Article

Challenges and Opportunities of Force-Feedback in Music

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Abstract: A growing body of work on musical haptics focuses on vibrotactile feedback, while musical applications of force feedback (FF), though more than four decades old, have been more sparse. In this paper, we review related work combining music and haptics, focusing on force feedback. We then discuss the limitations of these works and elicit the main challenges in current applications of force-feedback and music (FF&M): modularity, replicability, affordability, and usability. We call for opportunities in future research works on force-feedback and music: embedding audio and haptic software into hardware modules, networking multiple modules with distributed control, authoring with audio-inspired and audio-coupled tools. We illustrate our review with our recent efforts to develop an affordable, open-source and self-contained 1-Degree-of-Freedom (DoF) rotary force-feedback device for musical applications, the *TorqueTuner*, and to embed audio and haptic processing and authoring in module firmware, with *ForceHost*, and examine their advantages and drawbacks in light of the opportunities presented in the text.

Keywords: Haptics; Force-feedback; Musical interaction; Computer music

1. Introduction

Digital Musical Instruments (DMI) feature high-resolution gesture sensing and audio output, but poor gestural and bodily feedback, compared to traditional acoustic instruments, which passively produce and transfer: vibration from strings to fingers; kinesthetic feedback from drums to fingers, hands, forearms and arms of drummers; coupling of air columns between wind instruments and their players. In this article, we examine how DMIs can produce dynamic feedback to the sense of touch of their players, that is through haptic feedback.

The term *Haptics* involves both *touch* and *force-feedback*. Touch feedback, specifically *vibrotactile* feedback, has been the focus of much research and development in the last two decades using devices that cause vibrations felt by mechanoreceptors in the skin. A review of mechanoreceptors types and functions is available in Halata and Baumann (2008). This paper focuses on force-feedback applications in audio, music and media control. Touch or vibrotactile feedback is discussed in length in other papers part of the same special issue "Feeling the Future—Haptic Audio" as our article, as well as in a recent reference edited by Papetti and Saitis (2018). Burdea and Coiffet (2003) define *force-feedback* as a simulation that "conveys real-time information on virtual surface compliance, object weight, and inertia. It actively resists the user's contact motion and can stop it (for large feedback forces)". While vibrotactile feedback mainly stimulates the skin, force-feedback extends the possibilities of stimulation to a larger set of the body, with the capability of responding finely to subtle movements from our limbs. And musicians employ as much of their whole body as they are able to while playing music.

Research in force feedback and music intersects with research on *mulsemedia* systems, or *multisensory multimedia*, as defined by Covaci et al. (2018), facing similar challenges as

Citation: Frisson, C.; Wanderley, M. M. . 2023. Force-Feedback in Music. *Arts* 1: 0. https://doi.org/

Received:
Accepted:
Published:

reviewed by Ghinea et al. (2014). These include the difficulty of implementing systems, as reviewed by Saleme et al. (2019), and the need for authoring tools, as elicited by Mattos et al. (2021).

Force-feedback devices typically use electrical motors to display (output) forces, based on position inputs. This design, position in and force out, is known as *impedance control*. Devices then can be characterized in terms of the number of inputs and outputs they possess.

1.1. Force-feedback and Music

Research in force-feedback applied to music is not recent, with some of its early contributions dating back to the late 70s. Despite its longevity, it has been impeded by factors such as (rather exorbitant) hardware costs, software limitations (drivers), fast hardware and software obsolescence, as well as the lack of accessible platforms for prototyping musical applications. Though a body of work was developed over the years focusing on measurements, models and applications, musical force-feedback has never become widespread. The disruptive force-feedback musical application is yet to come.

Yet, the simulation of complex performer-instrument interactions in music is a promising research direction that aims at understanding musicians' highly skilled control strategies developed over years of intensive training.

In recent years a number of works addressed several aspects of this topic, proposing software platforms and simulation models with the potential to provide popular and/or advanced force-feedback tools for musical applications.

2. Previous works

In this section, we review previous works related to force-feedback and music, first hardware devices, then software environments.

