Foot Pedal Control: The Role of Vibrotactile Feedback in Performance and Perceived Control

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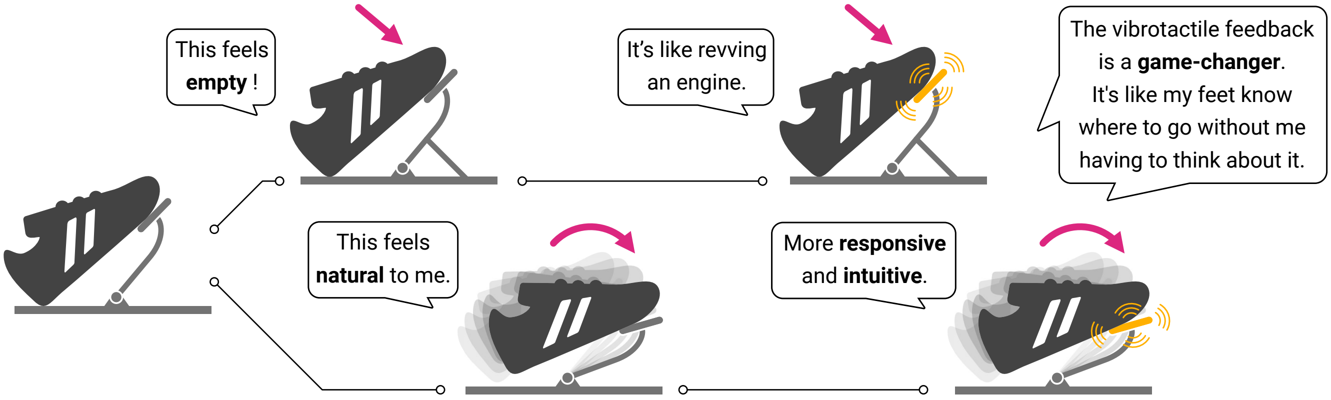

Figure 1: We built a pedal that can either move (bottom row) or is locked (top row). Further, we attached an actuator to augment the interaction with vibrotactile feedback (right). Each mode elicits certain qualities of experiences and perceived control of the pedal.

Abstract

Feedback on foot pedals affects the user's ability to control dynamic systems. However, the effects of the type of vibrotactile feedback and the interplay between objective performance and the user's perceived control has not been formally investigated for foot pedals. Thus, we evaluate this interplay for 4 pedal configurations: rigid and compliant pedals with and without vibrotactile feedback synchronized with user action. We conducted a within-subjects study with 12 participants, consisting of (1) a one-dimensional following task, (2) a driving task in VR to measure user performance, and (3) qualitative interviews for understanding users' subjective control. The objective performance metrics show no significant differences between the pedal configurations. In contrast, the analysis

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of the interviews reveals that motion-coupled vibrotactile feedback increases the participants' perceived control. These results offer possibilities for designing customized pedal feedback without compromising performance. This research emphasizes evaluating objective performance as well as perceived control while assessing control strategies for existing and novel interfaces.

CCS Concepts

• **Human-centered computing → Haptic devices**; *User studies*; Empirical studies in HCI.

Keywords

foot pedals, vibrotactile feedback, performance, perceived control, sense of agency, embodied mediation

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1 Introduction

The evolution of control mechanisms has continuously adapted to technological advancements. One notable shift is the transition from the early foot tools that applied both power and control – such as the foot pedal of treadle sewing machines – to modern pedals that predominantly serve as input devices for control [57]. Modern pedals are typically used as input devices to control aspects such as the acceleration of a car, the speed of a sewing machine, or to pan and zoom computer interfaces [26, 47, 54]. While pedals are used for a wide range of applications, a predominant use case of pedals is controlling the throttle and brakes of cars. Different feedback strategies, including force and vibrotactile feedback, have been used to improve the user's control on gas pedals [11, 40, 54, 72, 74]. However, this feedback is often symbolic in nature and needs to be interpreted by the user. This interpretation can be error-prone [37, 52] and can compromise driver safety [25]. One way to make vibrotactile feedback easier to interpret is by rendering material experiences, such as friction [61, 68]. This can be achieved using motion-coupled vibrotactile feedback [62].

Past research in HCI has primarily focused on motion-coupled vibrotactile feedback to render virtual compliance [35] and virtual textures [68], but also touched on a broader range of material experiences [29, 61, 66]. The underlying perceptual mechanism between virtual compliance and virtual texture share a common foundation: vibrotactile pulses synchronized with the measured human action generate material experiences. Specifically, vibrotactile feedback coupled to applied pressure induces an experience of virtual compliance while vibrotactile feedback coupled to user movement induces an experience of virtual textures [61]. Therefore, the type of user action plays a crucial role in creating these material experiences. In this research, we implement virtual compliance by coupling vibration feedback with user applied pressure on a rigid pedal configuration. Further, for rendering virtual textures, vibrotactile feedback is coupled with the user movement on a compliant pedal configuration. Thus, compliance illusion can be rendered over a rigid pedal configuration to make it appear as if the pedal can be pushed. On the other hand, virtual textures can be rendered over the compliant pedal configuration so that the user has an experience of the pedal moving over a texture. Doing so presents us with an interesting set of questions: 'If a rigid pedal can be made to feel compliant using vibrotactile augmentation, would the user interact with it as though it were rigid or compliant?', 'Does this augmentation help the user achieve finer motor control, potentially improving task performance?', 'How does the user's subjective perception of control align with their objective performance when vibrotactile feedback is applied?'

