

Feeling the Sound: A Survey of Haptic Digital Musical Instruments

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Abstract

Haptic feedback connects a digital musical instrument's interface to its sound and behavior. This systematic literature review examines feedback selection for digital musical instruments (DMIs), how technical implementation shapes musical mappings, and methods for evaluating subjective playing experience.

We searched the ACM Digital Library and NIME proceedings on 7 July 2026, and OpenAlex on 16 July 2026. Backward and forward citation searches also took place on 16 July. Publications qualified through active DMI haptics or actionable perceptual or design evidence. Immersive environments, applications outside the musical scope, and course materials were excluded. Narrative synthesis compared 109 reports, including technical measurements, player studies, system descriptions, and reviews.

Detents improved pitch accuracy compared with no active force feedback in a rotary-knob task. Sound-related vibration improved rated expression and enjoyment on a touch surface; benefits on an electric cello remained uncertain. Technical constraints prompted changes to sensing and feedback signals. Ratings, interviews, and extended use addressed different aspects of experience. Preference and measured performance sometimes differed.

Differences in instruments, tasks, and samples limit transfer. The evidence does not establish when active force feedback is preferable to vibration on a comparable instrument. One reviewer made the selection decisions; no formal risk-of-bias assessment was performed. The guidance requires testing in new settings. The review received no funding and was not registered.

Überblick

Haptisches Feedback verbindet die Schnittstelle eines digitalen Musikinstruments mit dessen Klang und Verhalten. Diese systematische Literaturübersicht untersucht die Feedbackwahl für digitale Musikinstrumente (DMIs), den Einfluss der technischen Umsetzung auf musikalische Mappings und Methoden zur Erfassung des subjektiven Spielerlebnisses.

Am 7. Juli 2026 haben wir die ACM Digital Library und die NIME-Proceedings durchsucht, am 16. Juli 2026 OpenAlex. Die Rückwärts- und Vorwärtssuche über Referenzen erfolgte ebenfalls am 16. Juli. Publikationen qualifizierten sich durch aktive DMI-Haptik oder konkrete Wahrnehmungs- oder Gestaltungserkenntnisse. Ausgeschlossen wurden immersive Umgebungen, Anwendungen außerhalb des musikalischen Untersuchungsrahmens und Lehrmaterialien. Eine narrative Synthese verglich 109 Berichte, darunter technische Messungen, Spielerstudien, Systembeschreibungen und Übersichtsarbeiten.

Rastpunkte verbesserten bei einer Drehregleraufgabe die Tonhöhengenaugigkeit gegenüber fehlendem aktivem Force Feedback. Klanggekoppelte Vibration erhöhte auf einer Touch-Oberfläche die bewertete Expressivität und den Spielspaß; bei einem E-Cello blieb der Nutzen unklar. Technische Grenzen führten zu Anpassungen der Sensorik und Feedbacksignale. Bewertungen, Interviews und längerer Gebrauch erfassten unterschiedliche Aspekte des Spielerlebnisses. Präferenz und gemessene Leistung fielen teilweise auseinander.

Unterschiede zwischen Instrumenten, Aufgaben und Stichproben begrenzen die Übertragbarkeit. Die Befundlage klärt nicht, wann aktives Force Feedback bei einem vergleichbaren Instrument der Vibration vorzuziehen ist. Ein Reviewer traf die Auswahlentscheidungen; eine formale Bewertung des Verzerrungsrisikos erfolgte nicht. Die Empfehlungen müssen in neuen Kontexten geprüft werden. Das Review wurde nicht gefördert und nicht registriert.

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Finally, I would like to thank my family and friends for their support, especially my father, whose nearly weekly calls to ask how my thesis was progressing kept me motivated.

Conventions and Tools

Throughout this thesis we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.

Short excursions and definitions are set off in colored boxes.

EXCURSUS:

Excursions are set off in orange boxes.

Where appropriate, paragraphs are summarized by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

AI tools were used in this thesis for coding and writing support, translation, and grammar.

Chapter 1

Introduction

*“It’s not thrilling to make music by typing lines
of code. Something is missing ...”*

—Claude Cadoz, interviewed by Marcelo M.
Wanderley and Christian Frisson, *Arts* 12(4), 2023

Making music is a physical form of art. A violinist leans into the string, a drummer feels the stick rebound, and a pianist learns the weight of each key. When a musician plays an acoustic instrument, its mechanical response helps shape the movements used to play it [Davison et al., 2026]. The instrument is felt as well as heard. For string players, contact with vibrating strings or the instrument’s body provides tactile information; reed players can feel vibration in the mouth [Marshall and Wanderley, 2006]. These vibrations provide *tactile feedback*: the skin picks them up through contact, and the fingers sense the vibrations [Marshall and Wanderley, 2006]. Drawing on the earlier work of Keele [1973], Marshall and Wanderley [2006] distinguish between beginners’ strong reliance on visual information and the primary role of tactile and kinesthetic feedback in expert performance. Davison and McPherson [2026] describe the physical interaction between musician and instrument as a “bidirectional, reciprocal coupling” that helps shape what the player perceives and does.

Acoustic instruments
provide tactile
feedback.

DMIs can separate the control interface from sound synthesis.

In *digital musical instruments* (DMIs), the control interface can be separated from sound synthesis [Davison and McPherson, 2026]. These two components appear in the definition given by Zheng et al. [2022]:

Definition:
Digital musical instruments

DIGITAL MUSICAL INSTRUMENTS:

"Digital Musical Instruments (DMIs) are musical instruments consisting of a physical interface and computer-based synthesis of sound and other feedback modalities." [Zheng et al., 2022]

Many DMIs follow a model of unidirectional control.

Separating the control interface from sound synthesis allows each to be developed independently [Davison and McPherson, 2026]. In many DMIs, sensor measurements control synthesis parameters, so information flows from the interface to the synthesizer. Davison and McPherson [2026] describe this as "unidirectional control" and warn that the separation may lead to a "loss of intimacy" between musician and instrument. Changing the sound assigned to a pad, for example, need not change how the pad feels when played. Marshall and Wanderley [2006] argue that sound and visual cues alone provide less information about how gestures affect the instrument.

This review considers vibrotactile and force feedback.

This review focuses on two forms of *haptic feedback*: vibrotactile feedback and force feedback. Designers can add a return path for *vibrotactile feedback* through actuators [Davison and McPherson, 2026]. Such a return path can inform the performer about the state of the digital system, or it can simulate the vibrations of a virtual instrument [Davison and McPherson, 2026]. With *force feedback*, actuators can resist the performer's movements: a rotary knob, for example, can oppose the player's turning movement, and a haptic fader can resist the player's sliding [Frisson and Wanderley, 2023]. Both forms raise questions about what the performer should feel and how that feedback should relate to the musical interaction.

Adding haptic feedback involves several design choices.

A designer who wants to add haptic feedback to DMIs faces a series of choices: which actuators to use, which feedback signals to generate, and how the feedback should relate to the sound [Birnbaum, 2007; Marshall and Wander-

ley, 2011]. This last relation is a *mapping*: it specifies how inputs, such as gestures or sound signals, affect outputs [Birnbaum, 2007]. These choices are connected. For reproducing acoustic-instrument vibrations, Marshall and Wanderley [2006] recommend linking vibrotactile feedback to sound production, with control over both vibration amplitude and frequency. Frisson and Wanderley [2023] note that musical applications of force feedback remain less common than those of vibrotactile feedback. They discuss expensive equipment, difficulties with software support, and limited access to tools for building musical prototypes as barriers to wider adoption.

To judge a feedback design, we also need to understand how players experience it. We refer to this as the player's *subjective experience*. Marshall and Wanderley [2011] examined the playing experience using the Viblotar, a DMI with loudspeakers embedded in its body. Five performers played it in two configurations: with external loudspeakers only and with the embedded loudspeakers producing sound and vibrotactile feedback together. Engagement ratings were higher with the embedded configuration, a difference the authors call "marginally significant" ($p = 0.07$) but which does not reach conventional statistical significance of $p < 0.05$. At the same time, controllability ratings were lower, although this difference was not statistically significant either [Marshall and Wanderley, 2011]. Because the embedded loudspeakers also moved the sound source into the instrument, the two configurations differed in more than vibration alone [Marshall and Wanderley, 2011].

Existing guidance addresses the development of force feedback in DMIs [Frisson and Wanderley, 2023] and the design and assessment of vibrotactile musical interfaces [Papetti et al., 2018]. Some guidance addresses specific applications: Giordano et al. [2018], for example, provide guidelines for *tactile icons* that convey musical information through clothing fitted with vibration actuators. In the same review, they also note that only a small number of haptic interfaces for music performance and practice had been evaluated in depth for their effectiveness [Giordano et al., 2018].

This review compares findings across these areas to exam-

Performers rated embedded sound and vibrotactile feedback together.

Existing guidance addresses different parts of the design problem.

We connect feedback selection, mapping, and evaluation to guide DMI design.

ine when they can inform the design of another instrument. We consider how the musical task informs feedback selection and how technical implementation shapes musical mappings. We also consider which evaluation methods address different aspects of the playing experience. The aim is to help designers judge which findings apply to their instrument and where further evaluation is needed.

1.1 Research Questions

A systematic review of
haptic feedback in
DMIs.

We systematically review research on vibrotactile and force feedback, focusing on technical implementations, musical mappings, and methods for assessing subjective experience. We report the review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [Page et al., 2021]. The final corpus contains 109 reports, selected through the process described in Chapter 3. The review addresses the following research questions:

- RQ1* What design guidelines can be derived from the literature for choosing between vibrotactile and force feedback in haptic DMIs?
- RQ2* How does the technical implementation of haptic feedback influence the mapping of musical parameters?
- RQ3* Which evaluation methods are suitable for assessing different aspects of subjective experience in haptic DMIs?

1.2 Outline

Related work, method,
synthesis, and limits.

Chapter 2 positions this work against existing reviews of musical haptics. Chapter 3 describes how we selected the corpus and how we applied the extraction schema. Chapter 4 answers the research questions through a synthesis of

the findings. Finally, Chapter 5 discusses the review's conclusion and limitations. It closes with directions for future research.

Chapter 2

Related Work

This chapter examines how prior work connects physical interaction, haptic mappings, and the evaluation of musical instruments. First, we discuss touch during playing, then the hardware and software built to provide feedback. We examine approaches to evaluation and related musical uses. We also explore the scope of current reviews. This comparison establishes how the present review brings evidence from different instruments and musical tasks together.

2.1 Physical Interaction

An early approach to musical haptics is the CORDIS system developed at ACROE (Association pour la Création et la Recherche sur les Outils d'Expression) by Cadoz et al. [1984]. Their starting point is the mechanism through which a gesture produces sound. They distinguish *excitation gestures*, which supply energy to the mechanism that produces sound, from *modulation gestures*, which change the instrument's physical configuration [Cadoz et al., 1984]. In their violin example, bowing supplies the excitation, while the position of a finger on the string determines pitch [Cadoz et al., 1984]. Their later Modular Feedback Keyboard combined displacement sensing and controlled force

Gesture and simulation
in CORDIS.

in modules that could be configured as different performance interfaces [Cadoz et al., 1990]. The interview with Claude Cadoz by Wanderley and Frisson [2023] connects this early work to later ACROE systems. Cadoz describes the continued development of modeling software and real-time force feedback, including concerts using the *Hélicante* platform, which combines physical modeling, real-time force feedback, and multichannel sound reproduction. The interview records Cadoz’s own account of this history. It appeared in the haptic-audio special issue introduced by the editorial of Paterson and Wanderley [2023].

A shared model for
touch and sound.

Castagné et al. [2004] explain why the sound of a digital instrument and the forces felt by its performer should be generated by the same simulation. Their argument concerns the exchange of mechanical energy between performer and simulated instrument. They support this design argument by discussing earlier systems and summarizing a virtual string experiment. This proposed explanation of expressive interaction provides a reason to investigate the approach, but does not by itself establish benefits across different instruments. O’Modhrain and Gillespie [2018] offer a related account by treating the body and instrument as a coupled mechanical system. In their drumming example, the player’s grip and the drumhead store and return energy, allowing repeated bounces. The drummer shapes this movement through hand and arm stiffness and the timing of driving actions that sustain the bouncing. The authors distinguish an inner loop from an outer loop involving perception and muscle commands. The inner loop can support rapid responses without a new cycle of neural feedback control for every bounce. Their account helps explain how the instrument’s mechanical response can help produce the player’s movement while also providing sensory information.

A proposed account of
learning.

In the same account, learning involves exploring the dynamics of the body and instrument and making useful movements repeatable [O’Modhrain and Gillespie, 2018]. The authors acknowledge that there is little direct evidence showing how learning to manage energy exchange between body and instrument supports musical skill acquisition. We therefore use this account to identify a possible

role of haptic interaction. Establishing an effect on learning requires evidence about how playing develops with practice.

Perceptual experiments also show why the player's contact with an instrument deserves attention. Fontana et al. [2018] report experiments for detecting vibration involving active finger pressing and piano playing. In the pressing experiment, detection thresholds varied with applied force. Finger contact areas also increased with higher forces. Their results suggest caution when applying thresholds measured under one contact condition to another, including during playing. Alongside the mechanical account of O'Modhrain and Gillespie [2018], this work gives two reasons to examine contact: it affects the physical interaction and the conditions under which vibration is perceived.

Perception during active contact.

Mayet et al. [2024] examine how people distinguish string diameter and tension while plucking. Their apparatus uses real strings without an actuator that generates feedback. This work provides perceptual evidence relevant to DMI design, while reproducing the string interaction with an actuator remains a separate engineering task.

String perception and interface design.

2.2 Implementation and Mapping

2.2.1 Hardware and Prototyping Platforms

Early platforms supported different playing movements. MIKEY used motor-driven keys to reproduce the feel of different keyboard mechanisms [Oboe and De Poli, 2002]. ERGOS separated its actuator and sensor base from interchangeable mechanical attachments, including a bowing interface [Florens et al., 2004]. The vBow explored bowing gestures, while the one-dimensional force-feedback slider explored linear movements [Nichols, 2002; Shahrokni et al., 2006]. These two reports describe working implementations alongside versions still under development. MATRIX offered another input shape: a surface of spring-loaded rods whose positions were sensed [Overholt, 2001].

Hardware shapes the available playing movements.

Its resistance was passive, so it illustrates physical input design without active force feedback.

Simple components
and software supported
prototyping.

The Plank pursued a simpler construction using a salvaged actuator and a local microcontroller [Verplank et al., 2002]. Its early prototype did not yet produce sound. A later report describes its use with granular synthesis, which builds sound from short fragments, in a composer workshop [Verplank and Georg, 2011]. HSP allowed forces for the Falcon haptic controller to be programmed directly in the music software Pure Data [Berdahl et al., 2009]. FireFader offered open hardware and software around motorized faders, or sliding controls, with reconfiguration and teaching as explicit goals [Berdahl and Kontogeorgakopoulos, 2012]. Physical models developed for FireFader were adapted for the rotary Haptic Capstans knobs [Sheffield et al., 2016], and FireFaders were used in compositions for the Laptop Orchestra of Louisiana [Berdahl et al., 2018]. They also involved practical constraints: the FireFader report describes control delay and stability issues, while the orchestra chapter discusses visual support and the practice needed for particular performance techniques [Berdahl and Kontogeorgakopoulos, 2012; Berdahl et al., 2018]. This history gives concrete context to the development barriers discussed by Frisson and Wanderley [2023]. These reports do not measure how widely the resulting platforms were adopted, but they document continued development and musical use.

2.2.2 Signals and Software Coordination

The function of a tactile
signal.

Mapping a haptic signal involves deciding what it should communicate. Giordano et al. [2018] distinguish feedback responding to the performer’s action from stimulation carrying information from another source, such as a score. Their taxonomy describes three functions of active tactile signals. Notification draws attention to an event. Translation conveys information from another sensory modality or recreates the vibration of a physical structure. Tactile languages use patterns for abstract communication [Giordano et al., 2018]. We use these distinctions to separate a signal’s

musical purpose from the device that produces it. This distinction allows us to consider how interfaces with similar actuators can serve different musical purposes.

Birnbaum and Wanderley [2007] provide an example of generating vibration from features extracted from sound. In their Tactilicious Flute Display, detected sound beginnings, or onsets, trigger vibration pulses. Audio loudness controls vibration amplitude, and spectral brightness controls vibration frequency. The authors thus translate selected features of the audio into a separately synthesized tactile signal. They describe their device as a display without user input, and the paper presents its mapping design without evaluating a playing technique [Birnbaum and Wanderley, 2007]. Compared with the shared physical simulation proposed by Castagné et al. [2004], this design uses a different relationship between touch and sound, since selected audio features determine the tactile output.

Mapping sound
features to vibration.

Whether such a mapping can be implemented depends on the actuator's response. Marshall and Wanderley [2006] compare vibrotactile devices through measurements of frequency response, amplitude range, and transient response (how quickly the output responds to changes in the driving signal). In their tested motor, vibration amplitude and frequency are linked, while the devices driven by audio signals allow these variables to be controlled independently [Marshall and Wanderley, 2006]. This matters for the separate frequency and amplitude mappings used by Birnbaum and Wanderley [2007]. A device that couples amplitude and frequency cannot directly implement both mappings independently in that configuration. The comparison concerns the devices tested by Marshall and Wanderley, without establishing a universal performance ranking for each actuator of those types [Marshall and Wanderley, 2006].

Actuator limits and
mapping choices.

Birnbaum and Wanderley [2007] report that fingertip contact alters the output of their voice coil actuators, and they investigate actuator placement beneath the display's finger holes. The active touch experiments of Fontana et al. [2018] address the perceptual side of contact, showing that vibration detection depends on the pressing conditions. Papetti et al. [2018] recommend measuring the device's actual vi-

Contact changes the
delivered signal.

bration output to check whether it delivers the intended feedback. Frisson and Wanderley [2023] organize devices by their degrees of freedom, including linear and rotary devices and systems supporting movement in several directions. Their review also examines software for generating force feedback and sound. They identify a lack of design guidelines for instruments combining the two. At the time of their review, they knew of only three authoring tools supporting both audio and haptic modalities: GENESIS, Synth-A-Modeler Designer, and ForceHost. Using separate tools for sound and force feedback can require additional development to coordinate their outputs [Frisson and Wanderley, 2023]. Implementing the shared simulation discussed earlier therefore involves coordinating sound and force generation as well as choosing a suitable physical interface.

Exchanging information
between touch and
sound.

DIMPLE (Dynamic Interactive Musically Physical Environment) used Open Sound Control messages to connect haptic simulations to audio software [Sinclair and Wanderley, 2007]. It sent information about simulated objects and events between processes with different timing requirements. The authors did not formally measure the delay between these processes [Sinclair and Wanderley, 2007]. Montag et al. [2011] combined a multitouch surface with vibration feedback driven by an audio signal. They measured the delay between touching the surface and the audio output. This measurement does not show when the vibration reaches the finger [Montag et al., 2011].

Connecting touch and
sound through software.

Regimbal and Wanderley [2021] used interpolation: moving a point between chosen examples on a screen changes sound and vibration settings together. Mudd [2013] instead mapped sound-file features to detents, or felt notches, and friction as the user moved through a sound file. These examples show different ways to connect sound information with haptic feedback. At the physical-model level, Berdahl et al. [2009] developed control junctions that connect a haptic device directly to a digital waveguide model, which simulates how waves travel through an instrument. The waveguide model serves both sound synthesis and haptic interaction [Berdahl et al., 2009].

2.3 Evaluation of Musical Instruments

An evaluation method needs to match the question asked about an instrument. The framework of O'Modhrain [2011] distinguishes the interests of players and composers, audiences, designers, and manufacturers. These perspectives involve different goals, including enjoyment, playability, robustness, and whether a design behaves as intended. O'Modhrain also distinguishes task performance from the experience of playing: sensor measurements can describe actions, while questionnaires and interviews can capture players' reflections [O'Modhrain, 2011]. For the present review, this means that results about control and enjoyment answer different questions. O'Modhrain et al. [2000] provide an example of combining measurements with listening judgments in a virtual bowed-string instrument. A haptic display simulates forces at string contact while an audio model generates sound. The study compares recorded bowing parameters with expert judgments of how closely the resulting sounds match a reference stroke [O'Modhrain et al., 2000]. This example shows how measurements of playing and judgments about sound can contribute to the same evaluation.

Evaluation goals and perspectives.

Barbosa et al. [2015] provide a related structure in their review of evaluation in New Interfaces for Musical Expression (NIME) publications. They distinguish the evaluation target, stakeholder perspective, goal, criteria, approach, methods, and duration. They examined papers and posters from 2012 to 2014, but collected evaluation details only where authors explicitly used the term *evaluation*. Their findings therefore describe reported practices within that selection. Their duration category distinguishes a single session from evaluation over time, without recording exact study lengths [Barbosa et al., 2015]. Together with O'Modhrain's framework, these categories help us compare what studies examine and how they collect evidence.