2.1. Force-feedback Devices

The availability of general-purpose force-feedback devices used in real-time to provide the closest similarity to the real instrumental situation is a major issue, both in terms of the cost of such devices (typically several thousand dollars) and the relatively rapid obsolescence of communication protocols used by them (e.g. communication using the parallel port in some of the older models), limiting the usefulness of such investment.

As for device specification requirements for FF&M, a large workspace is typically desired, both in translation and rotation, strong motors are required to present stiff walls (necessary in the percussive case), and low tip inertia and friction to increase the transparency of the device vis-à-vis the simulated action.

Common devices used in force-feedback research (including musical applications) are typically 3 DoF devices in the form of a stylus or spherical end effector, providing 3 output forces in the X, Y and Z axes. Some of these devices measure positions in 3 DoF (e.g. *Novint Falcon* with 3 DoFs in translation), while others measure position in 6 DoF (for instance 3 DoFs in translation and 3 DoFs in rotation between the stylus and the arm of the end effector), whilst still providing a 3 DoF force output, e.g. *3D Systems*'s *Touch X*, formerly *SensAble*'s *Phantom Desktop*. Devices which output 6 DoF (forces in X, Y and Z, as well as torques around the three axes) are more expensive, though also relatively common, with 6 DoF positional sensing, e.g. *3D Systems' Phantom Premium* or *MPB Technologies' Freedom 6S*.

Apart from the specifics about positional sensing and force-feedback, devices differ in terms of a) the usable workspace they provide, the larger the workspace volume, the more expensive the device (and typically displaying lower output forces), as well as b) their mechanical construction: *serial* or *parallel* devices.

The *Touch X*, *Phantom Premium* and *Freedom 6S* are three examples of variable workspace and force distributions, based on data collected for and categorized in *Haptipedia* by Seifi et al. (2019): the *Touch X* has a small translational workspace of $16 * 12 * 12$ cm^3 and large rotational workspace of $360 * 360 * 180$ deg^3 and outputs translational forces of 7.9 N (peak) and 1.75 N (constant), the *Phantom Premium* has a large translational workspace of $82 * 59 * 42$ cm^3 and large rotational workspace of $330 * 330 * 220$ deg^3 and outputs translational forces of 22 N (peak) and 3.00 N (constant), the *Freedom 6S* has a medium translational workspace of $33 * 22 * 17$ cm^3 and medium rotational workspace of $340 * 170 * 130$ deg^3 and outputs translational forces of 2.5 N (peak) and 0.60 N (constant).

In serial devices, the three output motors are connected to the end effector through a common structure, while in parallel devices each motor connects directly to the end effector. The *Touch X*, *Phantom Premium* and *Freedom 6S* are serial devices, whilst the Falcon is a parallel device.

Figure 1 shows several commercial devices used in musical applications at the *Input Devices and Musical Interaction Laboratory* (*IDMIL*), McGill University.

