both	Both	2	2	Both	Both	Both	2
P15	53.0	No	2	1	Both	1	2	2	Both	1	2	1
Good answer	nan	nan	2	1	Both	1	2	2	Both	1	1	2

Participant	Age	Msical Background	Part 1-81	Part 1-82	Part 1-83	Part 1-84	Part 1-85	Part 1-86	Part 1-87	Part 1-88	Part 1-89	Part 1-90
P1	63.0	No	Both	1	1	2	2	2	1	Both	2	1
P2	28.0	No	Both	2	1	Both	2	1	1	2	Both	1
P3	17.0	No	Both	2	Both	Both	2	Both	2	Both	2	1
P4	28.0	Yes	Both	2	1	Both	2	1	2	Both	2	2
P5	39.0	Yes	2	2	1	Both	2	1	1	Both	2	1
P6	28.0	Yes	Both	2	1	Both	2	1	1	1	2	1
P7	26.0	No	1	2	1	1	2	1	1	Both	2	1
P8	27.0	Yes	2	2	1	Both	Both	2	1	Both	2	1
P9	82.0	No	1	2	1	2	Both	1	1	Both	Both	Both
P10	84.0	No	2	2	1	Both	2	Both	1	2	2	1
P11	58.0	No	2	Both	Both	2	2	Both	2	Both	1	2
P12	23.0	No	Both	2	2	Both	2	1	1	Both	2	2
P13	23.0	Yes	Both	2	1	Both	2	1	1	Both	2	1
P14	23.0	No	Both	2	1	Both	2	1	1	Both	2	1
P15	53.0	No	Both	2	1	Both	2	1	2	Both	2	2
Good answer	nan	nan	Both	2	1	Both	2	1	1	Both	2	1

Participant	Age	Msical Background	Part 2-1	Part 2-2	Part 2-3	Part 2-4	Part 2-5	Part 2-6	Part 2-7	Part 2-8	Part 2-9	Part 2-10
P1	63.0	No	Medium	Light	Light	Strong	Light	Medium	Medium	Light	Strong	Light
P2	28.0	No	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light
P3	17.0	No	Strong	Medium	Light	Medium	Light	Strong	Strong	Medium	Strong	Light
P4	28.0	Yes	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light
P5	39.0	Yes	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light
P6	28.0	Yes	Strong	Strong	Medium	Strong	Light	Medium	Strong	Medium	Medium	Light
P7	26.0	No	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Medium
P8	27.0	Yes	Medium	Strong	Medium	Strong	Light	Strong	Strong	Light	Strong	Light
P9	82.0	No	Light	Medium	Light	Medium	Light	Medium	Medium	Medium	Medium	Light
P10	84.0	No	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light
P11	58.0	No	Medium	Strong	Light	Strong	Light	Light	Medium	Light	Strong	Light
P12	23.0	No	Medium	Strong	Light	Strong	Light	Strong	Strong	Medium	Strong	Light
P13	23.0	Yes	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Light	Strong
P14	23.0	No	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light
P15	53.0	No	Strong	Strong	Light	Strong	Light	Strong	Strong	Light	Strong	Light
Good answer	nan	nan	Strong	Strong	Medium	Strong	Light	Strong	Strong	Medium	Strong	Light

Participant	Age	Msical Background	Part 2-11	Part 2-12	Part 2-13	Part 2-14	Part 2-15	Part 2-16	Part 2-17	Part 2-18	Part 2-19	Part 2-20
P1	63.0	No	Strong	Medium	Strong	Strong	Light	Medium	Strong	Medium	Medium	Strong
P2	28.0	No	Strong	Medium	Strong	Medium	Light	Medium	Strong	Strong	Medium	Strong
P3	17.0	No	Strong	Medium	Strong	Strong	Light	Strong	Strong	Strong	Medium	Strong
P4	28.0	Yes	Strong	Medium	Strong	Strong	Light	Medium	Medium	Strong	Medium	Strong
P5	39.0	Yes	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
P6	28.0	Yes	Strong	Light	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
P7	26.0	No	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
P8	27.0	Yes	Medium	Medium	Strong	Medium	Light	Medium	Medium	Strong	Medium	Medium
P9	82.0	No	Light	Light	Medium	Medium	Light	Light	Strong	Medium	Medium	Strong
P10	84.0	No	Strong	Medium	Strong	Medium	Light	Medium	Strong	Medium	Light	Medium
P11	58.0	No	Medium	Light	Strong	Medium	Light	Medium	Strong	Strong	Light	Strong
P12	23.0	No	Medium	Light	Strong	Strong	Light	Medium	Strong	Strong	Medium	Medium
P13	23.0	Yes	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
P14	23.0	No	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
P15	53.0	No	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong
Good answer	nan	nan	Strong	Medium	Strong	Strong	Light	Medium	Strong	Strong	Medium	Strong