Describing what an evaluation examines.

Different evaluation questions also appear in musical haptics. The detection experiments reported by Fontana et al. [2018] examine whether players perceive vibration under particular conditions. Papetti et al. [2023] review

Perception, experience, and performance.

their own studies of vibrotactile feedback, considering musicians' judgments of instrument quality and playing experience alongside measurements of task performance. They report positive responses to vibration, but leave open whether these perceived improvements also lead to better playing [Papetti et al., 2023].

Design guidelines need
evaluation in the context
of use.

Young [2016] proposes guidelines for tangible DMIs. These include actions that are easy to understand, consistent feedback, and clear and stable mappings between gestures and responses. These recommendations alone do not establish that each feature improves performance. Young also calls for methods to evaluate functionality, usability, and user experience, taking account of how and where the instrument is used. A task can also limit what an evaluation reveals. Papetti et al. [2023] explain that free playing allows researchers to assess musicians' experience, while measuring performance requires more controlled tasks. However, these tasks may be too easy for trained musicians. O'Modhrain [2011] notes that asking musicians to describe their thoughts while playing can interfere with the performance. Together, these concerns suggest considering the task, the player's musical background, and the study setting when judging whether findings may apply to another instrument.

Evaluation within
musical practice.

Performers' accounts can explain why an instrument's behavior is valued. The *self-resonating instruments* reviewed by Eldridge et al. [2021] sustain vibration through a feedback loop connecting a pickup, an actuator, and resonant material. The authors describe how players shape the sound by touching or damping the vibrating parts. Accounts quoted in the paper show that some performers enjoy the changing behavior and the attention it demands. A broader survey by Magnusson and Hurtado Mendieta [2007] also reports differing views of instrument constraints. Respondents often found acoustic limitations inspiring but were more critical of restrictions they attributed to software design. Some also valued digital limitations. For our review, these accounts motivate examining what participants mean by control or predictability in a particular musical activity. Their preferences should be considered in relation to what they wanted to do.

2.4 Existing Reviews

Existing reviews organize musical haptics around different technologies and activities. Frisson and Wanderley [2023] focus on force-feedback hardware, software, and the practical conditions for developing musical applications. Their discussion addresses modularity, replicability, affordability, and usability for designers. Remache-Vinueza et al. [2021] focus on *haptic music players*, which convey music through touch. Their classification explicitly separates these systems from DMIs with haptic feedback. Their review covers methods for rendering musical information through touch and for composing tactile music.

Reviews with different scopes.

The chapter by Giordano et al. [2018] examines tactile communication in musical performance and practice. It presents an interaction model and a short literature review, grouping tactile functions into notification, translation, and tactile languages. The authors also design and evaluate wearable score cues. Their preliminary study tested whether two musicians could identify tactile patterns and perform the melodies or expressive changes linked to them. This connects tactile mappings to specific musical tasks. Alongside the technologies and rendering methods reviewed by Remache-Vinueza et al. [2021], this functional taxonomy helps distinguish the roles of tactile signals in musical interaction.

From tactile functions to musical tasks.

Papetti et al. [2023] and Eldridge et al. [2021] connect instrument construction with playing experience through different approaches. Papetti and colleagues summarize their own work on three vibrotactile interfaces, covering their design and experiments with musically trained participants. Eldridge and colleagues examine a family of self-resonating instruments through technical descriptions and accounts from designers and players. Both are precedents for considering implementation and experience together. Their scopes differ in the instruments examined and in the evidence used to describe playing.

Syntheses linking design and experience.

2.5 Position of this Review

Comparison across
instruments and tasks.

Table 2.1 makes the scope differences explicit. Frisson and Wanderley [2023] organize force-feedback technology and authoring, while Remache-Vinueza et al. [2021] examine haptic music players. Giordano et al. [2018] review a broader range of interfaces, but their detailed evaluation concerns wearable score cues. Papetti et al. [2023] synthesize their own three interfaces, and Eldridge et al. [2021] examine self-resonating instruments. These works provide guidance within particular technologies, tasks, or instrument families.

Actuation can shape an
acoustic sound as well
as a felt response.

The wider corpus also contains actuated acoustic instruments. The Overtone Fiddle uses a transducer to vibrate its body, producing sound and sensations for the player [Overholt, 2011]. The Drum Modal Feedback paper describes its transducer as an audio output used to change a drum sound’s duration and timbre [Wolstanholme et al., 2025]. An actuator’s presence alone therefore does not establish that it provides haptic feedback to the player. For listeners, sound can be combined with recorded guitar vibrations or with vibrations delivered through the chair installation *Skin Music* [Hayes, 2015; McDowell and Furlong, 2018]. The Vibrochord allows users to compose tactile music for a vibrating chair [Branje, 2014]. Turchet [2022] discusses design choices for haptic listening. Other work examines musical instruction and perception. Haptic Tutor guides beginner drummers using vibration cues on their limbs [Tom et al., 2020]. Egloff and colleagues test whether participants can distinguish ascending melodic intervals from unison through vibration [Egloff et al., 2018]. The evaluation should therefore match the role of touch in the musical activity.

The contribution of this
review.

Our review brings vibrotactile and force-feedback research across instrument families into a common comparison of musical task, implementation, mapping, and evaluation. Its contribution is to examine how far guidance from one setting can inform another, while retaining the conditions under which the evidence was obtained. Chapter 3 defines

the scope and selection of the literature; Chapter 4 develops the comparison.

Work and scope boundary	Implementation and mapping	Evaluation perspective
Frisson and Wanderley [2023] Force-feedback technology and authoring	Devices, software, and tools for designing sound and force feedback	Design challenges and support for instrument developers
Remache-Vinueza et al. [2021] Haptic music players, distinguished from DMIs with haptic feedback	Actuators, music-to-touch mappings, and tactile composition	How users perceive music through touch
Giordano et al. [2018] Various musical interfaces; detailed study of wearable score cues	Interaction model; notification, translation, and tactile languages	Preliminary tests of cue recognition and musical responses
Papetti et al. [2023] Three vibrotactile interfaces from the authors' research	Sensors, actuators, and ways to produce vibrations	Playing-experience ratings and task performance from musically trained participants
Eldridge et al. [2021] Self-resonating instruments	Vibrating materials, pickups, actuators, and feedback processing	Designers' and performers' accounts of how construction affects playing

Table 2.1: The selected reviews and design syntheses cover different technologies, musical activities, and instrument families. The table compares their design focus and the evidence they discuss.

Chapter 3

Method

We conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines according to Page et al. [2021]. This chapter reports our literature search, screening and eligibility decisions, and backward and forward citation searching. We also describe data extraction and synthesis and provide a quantitative overview of the corpus.

3.1 Information Sources and Search Strategy

We searched three complementary sources: the ACM Digital Library, the proceedings of New Interfaces for Musical Expression (NIME), and OpenAlex. The ACM Digital Library and NIME cover the venues where haptic DMI research is published, and OpenAlex extends the search beyond them, so relevant work published in other venues is not missed by construction.

ACM DL, the NIME proceedings, and OpenAlex.

We did not apply a single query across all three sources. Because each database indexes different literature and varies in scope, we adapted the search query for each source. We

Each source got a query written for it.

provide the full text of all three queries to ensure the search can be reproduced.

Our search included a haptic term and a musical term.

For the ACM Digital Library we required a term from the haptic vocabulary and a term from the musical one:

```
(haptic OR vibrotactile OR "force feedback")
AND (music OR "digital musical instrument"
OR "digital musical instruments"
OR "digital music instrument")
```

For OpenAlex we expressed the same conjunction through its API filter syntax, in which comma-separated filters are combined with *AND* and the pipe character denotes *OR* within a filter:

```
"filter": 'title_and_abstract.search:
  haptic|vibrotactile|"force feedback",
title_and_abstract.search:
  music|"digital musical instrument"
  |"digital musical instruments"
  |"digital music instrument"'
```

The NIME search omitted the musical conjunct.

For the NIME proceedings, we searched only the haptic terms. Since the proceedings already focus on musical interfaces, requiring music-related terms could exclude relevant papers that do not use them:

```
haptic OR tactile OR vibrotactile
OR force feedback
```

The NIME query also included *tactile* as a term, which was absent from the ACM Digital Library and OpenAlex queries. It therefore covered a broader haptic vocabulary. This difference may have made the search more sensitive within NIME: a paper using only *tactile*, without *haptic* or *vibrotactile*, could be found through the NIME query but missed elsewhere.

The ACM Digital Library was searched through its own interface, with the query applied to title, abstract and keyword fields. The NIME and OpenAlex searches were run by scripts written for this review, which retrieve and export the records without manual intervention. Those scripts are published so that the search can be re-executed. The ACM Digital Library and the NIME proceedings were searched on 7 July 2026, and OpenAlex on 16 July 2026. The review therefore does not cover work indexed after those dates.

Searches used the ACM interface and published scripts for NIME and OpenAlex.

3.2 Eligibility Criteria

We established inclusion and exclusion criteria prior to screening. A publication was eligible for inclusion through either of two defined routes.

3.2.1 Inclusion Criteria

Under Route 1, we included publications that present, evaluate or review *active haptic feedback* integrated into a digital musical instrument. In this review, *active haptic feedback* denotes motorized *force feedback* or *vibrotactile* actuation, distinguishing actuated systems from the mechanical resistance of unactuated controls.

Included for active DMI haptics or actionable perceptual/design evidence.

Route 2 provides a way to include publications in which *active haptic feedback* is absent. A publication lacking *active haptic feedback* is included in the corpus if it supplied actionable perceptual or design evidence for at least one research question. The finding had to identify a specific DMI component or parameter and support a particular design choice, technical limit, or trade-off. For example, a study of human sensitivity to vibration qualified if its findings helped determine the frequency range a DMI actuator needed to produce. A study of how touch receptors work did not qualify unless it provided guidance for device design. Eligible publications included empirical experiments, system designs, toolkits, dissertations, and literature reviews.

3.2.2 Exclusion Criteria

We excluded non-musical or spatially confounded haptics.

We excluded studies set in Virtual, Augmented, or Extended Reality and in spatial computing, where the surrounding environment introduces variables we cannot separate from the haptic interaction itself. We also excluded therapeutic and medical applications, including disability studies, rehabilitation, and prosthetics, along with industrial and teleoperation contexts. In each case the *haptic feedback* serves a purpose other than musical performance. Their findings may still help inform musical interface design, but assessing this was outside the scope of the review. Finally, we excluded course materials and conference slide decks, which appear in graphics-conference proceedings but are not research reports.

3.3 Selection Process and Data Management

Publications deduplicated and screened in Rayyan, managed in Zotero.

We imported the retrieved records into [Rayyan](https://www.rayyan.ai/)¹, which detected duplicates and supported title and abstract screening. After screening, we moved the remaining articles into [Zotero](https://www.zotero.org/)². We used Zotero to retrieve full texts through our institutional access and organize the eligibility assessment and data extraction.

Fixed criteria and published records make the selection decisions inspectable.

One person, the author, made all screening and eligibility decisions. PRISMA 2020 guidelines ask how many reviewers screened each record and how disagreements were resolved [Page et al., 2021]. Because no second reviewer was involved, there were no disagreements to resolve, and inter-rater reliability could not be measured. Consistency therefore depended on the author applying the criteria uniformly. We took three steps to make the decisions more transparent. First, we fixed the eligibility criteria before screening and report them above. Second, we recorded and individually report the reason for every full-text exclu-

¹ <https://www.rayyan.ai/>, last accessed September 15, 2026

² <https://www.zotero.org/>, last accessed September 15, 2026

sion. Third, we publish the extraction records and matrix so readers can inspect the extracted data and screening decisions. These steps support transparency but do not replace independent screening.

3.4 Study Selection Outcomes

The database search identified 7,022 records: 5,770 from the ACM Digital Library, 1,064 from OpenAlex, and 188 from the NIME proceedings. Automated and manual deduplication in Rayyan¹ removed 599 duplicate records, leaving 6,423 unique records. Title and abstract screening excluded 6,311 records that failed the eligibility criteria, leaving 112 sought for retrieval. Two of the 112 reports could not be obtained through institutional library access or direct author contact and are reported separately under PRISMA 2020 guidelines. Fujisaki et al. [2001] is published in Japanese and behind a paywall. Katsinas and Visser [2026] is also behind a paywall, and the authors did not respond to a request for access. Because neither report was read, neither was assessed for eligibility.

The search found 7,022 records, with 112 remaining after initial screening.

Of the 110 retrieved reports, we excluded seven after reading the full text: two were outside the scope, one provided no haptic feedback, one duplicated an already-retained publication, and three were course publications rather than complete research reports. Table A.5 identifies these entries and their exclusion reasons. Full-text assessment therefore left 103 eligible reports from the database searches.

Seven of the 110 retrieved reports were excluded on four grounds.

We supplemented the database search with backward and forward citation searching from two reviews central to the field [Eldridge et al., 2021; Frisson and Wanderley, 2023]. We conducted both the backward and forward citation searches on 16 July 2026, the same date as the OpenAlex search. We followed their reference lists and the works citing them, thereby identifying eleven eligible reports. These eleven reports entered the separate citation-searching branch of the PRISMA diagram, bringing the total number of reports entering data extraction to 114.

Citation searching added eleven further reports.

Five reports failed the inclusion criteria during extraction.

During detailed data extraction, close reading revealed that five reports from the database search did not satisfy the inclusion criteria in 3.2.1, because they lacked qualifying haptic feedback or actionable design evidence, or concerned an application outside the musical scope. Table A.5 gives the individual reasons and qualifications. We classify these five late removals as screening corrections and show them in a dedicated exclusion box in the PRISMA flow diagram. The final included corpus therefore comprises 109 reports: 98 from database searching and 11 from citation searching.

The corpus therefore comprises 109 reports. Figure 3.1 shows the identification, screening, and inclusion phases with the numbers at each step. The citation searching alongside the database searching is also included.

3.5 Data Extraction

A common set of fields connected each report to the research questions.

We extracted the information summarized in Table 3.2 from the included reports. Appendix A summarizes the corpus and presents selected fields in two linked tables, each with one row per report. A report could describe several devices or experiments; rows therefore do not necessarily represent independent instruments or participant samples.

Evaluation fields distinguish procedures, observations, and findings.

Evaluation methods describe the procedure, measures identify observations or ratings, and findings retain comparisons, results, and reported statistics. Participant entries retain sample size and experience. The accompanying field guide defines these fields.

Modality coding followed the feedback delivered to the performer.

We classified reports as vibrotactile, active force feedback, both, reviews covering both, or neither. The combined category included selectable force and vibration modes. Passive mechanics and programmable resistance alone were excluded from active force feedback. Modality describes the feedback covered by a report; eligibility followed the routes in Section 3.2.1.

Evidence for the research questions retained the basis of each finding.

We also recorded findings relevant to the research questions with supporting passages or source locations. These

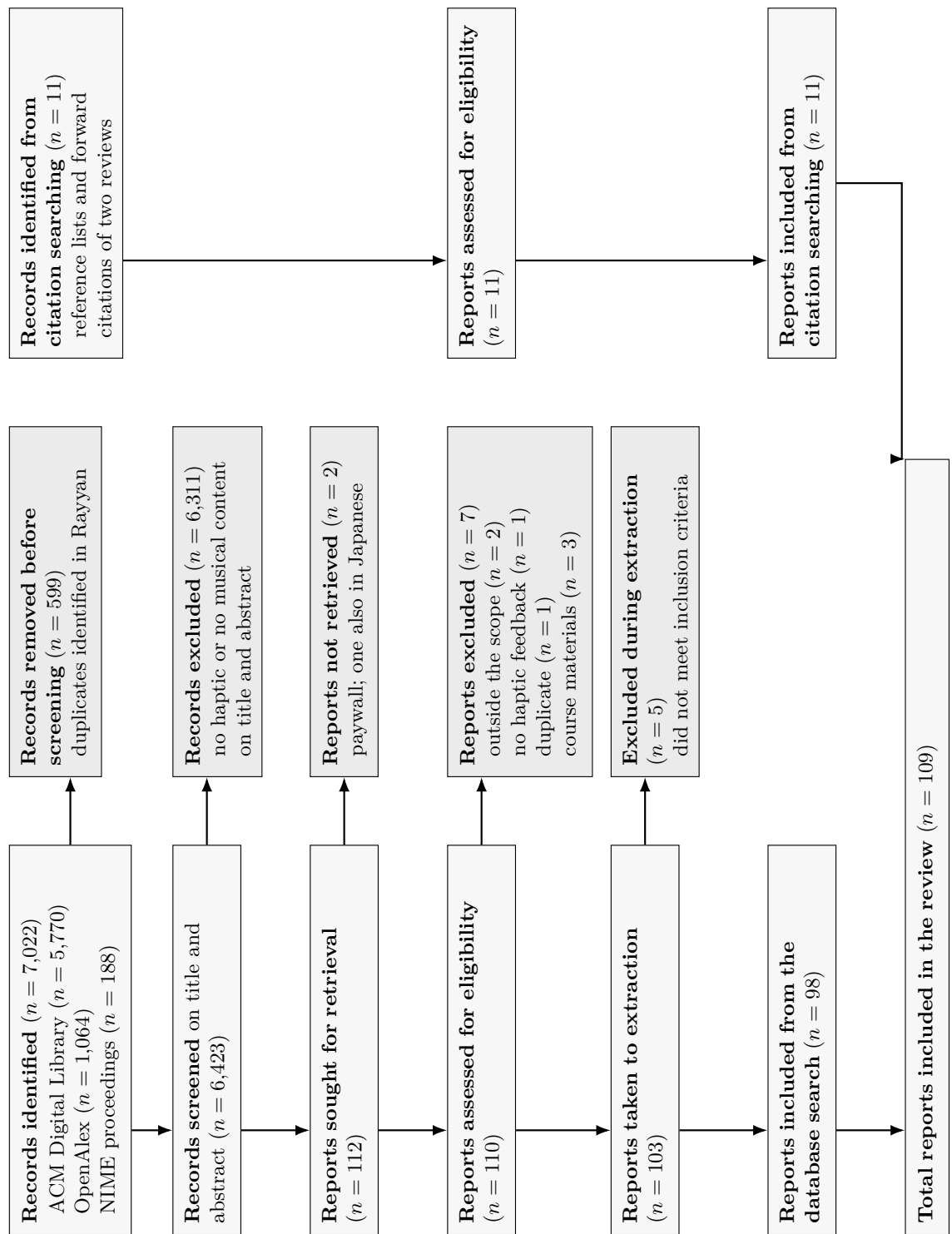


Figure 3.1: PRISMA 2020 flow diagram showing database and citation searches separately. Title and abstract screening excluded 6,311 of 6,423 unique records. A separate box shows five reports excluded during extraction after passing full-text assessment.

Field group	Information recorded
Publication	Author, year, venue, and publication type.
Instrument and feedback	Instrument or apparatus, physical form, and feedback modality.
Technical implementation	Actuator or implementation, technical frequency data, and latency or delay.
Evaluation	Evaluation method, participants, measures, and principal findings, where available.
Evidence for the RQs	Findings about feedback selection, musical mappings, and evaluation of performer experience, with supporting source passages or locations.

Table 3.2: Fields recorded for the review. The appendix presents a compact selection; publication details and evidence for the research questions were also retained in the extraction records.

records distinguish measurements, participant judgments, author suggestions, and reviewer interpretations. Evaluation evidence retained the task, participant experience, comparison conditions, measures, and limitations where available. This context supported the comparisons in Chapter 4.

3.6 Historical Overview of the Corpus

Publication years and venues place the included reports in context.

We summarized the corpus by publication year and venue to describe the literature on which the synthesis rests. A CSV file contains one row per included report, linking its identifier and publication year to the modality and venue categories summarized in Appendix A. A Python script counts these entries and produces Figures 3.3 and 3.4. The CSV and script accompany the thesis. Each report contributes once to each figure, including reports that describe related instruments or experiments.

We used the year of the included publication, taking thesis dates from their title pages and journal dates from the published issue. Where this differs from the extraction record, the CSV retains both years and a note explaining the choice. The figures use the modality categories defined in Section 3.5; reviews covering both modalities remain separate. For the venue figure, we grouped related conferences and publication types while retaining the individual venues and degree types in the CSV and appendix.

Dates refer to the version included in the review.