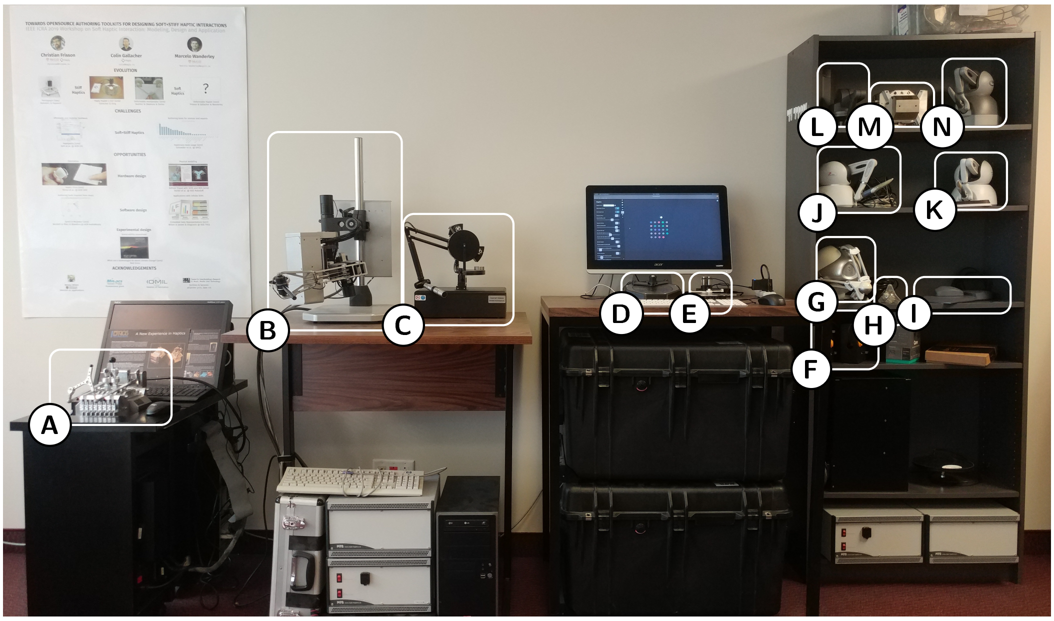

Figure 1. Several force-feedback devices used in force-feedback musical applications at the IDMIL. From bottom-left to top-right: (A) *ACROE ERGOS*, (B) *MPB Technologies Freedom 6S*, (C) *SensAble Phantom Premium*, (D) & (E) two *Haply Pantographs*, (F) two *FireFaders* built at *IDMIL*, (H) *Novint Falcon* and (G) removable end-effector, (I) *Logitech WingMan* mouse, (J) & (K) two *SensAble Phantom Omni* , (L) *SensAble Phantom Desktop*, (M) a second *ACROE ERGOS*, and (N) *3D Systems Touch*.

One interesting example of a force-feedback device is the *ERGOS*, a high-quality, flexible DoF device developed by the *Association pour la Création et la Recherche sur les Outils d'Expression* (*ACROE*). The *ERGOS'* actuator consists in "a stack of flat moving coils that are interleaved with flat magnets" as explained by Florens et al. (2004).

The *ERGOS* is innovative in several aspects as explained by Cadoz et al. (1990): a) it consists of multiple 1-DoF *sliced motors* (motors sharing a single magnetic polarization circuit for use as motor modules in a FF keyboard) which share a common magnetic field, allowing for individual sliced motors with reduced size; b) Several sliced motors can be combined together in a single *ERGOS* device (4, 6 12 or more motors); c) Individual motors can be connected through mechanical add-ons to create integral 2 to 6 DoF effectors ; d) It has been primarily designed with artistic applications in mind.

The *ERGOS* was used in several artistic/musical projects at *ACROE*, e.g. "pico..TERA" by Cadoz et al. (2003), as well as at the IDMIL by Sinclair et al. (2009) and Tache et al. (2012).

Several force-feedback devices, either generic or specifically designed for musical applications, have been used over the last several decades for the simulation of instrumental actions. We review these force-feedback devices along to the amount of degrees of freedom that they produce.

2.1.1. 1-DoF Devices

1-DoF devices are very useful as they allow for detailed explorations of haptic effects in constrained situations. Several applications can be simulated with 1-DoF devices, for instance, feeling bumps or valleys, simulating springs, etc.

A few devices introduced in the literature, for instance, by Verplank and Georg (2011), have 1-DoF, measuring linear position (or rotation) at the input and displaying a force (or torque). They are known as *haptic faders* or *haptic knobs*. Examples of linear 1-DoF force-feedback faders are actuated sliders used in automated mixing consoles and in the *FireFaders* by Berdahl and Kontogeorgakopoulos (2013). Rotary 1-DoF devices include the *Haptic Knob* by Chu (2002), *the Plank* by Verplank et al. (2002), a low cost haptic knob by Rahman et al. (2012), the *Haptic Capstans*, derived from the *FireFader* by Sheffield et al. (2016) and more recently the *TorqueTuner* by Kirkegaard et al. (2020); Niyonsenga et al. (2022).

Among these 1-DoF force-feedback devices, *TorqueTuner* by Kirkegaard et al. (2020); Niyonsenga et al. (2022) is singular: this module embeds haptics loop and effect presets in its microcontroller and exposes input and output controls for mapping with external sound synthesis engines, and comes in modular form-factors as illustrated in Figure 2.