Participant	Age	Msical Background	Part 2-21	Part 2-22	Part 2-23	Part 2-24	Part 2-25	Part 2-26	Part 2-27	Part 2-28	Part 2-29	Part 2-30
P1	63.0	No	Medium	Medium	Light	Medium	Medium	Light	Medium	Light	Medium	Medium
P2	28.0	No	Strong	Strong	Light	Medium	Strong	Light	Strong	Light	Medium	Strong
P3	17.0	No	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong
P4	28.0	Yes	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong
P5	39.0	Yes	Medium	Strong	Medium	Light	Medium	Light	Strong	Medium	Medium	Strong
P6	28.0	Yes	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong
P7	26.0	No	Medium	Strong	Light	Medium	Light	Light	Strong	Light	Medium	Strong
P8	27.0	Yes	Medium	Medium	Light	Medium	Light	Medium	Strong	Medium	Medium	Strong
P9	82.0	No	Medium	Strong	Light	Medium	Strong	Medium	Strong	Light	Medium	Medium
P10	84.0	No	Medium	Strong	Light	Medium	Medium	Medium	Strong	Light	Medium	Strong
P11	58.0	No	Light	Strong	Light	Medium	Light	Light	Strong	Light	Strong	Strong
P12	23.0	No	Medium	Strong	Light	Light	Medium	Light	Strong	Light	Medium	Strong
P13	23.0	Yes	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong
P14	23.0	No	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong
P15	53.0	No	Medium	Medium	Light	Light	Medium	Light	Medium	Light	Medium	Strong
Good answer	nan	nan	Medium	Strong	Light	Medium	Medium	Light	Strong	Light	Medium	Strong

Participant	Age	Msical Background	Part 3-1	Part 3-2	Part 3-3	Part 3-4	Part 3-5	Part 3-6	Part 3-7	Part 3-8	Part 3-9	Part 3-10
P1	63.0	No	2 Medium	1->2 Medium	1 Strong	2 Light	2 Medium	1 Light	2->1 Strong	2 Strong	2 Strong	1 Medium
P2	28.0	No	1 Medium	2->1 Medium	1 Strong	2 Light	Both Light	1 Light	2->1 Strong	Both Strong	2 Strong	1 Strong
P3	17.0	No	2 Medium	1->2 Medium	2 Strong	2 Medium	2 Medium	2 Light	2->1 Medium	2 Strong	2 Strong	Both Strong
P4	28.0	Yes	2 Light	1->2 Medium	2 Medium	Both Light	2 Strong	2 Light	2->1 Strong	2 Strong	2 Strong	Both Medium
P5	39.0	Yes	2 Medium	1->2 Medium	1 Strong	2 Medium	2 Strong	2 Light	2->1 Strong	Both Medium	2 Strong	1 Strong
P6	28.0	Yes	2 Medium	1->2 Medium	Both Medium	2 Light	2 Medium	2 Light	2->1 Strong	Both Medium	2 Strong	Both Medium
P7	26.0	No	1 Medium	2->1 Medium	2 Medium	2 Medium	2 Medium	1 Light	2->1 Strong	2 Medium	2 Strong	Both Medium
P8	27.0	Yes	2 Light	1->2 Medium	1 Medium	Both Light	2 Medium	1 Medium	2->1 Medium	Both Strong	2 Medium	Both Strong
P9	82.0	No	1 Light	Both Medium	Both Strong	1 Medium	2 Medium	1 Light	Both Strong	2 Strong	2 Strong	1 Strong
P10	84.0	No	2 Light	1->2 Medium	2 Strong	1 Medium	2 Medium	2 Medium	1->2 Strong	2 Strong	2 Medium	2 Strong
P11	58.0	No	2 Light	1->2 Light	1 Medium	1 Light	1 Medium	2 Light	2->1 Medium	2 Strong	2 Strong	1 Strong
P12	23.0	No	2 Light	1->2 Medium	1 Strong	Both Medium	2 Medium	1 Light	2->1 Strong	Both Strong	2 Strong	1 Medium
P13	23.0	Yes	2 Medium	1->2 Medium	1 Strong	Both Medium	2 Light	1 Light	2->1 Medium	Both Medium	2 Strong	1 Strong
P14	23.0	No	2 Light	1->2 Medium	1 Strong	2 Light	2 Medium	1 Light	2->1 Strong	Both Medium	2 Medium	1 Medium
P15	53.0	No	2 Light	1->2 Medium	1 Strong	1 Light	2 Medium	1 Light	2->1 Strong	Both Strong	2 Strong	1 Strong
Good answer	nan	nan	2 Light	1->2 Medium	1 Strong	Both Light	2 Medium	1 Light	2->1 Strong	Both Medium	2 Strong	1 Strong