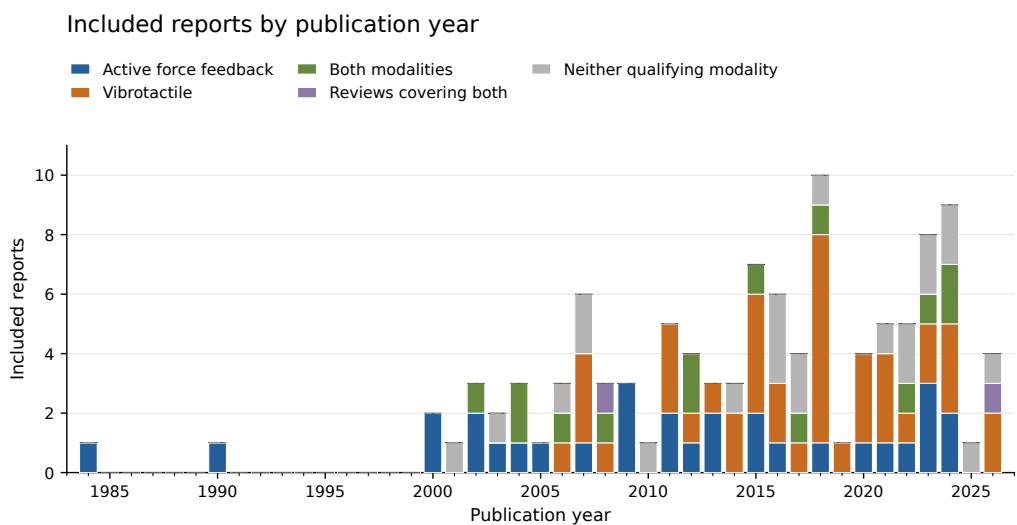


Figure 3.3: Included reports by publication year and modality. Counts describe the selected corpus; an empty year does not establish the absence of relevant research. Coverage of 2026 is partial because the database searches ended in July.

Figure 3.3 spans 1984–2026. The earliest included reports concern active force feedback. The first report classified as covering both modalities dates to 2002, while the vibrotactile category first appears in 2006. These dates describe the included publications and do not establish when either approach originated. The largest annual count is 10 reports in 2018, of which 8 are chapters in *Musical Haptics*. This concentration shows how a single publication can shape the annual distribution.

The selected literature spans several decades, with uneven annual coverage.

Figure 3.4 places 46 of the 109 reports at NIME (42.2%). The corpus also includes theses, specialist haptics venues, other conferences, journals, and book chapters. NIME’s promi-

NIME accounts for the largest share of the included reports.

Included reports by venue and publication type

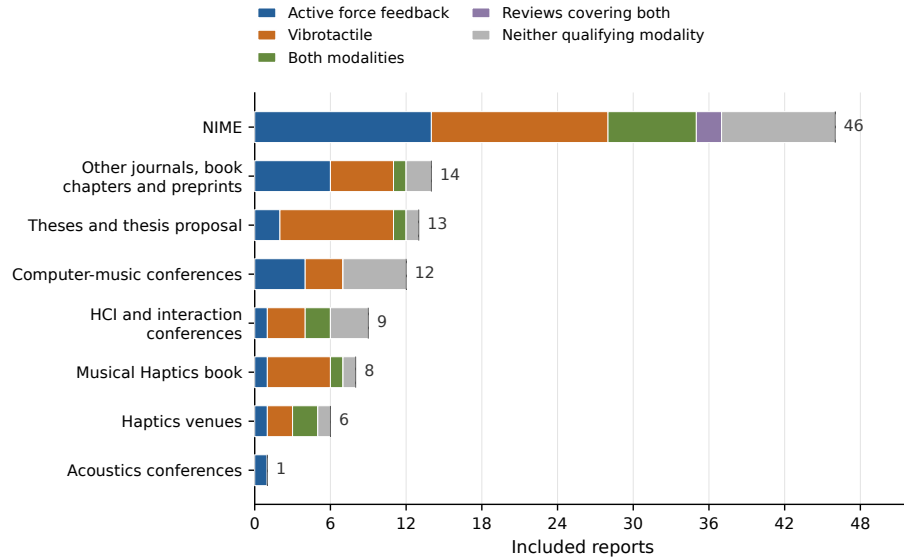


Figure 3.4: Included reports by grouped venue or publication type, subdivided by modality. The appendix provides the detailed venue counts. Each report belongs to one group; haptics venues include specialist conferences and IEEE Transactions on Haptics.

nence should be read alongside the search strategy, which searched its proceedings directly. These distributions describe the sources available to this review. They do not estimate the relative size of research communities, and publication counts alone cannot explain changes in feedback design or establish the quality of the evidence.

3.7 Synthesis Procedure

The synthesis grouped findings by the three research questions.

We organized the findings into a narrative synthesis. RQ1 compared feedback choices against their musical purpose, benefits, and limitations. RQ2 examined how implementation properties shaped mappings between gestures, haptic output, and musical parameters. RQ3 compared evaluation methods according to the aspects of performer experience they assessed. Sections 4.2, 4.3, and 4.4 present these comparisons.

Technical measurements, player studies, system descriptions, and reviews address different instruments, tasks, and outcomes. Narrative synthesis retained these differences. The comparison tables in Chapter 4 connect design questions to supporting findings and their limits.	Different kinds of evidence required narrative comparison.
Comparisons retained devices, tasks, participants, and measures, including conflicting findings and limitations. We interpreted performance and subjective judgments separately and considered overlapping experiments or participants together. Report counts describe literature coverage; they do not establish the strength of a recommendation.	Comparisons retained the conditions under which findings were obtained.
The synthesis draws on RQ-linked findings in the extraction records. Comparisons address shared questions, such as reaching target positions or assessing perceived control. Source passages and locations preserve the context. We did not calculate a common effect estimate.	RQ evidence links the comparisons to the extraction records.
We assessed support for individual claims without overall study-quality scores or pooled effects. We performed no formal study risk-of-bias assessment, assessment of bias due to missing results, certainty assessment, or sensitivity analysis. Design suggestions retain their source conditions and limitations.	The review assessed support for individual claims without assigning overall quality scores.
The GitLab repository in Appendix B requires institutional network or VPN access.	

Chapter 4

Synthesis

This chapter presents the findings for the three research questions. Section 4.2 examines how musical tasks inform the choice of feedback modalities. Section 4.3 links technical constraints to musical mappings. Section 4.4 considers which evaluation methods can assess different aspects of the playing experience.

4.1 Interpreting the Evidence

The reports include actuator measurements, studies with musicians, instrument descriptions, and design proposals. Actuator measurements show what a device produces, such as vibration amplitude in Bukkapatnam et al. [2020]. Studies with musicians can measure task performance and ask players about their experience. For example, Young et al. [2018] measured pitch selection speed and accuracy and collected participants' views through questionnaires and interviews.

Different studies answer different questions.

When we suggest how the findings might apply to another instrument, we make our interpretation explicit. The tables concluding the three RQ sections summarize these suggestions and their limits.

We distinguish reported findings from our interpretation.

4.2 RQ1: Choosing Between Vibrotactile and Force Feedback

What should the feedback help the player do or feel?

RQ1 asks what guidelines we can derive from the literature for choosing between vibrotactile and force feedback in haptic DMIs. We start with the proposed roles of each modality, then examine the choices that comparisons support. These choices include whether to add actuation, which force effect or vibration signal to use, and whether to combine actuators. We distinguish measured task performance, reported experience, and measured device output.

4.2.1 What the Haptic Feedback Should Do

Force and vibration have proposed roles that overlap.

Pedrosa [2007] proposes using force feedback to help players control sound and vibration to make the interface feel like a musical instrument. He also suggests using vibration to convey timing and rhythm cues. In his proposal, both forms of feedback can therefore contribute to control [Pedrosa, 2007]. We use these proposed roles as a starting point. The comparisons below examine which effects, signals, and physical arrangements support each role.

Hardware requirements limit the available design choices.

Berdahl et al. [2008] explain that, in practice, a force-feedback system must sense movement along the axis in which it applies force. Kirkegaard et al. [2020] link the required force range to actuator size and power, and identify cost as another constraint. Giordano et al. [2018] explain that the size of force-feedback devices makes them difficult to integrate into portable or wearable musical interfaces. These constraints can narrow the available feedback choices.

4.2.2 Accounting for Feedback Already Present

The Haptic Bowl combined passive resistance with active vibration.

The Haptic Bowl paired spring tethers with vibration actuators in gloves [Young and Murphy, 2015]. The springs pro-

vided a return force and were strengthened to help players locate their hands relative to the instrument [Young et al., 2018]. The glove vibration followed the synthesized sine wave [Young et al., 2018].

In a qualitative study with six participants, the preference order was combined feedback, force feedback, tactile feedback and no feedback [Young et al., 2017]. A pitch selection study with twelve musicians compared these four conditions. It found no statistically significant differences in movement time or pitch selection accuracy [Young et al., 2018]. Participants rated the task easier with combined or force feedback than with no feedback. Combined feedback received the highest median rating for willingness to use the device outside the experiment [Young et al., 2018].

Preference and task performance gave different results.

Here, "force feedback" refers to passive springs [Young et al., 2018]. The vibration-only and no-feedback conditions used a contactless device that allowed less restricted movement [Young et al., 2018]. The comparison therefore changed both the feedback and the sensing arrangement. It cannot establish an advantage of motorized force feedback over vibration because motorized force feedback was not tested.

The spring comparison also changed the sensing arrangement.

Passive resistance is also part of the Daïs: its elastic suspension resisted movement of the disk, while voice coils supplied vibration [Christensen et al., 2020]. In the electric-cello study, the strings still produced vibration when the added feedback was switched off [Järveläinen et al., 2024]. We therefore recommend identifying the resistance and vibration an instrument already provides, then evaluating what added feedback contributes.

Establish what the instrument already provides before adding actuation.

4.2.3 Matching Force Effects to the Movement

A *detent* is a felt stop or notch that marks a position on a control. In a study with twenty trained musicians, a rotary knob provided Detent, Spring, and No-FF modes during vibrato imitation [Piao et al., 2024]. Vibrato is a repeated

A force effect should match the positions the task requires.

variation in pitch. Spring pulled the knob toward its starting position. In No-FF, the motor produced no active force. All modes used the same knob and visual feedback [Piao et al., 2024]. Detent reduced pitch error compared with No-FF ($p = 0.007$). Neither Spring versus No-FF nor Detent versus Spring showed a significant difference in pitch error [Piao et al., 2024]. The result supports considering this detent effect for reaching the target pitch repeatedly with a rotary knob. It does not establish a pitch-error advantage over Spring. The paper reports removing outliers but does not explain how it then matched each participant's results across feedback modes [Piao et al., 2024].

Resistive markers can support precise target selection.

An abstract task provides a related result. Ten participants used a knob to match a cursor to visible targets [De Pra et al., 2021]. Resistance at the markers reduced position error, while completion time did not differ significantly between feedback conditions [De Pra et al., 2021]. This supports considering resistive markers for precise selection with visual guidance.

Allow users to select values between detents.

The placement of detents can also obstruct a task. In a slider study, target values 25 and 75 coincided with detents, while 40 and 60 were impossible to reach exactly in that mode [Helppolainen, 2024]. The author recommended allowing users to switch the mode off to reach intermediate positions [Helppolainen, 2024]. Taken together, these studies suggest placing detents at useful target values and preserving access to intermediate values, for example by allowing users to switch detents off. They inform the choice of feedback effect but do not establish whether force feedback or vibrotactile feedback is preferable.

4.2.4 Choosing Vibration for Playing Experience

Sound-related vibration improved rated experience on a touch surface.

Twenty-nine musicians or music students compared vibrating and nonvibrating versions of the HSoundplane touch surface [Papetti et al., 2023]. Sine vibration followed the sound's pitch and varied in strength with finger pressure [Papetti et al., 2023]. Audio vibration used the sound signal after filtering it to 10–500 Hz [Papetti et al., 2023]. Both

improved ratings, with the strongest effects on expression and enjoyment. Ratings for noise with fixed strength did not show a clear improvement [Papetti et al., 2023]. We therefore consider sound-related vibration a supported option for improving these aspects of experience on similar surfaces. The conditions differed in both frequency content and how vibration strength responded to playing. The comparison therefore does not show how much each feature contributed to the improved ratings.

In an electric-cello study, eleven cellists compared added vibration with the instrument’s existing string vibration [Järveläinen et al., 2024]. Neither vibration from the bridge signal nor synthesized noise showed a clear benefit on preference, power, liveliness, or feel. All eight 95% credible intervals included 0.5, the point of equal ratings for added vibration and the reference condition [Järveläinen et al., 2024]. The noise followed the bridge signal’s intensity, unlike the fixed-strength noise on the HSoundplane [Järveläinen et al., 2024]. The two studies therefore differed in their baseline vibration, feedback signals, and rated qualities. Our recommendation is strongest for the touch surface and experience outcomes studied. Better experience ratings also do not establish better task performance. Separate piano-scale and pitch-matching tasks did not demonstrate performance gains from added vibration [Papetti et al., 2023].

The cello study did not establish a clear benefit from added vibration.

The information needed for a task also matters. Section 4.3.5 compares preserving sound features with reducing vibration to timing cues. A signal suited to identifying a sound need not be the best signal for marking a beat.

4.2.5 Choosing an Actuator for the Required Signal

Giordano et al. [2012] tested a Phantom Omni with an added vibration actuator in its handle switched off and on. With the actuator on, the force signal was split between the device’s motors and the vibration actuator. In a bowed-string simulation with a fundamental frequency of 110 Hz, the force-only response lacked peaks at 110 and 330 Hz. The

A separate vibration actuator can extend a force device’s output.

combined setup reproduced a wider range of frequencies [Giordano et al., 2012]. This illustrates a reason to combine actuators: the force device provides resistance, while the vibration actuator supplies signal components it cannot reproduce adequately [Giordano et al., 2012]. This is a measured hardware benefit; the study did not establish improved playing experience [Giordano et al., 2012].

Actuator measurements
show which signals a
component can
produce.

Marshall and Wanderley [2006] compared five actuator types. They reported that the voice coil could vary vibration strength over a wide range and produce the strongest vibration among the tested devices. They also noted that voice coils and piezo elements generated audible sound [Marshall and Wanderley, 2006]. A later study measured two voice coils and one piezoelectric actuator [Bukkapatnam et al., 2020]. The authors reported relatively even frequency responses from 100 to 1000 Hz for the unloaded voice coils. The piezo's response weakened below 300 Hz [Bukkapatnam et al., 2020]. These measurements support choosing a component that can produce the required signal. They describe the tested devices and conditions, rather than every device of each type.

Contact layout can
justify a different
actuator choice.

Papetti et al. [2015] used piezo discs to create vibrations at multiple points on a thin surface. Their choice reflected thickness, response speed, the ability to use audio signals, and cost [Papetti et al., 2015]. This example supports considering both the arrangement of touch points and the required vibration signal when choosing actuators.

Mounting and loading
change the delivered
vibration.

Attaching a voice coil to an 897 g stone pestle reduced its overall vibration response by about 20 dB [Bukkapatnam et al., 2020]. On the Touch-Box, weights used to simulate finger pressure changed vibration strength and, for noise stimuli, the vibration spectrum [Papetti et al., 2018]. These results support measuring vibration on the assembled interface under conditions that resemble playing. An unloaded actuator measurement alone cannot establish the vibration available at the player's contact point.

4.2.6 Accounting for Perception and the Playing Task

The perceptual measurements give useful starting ranges, but their conditions matter. A study using vibration gloves reported peak sensitivity between 160 and 200 Hz [Young, 2016]. In a piano study, participants detected natural key vibration above chance when playing long, loud A4 notes (440 Hz). Detection fell to chance at D5 (about 587 Hz) and A5 (880 Hz) [Fontana et al., 2018].¹ In another study, participants with hearing impairments detected signals at 2000 and 4000 Hz while resting an open hand on a flat vibrating surface. Detection required amplitudes about 30–40 dB higher than at 250 Hz [Wyse et al., 2012]. We would use these results to choose a frequency range for testing. The piano results alone do not establish a general upper frequency limit for added vibration.

Sensitivity depends on the stimulation conditions.

The studies also differ in how waveform affects detection. Fontana et al. [2018] reported a lower threshold for a 250 Hz sine than for noise spread over 50–500 Hz. In a panel setup with whole-hand contact, Wyse et al. [2012] found higher thresholds for sine stimuli than for square waves, modulated signals, and frequency sweeps at 250 and 500 Hz. These studies used different comparison signals and contact conditions. Their results support testing the intended waveform and contact arrangement before adopting a threshold from another setup.

Test the waveform and contact conditions before adopting a threshold.

Compensation adjusts the vibration signal to account for differences in output or sensitivity across frequencies. Marshall [2008] compared compensation for the actuator’s response with compensation that also accounted for skin sensitivity. Both improved accuracy on a frequency-change task compared with no compensation. Accuracy was higher with actuator compensation alone than with both forms of compensation [Marshall, 2008]. However, Marshall notes that participants may have mistaken changes in perceived vibration strength for frequency changes, which could partly explain this advantage [Marshall, 2008]. We

Test compensation in the intended perceptual task.

¹ Letters name notes; numbers name octaves. Frequency equivalents assume equal temperament with A4 at 440 Hz.

therefore recommend testing compensation in the intended perceptual task.

A haptic effect can interfere with an established playing technique.

Beatmatching aligns the beats of two recordings. In the D’Groove turntable study, expert DJs relied on listening for this task and objected to effects such as resistance when they disrupted that process [Beamish, 2003]. A bowed-string simulation revealed a different conflict. Six experienced string players imitated recorded bow strokes with and without added friction. Most preferred friction, but independent raters judged their strokes less similar to the reference when friction was present [O’Modhrain, 2000]. Both conditions retained normal force, which resisted pressing into the simulated string [O’Modhrain, 2000]. This comparison therefore concerned different force effects. Practice was brief, and the author attributed the poorer performance to an insufficiently realistic friction model [O’Modhrain, 2000]. Together, these cases support checking whether the chosen effect preserves the technique it should assist. Preference for its feel alone cannot establish that benefit.

The usable feedback strength needs to be established with players.

Participants in a force-feedback slider study described some effects as too strong, and its author recommended configurable strength [Helppolainen, 2024]. A musician in a knob study also described excessive resistance in the spring mode [Piao et al., 2024]. In a bowed-string simulation, some participants initially failed to notice the feedback, while others found the vibration stronger than they expected from a real instrument [Tache et al., 2012]. These reports support testing a range of levels and providing adjustment where the interaction permits it, but they do not establish a fixed preferred level for either novices or experienced musicians.

Table 4.1 connects the conditions examined above to the choices they support. Some comparisons inform whether to add actuation; others inform which force effect, vibration signal, or actuator to use. Their limits differ accordingly.

RQ1 yields choices tied to specific tasks, outcomes, and hardware.

Our answer to RQ1 is to first identify what the feedback should help the player do or feel, then choose a configuration suited to the task and the instrument’s hardware

Design condition	Choice supported	Evidence and limit
Existing mechanics already provide feedback	Check what added actuation must contribute.	Bowl, Daïs, and cello examples retain passive resistance or vibration (Section 4.2.2).
Useful values can be marked by felt positions	Consider detents; preserve access to intermediate values when needed.	Knob and slider studies support choices for specific tasks, but do not establish whether force or vibration is preferable (Section 4.2.3).
The goal is perceived expression or enjoyment	Consider sound-related vibration on similar touch surfaces.	HSoundplane ratings support this choice; the cello study did not establish the same benefit (Section 4.2.4).
The force device cannot adequately reproduce required vibration components	Consider adding a separate vibration actuator.	The augmented handle extended measured output; improved playing experience was not established (Section 4.2.5).
The signal must reach the player's contact points	Select components by their mounted output and contact layout; check detection under the intended conditions.	Component measurements and detection thresholds apply to the tested setups (Sections 4.2.5–4.2.6).
The effect must suit the player's technique and comfort	Check task performance and preferred feel separately; allow strength adjustment where possible.	Turntable, bowing, slider, and knob studies report interference or differing perceptions of strength; they establish no generally preferred level (Section 4.2.6).

Table 4.1: Design implications for feedback selection. The limits refer to the evidence discussed in the indicated sections.

constraints. The comparisons support considering detents at useful target positions while preserving access to intermediate values when needed. They support sound-related vibration for rated expression and enjoyment on similar touch surfaces, and combined actuation where a force device cannot adequately reproduce required vibration components. Existing feedback, contact conditions, and compatibility with playing technique further qualify these choices. These are conditional guidelines from our synthesis. The comparisons reviewed here do not establish when active force feedback should be preferred to vibration on an otherwise comparable instrument.

4.3 RQ2: How Implementation Shapes Musical Mappings

Implementation can change the mapping or how the player experiences it.