(a) Standalone haptic knob (Mechaduino-based) by Kirkegaard et al. (2020)

(b) T-stick adapter (Mechaduino-based) by Kirkegaard et al. (2020)

(c) Workbench with presets (Moteus-based) by Niyonsenga et al. (2022)

Figure 2. Modularity and evolution of *TorqueTuner*, from Kirkegaard et al. (2020); Niyonsenga et al. (2022). The first two models, 2a and 2b, are based on the Mechaduino platform. The right model, 2c, is based on the Moteus platform, due to the recent unavailability of the Mechaduino.

2.1.2. How Many DoFs?

There is no simple answer to this question, as devices with different numbers of DoFs might be helpful in a given musical interaction. Therefore the choice of the device should consider the intended use and the budget available for the project.

Though, as shown before, simpler 1-DoF devices might be appropriate for certain interactions, e.g. plucking a string, many musical situations in the real world involve many DoFs. Two examples include percussion and bowed-string instruments. Specifically:

- In percussion instrumental actions, the performer holds the stick at one end while the other end is launched in a ballistic gesture toward the target. Rebound force is experienced by the player's hand, *cf.* Bouënard et al. (2010). This force is generated at the stick-target interaction point but is transmitted along the stick to the hand, at which point it becomes a torque. This torque plays an active role in percussion performance, influencing the timing of subsequent hits and enabling the "drum roll" action. Simulation of such actions can be achieved with voice coils, as impressively done by Rooyen et al. (2017).
- In violin bowing, the performer holds the bow at the frog, while the hair-string interaction point varies away from the frog throughout a downward stroke. Several works in the literature, e.g. by Nichols (2000), O'Modhrain et al. (2000), Tache et al. (2012), have tried to simulate bowing interactions, most of the time using three or fewer DoFs. Four DoFs were used in the second version of VBow by Nichols (2002). Indeed, as shown by Schoonderwaldt et al. (2007), forces such as bow weight, pull along the string orthogonal to the bow, application of pressure on the string by the

player, and rotation around the strings to select which string is bowed, are all exhibited as torques when translated from the bow-hair interaction point along the bow to the player's hand.

2.1.3. 3-DoF and 6-DoF Devices

Several commercial 3-DoF and 6-DoF devices exist. Though typically designed for industrial applications, many have been used in musical simulations.

Simulations of musical actions involving six DoFs (force-feedback in three translational and three rotational directions) are more complicated. Unlike 3-DoF devices, 6-DoF requires more advanced mechanical technologies and complex computer modeling to integrate torque feedback seamlessly.

The effective difference between 3-DoF and 6-DoF haptic rendering is, though, striking: the former is limited to the rendering of point-like interaction, a single point of contact between an object and a sphere, such that the reaction force vector extends towards the human-machine holding position; in contrast, the latter allows for off-axis forces, meaning the simulation of arbitrary object-object interaction with multiple points of contact. In other words, 6 DoF rendering can be used to simulate the holding of objects that are not balanced and which are in contact with an arbitrary environment.

2.1.4. Multi-DoF Force-Feedback Devices

The Touch Back Keyboard by Gillespie (1992) with 1-DoF per key on eight keys and the MIKEY (Multi-Instrument active KEYboard) by Oboe (2006) with one DoF per key on three keys are two examples that illustrate the complexity of increasing the amount of DoFs in actuation to augment key-based instruments that already feature a large amount of DoFs in sensing.

One of the earliest developments of a force-feedback device developed to be used in sound and music interactions was *coupleur gestuel retroactif*, developed by Florens (1978) at *ACROE*, in Grenoble, France. This is the first of a long series of devices explicitly designed for artistic/musical applications from the late 70s to the 2010s, as reviewed by Cadoz et al. (2003); Leonard et al. (2018). Though a few of these designs will be mentioned here, it is hardly possible to overstate the contribution of *ACROE* to the area of force-feedback and music, also in part because these devices were conceived in the context of multi-pronged research on force-feedback, sound synthesis and animated images since the inception of the association, as discussed by Cadoz et al. (1984). The iterations of Force Feedback Gesture Transducers by Cadoz et al. (2003) go beyond the form factors of traditional musical instruments to enable multi-DoF digital musical instruments with customizable form factors and end effectors with up to 16 DoFs. Their contributions' novelty, quality and coherence over more than four decades are unique in computer music and haptics. Some of the most recent works from the group showed the feasibility of real-time, high-quality simulations of haptic/audio/visual environments controlled by force-feedback devices by Leonard et al. (2018), opening up the possibilities for interactive multimedia performances using force-feedback.