Participant	Age	Msical Background	Part 3-11	Part 3-12	Part 3-13	Part 3-14	Part 3-15	Part 3-16	Part 3-17	Part 3-18	Part 3-19	Part 3-20
P1	63.0	No	1->2 Light	2 Strong	2->1 Medium	2 Medium	1 Medium	2 Medium	2 Strong	2->1 Light	2 Strong	1->2 Light
P2	28.0	No	1->2 Light	Both Strong	2->1 Medium	1 Strong	2 Strong	2 Medium	2 Strong	1->2 Light	1 Medium	1->2 Medium
P3	17.0	No	1->2 Light	1 Strong	2->1 Light	2 Medium	2 Medium	2 Strong	2 Strong	1->2 Medium	1 Strong	2->1 Medium
P4	28.0	Yes	1->2 Light	Both Strong	2->1 Light	Both Medium	2 Medium	1 Medium	Both Medium	2->1 Light	1 Medium	1->2 Medium
P5	39.0	Yes	1->2 Light	2 Strong	2 Light	1 Strong	2 Strong	2 Medium	Both Strong	2->1 Light	1 Strong	1->2 Medium
P6	28.0	Yes	1->2 Light	Both Strong	2->1 Light	1 Medium	Both Medium	2 Medium	Both Medium	1->2 Light	1 Medium	2->1 Medium
P7	26.0	No	2->1 Light	1->2 Strong	1->2 Medium	1 Strong	2 Strong	Both Light	Both Medium	2->1 Light	Both Strong	2->1 Medium
P8	27.0	Yes	1->2 Light	2 Strong	1->2 Light	1 Medium	2 Medium	2 Medium	Both Light	1 Light	1 Strong	1->2 Medium
P9	82.0	No	1->2 Light	2 Strong	1 Light	2 Medium	1 Light	1 Medium	2 Medium	2 Light	2 Medium	2 Strong
P10	84.0	No	2->1 Light	2 Strong	1 Medium	2 Strong	1 Medium	2 Light	Both Strong	2->1 Light	1 Strong	2->1 Medium
P11	58.0	No	1->2 Light	1 Strong	2->1 Light	1 Strong	1 Strong	2 Medium	Both Strong	Both Light	1 Medium	2->1 Light
P12	23.0	No	1->2 Light	Both Strong	2->1 Light	1 Strong	2 Medium	2 Light	Both Medium	1->2 Light	1 Medium	2->1 Medium
P13	23.0	Yes	1->2 Light	Both Strong	2->1 Light	1 Medium	2 Medium	2 Medium	Both Medium	1->2 Light	1 Medium	2->1 Medium
P14	23.0	No	1->2 Light	1 Strong	2->1 Light	1 Strong	2 Medium	2 Medium	2 Medium	1->2 Light	1 Strong	2->1 Medium
P15	53.0	No	1->2 Light	Both Strong	2->1 Light	1 Strong	2 Medium	2 Medium	Both Strong	1->2 Light	1 Medium	2->1 Medium
Good answer	nan	nan	1->2 Light	Both Strong	2->1 Light	1 Strong	2 Medium	2 Medium	Both Strong	1->2 Light	1 Strong	2->1 Medium

Participant	Age	Msical Background	Part 3-21	Part 3-22	Part 3-23	Part 3-24	Part 3-25	Part 3-26	Part 3-27	Part 3-28	Part 3-29	Part 3-30
P1	63.0	No	1 Light	2->1 Strong	2 Medium	2 Medium	2->1 Medium	2 Light	1 Light	Both Medium	2->1 Medium	1->2 Light
P2	28.0	No	Both Medium	1->2 Strong	1 Medium	1 Medium	2->1 Strong	Both Medium	1 Light	Both Strong	1->2 Strong	1->2 Light
P3	17.0	No	2 Medium	1->2 Strong	1 Strong	2->1 Medium	2->1 Strong	2 Strong	2 Light	2 Medium	1->2 Medium	2->1 Light
P4	28.0	Yes	Both Light	2->1 Strong	1 Medium	1 Light	2->1 Strong	2 Medium	nan	Both Medium	1->2 Medium	1->2 Light
P5	39.0	Yes	1 Light	1->2 Strong	2 Medium	1 Medium	2->1 Strong	2 Medium	1 Medium	Both Medium	1->2 Light	1 Light
P6	28.0	Yes	Both Light	1->2 Strong	1 Medium	1 Light	2->1 Medium	Both Medium	1 Light	Both Medium	1->2 Medium	2->1 Light
P7	26.0	No	1 Light	1->2 Strong	1 Strong	1->2 Medium	2->1 Strong	2 Medium	2 Light	1->2 Light	1->2 Medium	1->2 Light
P8	27.0	Yes	1 Light	1->2 Strong	1 Medium	2 Light	2->1 Medium	2 Medium	2 Light	Both Medium	1->2 Medium	1->2 Light
P9	82.0	No	1 Light	2 Strong	2 Strong	2->1 Light	2 Strong	1 Medium	1 Light	Both Strong	Both Light	2 Light
P10	84.0	No	2 Light	1->2 Medium	1 Medium	1 Light	2->1 Medium	2 Light	1 Light	Both Medium	1->2 Medium	2 Light
P11	58.0	No	2 Light	2->1 Medium	2 Light	1 Light	1->2 Medium	2 Medium	2 Light	2 Strong	2->1 Medium	1->2 Light
P12	23.0	No	2 Light	1->2 Strong	1 Medium	Both Medium	2->1 Strong	2 Medium	1 Light	Both Medium	1->2 Medium	2->1 Light
P13	23.0	Yes	2 Light	1->2 Strong	1 Medium	Both Light	2->1 Strong	2 Medium	1 Light	Both Medium	1->2 Strong	2->1 Light
P14	23.0	No	2 Light	1->2 Strong	1 Medium	2 Light	2->1 Strong	2 Medium	2 Light	1 Medium	1->2 Medium	2->1 Light
P15	53.0	No	2 Light	1->2 Strong	1 Medium	Both Medium	2->1 Strong	2 Medium	1 Light	Both Light	1->2 Light	2->1 Light
Good answer	nan	nan	2 Light	1->2 Strong	1 Medium	Both Light	2->1 Strong	2 Medium	1 Light	Both Medium	1->2 Medium	2->1 Light