RQ2 asks how technical implementation influences the mapping of musical parameters. The cases below show changes to the gestures an instrument can sense, the relations programmed between signals, and the feedback that reaches the player. They also show that timing can change the experience of a mapping whose programmed relation stays the same. We distinguish changes reported by the sources from implications we draw across cases.

4.3.1 Control Rate and Coupled Models

Device limits can require a model signal to be split between outputs.

The *control rate* is the rate at which a controller updates its output. The haptic control loop and sound model can run at different rates [Berdahl et al., 2008]. In a bowed-string system, the model ran at 48 kHz, while the Phantom Omni force device accepted 1000 updates per second. When using the Omni alone, the authors reduced higher frequencies with a 480 Hz low-pass filter before sending the force signal to the device. With an added Haptuator vibration actuator, they split the force signal around 100 Hz. Lower frequencies went to the Omni motors, while higher frequencies went to the Haptuator [Giordano et al., 2012]. The two devices therefore delivered different frequency ranges from the same simulated bowing interaction to the hand. This arrangement addressed limits in both the Omni’s update rate and its mechanical response (Section 4.2.5).

Computing a model and delivering its force are related limits.

In R-FF, a motorized knob controlled a simulated clarinet. When users pushed the effects to their limits, the authors attributed audible oscillations to aliasing in the knob’s haptic update rate [Gentili-Morin and Wanderley, 2024]. *Aliasing* occurs when sampling is too slow and high frequencies appear as lower frequencies. Processing power can also limit model size. A predecessor of the MSCI platform ran its haptic loop at 44.1 kHz, but could compute only small physical models [Leonard et al., 2018]. MSCI ran different parts of the model at different rates. Simulated

mechanical structures acted as filters to reduce distortion caused by converting signals between these rates [Leonard et al., 2018]. These cases show why both update rate and processing power matter when choosing a physical model. A high update rate alone does not guarantee that the system can compute the model and deliver its intended feedback.

In a double bass that used feedback to sustain its strings, feedback on one string could prevent the others from sustaining their own oscillations. The designer introduced the Amplitude Sync algorithm, which adjusted each string's amplification by comparing its amplitude with the average amplitude of two other strings [Melbye, 2023]. Each string's amplification therefore depended on the activity of other strings. Although the algorithm aimed to balance their amplitudes, lasting stability was difficult to achieve. Its changing behavior became a resource for composition and performance, and equal string levels became only one of its goals [Melbye, 2023].

Coupling between strings can shape how amplification is controlled.

4.3.2 Latency and Jitter

Latency is the delay between an action and a response; *jitter* is variation in that delay. A study with eleven musicians varied the delay between striking an instrument and hearing its sound [Jack et al., 2016]. For five of the six quality measures, ratings at a stable 10 ms delay did not differ significantly from those in the near-zero condition. Naturalness was the exception. Participants rated delays of 20 ms and 10 ms with ± 3 ms jitter less favorably than the near-zero condition [Jack et al., 2016]. In both conditions, they felt less able to control sound level. The software still detected strikes and triggered notes in the same way [Jack et al., 2016]. These results suggest that the same triggering rules can produce different experiences of control when timing changes. In a Haptic Bowl study, a participant comment also described having to adjust to latency [Young, 2016].

Delay can change perceived control even when note triggering stays the same.

Designers can incorporate delay into an effect or change the processing path.

The HaptiCoupler used the same transducer to sense gestures and produce haptic feedback. Its USB audio setup had a round-trip delay of about 35 ms [Davison and McPherson, 2026]. One designer used this delay as part of an effect that sustained itself through a feedback loop. Another let the felt response guide the timing of the next strike. A third designer needed less delay to control resonances in a guitar’s body. He therefore ran the required filtering directly on the HaptiCoupler’s processor [Davison and McPherson, 2026]. These are different responses to a timing constraint: changing the effect, adapting the playing, or changing the implementation. Their suitability depends on the intended musical interaction.

Timing figures describe particular paths through the instrument.

On two commercial keyboards, Schmid et al. [2024] measured the delay from a key contact closing to its MIDI message reaching the computer. This delay varied by up to 8 ms between key presses. The authors suspected USB polling as the cause. ForceHost ran sound and haptic processing on the device to avoid latency variation from host computers. This was a design rationale, not a measured improvement in mapping quality [Frisson et al., 2022]. An electric-cello study reported a measured signal round trip of 7.7 ms and an estimated additional actuator delay of 4.4–5.2 ms [Järveläinen et al., 2024]. These reports concern different signal paths and distinguish delay from variation in delay. They therefore do not establish a common latency target. A timing requirement for a mapping must specify which action and response it connects.

4.3.3 Frequency Range and Separate Controls

The intended information can lead to a change of actuator or signal.

Knutzen chose voice coils over vibration motors to explore more detailed vibration signals, including cues for pitch, rhythm, and timbre. This was the author’s reason for the choice, rather than a measured advantage in a musical task [Knutzen, 2013]. In the resulting glove, one mapping set the vibration frequency to half the sound’s fundamental frequency. The aim was to keep the vibration within a sensitive tactile range while maintaining a frequency relationship of one octave below the sound [Knutzen et al., 2014].

Some signals were also low-pass filtered at 800 Hz to reduce audible sound from the actuators [Knutzen et al., 2014]. The intended feedback therefore guided both the actuator choice and the adjustment of the vibration signal.

Marshall [2008, p. 138] explains that an uneven actuator response can cause vibration amplitude to change when frequency changes. If frequency and amplitude represent separate musical parameters, the actuator response mixes their effects. A vibrating keyboard used *equalization*, adjusting signal strength at different frequencies, to compensate for the response of its actuators and structure [Papetti et al., 2018]. The audio interface also matters: an inexpensive interface tested for one toolkit weakened frequencies below about 100 Hz [Bukkapatnam, 2019]. We therefore recommend testing the complete output path when frequency and vibration strength represent separate parameters. Changing one should not unintentionally change the other.

A change in frequency can unintentionally change vibration strength.

The Cyclotactor tracked a finger's position above an electromagnet. Averaging the position measurements provided a distance control, while the finger's vibration was used to estimate how stiffly it was held. Distance also affected vibration strength. To account for this, the system was calibrated using vibration measurements taken at several distances with the finger held stiff and relaxed. The two resulting controls were mapped to one noise sound: distance changed the center of its frequency range, and stiffness changed the width of that range [de Jong, 2008]. This processing produced two control values; the demonstration did not establish how accurately players could control them independently.

Accounting for distance makes finger stiffness available as a second control.

In another actuator test, attaching a voice-coil actuator to a stone changed its frequency response and harmonic distortion [Bukkapatnam et al., 2020]. For a single-frequency input, harmonic distortion adds components at whole-number multiples of that frequency. The study also tested an equalization method on an unfinished T-Stick chassis. This method adjusted vibration strength across frequencies but was not designed to correct harmonic distortion. Evaluation in a finished instrument remained future work

Compensation applies to the conditions in which it was tested.

[Bukkapatnam et al., 2020]. We therefore cannot assume that equalization preserves the intended waveform under different loads or contact conditions. A mapping that relies on a particular vibration quality needs that quality checked after mounting and under the intended contact conditions.

4.3.4 Sensing Determines Which Gestures Can Be Mapped

Sensor mechanics change the movement and signals available for mapping.

In the STRIMIDILATOR, attaching a position sensor stopped a released string from vibrating freely. The final instrument used position sensors on two strings and pickup coils that detected vibration on the other two [Baalman, 2003]. In one performance, the position signals controlled the frequency of an engine-like sound [Baalman, 2003]. The sensor choice thus changed both the string's behavior and the kind of input available: displacement on one pair, vibration on the other.

A usable gesture can require different sensing and calibration.

On the Dais, estimating disk rotation from three optical distance sensors was sensitive to noise and calibration errors, making rotation control nearly unusable. The designers replaced this arrangement with an inertial sensor to measure disk tilt and one distance sensor to measure downward displacement [Christensen et al., 2020]. Disk tilt could then control simulated bow speed without the player having to keep the disk moving [Christensen et al., 2020]. A different adjustment was needed on the vibrating keyboard. Because of differences in their mechanics, the keyboard and its reference acoustic pianos had different MIDI velocity responses. The designers used a separate conversion of velocity values for each reference piano to match the keyboard's velocity response to it [Papetti et al., 2018]. These cases show that achieving the intended response to a gesture can require changes to sensing or input conversion.

Combined sensing and actuation can shape the sound model and available controls.

A moving-coil transducer that both sensed and actuated was poor at detecting high frequencies. The designers used two connected virtual plates whose simulated interaction generated a wider range of frequencies from the limited input [Davison et al., 2024]. The sound model therefore

generated additional frequency content from the sensed input. In later deployments, mounting the transducer on a cello or guitar already reduced its vibration. Those designers did not use the separate control value derived from the transducer's damping [Davison and McPherson, 2026]. Two other designers found it difficult to make fine changes through touch at high frequencies [Davison and McPherson, 2026]. Generating a wider range of sound frequencies therefore does not, by itself, demonstrate finer control through touch.

4.3.5 Mapping Approaches and Their Conditions

We group the examples into four approaches: passing sound to vibration, representing system state through force, computing sound and force from a shared model, and encoding information in tactile patterns. This grouping compares how the mappings work. An instrument can combine approaches.

Four approaches use these capabilities in different ways.

In *audio passthrough*, the sound signal also drives vibration. On the HSoundplane, a filter retained frequencies between 10 and 500 Hz before the signal reached the actuators [Pappetti et al., 2023]. The electric-cello study used two alternative vibration signals: a processed bridge signal and a separately generated noise signal. For the noise, the detected pitch controlled a high-pass filter's cutoff, while the bridge signal's amplitude controlled its strength [Järveläinen et al., 2024]. These examples show two ways of linking vibration to sound: processing the sound signal itself, or using selected sound properties to shape a new signal. Section 4.2.4 discusses their effects on playing experience.

Using the sound signal still requires decisions about what reaches the hand.

In Pedrosa's rhythm-following experiment, adding haptic cues did not clearly improve participants' performance. Pedrosa suggests that the audio-derived cue's unclear onset may partly explain this result [Pedrosa, 2007]. He also proposes testing sharper stimuli and different waveforms [Pedrosa, 2007]. Building on this suggestion, we propose testing whether a separately generated pulse with a sharp onset could provide a clearer timing cue. Such pulses can

Changing the signal can preserve one kind of information and remove another.

preserve beat timing while omitting sound features such as frequency content [Altinsoy and Merchel, 2018]. In a series of experiments with twenty participants, Altinsoy and Merchel reported better loop identification with vibration derived from filtered or octave-shifted audio than with beat-triggered pulses [Altinsoy and Merchel, 2018]. Average identification took about six seconds per loop with the audio-derived vibrations and ten seconds with pulses [Altinsoy and Merchel, 2018]. These comparisons require caution: the figures label different instruments across conditions, leaving unclear whether the same loops were used [Altinsoy and Merchel, 2018]. We infer that signal adjustment should preserve the information needed for the task. Identifying a loop and playing in time are different tasks, so these results do not establish which cue best supports rhythmic performance.

A programmable control
can feel different for
different parameters.

In *state-to-force mapping*, a haptic effect represents a parameter or instrument state. Verplank [2005, p. 257] describes a stick that controls pitch, with note positions marked by valleys between shallow bumps. A programmable knob changed its feedback according to the selected sound control: discrete choices used detents, while some continuous controls used constant or variable resistance [De Pra et al., 2021, p. 118]. This allows the same physical control to feel different for different parameters. When detents are used, the designer must decide which parameter values they mark (Section 4.2.3).

A shared model lets the
player act on the virtual
object that produces
sound.

A *shared physical model* computes sound and force from the same simulated interaction. Castagné et al. [2004] describe connecting the player’s movement and force to the sound-producing mechanism in this way. For the MSCI platform, the authors describe several possible interactions with individual points of a simulated string. Pressing it against a fretboard can change its pitch, while light pressure at selected points can produce natural harmonics. Pressure near the bridge can damp the string [Leonard et al., 2018]. The resulting sound and force depend on where and how the player interacts with the model. These interactions depend on the model’s update rates and its coupling to the haptic device (Section 4.3.1).

In *symbolic mappings*, tactile patterns have assigned meanings that the player can learn. Michailidis [2015] developed patterns that marked events, continued while a function was active, or signaled upcoming changes in the music or electronics. A related glove mapping varied how quickly vibration strength repeatedly rose and fell as the sound changed from dull to bright [Knutzen et al., 2014]. These examples convey selected information without reproducing the sound waveform. We infer from the response limits in Section 4.3.3 that the hardware must preserve the signal differences that carry this information. Whether players can distinguish and interpret these differences also needs testing in the intended musical task.

Tactile patterns can convey selected events, states, and sound features.

Table 4.2 brings these connections together. It distinguishes reported changes from the implications we draw for further design.

The comparisons identify specific adjustments to mappings.

Our answer to RQ2 is that implementation can change both the musical controls an instrument offers and how the player experiences them. Designers replaced or calibrated inputs and changed how signals depended on one another. They also filtered or rebuilt feedback to convey selected musical information. Shared models allowed interactions at different contact points to shape sound and force. Timing changed perceived control even when the programmed triggering rules stayed the same. These cases identify several reasons to adjust a mapping: sensing may limit the intended control, the delivered feedback may lose relevant distinctions, or delay may disrupt the intended interaction. The proposed adjustments need testing when applied to another instrument or musical task.

Implementation shapes available controls, feedback, and the experience of playing.

4.4 RQ3: Matching Evaluation Methods to Subjective Experience

RQ3 asks which evaluation methods are suitable for assessing different aspects of subjective experience. An earlier framework included both functional tests and an exploratory study in a creative setting [Young, 2016]. We examine how studies in the corpus use these methods to assess perceived control, engagement, comfort, and preference. We also consider how these experiences change with

Evaluation methods should match the aspect of experience being studied.

Implementation condition	Reported effect on mapping or control	Implication and limit
Different update rates and device responses	A bowed-string model's output was split between force and vibration devices.	Consider separate outputs for different frequency ranges; benefits for playing experience still require testing (Section 4.3.1).
Delay in sensing and feedback	Delay changed perceived control. Designers also incorporated delay into effects or moved processing onto the instrument.	Set timing requirements for the intended musical interaction; these cases establish no universal delay target (Section 4.3.2).
Frequency range and uneven response	Glove signals were shifted in frequency; keyboard vibration was equalized.	Adjust and test the delivered vibration under the intended mounting and contact conditions (Section 4.3.3).
Coupled or unreliable input measurements	The stiffness estimate was calibrated for distance; unreliable disk sensing was replaced before mapping tilt to bow speed.	Check that the inputs support the intended controls. Independent control of distance and stiffness still needs evaluation on the Cyclotactor (Sections 4.3.3 and 4.3.4).
Access to model points or programmable force	MSCI authors described possible string contacts for changing pitch, producing harmonics, and damping. A knob changed feedback with its selected parameter.	Choose contact points or force effects that support the intended interaction; these examples do not establish which approach works better (Section 4.3.5).

Table 4.2: Selected connections between implementation and musical mappings, with the design implications and limits we draw from them.

practice. For each method, we compare what it revealed, the playing context, and the questions it left unanswered.

4.4.1 Perceived Control and Responsiveness

Perceived control and measured performance can give different answers.

The Haptic Bowl comparison found differences in reported experience without significant differences in movement time or pitch-selection accuracy [Young et al., 2018]. The latency study found lower ratings of instrument quality, including temporal and dynamic control, under 20 ms latency and under 10 ms latency with ± 3 ms jitter. Mean tim-

ing error in a separate metronome task did not differ significantly between latency conditions. However, timing variability was greater with $10 \text{ ms} \pm 3 \text{ ms}$ jitter than with zero or constant 10 ms latency for quarter and eighth notes [Jack et al., 2016]. These results show that mean timing error or accuracy alone does not capture participants' reported experience or every aspect of performance. Evaluations should therefore report subjective ratings and relevant task measures separately, including both average performance and timing variability.

In the latency study, some participants felt that the instrument responded differently to their strikes when latency was added. Some reported having to hit harder, although the routine that detected strikes and triggered sound was unchanged [Jack et al., 2016]. The interviews helped explain the poorer dynamic control ratings: some players felt they needed more force to produce the sound they wanted. We recommend pairing control ratings with questions about specific gestures and responses. These accounts describe the difficulty players experienced, but cannot establish its technical cause on their own.

Interviews can clarify what a control rating means.

The experiments summarized by Papetti et al. [2023] used free playing to assess qualities such as engagement, naturalness, and dynamic control. The authors argued that restricting how participants played would limit their expression. Their separate performance tests used simpler tasks to make the conditions easier to compare. The authors questioned whether these tasks were too easy for trained musicians to reveal a possible benefit [Papetti et al., 2023]. These examples support matching the task to the outcome being assessed. Free playing gives musicians room to explore the instrument before rating their experience. A performance task may fail to reveal a difference if it is too easy for the participants. The concern about task difficulty does not establish that an undetected benefit exists.

The playing task must allow the quality being rated to emerge.

4.4.2 Engagement, Stimulation, and Preference

Different experience questions can produce different results.

After short composition tasks, participants gave the touch-screen interface higher stimulation ratings when tactile feedback was present. On the questionnaire, it was rated as more "innovative", "captivating", and "challenging". Ratings of practical usability did not differ significantly [Altinsoy and Merchel, 2018]. PalmBeat illustrates another distinction. Twenty-four non-musicians listened to music with or without force feedback. Ratings of the urge to move, used there to measure groove, differed between conditions; engagement ratings did not differ significantly. Groove ratings were collected after each excerpt, while engagement ratings were collected after each condition [Sun et al., 2021]. This was a listening study, so it does not establish how the device affects playing experience. Together, these cases support choosing questions that address the intended quality and stating when each rating was collected. Results for each quality should be reported separately.

A preference judgment and the reasons behind it need different questions.

In the electric-cello study, players could switch between two setups while playing. They then stopped and rated one quality at a time, including preference [Järveläinen et al., 2024]. In the knob study, an interview asked which modes participants liked most and least, and why [Piao et al., 2024, Table 1]. Two participants preferred the Smooth mode's low resistance, while another found its lack of force feedback difficult for rapid vibrato [Piao et al., 2024]. We therefore distinguish recording a preference from explaining it. A preference rating records the participant's judgment. Questions about playing help explain what they found helpful or difficult.

A questionnaire's items may not form a consistent scale in a particular sample.

In a Haptic Bowl evaluation with ten musicians, three User Experience Questionnaire scales showed poor *internal consistency*. Responses to items within the efficiency, dependability, and novelty scales were weakly related in this sample [Young and Murphy, 2015]. The scores for these scales therefore need cautious interpretation. This supports reporting internal consistency for each scale in the study. The finding does not show that questionnaires generally fail in small samples.

4.4.3 Comfort and the Physical Experience of Playing

The knob study collected comfort ratings after participants completed the vibrato task in each mode. It described comfort as feeling "physically pleasant and stress-free" during the task [Piao et al., 2024]. The interviews linked participants' preferences to feedback strength and the ease of making rapid movements [Piao et al., 2024]. We therefore suggest collecting a comfort rating after a defined task, then asking which movements or force levels influenced it. Comfort ratings did not differ significantly between modes in this study [Piao et al., 2024].

Comfort questions should address the physical interaction directly.

The Haptic Bowl evaluation with ten musicians also used the NASA Task Load Index. It asked separately about mental demand, physical demand, and how hard participants felt they worked [Young and Murphy, 2015]. These workload ratings do not identify where discomfort occurs or show how comfort changes during longer playing. The reports of excessive feedback strength in Section 4.2.6 motivate a further proposal. We suggest repeating comfort and effort questions during longer playing sessions. Each rating should be linked to the movement, feedback level, and time spent playing. This would help identify whether and when discomfort or effort changes.

Physical demand, effort, and comfort should remain distinct.

4.4.4 Adaptation, Expressivity, and Musical Practice

In the HaptiCoupler study, seven designers completed an exploration in their own working environments. They had at least three weeks to work with the kit. Concluding interviews examined the designs and participants' experiences of using them [Davison and McPherson, 2026]. The accounts described changes to materials, mounting, and ways of playing, along with the designers' reasons for these choices. The study did not measure improvement in playing skill over time. Its findings came mainly from the resulting designs and final interviews, while the instruments themselves were changing.

Extended use can reveal how a technology enters design practice.

Rehearsal and withdrawal can show that feedback has become expected.

In Michailidis's case study, a performer rehearsed using footpedals that triggered vibration on his shins. After the vibration was switched off without warning, he stopped and asked whether the motors were working [Michailidis, 2015]. Later, the same performer said that using the pedals without vibration would feel unnatural [Michailidis, 2015]. These observations support a specific conclusion: the feedback had become expected in that interaction. Weekly rehearsals also involved changes to the hardware, software, and score [Michailidis, 2015]. The case therefore cannot isolate an improvement in expression caused by vibration alone. To study changes with practice, we would record the player's behavior alongside changes to the instrument and score.