2.2. *Software Environments*

When using force-feedback devices, one needs to define the behavior of the system comprising the device & the application context. For instance, using a 3-DoF FF controller, the feel of the device (forces output by the device) will depend on the model upon which the device is used. If the environment simulates a virtual wall, the FF device end-effector (e.g. a stylus) will tend to be stopped when touching/trying to move through the wall (to a certain extent, depending on the characteristics of the simulation and the device used). If the environment consists of a pair of objects, one grounded to the floor and the other connected to the first one through a virtual spring, pushing the second one on the axis of the spring will make it oscillate harmonically (if no friction is added to the environment). It is clear then that what the forces the device will output depend on both the device and the model being simulated.

Creating such models and virtual environments typically require the use of software tools to develop haptic simulations. Having been created mainly for industrial or other non-artistic applications, such tools are not user-friendly for artists/musicians who do not possess a strong programming expertise. Furthermore, they have limited capabilities when dealing with advanced sound generation/manipulation.

While many related works explore creative solutions for authoring haptic feedback, as reviewed by Schneider et al. (2017), Covaci et al. (2018) and Seifi et al. (2020); in this work we focus on frameworks that couple force and sound feedback in musical applications.

2.2.1. Physical modelling for audio-haptic synthesis

CORDIS-ANIMA

Cadoz et al. (1993) pioneered the use of mass-interaction modeling for multisensory simulation. With *CORDIS-ANIMA*, designers design physical behaviours with scenes composed of interconnected masses, springs, non-linear links, and friction elements. The resulting simulation is displayed through haptic, audio and visual outputs, all rendered with the same physical model. Villeneuve et al. (2015) introduced signal modelling features more recently.

DIMPLE

DIMPLE (*Dynamically Interactive Musically Physical Environment*) by Sinclair and Wanderley (2008) is a software framework allowing the creation of instrumental interactions using 3D objects with responsive behaviors (visual, haptic and sound). In *DIMPLE*, a physical simulation of a virtual environment is constructed and can be manipulated by a force feedback device. It uses *Open Sound Control* (*OSC*) by Wright and Freed (1997) and audio programming tools such as *PureData* (*Pd*) by Puckette (1997) to create force-feedback-enabled virtual environments in *CHAI3D* by Conti et al. (2005). Objects in the environment can send back messages about their own properties or events such as collisions between objects using *Open Dynamics Engine* (*ODE*). This data can be used to control events in sound synthesis or in other media. *DIMPLE* has proven useful for multidisciplinary research in experimental psychology, multimedia, arts, and computer music, e.g. work by Erkut et al. (2008).

Synth-A-Modeler

Synth-A-Modeler (*SaM*) *Compiler* by Berdahl and Smith III (2012) and *Designer* by Berdahl et al. (2016) together constitute an interactive development environment for designing force-feedback interactions with physical models. With *SaM*, designers interconnect objects from various paradigms (mass-interaction, digital waveguides, modal resonators) in a visual programming canvas reminiscent of electronics schematics and mechanical diagrams, and compile applications generated with the *Faust* digital signal processing (DSP) framework. *SaM Designer* does not support real-time visual rendering of models, and the possibilities of run-time modifications are limited to the tuning of object parameters.

MIPhysics

A more recent environment for prototyping force-feedback applications is *MIPhysics*, by Leonard and Villeneuve (2020) (mi-creative.eu). Their collective *MI-Creative* uses mass-interaction physical modelling to create artistic applications generating physically-based sound synthesis, allowing fast prototyping of audio-haptic interactive applications also by Leonard and Villeneuve (2019). With *MIPhysics*, designers script interactive simulations, rendered with audio, haptic and visual feedback. Leonard and Villeneuve also developed a 1-DoF mass-interaction framework for *Faust* Leonard et al. (2019), aiming at designing larger physical models, but with no direct support for using haptic devices as input.