Participant	Age	Msical Background	Part 4-1	Part 4-2	Part 4-3	Part 4-4	Part 4-5	Part 4-6	Part 4-7	Part 4-8	Part 4-9	Part 4-10
P1	63.0	No	Point	Start	Start	Pulse	Stop	Increase	Stop	Start	Start	Pulse
P2	28.0	No	Point	Start	Stop	Pulse	Stop	Increase	Start	Pulse	Start	Pulse
P3	17.0	No	Point	Decrease	Pulse	Pulse	Start	Increase	Start	Pulse	Increase	Pulse
P4	28.0	Yes	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Start	Start	Pulse
P5	39.0	Yes	Point	Decrease	Start	Increase	Stop	Increase	Stop	Decrease	Stop	Pulse
P6	28.0	Yes	Point	Start	Start	Pulse	Stop	Start	Stop	Start	Start	Pulse
P7	26.0	No	Point	Decrease	Stop	Pulse	Start	Start	Stop	Increase	Decrease	Increase
P8	27.0	Yes	Point	Decrease	Start	Pulse	Stop	Start	Stop	Decrease	Start	Pulse
P9	82.0	No	Point	Decrease	Start	Pulse	Stop	Start	Stop	Stop	Start	Pulse
P10	84.0	No	Point	Pulse	Decrease	Pulse	Increase	Decrease	Stop	Pulse	Increase	Pulse
P11	58.0	No	Point	Decrease	Start	Pulse	Stop	Decrease	Start	Decrease	Decrease	Pulse
P12	23.0	No	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Decrease	Start	Pulse
P13	23.0	Yes	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Increase	Start	Pulse
P14	23.0	No	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Decrease	Start	Pulse
P15	53.0	No	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Decrease	Start	Pulse
Good answer	nan	nan	Point	Decrease	Start	Pulse	Stop	Increase	Stop	Decrease	Start	Pulse

Participant	Age	Msical Background	Part 4-11	Part 4-12	Part 4-13	Part 4-14	Part 4-15	Part 4-16	Part 4-17	Part 4-18
P1	63.0	No	Increase	Point	Start	Start	Stop	Point	Stop	Increase
P2	28.0	No	Increase	Point	Start	Start	Stop	Point	Increase	Pulse
P3	17.0	No	Increase	Point	Decrease	Decrease	Stop	Point	Increase	Pulse
P4	28.0	Yes	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P5	39.0	Yes	Start	Point	Stop	Start	Stop	Point	Start	Increase
P6	28.0	Yes	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P7	26.0	No	Decrease	Point	Increase	Decrease	Increase	Point	Decrease	Pulse
P8	27.0	Yes	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P9	82.0	No	Stop	Point	Decrease	Increase	Point	Stop	Increase	Decrease
P10	84.0	No	Increase	Point	Pulse	Decrease	Stop	Point	Increase	Pulse
P11	58.0	No	Increase	Point	Decrease	Increase	Stop	Point	Decrease	Pulse
P12	23.0	No	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P13	23.0	Yes	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P14	23.0	No	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse
P15	53.0	No	Stop	Point	Decrease	Start	Stop	Point	Stop	Pulse
Good answer	nan	nan	Increase	Point	Decrease	Start	Stop	Point	Increase	Pulse