Interviews can connect reported experience to specific musical tasks.

In a Haptic Bowl study, six musicians took part in individual studio sessions lasting about four to five hours. After each feedback condition, interviews asked which feedback features had helped or hindered the musical tasks [Young et al., 2017]. The authors derived their preference ordering from these accounts; the paper reports no separate ranking measure [Young et al., 2017]. This approach connects reported experience to specific musical activities. The participants had taken part in earlier experiments and already knew the devices. These sessions therefore do not show how new users would learn to play them.

4.4.5 Interviews and Observation Across Experience Questions

Interviews can clarify different kinds of support during group playing.

In an ensemble study, twenty-one participants played in seven trios. Data corruption left nineteen usable responses for some questionnaire items [Preuschoff et al., 2026]. No questionnaire item showed a significant difference between the three feedback modes. Interviews revealed different experiences of feedback from each player's own instrument. Some participants said it helped them identify their own sound, while others felt less aware of the group [Preuschoff et al., 2026]. These accounts distinguish recognizing one's own contribution from remaining aware of other players. They can inform more specific evaluation questions, but

do not establish a statistically significant advantage for any mode.

In the Daïs evaluation, one of six participants mentioned haptic feedback without a specific prompt. All six reported noticing it when asked directly [Christensen et al., 2020]. This suggests that participants may notice haptic feedback without mentioning it in response to open questions. We therefore recommend starting with open questions, then asking neutral questions about touch. The analysis should distinguish spontaneous comments from responses to these direct questions. However, the responses do not establish why participants had not mentioned the feedback earlier. The authors suggest that it either had too little effect on playing to prompt a comment or felt like a natural part of playing [Christensen et al., 2020].

Direct questions can reveal haptic experiences that participants do not mention on their own.

4.4.6 Attributing Differences to Haptic Feedback

The knob comparison in Section 4.2.3 used the same device with and without programmed force feedback. The Haptic Bowl comparison also changed the sensing arrangement and movement restrictions (Section 4.2.2). Changes in the Bowl ratings therefore cannot be attributed to feedback alone. We recommend documenting differences between conditions in sensing, movement restrictions, and sound delivery. Each condition should also describe any passive resistance and vibration that remain when added feedback is switched off. For example, the electric cello retained vibration from its strings in the reference condition [Järveläinen et al., 2024]. A condition labeled “no feedback” therefore needs a clear definition of what was removed and what remained.

A comparison must identify what changed besides the feedback.

In the subjective comparison of the latency study, participants were asked to compare instrument settings without being told that delay was changing. The sound samples also changed to help conceal the latency changes [Jack et al., 2016]. In the cello study, participants were not told how the two setups differed or that the experiment concerned vibration. They wore earmuffs over earphones to re-

Report what participants were told and how unwanted sound was reduced.

duce sounds coming directly from the instrument and actuator [Järveläinen et al., 2024]. These procedures address different possible influences on participants' judgments. Reports should explain what participants were told, what was concealed, and how unwanted sound was reduced.

Sound and musical
material can influence
ratings.

In a separate perception experiment reported by Altinsoy and Merchel [2018], participants rated the same tactile feedback as stronger when the accompanying sound was louder. The PalmBeat authors reported that musical excerpts had a greater influence on urge-to-move ratings than the feedback condition [Sun et al., 2021]. These findings support keeping sound and musical material constant, or systematically varying them, when evaluating the effect of haptics. If the intended experience combines sound and touch, the conclusion should make clear that it concerns this combined experience.

4.4.7 Participants and Uncertainty

Experience matters in
relation to the task
being evaluated.

O'Modhrain used different study designs for participants new to bowed instruments and experienced string players. Comparing their results therefore does not isolate an effect of expertise [O'Modhrain, 2000]. In an audio-latency task, higher scores on the Gold-MSI self-report questionnaire were linked to detecting smaller differences in delay. The questionnaire assesses musical sophistication [Schmid et al., 2024]. In a separate vibration-detection study, an overall musician advantage could not be confirmed [Fontana et al., 2018]. These studies measured different abilities. They support describing participants' relevant experience and how it was measured, then examining how it relates to the specific outcome.

An average should be
accompanied by
variation and
uncertainty.

Participants in the latency study disagreed about which conditions they preferred [Jack et al., 2016]. The cello study showed widely spread ratings and reported 95% *credible intervals*. These intervals express uncertainty about the estimated mean ratings under the study's statistical model. All eight included the point at which the added-vibration and reference setups were rated equally [Järveläi-

nen et al., 2024]. We therefore recommend showing participant variation alongside estimates and their uncertainty. Intervals that include equal ratings do not establish that the conditions give the same experience.

Table 4.3 connects the experience questions to methods used in these cases. Its recommendations depend on choosing an activity suited to the question and keeping conclusions within the limits of the evidence.

Each method supports a particular kind of answer.

Experience question	Method supported by the cases	What the answer establishes
Does the instrument feel controllable and responsive?	Rate perceived control for a defined playing task, then ask about particular gestures.	Perceived control; add timing or accuracy measures to examine performance separately (Section 4.4.1).
Is the interaction engaging or stimulating?	Use questions for the named quality, state when ratings were collected, and report internal consistency for each scale.	The named quality in the tested activity; engagement and stimulation should be interpreted separately (Section 4.4.2).
Which condition is preferred, and why?	Compare conditions directly, then ask what helped or hindered the playing.	Preference and participants' reasons; these do not establish better performance (Section 4.4.2).
Is the physical interaction pleasant or demanding?	Ask about comfort, physical demand, and effort separately, tied to the task and feedback level.	Experience during the tested playing period; comfort over longer periods requires repeated assessment (Section 4.4.3).
How does feedback enter musical practice?	Follow rehearsals or deploy the instrument, then examine its use and changes through observation and interviews.	How feedback becomes expected or is used in that setting; changes to the instrument limit attribution to feedback alone (Section 4.4.4).

Table 4.3: Evaluation methods linked to the experience questions they can address.

Our answer to RQ3 is to match the method to both the experience question and the playing situation. Ratings compare named qualities; interviews tied to particular gestures explain participants' judgments; repeated work with an instrument can reveal how feedback becomes expected or enters practice. The cases show why preference, physical demand, and measured performance must remain separate results. Attributing a difference to haptics also depends

The experience question, playing task, and evidence must fit together.

on the comparison condition, sound, and what participants know. These are not a validated protocol for every instrument, but conditional method choices.

4.5 Limits of the Design Guidance

The comparisons leave
important choices
unresolved.

The evidence discussed in this chapter does not settle whether active force feedback or vibration is preferable on an otherwise identical instrument. The Haptic Bowl comparison involves passive resistance and different sensing arrangements (Section 4.2.2). Measurements of individual actuators identify implementation constraints, but they do not establish improvements in musical experience by themselves (Section 4.2.5). These are limits on what the present comparisons support.

Transfer requires
checking the conditions
that made a finding
relevant.

The resulting guidance is conditional. A designer should identify the musical role of the feedback, check whether the implemented system can deliver it, and evaluate the quality she intends to change. The next comparison should address what remains unresolved for that instrument. It might test whether passive resistance is sufficient, how processing changes the feedback signal, whether players feel more control, or how their use changes with practice. These questions connect the three research questions and define where further evaluation is needed.

Chapter 5

Summary and Future Work

5.1 Summary

This thesis examined how research on haptic feedback can guide the design of digital musical instruments. We reviewed a corpus of 109 reports selected through the process described in Chapter 3. The synthesis connects feedback selection, technical implementation, musical mappings, and evaluation of the playing experience. Its contribution is to explain when findings from one instrument can inform another and which conditions require further testing.

Connecting the design decisions.

For RQ1, the synthesis derives choices from specific task requirements and outcomes (Section 4.2). Detents can mark useful target positions but need a bypass when intermediate values matter. Sound-related vibration improved rated expression and enjoyment on a touch surface, with uncertain benefits on an electric cello. A separate vibration actuator extended the output of a force device that lost required frequency components. Existing feedback, contact conditions, and playing technique qualify these choices. The comparisons inform particular configurations; they leave the choice between active force and vibration unresolved on an otherwise comparable instrument.

Feedback choices depend on the task and intended outcome.

Implementation shapes the mapping.	For RQ2, the synthesis explains how implementation led designers to change their mappings (Section 4.3). It connects sensing, processing, and actuation to specific adjustments in musical control. It also distinguishes these changes from timing effects on the experience of an unchanged mapping. The resulting guidance identifies what may need adjustment and why; applying it to another instrument requires further testing.
Evaluation follows the question.	For RQ3, the synthesis connects the experience question, playing task, and evidence (Section 4.4). Ratings compare named qualities, while questions about particular gestures explain the judgments. Rehearsals and deployments reveal how feedback enters practice. The comparisons also show why comfort, preference, and task performance need separate answers. The guidance identifies what each method can establish and how comparison conditions, participant knowledge, and uncertainty limit claims about what haptics changed.

5.2 Limitations

Limits of the search.	The review's coverage is bounded by its search and eligibility decisions. As described in Section 3.1, the database queries used different vocabularies: only the NIME query included the term <i>tactile</i> . Relevant work using that term alone could therefore have been missed elsewhere. The searches also ended in July 2026, and some candidate reports could not be obtained (Section 3.4). The exclusions in Section 3.2.2 further limit the contexts represented. These choices mean that the corpus provides a defined basis for comparison, with possible omissions.
Limits of the review process.	The author alone made the screening and eligibility decisions, as reported in Section 3.3. No second human reviewer independently checked the extracted data. We performed no formal study-quality, risk-of-bias, reporting-bias, or certainty assessment, and no sensitivity analysis. Selection errors and errors in interpreting the reports may therefore remain. The conclusions should be read with these limits in mind.

The evidence supports benefits in particular settings, with different limits on what each result establishes. In the HSoundplane study, vibration consistent with the sound's pitch and dynamics improved perceived expressiveness and enjoyment [Papetti et al., 2023]. Detent feedback improved vibrato pitch accuracy compared with no force feedback in a knob study [Piao et al., 2024]. Technical output, enjoyment, and task accuracy are different outcomes; evidence for one cannot substitute for evidence about another (Section 4.1). These findings can inform design together, while the guidance remains conditional on the instrument, task, and evaluation (Section 4.5). The suggested connections provide starting points for design, but they still require testing when applied in another setting.

Limits of transfer.

5.3 Future Work

A direct next step is to extend earlier work on combining vibrotactile and active force feedback on a common instrument. Pedrosa [2007] proposed separate and combined feedback configurations, with musical accuracy and comfort measures. Giordano et al. [2012] implemented a force-feedback device with added vibration and compared its measured output with the vibration actuator switched off. Building on this work, we propose a player study comparing vibration, active force, their combination, and no added actuation. It would address the comparison limits identified in Section 4.2.2. The sensing arrangement and sound should remain comparable, and each condition should document its passive resistance and residual vibration. Measuring performance in a defined musical task alongside ratings of control and comfort would relate task outcomes to the player's experience.

Comparing feedback on one instrument.

A second direction is to extend a mapping comparison while varying contact conditions (Section 4.3). Knutzen et al. [2014] compared sound-derived and synthesized cues and proposed testing them in defined musical tasks. Other comparisons already include loop identification [Altinsoy and Merchel, 2018] and pitch matching [Papetti et al., 2023]. We propose comparing sound-derived vibration with beat-

Testing the delivered mapping.

triggered pulses on one instrument under different hand contact forces. Measurements would characterize the delivered signals under each condition. With the sound muted, participants would identify short loops from their vibration, choosing from a fixed set. Accuracy and identification time would show whether contact force changes the usefulness of either mapping. Keeping the interface and loops fixed would isolate this comparison from changes in the musical material.

Following changes with
practice.

Repeated sessions could extend existing observations of how feedback becomes part of a player's technique. Michailidis [2015] followed a performer through months of rehearsals, including changes to the technology and responses to feedback withdrawal. Marshall and Wanderley [2011] also proposed tracking ratings as players developed skill. We propose building on these approaches with repeated ratings of comfort, effort, and control during practice, alongside observation and interviews. These measures would address the questions discussed in Sections 4.4.3 and 4.4.4. Periods with unchanged instrument settings would allow changes during practice to be examined under stable conditions. The study should also record any redesigns alongside changes in playing, to help interpret their effects. This would provide a more consistent basis for comparing reported comfort and effort across sessions.

Testing the guidance in
design.

Finally, the guidance itself could be evaluated through the development of further instruments. Young [2016] provides a precedent by applying an evaluation framework to prototype instruments. Designers could use Tables 4.1, 4.2, and 4.3 to record their feedback choices, technical assumptions, and evaluation questions. They could then compare those assumptions with measurements and players' accounts. Applying this process to different instrument families would test whether these particular tables identify useful design questions and where they need revision. The resulting comparisons could show which recommendations transfer across instruments and which require narrower conditions.

Appendix A

Corpus Overview and Extraction Matrix

A.1 Corpus Overview

Tables A.1 and A.2 summarize the 109 included reports by haptic modality and publication venue or document type. Each report is counted once within each table, including reviews and related publications. These totals describe the corpus rather than independent instruments or experiments.

Category	Reports
Vibrotactile feedback	41
Active force feedback	30
Both modalities	14
Reviews covering both modalities	2
Neither qualifying modality	22
Total	109

Table A.1: Haptic modality under the definitions in Section 3.5.

Category	Reports
NIME	46
ICMC	4
Audio Mostly	3
CHI	2
CMMR	2
DIS and DIS Companion	2
EuroHaptics	2
IEEE Haptics Symposium	2
Sound and Music Computing	1
Haptic and Audio Interaction Design	1
TEI	1
NordiCHI	1
Creativity and Cognition	1
SIGGRAPH Emerging Technologies	1
Digital Audio Effects	1
Augmented Human	1
International Congress on Acoustics	1
Music Technology Workshop	1
Arts	5
Computer Music Journal	2
Actuators	1
IEEE Transactions on Haptics	1
Journal on Multimodal User Interfaces	1
Multimodality and Society	1
Sensors	1
Vibration	1
Musical Haptics (book chapters)	8
Other book chapter	1
PhD theses	6
MSc theses	2
MA theses	3
Master's thesis (degree unspecified)	1
MSc thesis proposal	1
arXiv preprint	1
Total	109

Table A.2: Publication venues and document types of the included versions. NIME includes its 2001 CHI workshop; the arXiv version is counted separately. Master's degrees and the MSc proposal are distinguished.

A.2 Extraction Matrix

How to read the matrix. Tables A.3 and A.4 present hardware and evaluation information, respectively, for the included reports. Each report has one row in each table. Reports may describe several devices or overlapping experiments; participant counts retain their stated study and condition.

Modality. VT: vibrotactile feedback; FF: active force feedback; VT/FF: both; REV: a review or synthesis covering both; N: neither under these definitions. FF requires active force actuation; passive mechanics and programmable resistance alone are excluded.

Technical data. Frequency entries distinguish actuator ratings, measured response, signal filters, stimuli, and sensing. Latency entries identify the relevant path, configuration, and bounds where available. Estimates and information about earlier systems retain their qualifications. A dash (–) marks a missing or inapplicable entry