ForceHost

ForceHost by Frisson et al. (2022) is a firmware generation toolkit for *TorqueTuner* by Kirkegaard et al. (2020) that extends the *Faust* programming language toolkit to embed in modules not only haptics and mappings, but as well a scriptable web-based user interface and sounds synthesis, as illustrated in Figure 3.

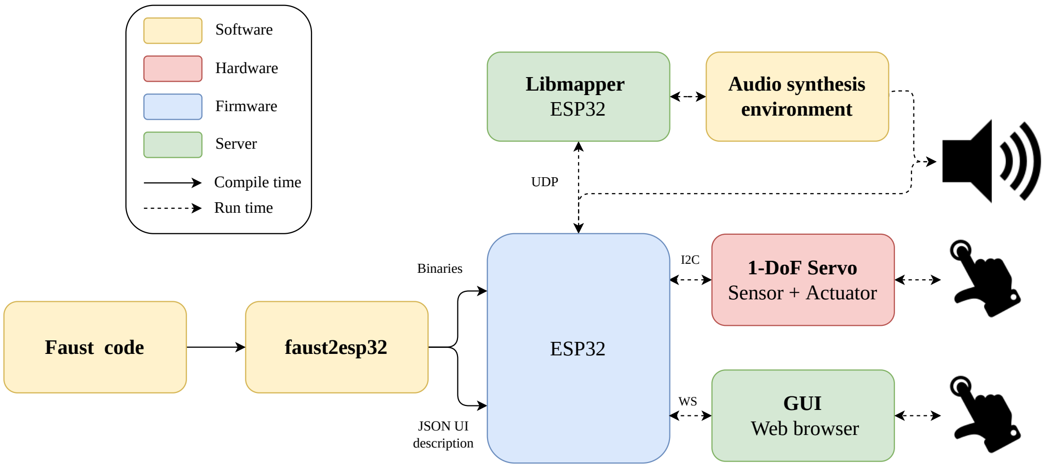

Figure 3. Architecture of *ForceHost*, from Frisson et al. (2022).

2.2.2. Force-feedback for sample-based music creation

Beamish et al. (2004) have proposed with *D'Groove* force-feedback control techniques inherited from how disk jockeys (DJs) manipulate turntables. Frisson (2013 2015) and colleagues have investigated how force-feedback haptics would support multimedia browsing, including for musical practices such as *comprovising* (or composing by improvising with) soundscapes by navigating in collections of sounds. They first devised prototypes to explore mappings between audio features and force-feedback controls with *DeviceCycle* by Frisson et al. (2010). They later created content-based force-feedback effects for browsing collections of sounds: using motorized faders to recall sound effects applied to individual sounds in *MashtaCycle* by Frisson et al. (2013), adding friction when hovering sound items with a haptic pointer, pulling the pointer towards the closest neighbor in a content-based similarity representation with *Tangible Needle* and *Digital Haystack* by Frisson et al. (2014).

3. Challenges

We identify four challenges in force-feedback musical instruments: modularity, replicability, affordability, and usability.