Table A.3: Hardware, modality and technical data for the 109 reports.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Altinsoy and Merchel [2018] altinsoy-2018	Audio-driven vibrotactile touchscreen groovebox and mixing prototype	Touchscreen	VT	electrodynamic exciter (Monacor BR-25)	Tactile-signal low-pass cutoff: 1 kHz.	Background touchscreen limits (Kaaresoja): tactile ≤ 25 ms; audio ≤ 100 ms.
Baalman [2003] baalman-2003	The STRIMIDILATOR	String controller (pull/push deviation and vibration)	N	Two linear sensors on the inner strings; two pickup coils on the outer strings (sensing).	–	–
Bak et al. [2015] bak-2015	Motors & Music platform: Plank and motorized sliders	Motorized faders and a single-axis lever	VT/FF	Plank: voice coil; motorized sliders: DC motors.	Initial audio-engine sampling: 15 kHz.	–
Battay et al. [2015] battay-2015	Haptic software toolkit and test cases, culminating in the Multistate Complex Arpeggiator	Phantom Omni haptic arm.	FF	Phantom Omni haptic device.	Technical background distinguishes audio processing (e.g. 44.1 kHz), Pd/Max control rate (1000 Hz), and OSHA/Max audio vector size of one sample; these are not measured prototype bandwidth.	General force-feedback specification: latency ≤ 1 ms, with very little jitter.
Beamish [2003] beamish-2003	D/Groove: haptic turntable, motorized Q-slider and pitch slider	Turntable, Q-slider and pitch slider, with graphical interface	FF	turntable: Maxon RE035 DC motor; Q-slider: Faulhaber 1524-SR DC micromotor	Sensing/control loops: 1 kHz (two motor loops and pitch-slider sensing); audio: 44.1 kHz, 128-sample buffer; GUI polling: 10 Hz.	D/Groove reported latency < 6 ms; audio-playback component measured at 3 ms on a 1.2 GHz system.
Berdahl and Kontogeorgakopoulos [2012] berdahl-2012	FireFader and derivatives: Sound Flinger, PROJECT SQUEEZE pincher and String-U-Topia	Slider/fader and derivative interfaces, including a pincher	FF	Motorized fader: linear potentiometer coupled to a DC motor.	–	Measured average control round trip: ≈ 3.5 ms (OS X, Max/MSP 5).
Berdahl et al. [2008] berdahl-2008	Haptic Drum and Cellomobo examples in a practical overview	Percussion (Haptic Drum) and bowed (Cellomobo)	REV	Implemented examples: servomotors with encoders, Cellomobo shaker, and haptic-drum woofer. The paper also reviews other actuator options.	Reviewed control platforms, maximum sampling rates (Table 2): ATMEL ≈ 20 kHz, DIMP 1 kHz, TFCS 40 kHz; ASP 96 kHz typical.	Cellomobo: ≈ 20 ms system delay in the audio signal processing environment.
Berdahl et al. [2009] berdahl-2009	HSP platform with NovInt Falcon; haptic drum and force-profile examples	Three-dimensional grip	FF	NovInt Falcon controlled from Pure Data through the np_nifalcon external and HSP wrapper; grip position input and commanded 3D force output.	–	–
Berdahl et al. [2009] berdahl-2009b	Haptic virtual instrument using explicit or implicit digital-waveguide control junctions	Virtual string (plucked, bowed and finger-damped)	FF	Phantom Model T haptic device directly coupled to a digital-waveguide model through a control junction.	Servo/audio sampling: 19 kHz (Phantom Model T bowing demonstration).	Explicit control junction: two single-sample delay units.
Berdahl et al. [2018] berdahl-2018	FireFader-based instruments for the Laptop Orchestra of Louisiana	Slider/fader	VT/FF	FireFader: two motorized faders per device; one device built for each performance station.	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Birnbaum [2007] birnbaum-2007	Touch Flute, Breakflute and FA/SA vibration synthesizer	Keyed wind controller (Touch Flute) and open-tonehole flute (Breakflute)	VT	Both flutes: voice-coil mouthpiece Skin Stimulator; miniature voice coils on Touch Flute keys; modified loudspeakers in Breakflute toneholes.	FA/SA (Fast Affrent, Slow Affrent) synthesized vibrotactile-event signal bandpass: 0.4–500 Hz.	–
Birnbaum and Wanderley [2007] birnbaum-2007b	Tactilicious Flute Display (TFD)	Open-tonehole flute body used as a vibrotactile display, with no controller input	VT	Modified miniature voice-coil stimulators.	Vibrotactile pitch mapping: 40–400 Hz.	–
Branje [2014] branje-2014	Vibrochord, Emoti-Chair and Toronto System of Vibrotactile Music (TSVM)	U-shaped keyboard controller driving a chair-based vibrotactile display	VT	voice coils (16 in the Emoti-Chair; 8 independent channels)	TSVM: eight stimulus notes, 40–421.65 Hz (Table 3); opening prose gives 412.65 Hz.	–
Bukkapatnam [2019] bukkapatnam-2019	Pre-characterized vibrotactile toolkit	Actuator and amplifier toolkit; demonstrated in an unfinished tubular gestural controller chassis	VT	Haptuator voice-coil actuators in the final toolkit; TDK piezoelectric actuator tested and excluded.	Reported toolkit bandwidth: 40–1000 Hz; lowest characterized total harmonic distortion: 150–1000 Hz.	Reviewed prior Soundplane interface [8]; low latency of a few milliseconds; attributed to the interface underlying HSoundplane, not to this thesis prototype.
Bukkapatnam et al. [2020] bukkapatnam-2020	Pre-characterized vibrotactile toolkit	Actuator and amplifier toolkit; demonstrated in an unfinished tubular gestural controller chassis	VT	Haptuator voice-coil actuators in the final toolkit; TDK piezoelectric actuator tested and excluded.	Unloaded voice coils: broadly uniform at 100–1000 Hz; sandbag-mounted mk-II attenuates below 300 Hz at 0.5 V RMS white noise. Test band: 40–1000 Hz.	–
Cadoz et al. [1990] cadoz-1990	Modular Feedback Keyboard (MFK)	Keyboard	FF	“Sliced motor”: flat moving coils interleaved with polarization magnets.	Mechanical-phenomena design requirement: up to 700–800 Hz (not a measured device response).	Measured actuator input-control response delay: 0.2 ms with coil movement blocked.
Cadoz et al. [1984] cadoz-1984	CORDIS system with Florens’ stick/carriage and single retroactive key	Sliding stick and piano-like key	FF	electric motor with electrodynamic clutches; motorized key transducer	–	Algorithmic one-step delay: positions at n use forces at n-1.
Carlson et al. [2011] carlson-2011	The Sound Flinger	Motorized linear faders around a square enclosure	FF	Four motorized linear potentiometers (ALPS RSA0N11M9A05).	–	–
Castagné et al. [2004] castagne-2004	Position paper; summarizes TGR with an ERGOS adapter for a virtual bowed string	Bowed-string case study; no new artifact	FF	Reported violin case study: TGR haptic device with a specific mechanical adapter from the ERGOS system.	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Christensen et al. [2020] christensen-2020	The daïs	Box with a disk suspended on elastic string above proximity sensing	VT	Two voice-coil vibration transducers with attached masses.	Sensing: IMU 100 Hz; proximity sensor 2.5 ms per measurement (reported maximum rate).	–
Davison and McPherson [2026] davison-2026b	HaptiCoupler kit, incorporated into participants' varied musical systems	Enclosed transducer with added plates, bowing tops, or cello-body and guitar installations	VT	Single voice-coil transducer for simultaneous sensing and actuation.	Wide-audio-band actuation; sensing response declines above approximately 500 Hz; transducer impedance resonance at 100 Hz.	≈35 ms USB-audio round-trip latency.
Davison et al. [2024] davison-2024	Self-sensing voice coil controller for a two-plate nonlinear physical modelling synthesizer	Surface transducer with fingertip contact on its enclosure	VT	Voice-coil surface transducer.	Second-order low-pass filters at 1 kHz on actuation and sensed excitation signals; selected transducer resonance: 350 Hz.	–
Davison et al. [2026] davison-2026	Review; cites HaptiCoupler and self-sensing voice coil system as prior work	No new artifact	REV	Review examples include self-sensing voice-coil transducers for physical modelling synthesis and motorised faders using a DC motor actuator.	Audible-band control requirement: sample-by-sample processing with round-trip rates exceeding 40 kHz; audio sampling rate alone is insufficient.	Background digital-system round trip: near 1 ms (purpose-built embedded); multiple ms (general-purpose computers).
de Jong [2008] de-jong-2008	Cyclotactor	Finger-worn magnet and reflector moving vertically above an electromagnet	VT/FF	electromagnet acting on a finger-worn permanent magnet	Tactile output sampling: no higher than 200 Hz; proximity input sampling: 400 Hz (previously 100 Hz).	Claimed sensor → audio ≤10 ms; cited sensor → tactile target 1–2 ms for recreating the kinaesthetic sense of touching a surface, with output-rate/actuator-response improvements needed.
Egloff et al. [2018] egloff-2018	Psychophysical apparatus with fingertip and flank actuators	Bench apparatus: fingertip contactor in a block and contactors strapped to the flank	VT	Broadband voice-coil actuators.	Actuator response described as flat at 65 Hz per hardware specifications; actual transfer functions unmeasured.	Programmed experimental timing: 500 ms inter-stimulus interval within each melodic interval, 1000 ms between successive melodic intervals, and 750 ms inter-trial interval; not measured system latency.
Eldridge et al. [2021] eldridge-2021	Review; includes Feedback Cello, halldorphone and Overtone Fiddle	Survey: bowed and plucked strings, springs, wind instruments, drum membranes and devices for varied surfaces	VT	SRI mechanism: actuator and pickup coupled through resonant material in an analog/digital feedback loop.	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Florens et al. [2004] florens-2004	ERGOS modular force-feedback system	Tabletop base with keyboard, joystick/stick, ball, pliers and bowing-stick adapters	VT/FF	ERGOS: linear electrodynamic voice-coil actuator with stacked flat moving coils.	Position-sensing bandwidth: 0 to >10 kHz. Bowed-string application: computation 30 kHz; reactive loop 3 kHz.	Force setting: 100 μ s (0→200 N); 50 μ s (0→50 N).
Fontana et al. [2018] fontana-2018	Touch-Box test rig (Experiment 1) and keyboard apparatus (Experiment 2)	Flat panel pressed with one finger and keyboard	VT	Touch-Box: Tactile Labs Haptuator mark II moving-magnet voice-coil actuator (technical details in the companion chapter).	Experiment 1 stimuli: white noise band-passed at 50–500 Hz (48 dB/octave cutoffs) and a 250 Hz sine.	–
Frisson and Wanderley [2023] frisson-2023	Review illustrated with TorqueTuner and ForceHost	Illustrative rotary module; reviewed keyboards, bowed, percussion, fader, turntable and stylus devices	FF	Review of electrical-motor force-feedback devices: impedance control, serial/parallel mechanisms, commercial 3/6-DoF devices and modular TorqueTuner implementations.	–	–
Frisson et al. [2022] frisson-2022	ForceHost firmware toolchain	Rotary motor interfaces and turntable example; linear and multi-axis support proposed	VT/FF	ForceHost on ESP32 hosts; Mechaduino guest board for stepper motors and Mjbots Moteus for BLDC motors, linked through I2C.	Tested Mechaduino loop: ≤ 6 kHz with I2C; haptic control rate equals audio sample rate divided by buffer size.	–
Gentili-Morin and Wanderley [2024] gentili-morin-2024	R-FF (Reed Force Feedback) library on TorqueTuner	Knob/rotary	FF	brushless motor	–	–
Giordano et al. [2012] giordano-2012	Vibration-enhanced Phantom Omni	Haptic-arm handle controlling a bowed-string model	VT/FF	Tactile Labs Haptuator vibration actuator; Phantom Omni motors.	Haptuator rated: 50– ≥ 500 Hz; Omni chirp-response notches near 20, 37–50 and 90–120 Hz, varying with axis and amplitude.	Estimated unfiltered audio-path delay: ≈ 22 ms (Omni accelerometer response to Haptuator control voltage); excludes 1 ms closed-loop feedback delay.
Giordano et al. [2018] giordano-2018	Tactile-augmented garments for a wearable score	Wearable belt and elastic band	VT	Garments: eccentric rotating mass actuators.	Legato tacton amplitude envelope: two sine-wave periods over 1000 ms, varying from 20% to 100% duty cycle (envelope modulation, not vibration carrier frequency).	Programmed tacton gaps: symbolic-pattern repetitions are separated by 300 ms; the three staccato vibrations have 100 ms intervals. Stimulus timing, not measured system latency.
Havryliv et al. [2009] havryliv-2009	Haptic Carillon baton prototype for an electronic practice clavier	Carillon keyboard with downward-struck batons	FF	Electromagnetic linear actuator controlling baton position.	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Hayes [2015] hayes-2015	Skin Music installation	Chaise longue for a reclining listener	VT	Six vibration motors driven by pulse-width modulation; two tactile transducers for 60–70 Hz signals.	Tactile-transducer drive signals: 60–70 Hz.	–
Helppolainen [2024] helppolainen-2024	HapSynth	Slider / fader	VT/FF	motor in Bourns PSM60-081A-103B2 motorized slide potentiometer	–	–
Hinrichsen and Bovermann [2016] hinrichsen-2016	3DMIN prototypes: Organum Vivum, Entangle, S/A/S/A, SUM 0.2, Surface2, Euclidomat, PushPull, Tensegrity, Half-closed loop, Wavesetter, Impro Instruments	Mixed forms: cellulose touch surface, hand-worm rig, tangible blocks, capacitive matrix, drums, bellows, tensegrity strings, pads, balloons and tubes	N	Multiple prototypes: Euclidomat uses solenoids striking resonating objects; Half-closed loop uses structure-borne drivers, and Tensegrity uses attached sound transducers/actuators.	–	–
Järveläinen et al. [2024] jarvelainen-2024	Haptic e-cello prototype	Bowed	VT	Tactile Labs Haptuator BM3C vibrotactile transducer	30–1000 Hz actuator-rated range and vibration-signal passband.	Measured signal/action-to-sound round trip: 7.7 ms; actuator adds an estimated 4.4–5.2 ms, giving estimated total tactile delay <13 ms.
Jack et al. [2016] jack-2016	Percussive DMI with piezo-equipped ceramic tiles	Percussion	N	Passive ceramic-tile tapping interface with piezo-disk sensors feeding Bela analog inputs; foam damping.	Bela sampling: 44.1 kHz; audio buffer: 16 samples.	0.8 ms base action-to-sound latency (zero-latency condition).
Kirkegaard et al. [2020] kirkegaard-2020	TorqueTuner, demonstrated as a standalone knob and a rotary joint between two T-Sticks	Knob / rotary	FF	stepper motor under servo control	Haptic update: 1 kHz.	–
Knutzen [2013] knutzen-2013	Vibrotactile glove with two open-air DMI prototypes	Gestural controllers with a wearable glove display	VT	Voice coil implemented; eccentric rotating mass actuator explored then discarded.	Amplifier: measured at 3 V with a 1–2500 Hz sweep and described as relatively flat; Vicon capture: 100 Hz.	Android/libpd wireless synthesis had intolerably high latency; the wired implementation reduced latency. Proposed wireless remedies were untested.
Knutzen et al. [2014] knutzen-2014	Vibrotactile glove with two motion-capture-controlled open-air DMI prototypes	Gestural controllers with a wearable glove display	VT	Four Hiwave 11 mm voice-coil actuators in a glove.	Some tactile signals low-pass filtered at 800 Hz; Vicon motion capture: 100 fps.	–
Kontogeorgakopoulos [2023] kontogeorgakopoulos-2023	Falcon 3D robot; FireFader-derived haptic faders (three custom versions)	Motorized faders and Falcon robotic feedback device	FF	Motorized faders in custom FireFader interfaces.	–	Interpersonal: latency problems in the long-distance network version are identified as requiring further systematic research (unquantified).

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Lane-Smith et al. [2023] lane-smith-2023	The Hapstrumment	Bimanual pantograph interfaces for simulated plucking and bowing, with graphical pitch selection	VT/FF	Two Haply 2diy force-feedback devices, each with two degrees of freedom; one for each hand.	–	–
Leonard and Cadoz [2015] leonard-2015	GENESIS-RT platform and virtual musical instruments	Piano-key interfaces; joystick and bowing alternatives also named	FF	TGR (transducteur gestuel rétroactif) haptic device.	Current RTOS: haptic/mechanical 4.41 kHz, acoustic 44.1 kHz; multirate haptic scheme 1–10 kHz. Earlier TORO: common 44.1 kHz loop, single-sample latency.	First TORO prototype: single-sample latency in a 44.1 kHz computational loop.
Leonard et al. [2013] leonard-2013	Real-time haptic modeller / simulator connecting GENESIS and ERGON_X	Piano-key interfaces; bows, joysticks, pliers and stylus named as other end effectors	FF	TGR keys: electromagnetic actuators for force feedback.	Synchronous hard-real-time simulation: 44.1 kHz (TORO DSP).	TGR force-feedback output: one-sample delay; simulation at 44.1 kHz.
Leonard et al. [2018] leonard-2018	MSCI platform	Keyboard end effectors; bowing end effector shown and other configurations named	FF	TGR (transducteur gestuel rétroactif) force-feedback device; 12 modules in the MSCI platform.	Reported TGR mechanical bandwidth: up to 15 kHz.	Haptic loop requires single-sample latency; approximately 20–100 μ s covers conversion, communication and computation.
Magnusson and Hurtado Mendieta [2007] magnusson-2007	Questionnaire survey of instrumentalists and instrument builders	No artifact; respondents discuss acoustic and digital instruments	N	–	–	Survey discussion: audio delay may reach 50 ms with hardware controllers and many seconds in networked performance.
Malloch and Wanderley [2007] malloch-2007	T-Stick instrument family: two built, two further instruments planned	Cylindrical gestural controller, held in the hands or supported on the floor	N	Passive contact implementation: foam-covered pressure sensors; piezoelectric contact microphone for sensing jarring, bending and twisting.	QT161 sensing ICs clocked at 20 MHz instead of the standard 10 MHz; these are crystal-oscillator frequencies.	–
Marshall [2008] marshall-2008	Viblotar, FM Gloves, T-Box and two gesture-controlled spatialization systems	Desk or stand-mounted box instrument, wearable gloves and gestural controllers	VT	Viblotar: loudspeaker voice coils; FM Gloves: small DC-driven vibration motor.	Target vibrotactile range: at least 40–1000 Hz; tested solenoid limited to 45 Hz.	Prior LaserBass factor experiments (Bongers 1997): drive delay contributed to actuator unsuitability (qualitative report).

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Marshall and Wanderley [2006] marshall-2006	Viblotar and Vibloslide; bench comparison of vibrotactile actuators	Monochord-like lap/table instrument and slide-whistle-like wind controller	VT	Implemented instruments: voice coils. Five classes bench-tested: tactors, piezoelectric elements, voice coils, motors, and solenoids.	Tested frequency response over tactile range: 40–1000 Hz.	Tested qualitative transient response: Table 1 rates tactor and solenoid good, motor poor, and piezo-electric and voice-coil devices excellent; accompanying prose groups motor and solenoid as worse than the other devices.
Marshall and Wanderley [2011] marshall-2011	Viblotar	Monochord-like lap instrument with linear position and force sensors	VT	Voice coils in two instrument-body loudspeakers.	Measured vibration spectra for an 82 Hz played note (acoustic guitar and Viblotar; Figures 3–4).	–
Mayet et al. [2024] mayet-2024	Psychophysical apparatus comprising guitar-string benches	Plucked-string bench apparatus	N	Sensing: three PCB Piezotronics M352C65 piezoelectric accelerometers, one beneath each string bench.	Accelerometer acquisition: 51.2 kHz.	–
McDowell and Furlong [2018] mcdowell-2018	Haptic-listening system: DIY Haptic Guitar and trial prototype	Held against the sternum (Experiment 1); strapped to the sternum (Experiment 2)	VT	Two acoustic shaker prototypes: initial home-built shaker and subsequent Reckhorn BS-200i body shaker.	–	–
Mehes et al. [2017] mehes-2017	Virtual-acoustic string-plate instrument with string-board controller and Knobbee 32	String-board for plucking, bowing, scraping and tapping; board percussion and rotary parameter controls	N	Passive string-board with bridge pistons resting on piezoelectric sensing disks; Knobbee32 parameter controller.	Parameter control: 400 Hz; audio synthesis: 48 kHz with a 120-sample buffer.	–
Melbye [2023] melbye-2023	FAAB augmented bass and 'What the Frog's Eye tells the Frog's Brain'	FAAB: double bass; Frog: horizontal bass body played by hand pressure.	VT	FAAB: Eighteensound 8NMB420 speaker; Frog: Dayton DAEX30HESF-4 or DAEX25FHE-4 tactile transducers.	FAAB loudspeaker selection range: 60–5500 Hz; CTAG audio sampling: 48 kHz.	Calculated audio round trip: 1.875 ms at 48 kHz with a 16-sample buffer.
Michailidis [2015] michaillidis-2016	TfTool and pressure-sensor glove; compositions Barbarophonos, Big Bang... ..Big Crunch and Live Mechanics	Wearable motors with sensor glove and footpedals; motors on piano strings in Live Mechanics	VT	Glove and pedal cases: 10 mm coin motors (310-113); Live Mechanics: five varied motors on piano strings.	Glove motor specification: 260 Hz.	Trumpet glove: unmeasured latency, no reported adverse performance impact. Pedal case: significant wireless visual-feedback delay; shin vibration calibrated for immediate perception.

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Montag et al. [2011] montag-2011	Second-generation FTIR multi-touch table with haptic feedback	Table	VT	Aura AST-1B-4 tactile transducer; DC motor tested as an earlier alternative.	Table camera: 100 fps; test audio interface: 44.1 kHz with 256-sample buffer.	Measured mean touch-to-audio-output delay: 30 ms (PlayStation Eye table); the audio output simultaneously drives the tactile transducer.
Mudd [2013] mudd-2013	Haptic soundfile-scanning system using Novint Falcon	Falcon haptic interface	FF	Novint Falcon force-feedback device.	Falcon capability: force updates every 1 ms (equivalent to 1 kHz).	–
Mudd [2023] mudd-2023	Study of a no-input mixing desk	Mixing desk with rotary controls, buttons and faders	N	Analogue mixer audio outputs or auxiliary sends routed back to channel inputs.	Analogue audio feedback may contain <1 Hz and >20 kHz components.	Performers described analogue mixers as responding as fast as acoustic instruments; digital interfaces felt slower (qualitative interviews).
Müller et al. [2010] muller-2010	GUI// //RO	Stylus on a touchscreen	N	Electromagnetic coil attracting a steel ball to vary stylus friction.	–	–
Nichols [2002] nichols-2002	vBow (versions 1, 2 and 2.1)	Bowed	VT/FF	vBow: servomotors; first version renders frictional vibration; second-version software under development.	–	Planned second-version RTLinux migration aimed to eliminate latency caused by Windows.
O'Modhrain [2000] omodhrain-2000b	Virtual bowed string and virtual Theremin on the Moose haptic display	Planar puck interface for bowed-string and gestural Theremin interaction	FF	Moose: two linear voice-coil motors	Haptic sampling: 1 kHz for Theremin and bowed-string systems; bowed-string audio: 22 kHz.	Bowed-string model: MIDI parameter updates every 200 ms; detectable lag reported.
O'Modhrain and Gillespie [2018] omodhrain-2018	Position chapter modelling the player-instrument system	No device; piano action, snare drum, violin bow and touchscreen examples	N	–	Analytical background: neural and cognitive delays of about 100 ms would preclude stable control of a lightly underdamped oscillator above about 5 Hz [17], while piano trills can exceed 10 Hz [18].	Human neural/cognitive processing context: ≈ 100 ms.
O'Modhrain et al. [2000] omodhrain-2000	Virtual bowed string controlled through the Moose haptic display	Bowed	FF	The Moose: haptic display with two degrees of freedom.	Haptic-model data: 1 kHz; bowed-string audio: 22 kHz.	–
Oboe and De Poli [2002] obo-2002	MIKEY multi-instrument active keyboard	Keyboard	FF	Rotational voice-coil motors recovered from hard disk drives.	Sensor A/D and force-output D/A: 44.1 kHz; transconductance-amplifier bandwidth: 40 kHz.	–
Ogawa et al. [2016] ogawa-2016	HapTONE	Keyboard	VT	Vp408 vibrator (Acouue Laboratory).	Reported driven vibrator range: 30–1000 Hz; key-unit resonances at 50, 90, and 110 Hz.	Locally stored vibration waveforms reduce action-to-haptic latency (author claim; unquantified).

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Onofrei et al. [2022] onofrei-2022	Bowed virtual strings controlled with a 3D Systems Touch stylus	Bowed	FF	3D Systems Touch haptic device with internal force-feedback motors.	Current haptic callback: 1 kHz; separately reported Figure 1a string simulation: 44.1 kHz.	–
Overholt [2001] overholt-2001	The MATRIX (Multipurpose Array of Tactile Rods for Interactive eXpression)	Spring-mounted rod-array surface	N	MATRIX: 144 passive spring-mounted rods in a 12x12 grid; infrared quadrature position sensing and FPGA processing.	Sensing frames: ≈ 30 Hz over a 57.6 kbaud serial link	Preliminary MIT $\leftrightarrow$ Dublin OSC network tests with high-speed access at both ends: delay much less than 0.5 s in almost all cases.
Overholt [2011] overholt-2011	The Overtone Fiddle	Bowed	VT	Voice-coil tactile sound transducers exciting acoustic instrument bodies.	Bow orientation sensing: 300 Hz; separate CUI32 analog-input connectivity example sends sensor messages every 10 ms (orientation sensor unused).	–
Overholt [2022] overholt-2022	Design-space overview; cites MATRIX as prior work	No new artifact	N	Reviewed sensing examples: Exos Dextrous Hand Master with Hall-effect joint-angle sensors; mechanical knobs and sliders.	Review data: typical HCI sensor sampling 100–2000 Hz; scanned-synthesis control 0–20 Hz and audio 20 Hz–20 kHz.	Sensing guidance: typically 1–10 ms from movement to sensor-data receipt; >10 ms deemed insufficient for MITDS.
Papetti et al. [2015] papetti-2015	HSoundplane	Flat wooden multi-touch, pressure-sensitive surface	VT	HSoundplane: piezoelectric transducer elements.	Stimulus bandpass: 40–400 Hz	–
Papetti et al. [2018] papetti-2018	Touch-Box, VibroPiano and HSoundplane	Flat panel test rig, keyboard and multi-touch table	VT	Touch-Box: Haptuator mark II moving-magnet voice-coil actuator; VibroPiano: Clark Synthesis TST239 tactile transducers; HSoundplane: piezoelectric disks.	HSoundplane response measurement sweep: 20–1000 Hz	Soundplane sensing: tracking time of a few ms (reported background specification).
Papetti et al. [2023] papetti-2023	VibroPiano, HSoundplane and TouchBox	Keyboard, multi-touch surface and force-sensing touch panel	VT	HSoundplane: piezoelectric disks; VibroPiano: Clark TST239 tactile transducers; TouchBox: voice-coil actuator.	Signal bands: VibroPiano synthetic-noise condition 20–500 Hz; HSoundplane 10–500 Hz; TouchBox noise 40–360 Hz. BiVib source files: 96 kHz.	Disklavier MIDI-note playback has a systematic, key-dynamics-dependent delay; initial silence removed during sample preparation (unquantified).
Paterson and Wanderley [2023] paterson-2023	Editorial	No device	N	–	–	–
Pedrosa [2007] pedrosa-2007	Korg PadKontrol pilot rig with voice coil; PHANTOM platform proposed	Percussion pilot rig; grounded gestural platform proposed	VT	voice coil (completed experiment); PHANTOM Premium 1.5 (proposed platform)	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Piao et al. [2024] piao-2024	Bend-aid sequencer and pitch-contour editor with TorqueTuner and added grip	Knob / rotary	VT/FF	TorqueTuner DC motor for programmable force feedback.	Bend-aid MIDI sequencer pitch range: C1–C8; this is the sound-control note range, not a haptic carrier frequency or control rate.	–
Piao et al. [2024] piao-2024b	Bend-aid sequencer with standalone TorqueTuner and added grip	Knob / rotary	FF	TorqueTuner direct-current motors for programmable force feedback.	Task stimulus: 120 bpm; three vibrato oscillations within each 3 s note.	–
De Pra et al. [2021] pra-2021	Endless-knob resistive-feedback controller and real-time EMS VCS3 filter implementation	Knob / rotary	N	Electromagnetic clutch used as a knob braking system.	PWM carrier example: up to 62.7 kHz (Arduino NANO timer, 16 MHz / 255; chosen to avoid audible noise).	Effect duration examples: soft detent 50 ms; haptic marker 100 ms; hard detent 350 ms.
Preuschoff et al. [2026] preuschoff-2026	Collaborative music exhibit: Drums, Keys, Bellow-Pipe and vibrotactile floor platforms	Collaborative exhibit with instruments and vibrotactile floor platforms	VT	High-power exciters in the floor plates; two small haptic exciters and seven fans in the Bellow-Pipe.	Reported floor-platform exciter vibration range: approximately 30–300 Hz.	–
Regimbal and Wanderley [2021] regimbal-2021	‘interpolate’ Pure Data external with ADSR and spatial/harmonic demonstration patches	Wearable	VT	Two Haptuator voice-coil actuators in proof-of-concept patches.	–	–
Remache-Vinueza et al. [2021] remache-vinueza-2021	Review of haptic music players: installations, wearables and hybrids	Seats, mattresses, platforms and wearable displays; also vibrotactile music input devices	VT	Review covers voice-coil, linear-resonant, eccentric rotating-mass, piezoelectric and dual-mode actuators, plus loudspeakers in haptic music players.	Reviewed composition examples: Nintendo Switch tactile keyboard notes C-131 to C-262 Hz [62]; Vibrochord scale 40, 56, 78.4, 109.76, 153.66, 215.12, 301.18 and 421.65 Hz [66].	Review finding attributed to Hwang, Lee, and Choi [37]: ERM response to changes in dynamics is slow (unquantified).
Ronen and Wanderley [2024] ronen-2024	Sonic Touch toolkit with Expressive E Touché demonstrator	Software toolkit; touch-sensitive continuous controller with actuator under its faceplate	VT	HiAX13C02 voice coil attached to the Touché face plate.	Tactile tremolo carrier: 250 Hz sine wave.	Configurable delay between repeated haptic events; example setting: 0 ms.
Schmid et al. [2024] schmid-2024	Custom keyboard study apparatus	Keyboard with contact-fitted keys	N	Modified Nektar Impact GX61 keys with copper contacts trigger Raspberry Pi GPIO; passive key mechanics provide touch feedback.	Audio stimulus: 500 Hz square wave.	Measured internal interrupt-to-audio delay: 0.056–0.952 ms across 25 measurements.

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Shahrokni et al. [2006] shahrokni-2006	Force Feedback Slider: analogue platform and unfinished digital design; Catapult and FeelTheBeat applications	Slider/fader	VT/FF	motorized force-feedback slider	I2C bus: 400 kHz; slider microcontroller clock: 16 MHz.	Analogue prototype: high latency, mainly from conversion and OS sound mixing; preliminary digital-platform tests report much shorter delays (unquantified). –
Sheffield et al. [2016] sheffield-2016	The Haptic Capstans	Knob/rotary	FF	Rotational motors with integrated encoders, sourced from surplus stock.	–	–
Sinclair and Wanderley [2007] sinclair-2007	DIMPLE (Phantom Omni demonstration), with Force Stick and Bucket of Marbles scenes	Virtual environments operated through a haptic stylus	FF	DIMPLE proof of concept with SensAble Phantom Omni; CHAI 3D calculates device forces, ODE simulates object dynamics and LibLo handles OSC.	Architecture diagram: 1 kHz haptics; OSC example: force reports every 30 ms.	Background constraints: force-feedback latency ≤ 1 ms; audio-haptic asynchrony JND ≈ 24 ms.
Sinyor [2006] sinyor-2006	Gyrotyre (two prototypes) and Springwave	Hand-held spinning wheel and pedal-driven spring on a stand	N	Passive mechanical implementations: sensor-equipped bicycle wheel (Gyrotyre) and spring on a pedal-driven hi-hat stand with capacitive pickups (Springwave).	Springwave passive oscillation: ≈ 4.5 –8 Hz. Gyrotyre acquisition: up to 1000 Hz; received sensor data: 250 Hz.	Unquantified sensing-delay tradeoff: increasing the Gyrotyre accelerometer's smoothing capacitor reduces ripple but increases motion-to-signal delay. –
Steiner [2004] steiner-2004	StickMusic	Force-feedback joystick and vibrating mouse controlling a phase vocoder	VT/FF	Saitek Force joystick; Logitech iFeel mouse	–	–
Sun et al. [2021] sun-2021	PalmBeat	Hand-worn glove and linkage tapping the finger or palm	FF	Servo with connecting rods moving fingers or palm.	Music stimuli: 86–148 BPM (mean 108.13, SD 15.68); force-feedback timing followed recorded musician tapping rather than song BPM; intertap distributions in Fig. 4.	Some feedback felt slightly delayed; authors suggested listeners' beat perception may not match the force-feedback beats. –
Tache et al. [2012] tache-2012	ERGON_X interface with four virtual bowed-string simulations	Bowed	VT/FF	ERGON_X force-feedback system (Ergos Technologies).	Simulated string fundamental: 246.94 Hz.	–
Tom et al. [2020] tom-2020	Haptic Tutor, built on Vibropixels	Wearable	VT	Coin-type and cylindrical eccentric rotating mass actuators.	Reported motor operating frequencies: 200–250 Hz; both motors driven at constant 3.3 V.	Timestamp/accelerometer delay correction. Pre-vibration: design ≈ 150 ms attack; Experiment 1 specifies 50 ms before a 30 ms pulse. –
Trump and Bullock [2014] trump-2014	Orphion	Touchscreen	N	iPad application with libpd audio; vibrotactile pad-edge feedback proposed as future work.	–	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Turchet [2022] turchet-2022	Practitioner reflection on prior haptic systems	Wearables referenced; no new artifact	VT	Reviewed listener devices include vibrotactile loudspeakers under furniture, gloves with embedded actuators, and haptic jackets driven by musical features.	–	–
Verplank [2005] verplank-2005	FORCE-STICK teaching device and exercises	Motor-shaft-mounted stick with a force sensor	FF	Reliance Electric ES364 motor with encoder and microcontroller force feedback	–	–
Verplank and Georg [2011] verplank-2011	PLANK and FM Fader Synth; Haptic Drum and Cellomobo discussed as others' work	Cylindrical Plank surface and motorized fader	FF	motorized fader; hard-disk voice coil (PLANK)	Cited prior Haptic Drum [5]: drum-roll rate up to 70 Hz.	Cited prior Cellomobo [6]: left-hand string sensor controls the signal delay in the pickup-to-shaker feedback loop.
Verplank et al. [2002] verplank-2002	The Plank	Actuated translating/rotating surface	FF	voice-coil motor from computer disk drive	Servo update: up to 4 kHz (stated design figure); microcontroller A/D: ≈ 10 ksamples/s.	–
Wanderley and Frisson [2023] wanderley-2023	Historical account of ACROE force-feedback keys and TGR	Keyboard systems discussed retrospectively	FF	Custom moving-coil motors in the TGR.	Operation at 20 kHz reported; rapid heating/coil-failure risk	–
Wang et al. [2017] wang-2016	Virtual Guqin	Virtual plucked strings operated through a haptic stylus	VT/FF	Phantom Premium 3.0 6DoF haptic device.	Haptic update design aim: 1 kHz.	Haptic rendering computation (collision detection + response): <1 ms in most playing phases.
Williams and Overholt [2017] williams-2017	Pitch Fork	Iron tongues on a wooden frame, played by beater or hand	N	Sound transducers inside the wooden housing; iron tongues sensed by IR proximity sensors and piezoelectric pickups, with Arduino Mega and Pure Data Extended.	Pitch range: C4–C5; synthesis adds three even harmonics; piezo input is low-pass filtered.	Performer discussion reports that Pitch Fork reacts fairly quickly to player activity (unquantified author observation).
Wolstanholme et al. [2025] wolstanholme-2025	Drum Modal Feedback concept design	Acoustic drum with trigger and tactile transducer	N	Dayton Audio DAEX25CT-4 and DAEX58FP transducers in different artistic configurations.	Illustrative configurable modal-selection range: 220–880 Hz, with at least 400 cents separation; example setting, not a measured device bandwidth.	–
Wu et al. [2026] wu-2026	SlimeUI	Deformable fluid handled in a container and on a table	N	Optical sensing: a front-facing camera in Playground One and an overhead camera in Playground Two.	–	–
Wyse et al. [2012] wyse-2012	Haptic display derived from the Haptic Chair hand-stimulation component	Supported vibrating wooden panel for hand contact	VT	MSE Audio SolidDrive SD1sm contact speaker.	Hand-loaded panel response characterized at four locations with a three-second 50–5000 Hz sweep.	–

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Table A.3 continued.

Source and key	Instrument or apparatus	Form	Mod.	Actuator / implementation	Technical frequency data	Latency / delay
Young [2016] young-2016	Haptic Bowl, Non-Haptic Bowl and Audio-Tactile Glove	Free-space gestural controllers in bowl-shaped table units and wearable actuator gloves	VT	Voice-coil actuators	Glove threshold-test procedure: 10–1000 Hz; peak sensitivity: 160–200 Hz. Waveform-experiment DAC: 96 kHz.	Arduino HID upgrade reportedly reduced communication latency; participants still reported latency in haptic tasks and jitter/latency without feedback.
Young and Murphy [2015] young-2015	The Haptic Bowl	Open-air / gestural	VT	Vibrotactile actuators embedded in gloves.	Pitch-selection experiment: 11 target pitches across 110–987.77 Hz; target width 3 Hz below 500 Hz, increasing approximately 0.6% toward 1 kHz (threshold from [8]).	Replacing the original HID circuitry with Arduino Uno SMD reduced internal latency (unquantified author report).
Young and Crowley [2016] young-2016b	Position paper	No instrument built	N	–	–	–
Young et al. [2017] young-2017	Haptic Bowl and Non-Haptic Bowl paired prototypes	Tethered bimanual controller and camera-tracked gestural counterpart	VT	Audio-Tactile Glove vibrotactile actuators, fed by the Haptic Bowl audio connection.	Audio-frequency vibrotactile feedback from the sound generator.	Arduino Uno upgrade reduced communication latency; tactile-only trials raised concerns about perceived latency.
Young et al. [2018] young-2018	Haptic Bowl and Non-Haptic Bowl paired prototypes	Open-air / gestural	VT	Voice-coil actuators embedded in gloves.	Sinewave tactile feedback follows audio; pitch-task targets: 110–987.77 Hz.	Unquantified reduction in communication latency after replacing the Haptic Bowl's original HID electronics with an Arduino Uno SMD.
Zheng et al. [2022] zheng-2022	Passive material probe samples N1–N12	Loose material samples handled on a desk	N	Material probes made from fabric, foams of different densities, rubber and copper; used to imagine hypothetical instruments.	–	–

Table A.4: Evaluation information for the same 109 reports.

Source and key	Evaluation
Altinsoy and Merchel [2018] altinsoy-2018	Two controlled psychophysical experiments: Experiment 1 (variants 1a–d), n=20; Experiment 2, n=18.
Baalman [2003] baalman-2003	Author reflections on two performances and practical testing.
Bak et al. [2015] bak-2015	Retrospective teaching experience across four years of workshops, with selected student projects and qualitative assessment of learning.
Battey et al. [2015] battey-2015	Proof-of-concept test cases with qualitative author assessments of wall contact, envelope sensing and arpeggiators; formal user assessment remained future work.
Beamish [2003] beamish-2003	Six expert DJs; exploratory sessions with think-aloud observations and structured interviews.
Berdahl and Kontogeorgakopoulos [2012] berdahl-2012	Instructional design case study using five FireFader prototypes; student design exercise and example projects.
Berdahl et al. [2008] berdahl-2008	Technical example analysis and informal functionality observations for Haptic Drum and Cellomobo, including robust Cellomobo operation despite system delay.
Berdahl et al. [2009] berdahl-2009	–
Berdahl et al. [2009] berdahl-2009b	Technical demonstrations: bowed-string Helmholtz motion; plucking and finger damping, with string-velocity and sound-pressure plots.
Berdahl et al. [2018] berdahl-2018	Laptop Orchestra of Louisiana case study using force-feedback instruments.
Birnbaum [2007] birnbaum-2007	Skin-extension measurements: three recorder players, five hole sizes; informal Touch Flute user comments.
Birnbaum and Wanderley [2007] birnbaum-2007b	Skin-extension design measurement: 3 recorder players, 5 hole sizes.
Branje [2014] branje-2014	Four studies: design interviews n=4; controlled comparison n=20; composition n=3; emotion-rating study with two phases, n=26 and n=30.
Bukkapatnam [2019] bukkapatnam-2019	Bench tests: 2 unloaded VCA mounting conditions; 5 noise repetitions per voltage level and 3 sine repetitions per frequency–magnitude setting.
Bukkapatnam et al. [2020] bukkapatnam-2020	Bench tests: 2 unloaded VCA mounting conditions; 5 noise repetitions per voltage level and 3 sine repetitions per frequency–magnitude setting.
Cadoz et al. [1990] cadoz-1990	Technical characterization of the modular sensor-motor: blocked-coil response delay measured at 0.2 ms; force, acceleration and friction specifications reported.
Cadoz et al. [1984] cadoz-1984	Sound-synthesis examples: series of 26 and 20 sounds.
Carlson et al. [2011] carlson-2011	Informal observations of novices discovering repeatable gestures; feedback from initial demonstrations identified visual location feedback as a requested feature.
Castagné et al. [2004] castagne-2004	Prior Florens violin experiment: linear string and simple nonlinear bow interaction; author reports natural production of relevant string sounds.
Christensen et al. [2020] christensen-2020	n=6; semi-structured interviews.
Davison and McPherson [2026] davison-2026b	1 design study; 10 recruited, 7 completed; semi-structured interviews and inductive thematic analysis.
Davison et al. [2024] davison-2024	Empirical technology study without research participants: measured transducer transfer function in damped/undamped conditions, preliminary sensing tests and qualitative interaction observations.
Davison et al. [2026] davison-2026	Literature-based comparison of sensing/actuation techniques, transducer constraints and applications; no research participants.

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Table A.4 continued.

Source and key	Evaluation
de Jong [2008] de-jong-2008	Demonstration: a displayed 6 s I/O interaction recording.
Egloff et al. [2018] egloff-2018	n=18; controlled psychophysical experiment using melodic-interval discrimination.
Eldridge et al. [2021] eldridge-2021	Reflective account drawing on designer/player reports and two named interviewees.
Florens et al. [2004] florens-2004	Technical specifications and application observations: perceptible virtual-bowing reactions and reported restitution of AFM tip contact.
Fontana et al. [2018] fontana-2018	Two psychophysical experiments: Experiment 1, n=27 sine and n=17 noise; Experiment 2, n=14 per upright/grand piano condition.
Frisson and Wanderley [2023] frisson-2023	Critical literature review comparing force-feedback hardware/software and assessing modularity, replicability, affordability and usability.
Frisson et al. [2022] frisson-2022	Technical validation through compatible hardware integrations, firmware examples and development-environment integration; author experience, no research participants.
Gentili-Morin and Wanderley [2024] gentili-morin-2024	Informal peer demonstrations during three development stages.
Giordano et al. [2012] giordano-2012	Acceleration comparison: 2 bowing gestures in each of 2 device conditions.
Giordano et al. [2018] giordano-2018	Same two musicians across two preliminary recognition sessions; separate live-performance case with one trombonist.
Havryliv et al. [2009] havryliv-2009	Model-measurement comparison: 3 bell types.
Hayes [2015] hayes-2015	–
Helppolainen [2024] helppolainen-2024	n=15; controlled parameter-matching experiment across four feedback modes; workload questionnaires.
Hinrichsen and Bovermann [2016] hinrichsen-2016	Reflective analysis of observations around ten 3DMIN prototypes, organized by materiality, corporeality, sonority and control; includes performance observations.
Järveläinen et al. [2024] jarvelainen-2024	1 controlled A/B rating study, n=11; 1 expert supported prototype development.
Jack et al. [2016] jack-2016	n=11; controlled latency comparison with continuous-scale quality ratings.
Kirkegaard et al. [2020] kirkegaard-2020	Qualitative author observations from two DMI integrations and three musical applications; spring mode conveyed T-Stick roll orientation.
Knutzen [2013] knutzen-2013	n=5 graduate students; informal evaluation of two prototypes.
Knutzen et al. [2014] knutzen-2014	n=5 graduate students; informal evaluation with controlled variation of feedback strategies and a no-feedback condition.
Kontogeorgakopoulos [2023] kontogeorgakopoulos-2023	Reflective artistic/technical analysis of five directions, grounded in collaborative works and personal experiments; includes a retrospective assessment of Engraving–Hammering–Casting.
Lane-Smith et al. [2023] lane-smith-2023	n=11; Hapstrum case evaluation with prescribed tasks, performance, and a post-test questionnaire.
Leonard and Cadoz [2015] leonard-2015	Informal novice-bowing observations: practice improved control; removing sound or haptic feedback made the task much harder.
Leonard et al. [2013] leonard-2013	DSP bench tests of execution time for basic CORDIS-ANIMA modules and representative musical models; comparative simulation-engine performance.
Leonard et al. [2018] leonard-2018	Technical/model analysis plus qualitative feedback from demonstration users; users explored single virtual instruments for up to 30 min. Hélios documents a public performance application.

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Table A.4 continued.