3.1. Modularity

Degrees of freedom (DoFs) for sensing and actuation add dimensions to the design space of interaction and display with force-feedback haptic devices. For instance, handheld manipulators of grounded force-feedback devices like the *3D Systems Touch* (formerly *SensAble Phantom Omni*) may feature 6 DoFs for position sensing (3 in translation, 3 in orientation) and 3 DoFs for actuation (motors actuating some joints of a serial arm resulting in translations in 3D spaces), among other possible combinations of DoFs, as illustrated by *Haptipedia*, an encyclopedia of force-feedback devices by Seifi et al. (2019). Larger amounts of degrees of freedom increase not only the potential complexity of interaction that the device can support, but also the initial complexity of engineering the mechanical, electrical and computational architecture of these devices, as for example the two force-feedback musical instruments: *Touch Back Keyboard* by Gillespie (1992) with 8 force-feedback keys and the *MIKEY* (*Multi-Instrument active KEYboard*) by Oboe (2006) with 3 force-feedback keys. Rather than combining off-the-shelf devices with predefined form factors and enclosures, designers of digital musical instruments may want to design their instruments by integrating their own selection of modules of degrees of freedom assembled in a mechanism that fits their instrument. *Force Feedback Gesture Transducers* by Cadoz et al. (2003) and *Probatio* by Calegario et al. (2020) are two use cases about challenges in modularity. The *Force Feedback Gesture Transducers* by Cadoz et al. (2003) went beyond the form factors of traditional musical instruments to enable multi-DoFs force-feedback digital musical instruments with customizable form factors and end effectors, but were designed by machine-engineered custom-ordered metal pieces, still hard to access for DMI designers, and pre-dating nowadays democratized 3d printing solutions. *Probatio* is a toolbox that enables designers of digital musical instruments to combine various DoFs and create different instruments adapted to various postures and metaphors of control instrumentists want to adopt while playing their instruments. Integrating force-feedback modules such as *TorqueTuner* by Kirkegaard et al. (2020) in the *Probatio* toolbox is part of future work, and poses challenges in supplying larger power for actuation, distributing haptic parameters while maintaining haptic loops.

3.2. Replicability

Designers and players of Digital Musical Instruments (DMIs) face issues in being able to redesign and replay instruments that are not necessarily mass-produced and available off-the-shelf. DMIs may not have been designed for longevity, as studied by Morreale and McPherson (2017). The design and development process of DMIs may not have been documented into enough depth to be replicated, as reviewed by Calegario et al. (2021).

In addition to the issues mentioned above that are generic to DMIs, force-feeback haptic DMIs bear their own specific issues. Hardware connectors and ports eventually become obsolete (funds spent in devices). Software drivers are generally closed-source and clash with new APIs introduced along OS generations. Operating systems manage real-time audio and haptic loops differently.

3.3. Affordability

The democratization of affordable open-hardware robotics platforms (*Arduino*, *ESP32*) and robotics application fields (electric devices for personal or light payload transportation such as electric bikes and skateboards and drones) has enabled the prototyping of force-feedback haptics beyond industrial facilities, in fabrication labs (fablabs), and driven down the cost of components, particularly of motors and electronic boards. In contrast, force-feedback devices are still not widespread although this expanded availability of open-hardware components has contributed to reduce their cost. Over time, force-feedback devices prices have gradually decreased from price ranges of laboratory equipment and professional musical instruments (tens of thousands of dollars, including: *Ergos TGR*, *MPB Technologies Freedom 6S*) to price ranges of computer peripherals and entry-level musical instruments (hundreds of dollars, including: *Novint Falcon*, *Haply Pantograph*, *TorqueTuner*), but still not yet to the state where the force-feedback devices are available in stores or homes as much as computer peripherals or entry-level musical instruments. Leonard et al. (2020) argue that affordable force-feedback devices are nowadays sufficient for "*thinking* and *designing* dynamic coupling with virtual musical instruments, but they do not yet entirely allow qualitative *feeling* of this coupling".

3.4. Usability

Seifi et al. (2020) reviewed the challenges met by novice force-feedback haptic designers ("hapticians") to create applications with 1 DoF devices throughout the Student Innovation Challenge at the World Haptics Conference in 2017. The authors concluded that novice hapticians have several needs for haptic design: theoretical and practical guidelines, tools for infrastructure and content, and an ecosystem of authoring tools. In addition, expert hapticians have been adopting design practices and tools from related fields generating content through audio and visual modalities.

Challenges met by novice and expert designs of non-audio haptic applications are merged when designing DMIs that combine force feedback and sound synthesis: not only design guidelines and tools are missing; but also need to support both audio and haptic modalities. Authoring tools for designing for both audio and haptic modalities are scarce, to our knowledge only: *GENESIS* by Villeneuve et al. (2015) and *Synth-A-Modeler Designer* by Berdahl et al. (2016) and *ForceHost* by Frisson et al. (2022), proposing physical modelling metaphors or signal-based approaches. When authoring tools support only one modality among audio or haptic, then designers need to devise strategies to synchronize streams, what often requires ad-hoc development.