Source and key	Evaluation
Magnusson and Hurtado Mendieta [2007] magnusson-2007	Qualitative questionnaire: 209 replies overall; thematic interpretation of narrative answers.
Malloch and Wanderley [2007] malloch-2007	Iterative design with performer collaboration in a seminar and the McGill Digital Orchestra Project; documented observations and design changes after hundreds of hours of practice/performance.
Marshall [2008] marshall-2008	2 haptic studies: n=10 psychophysical discrimination (+ same-cohort follow-up); n=5 controlled Vibrotact evaluation.
Marshall and Wanderley [2006] marshall-2006	Bench measurements of five actuator classes; informal player comments on the two instruments.
Marshall and Wanderley [2011] marshall-2011	n=5 experienced musicians; controlled comparison of two configurations with Likert ratings.
Mayet et al. [2024] mayet-2024	n=10; controlled psychophysical discrimination experiment using three-alternative forced choice.
McDowell and Furlong [2018] mcdowell-2018	2 experiments: exhibition questionnaire n=41; controlled listening questionnaire n=19.
Mehes et al. [2017] mehes-2017	n=4 musicians; case evaluation through short compositions and preliminary informal observations.
Melbye [2023] melbye-2023	Autoethnography with instrument and performance case studies.
Michailidis [2015] michailidis-2016	Four case studies: retained musician counts 6, 1, 1, and 1 respectively; two additional interviewees excluded from the first; interviews and longitudinal collaboration.
Montag et al. [2011] montag-2011	Audio-latency benchmark: at least 25 measurement trials per test case.
Mudd [2013] mudd-2013	Informal author comparison of continuous and discrete mappings; discrete mappings appeared more comprehensible, while rigorous testing had not been conducted.
Mudd [2023] mudd-2023	n=20; interviews (17 video, three email); reflexive thematic analysis.
Müller et al. [2010] muller-2010	—
Nichols [2002] nichols-2002	Informal author testing of first-version expressiveness and haptic feedback; qualitative timbral response observations.
O'Modhrain [2000] omodhrain-2000b	Four performance experiments: n=21 (19 analyzed), 15, 20 and 6; two string-player raters each for III/IV; earlier expert model-tuning pilot.
O'Modhrain and Gillespie [2018] omodhrain-2018	Conceptual synthesis of coupled dynamics and skill learning; cites earlier simulated-string and membrane experiments reporting improved simple-task accuracy with a haptic interface [29; 11,30].
O'Modhrain et al. [2000] omodhrain-2000	n=6; structured bowing experiment with observer ratings and objective signal analysis.
Oboe and De Poli [2002] oboe-2002	Bench command/current and simulated-motion traces; informal performer tests.
Ogawa et al. [2016] ogawa-2016	Technical characterization of key vibration response and optical distance-sensor calibration.
Onofrei et al. [2022] onofrei-2022	Offline Matlab model calibration; plots show displacement, relative velocity and frictional force for a 196 Hz string sampled at 44.1 kHz.
Overholt [2001] overholt-2001	Informal public demonstrations and user responses.
Overholt [2011] overholt-2011	Prototype connectivity test and author observations from initial improvisational performances.

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Table A.4 continued.

Source and key	Evaluation
Overholt [2022] overholt-2022	Analytical comparison of sensor options and calculated cumulative bit rates (MATRIX versus Monome); no user study.
Papetti et al. [2015] papetti-2015	Bench frequency-response measurements; informal author assessments of actuator feel and vibrotactile cross-talk.
Papetti et al. [2018] papetti-2018	Bench frequency-response measurements and informal evaluation of VibroPiano and HSoundplane.
Papetti et al. [2023] papetti-2023	Three studies, four tests: first cohort n=11 completed two tests; remaining cohorts n=29 and n=31; controlled comparisons and ratings.
Paterson and Wanderley [2023] paterson-2023	–
Pedrosa [2007] pedrosa-2007	n=16, two groups of eight; controlled comparison of four cue conditions; questionnaire.
Piao et al. [2024] piao-2024	Main study n=20 musically trained participants; controlled feedback comparison; questionnaires.
Piao et al. [2024] piao-2024b	Main study n=20 musically trained participants; controlled feedback comparison including no-force control; questionnaires.
De Pra et al. [2021] pra-2021	n=10; controlled target-matching experiment; mismatch and completion-time measures
Preuschoff et al. [2026] preuschoff-2026	design workshop n=7; comparative study n=21 (some survey items n=19); questionnaires, interviews, thematic analysis
Regimbal and Wanderley [2021] regimbal-2021	Author reflections on 2 proof-of-concept patches.
Remache-Vinueza et al. [2021] remache-vinueza-2021	Literature review using Scopus, Web of Science, PubMed and Google Scholar, with keyword searches; compares actuator technologies, haptic-music-player types and rendering/composition methods.
Ronen and Wanderley [2024] ronen-2024	Informal volunteer feedback on toolkit usability.
Schmid et al. [2024] schmid-2024	One controlled psychophysical study: 37 recruited; three excluded (two often pressed only one key, one received incorrect assigned latencies); 34 analyzed.
Shahrokni et al. [2006] shahrokni-2006	Prototype operation tests: analogue proof of concept exposed high latency and instability; preliminary digital tests showed shorter delays. Human perceptual performance evaluation was planned.
Sheffield et al. [2016] sheffield-2016	Composition adaptation and rehearsal with informal observations of gesture range, perceived stiffness and strumming.
Sinclair and Wanderley [2007] sinclair-2007	Informal observation found no problems with small object counts over loopback/local-network communication; formal OSC latency testing was explicitly not performed.
Sinyor [2006] sinyor-2006	informal observations (~15 Gyrotyre users); early Springwave tests
Steiner [2004] steiner-2004	Author's experiential case reflections on ensemble sessions and a solo performance.
Sun et al. [2021] sun-2021	Pilot tapping study n=12 musicians; controlled feedback study n=24 non-musicians; questionnaires.
Tache et al. [2012] tache-2012	Two series: 7 explored simulations with a 3-DoF knob; 16 attempted continuous sound with a stick. Nondirective interviews and qualitative analysis.
Tom et al. [2020] tom-2020	Two controlled experiments: Experiment 1 n=30 (three condition groups of 10); Experiment 2 n=16 (two groups of eight, new participants); post-experiment survey.
Trump and Bullock [2014] trump-2014	Six prototype testers; 822 app-store reviews; informal feedback and practice-based evaluation.

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Table A.4 continued.

Source and key	Evaluation
Turchet [2022] turchet-2022	Author reflections derived from literature, design practice, and the author's own user-evaluation experiments.
Verplank [2005] verplank-2005	Teaching exercises and informal author/student exploration of parameter settings and musical control.
Verplank and Georg [2011] verplank-2011	Descriptive demonstration cases and informal user and composer-workshop reactions.
Verplank et al. [2002] verplank-2002	Design informed by earlier Phantom experiments and qualitative friction-model observations; Plank remained a rough prototype.
Wanderley and Frisson [2023] wanderley-2023	Edited Cadoz interview (23 March 2023), including retrospective bow-simulation measurements attributed to Luciani et al. (2009).
Wang et al. [2017] wang-2016	n=7 psychophysical study; n=4 experienced Guqin players in a questionnaire study.
Williams and Overholt [2017] williams-2017	Preliminary informal observations and discussions with people trying Pitch Fork.
Wolstanholme et al. [2025] wolstanholme-2025	4 artistic case studies; reflective practice and annotated portfolio
Wu et al. [2026] wu-2026	n=8; formative gesture exploration with informal observations.
Wyse et al. [2012] wyse-2012	n=12 hearing-impaired participants; controlled psychophysical vibration-detection threshold experiment.
Young [2016] young-2016	Five studies: detection thresholds n=10; waveform discrimination 30 recruited / 27 retained; pitch discrimination n=30; functional study n=12; exploratory study reused four from n=12. Psychophysical, controlled, and exploratory methods.
Young and Murphy [2015] young-2015	n=10 musicians; controlled pitch-target experiment; questionnaires and informal interviews.
Young and Crowley [2016] young-2016b	—
Young et al. [2017] young-2017	n=6; interviews with critical-incident and content analysis
Young et al. [2018] young-2018	n=12 musicians; controlled comparison of four feedback conditions; questionnaires and informal interviews.
Zheng et al. [2022] zheng-2022	One material-probe study, n=15: China group n=7 and UK group n=8; interviews and thematic analysis.

A.3 Excluded Records and Reports

Table A.5 lists the removed entries with DOI-linked titles and recorded reasons. Section 3.4 summarizes the selection outcomes.

Table A.5: Excluded records and reports with exclusion stages, reasons, and qualifications.

Reference	Recorded stage	Reason and qualification
Frid (2019) Accessible Digital Musical Instruments—A Review of Musical Interfaces in Inclusive Music Practice	Eligibility phase	Recorded as outside the scope. The review deals with accessibility.
von Coler (2021) A system for expressive spectro-spatial sound synthesis	Eligibility phase	Recorded as no haptics.
Yamazaki et al. (2017) Hapbeat: single DOF wide range wearable haptic display	Eligibility phase	Recorded as outside the scope. A haptic display for virtual reality.
Ogawa et al. (2016) HapTONE: Haptic Instrument for Enriched Musical Play	Eligibility phase	Duplicate database record. Both entries have the same DOI; one copy of this publication remains in the corpus.
Lyons and Fels (2013) Creating new interfaces for musical expression	Full-text eligibility assessment	Course publication.
Fels and Lyons (2013) Advances in new interfaces for musical expression	Eligibility phase in reconciliation	Course publication.
Fels and Lyons (2015) How to design and build new musical interfaces	Eligibility phase in reconciliation	Course publication.
Gao and Hanson (2009) LUMI : Live Performance Paradigms Utilizing Software Integrated Touch Screen and Pressure Sensitive Button Matrix	During extraction	Passive controls, no haptic actuator, and no evaluation supplying the required design guidance.
Harriman (2014) Modular-Mus: towards an interaction design toolkit for music	During extraction	Toolkit demonstration; its actuators produce sound. No active haptic feedback or evaluation supporting the review questions.
Holland et al. (2016) Music and HCI	During extraction	Workshop summary; haptics appears in organizer biographies without a haptic system, study, or usable design guidance.
Suzuki and Suzuki (2015) A Novel Haptic Vibration Media and Its Application	During extraction	Active vibration for a beauty / massage application, outside the musical scope. The reason is not absence of active haptics.
Slager (2021) Designing and performing with Pandora's Box: transforming feedback physically and with algorithms	During extraction	Acoustic feedback instrument; vibration is part of sound production, without explicit haptic design guidance. Physical contact with the vibrating spring makes this a borderline decision.

Appendix B

PRISMA 2020 Checklists

Tables B.1 and B.2 map the PRISMA 2020 reporting items to the thesis and its English Abstract, respectively. **Reported** means that the requested information is provided. **Partial** identifies information that is reported incompletely. **Not done** marks an activity that was not performed, even when its absence is explicitly stated. Each entry identifies the relevant thesis location.

The checklist wording is reproduced from Page et al. [2021] under CC BY 4.0. The layout and response columns have been adapted. Locations refer to the thesis's printed page numbers. The abstract checklist assesses the English Abstract.

Funding, interests, and access. The review received no funding. The author declares no competing interests. The review was not registered, and no separate review protocol was prepared. Academic guidance and personal support are described in the Acknowledgments. The GitLab repository for review data and scripts requires institutional network or VPN access. Repository: <https://git.rwth-aachen.de/i10/thesis/thesis-labrik-gashi-music-haptics>.

B.1 PRISMA 2020 Checklist

Table B.1: PRISMA 2020 checklist

Section and topic	Item	Checklist item	Reporting status and location
Title Title	1	Identify the report as a systematic review.	Partial. Title page; Abstract (p. ix); Chapter 3 (p. 19). The title uses "Survey"; identification as a systematic review appears in the Abstract and Method.
Abstract Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Partial. Abstract (p. ix); Table B.2 (p. 88). The objectives, methods, findings, and limitations are summarized. Remaining abstract reporting gaps are identified in the abstract checklist.

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Table B.1: PRISMA 2020 checklist (continued)

Section and topic	Item	Checklist item	Reporting status and location
Introduction			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Reported. Chapter 1 (p. 1); Chapter 2 (p. 7). Motivation, prior research, and the rationale for this review are explained.
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Reported. Section 1.1 (p. 4). The three research questions address feedback selection, implementation and mapping, and evaluation.
Methods			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Reported. Section 3.2 (p. 21); Section 3.7 (p. 28). Inclusion and exclusion criteria and grouping by the three research questions are described.
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Reported. Section 3.1 (p. 19); Section 3.4 (p. 23). ACM DL and NIME were searched on 7 July 2026; OpenAlex and backward and forward citation searches on 16 July 2026. The two seed reviews are cited.
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Partial. Section 3.1 (p. 19); Section 3.4 (p. 23). Database query strings and ACM search fields are given. The forward-citation search platform, full citation-search procedure, and all search limits are not specified.
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Reported. Section 3.3 (p. 22); Section 3.4 (p. 23). The author alone screened records and assessed eligibility. Rayyan, Zotero, screening stages, and the absence of a second reviewer are described.
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Partial. Section 3.5 (p. 24); Section 5.2 (p. 58). Extraction fields and the absence of an independent second human check are described. The extractor count, investigator data-confirmation procedures, and extraction-specific automation details are not fully specified.
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Partial. Section 3.5 (p. 24); Table 3.2 (p. 26). Evaluation fields, findings, and evidence for the research questions are described. Complete outcome definitions and rules for selecting measures, time points, and analyses are not given.
Data items	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Partial. Section 3.5 (p. 24); Appendix A (p. 61). Selected publication, instrument, technical, and participant fields are described. Modality rules and missing-entry notation are given; complete variable definitions and handling of unclear data are not fully specified.
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Not done. Section 3.7 (p. 28). The thesis states that no formal study risk-of-bias assessment was performed.

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Table B.1: PRISMA 2020 checklist (continued)

Section and topic	Item	Checklist item	Reporting status and location
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Partial. Section 3.7 (p. 28); Chapter 4 (p. 31). Selected source statistics are presented, and no common effect estimate was calculated. Effect measures are not systematically defined for every outcome.
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Partial. Section 3.7 (p. 28). Findings are grouped by research question and compared around shared design questions. The process for choosing each comparison's contributing reports or findings is not fully specified.
Synthesis methods	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Partial. Section 3.5 (p. 24); Section 3.6 (p. 26); Appendix A (p. 61). Publication-year reconciliation, missing-entry notation, and contextual qualifications are described. Preparation of outcome statistics is not systematically described.
Synthesis methods	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Reported. Section 3.5 (p. 24); Section 3.6 (p. 26); Section 3.7 (p. 28). Extraction tables, corpus figures, and comparison tables for the three research questions are described.
Synthesis methods	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Reported. Section 3.7 (p. 28). Narrative synthesis compares technical measurements, player studies, system descriptions, and reviews while retaining differences in instruments, tasks, and outcomes.
Synthesis methods	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Reported. Section 3.7 (p. 28). Qualitative comparisons consider devices, tasks, participants, measures, conflicting findings, and limitations. No statistical subgroup analysis or meta-regression is described.
Synthesis methods	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Not done. Section 3.7 (p. 28). The thesis states that no sensitivity analysis was performed.
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Not done. Section 3.7 (p. 28). The thesis states that no formal assessment of bias due to missing results was performed.
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Not done. Section 3.7 (p. 28). The thesis states that no formal certainty assessment was performed.
Results			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Reported. Section 3.4 (p. 23); Figure 3.1 (p. 25); Table A.5 (p. 82). The identification, screening, retrieval, eligibility, and inclusion totals are reported in the text and flow diagram. The exclusion table identifies the stages and reasons. The final corpus contains 109 reports.
Study selection	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Reported. Table A.5 (p. 82). The twelve excluded entries are identified with DOI-linked titles, reasons, and relevant qualifications.

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Table B.1: PRISMA 2020 checklist (continued)

Section and topic	Item	Checklist item	Reporting status and location
Study characteristics	17	Cite each included study and present its characteristics.	Reported. Table A.3 (p. 64); Table A.4 (p. 77). Every included report is cited with instrument, modality, technical, and evaluation characteristics. Missing entries are explicit.
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Not done. Section 3.7 (p. 28). No formal study risk-of-bias assessment was performed, so no per-study assessment results are available.
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Partial. Chapter 4 (p. 31); Table A.4 (p. 77). Individual findings and selected statistics are presented. Group summaries, effect estimates, and their precision are not systematically reported for every applicable outcome.
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Partial. Section 4.2 (p. 32); Section 4.3 (p. 40); Section 4.4 (p. 47). The contributing devices, tasks, participants, and study limitations are discussed. No formal risk-of-bias assessments are available.
Results of syntheses	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Not done. Section 3.7 (p. 28). No statistical synthesis of study outcomes or meta-analysis was performed. The publication counts describe corpus composition.
Results of syntheses	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Reported. Section 4.2.4 (p. 34); Section 4.2.6 (p. 37); Section 4.4.6 (p. 53); Section 4.4.7 (p. 54). Qualitative comparisons discuss differences in signals, contact, baseline conditions, tasks, and participants.
Results of syntheses	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Not done. Section 3.7 (p. 28). No sensitivity analysis was performed, so no results are available.
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Not done. Section 3.7 (p. 28). No formal assessment of bias due to missing results was performed, so no assessment results are available.
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Not done. Section 3.7 (p. 28). No formal certainty assessment was performed. Conditional design guidance does not constitute a formal certainty rating.
Discussion			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Reported. Chapter 4 (p. 31); Section 5.1 (p. 57). Interpretation connects the findings with prior designs, studies, and reviews.
Discussion	23b	Discuss any limitations of the evidence included in the review.	Reported. Section 4.5 (p. 56); Section 5.2 (p. 58). Differences between instruments, comparison limits, uncertainty, and the conditions for transferring findings are discussed.

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Table B.1: PRISMA 2020 checklist (continued)

Section and topic	Item	Checklist item	Reporting status and location
Discussion	23c	Discuss any limitations of the review processes used.	Reported. Section 5.2 (p. 58). Search coverage, sole-reviewer selection, absence of independent human extraction checks, and omitted formal assessments are discussed.
Discussion	23d	Discuss implications of the results for practice, policy, and future research.	Reported. Section 5.3 (p. 59); Table 4.1 (p. 39); Table 4.2 (p. 48); Table 4.3 (p. 55). Conditional design guidance and proposals for further comparisons and evaluations are given.
Other Information			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Not done. Disclosure in Appendix B (p. 83); Abstract (p. ix). The thesis explicitly states that the review was not registered.
Registration and protocol	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Not done. Disclosure in Appendix B (p. 83). The thesis explicitly states that no separate review protocol was prepared.
Registration and protocol	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Not done. Disclosure in Appendix B (p. 83). There was no registration or separate protocol to amend.
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Reported. Disclosure in Appendix B (p. 83); Acknowledgments (p. xiii). The review received no funding. Academic guidance and personal support are acknowledged.
Competing interests	26	Declare any competing interests of review authors.	Reported. Disclosure in Appendix B (p. 83). The author declares no competing interests.
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Partial. Disclosure in Appendix B (p. 83); Section 3.1 (p. 19); Section 3.3 (p. 22); Section 3.6 (p. 26); Appendix A (p. 61). The repository link and access restriction are given; data and scripts are described. The public availability and location of every requested material are not fully specified.

B.2 PRISMA 2020 for Abstracts

Table B.2: PRISMA 2020 for Abstracts checklist

Section and topic	Item	Checklist item	Reporting status and location
Title			
Title	1	Identify the report as a systematic review.	Partial. Title page; Abstract (p. ix). The title uses "Survey"; the Abstract identifies the work as a systematic literature review.
Background			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Reported. Abstract (p. ix), paragraph 1. Feedback selection, technical implementation and mappings, and evaluation define the objectives.
Methods			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Reported. Abstract (p. ix), paragraph 2. The two eligibility routes and exclusions for immersive environments, applications outside the scope, and course materials are stated.
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Reported. Abstract (p. ix), paragraph 2. ACM DL and NIME were searched on 7 July 2026; OpenAlex and backward and forward citation searches on 16 July 2026.
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Not done. Abstract (p. ix), paragraph 4. The absence of a formal risk-of-bias assessment is stated.
Synthesis of results	6	Specify the methods used to present and synthesise results.	Reported. Abstract (p. ix), paragraph 2. Narrative synthesis is specified.
Results			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Partial. Abstract (p. ix), paragraph 2. The total of 109 reports and types of evidence are given. No independent-study total or deduplicated participant total is provided.
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Reported. Abstract (p. ix), paragraph 3. The main narrative findings and directions of effects are given. Counts per finding, requested preferably, are omitted.
Discussion			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Reported. Abstract (p. ix), paragraphs 3–4. Uncertain findings and differences in instruments, tasks, and samples limit transfer.
Interpretation	10	Provide a general interpretation of the results and important implications.	Reported. Abstract (p. ix), paragraph 4. The limits of the evidence for feedback selection are stated, and the guidance requires testing in new settings.
Other			
Funding	11	Specify the primary source of funding for the review.	Reported. Abstract (p. ix), paragraph 4. The review received no funding.
Registration	12	Provide the register name and registration number.	Not done. Abstract (p. ix), paragraph 4. The thesis states that the review was not registered; no registration identifier exists.

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