4. Opportunities

We identify three opportunities for further research in force-feedback and music: embedding audio and haptic software into hardware modules, networking multiple modules with distributed control, authoring with audio-inspired and audio-coupled tools.

4.1. Embedding

To overcome challenges in replicability and usability, we propose to embed audio and haptic processing and authoring in microcontrollers, including embedded haptic loops as in *TorqueTuner* by Kirkegaard et al. (2020) and embedded drivers and web-based control panels as in *ForceHost* by Frisson et al. (2022). By embedding these software components directly in microcontrollers required to interface hardware components, audio-haptic DMIs do not rely anymore on third-party operating systems to maintain and synchronize audio and haptic loops and become less sensitive to the evolution of APIs and to the adoption of peripheral connectors, as drivers and control panels are on-board and communicate with third-party computers with interoperability protocols such as *OSC* or require a default web browser for authoring.

4.2. Networking

To overcome challenges in modularity and replicability, we propose to network audio and haptic modules. Beyond reusing off-the-shelf force-feedback devices, audio-haptic DMI designers have now the opportunity to combine force-feedback modules such as the *Firefader* by Berdahl and Kontogeorgakopoulos (2013) (1 translational DoF) and the *TorqueTuner* by Kirkegaard et al. (2020) (1 rotational DoF) and compose their own modular user interface as with *Probatio* by Calegario et al. (2020). Further research is needed to understand how to best arrange all audio-haptic streams altogether and their level of synchronicity. One opportunity for networks of embedded modules is to investigate the nature of signals to map with solutions like *libmapper* by Malloch et al. (2013) and its web-based authoring tool *webmapper* by Wang et al. (2019), that is sparse event-based control signals, rather than audio or haptic loops that are embedded in each module.

4.3. Authoring

To overcome challenges in modularity, replicability, and usability, we propose to further develop audio-inspired and audio-coupled force-feedback haptic authoring tools.

Audio-inspired haptic authoring tools should reuse well-established features from audio authoring tools, such as digital audio workstations where graphical representations of waveforms and transfer functions are commonplace, where interoperability protocols such as *Musical Instrument Digital Interface* (*MIDI*), *MIDI Polyphonic Expression* (*MPE*) and *OSC* are well established, and where APIs for audio effects and synthesizers plugins allow to enrich the audio design space. Further research is needed to define what would be the interoperability protocols for force-feedback haptics, similarly to how *TUIO* by Kaltenbrunner et al. (2005); Kaltenbrunner and Echtler (2018) expanded *OSC* for tangible user interfaces; and what plugin API would be suitable for force-feedback haptics, what could also be approached by networking embedded modules.

Audio-coupled haptic authoring tools should facilitate the design of audio- and haptic feedback with a unified system, sharing one scripting language or one visual programming metaphor for the designs for both modalities. For instance, *ForceHost* by Frisson et al. (2022) explored how the *Faust* programming language for digital signal processing could be employed to unify the description of audio and haptic applications, including their control through auto-generated web-based user interfaces.

5. Conclusions

In this paper, we have reviewed the literature of research works combining music and force-feedback haptics. We have discussed the limitations of these works and elicited the main challenges in current applications of force-feedback and music: modularity, replicability, affordability, and usability.

We call for opportunities in future research works on force-feedback and music: embedding audio and haptic software into hardware modules, networking multiple modules with distributed control, authoring with audio-inspired and audio-coupled tools.

We have illustrated our review with our recent efforts to develop an affordable, open-source and self-contained 1-DoF rotary force-feedback device for musical applications, the *TorqueTuner* by Kirkegaard et al. (2020), and to embed audio and haptic processing and authoring in module firmware, with *ForceHost* by Frisson et al. (2022).

Acknowledgments: The authors would like to welcome past collaborators who were an integral part of several of the works described here, most notably Albert-Ngabo Niyonsenga, Mathias Kirkegaard, Mathias Bredholt, Stephen Sinclair, Olivier Tache, Jean-Loup Florens, and Marcello Giordano. Part of this work has been supported by multiple grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), through its Discovery, RTI (Research Tools and Instruments) and New Opportunities programs.

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