The above questions highlight an important aspect, namely, the objective control over an interface might be different from the subjective control the user feels while operating the system. Research highlights the differences between objective and subjective measures; however, they usually focus on the methods of evaluation or usability of the interface [4, 24] rather than on performance or control. This experience of being in control is related to the 'sense of agency' (SoA) [1] and is a crucial aspect in developing novel interfaces [15, 21, 65]. Past work has hinted at the similarities and differences between objective control and SoA; however, these have not been explicitly investigated [31, 66], hence our interest to understand the relationship between the user's perceived control (SoA) and their objective performance with the four pedal configurations.

In this research, we evaluate the user's perceived control and objective performance on an abstract line-following task and an ecological task in VR by conducting a within-subjects study with 12 participants. We compare objective performance and perceived controllability using four pedal configurations: ***Compliant and Non-augmented (CN); Compliant and Augmented (CA); Rigid and Non-augmented (RN); Rigid and Augmented (RA)***, as shown in Figure 1. As pedals in cars are a familiar interface for general users, we conduct an ecological driving study in VR as an additional measure of performance. We use qualitative interviews to understand the users' subjective experience of control and performance. Our results show that embodied vibrotactile feedback improves the users' perceived control, despite their objective performance remaining the same for the four pedal configurations. The quotes by the participants for each condition during the study are shown in Figure 1. Hence, an increase in perceived control (SoA) is not consequential to an improvement in performance. This paper makes three contributions:

- It proposes a novel perspective on foot pedals as interactive devices, integrating vibrotactile feedback methods to enrich user interactions.
- It provides insights from a user study evaluating motion-coupled vibrotactile feedback for foot pedals, improving our understanding of the links between feedback and user-action through objective and subjective measures.
- It demonstrates that rigid pedals can perform as well as compliant pedals, and vibrotactile augmentation can improve perceived control while not affecting the performance.

2 Related Work

Pedals have been used as control interfaces to manipulate devices ranging from potter wheels to automobiles. This section summarizes the research on pedals as controlled input devices, as well as haptic feedback on pedals. We also summarize the literature on motion-coupled vibration to provide embodied vibrotactile feedback and how augmentations affect the user's sense of agency.

2.1 Pedals for Controlled Input

In the field of HCI, pedals have been designed, optimized, and used as a control interface for many years [6, 33, 57, 73]. Pedals historically served as basic single-parameter control interfaces, initially functioning as binary switches for transcription with momentary or latched states, offering continuous kinesthetic feedback to users for maintaining active states [64]. Today, pedals are primarily used for controlling continuous parameters where the mapping of the pedal position to the parameter being controlled is crucial. For instance, Balakrishnan et al. [5] and Göbel et al. [26] used pedals that mapped the position to the parameter being controlled, whereas Saito and Raksincharoensak [63] and Kim et al. [37] preferred pedals that mapped the input to the rate of the parameter being controlled. However, Van Veelen et al. [75] mentioned that whatever the type of mappings, pedals are not fully controllable and suffer from a lack of feedback.

Input devices like the mouse and the joystick have been studied in regard to control with isotonic and isometric actions [58]. Isometric actions involve muscle contractions without joint movement through either force or torque, like pushing a wall. Isotonic actions encompass joint movement along with muscle contractions [81], such as the elbow moving when an object is picked up. There are two primary types of transfer functions based on the type of mappings of input devices, namely, position and rate control [58]. Position control, referred to as zero order control, is a linear mapping of the user input to the controlled artifact displacement, for example, when using a computer mouse to move a cursor. The cursor's displacement on the screen is directly proportional to the movement of the mouse. Rate control, on the other hand, maps the user's input to the derivative of the controlled artifact movement, i.e. velocity, which is used, for example, when controlling a drone's speed with a throttle stick. Research has shown position control to be better with isotonic devices, whereas rate control is better with isometric or elastic devices [81, 82, 84]. Moreover, performance was better when isometric sensing was combined with rate control and isotonic sensing with position control [83, 85].

Although multi-functional foot-based interfaces with movement and pressure have been studied [38, 40], to our knowledge, controllability of pedals with isotonic and isometric movements is yet to be investigated. This study focuses on investigating the control of pedals with isometric (rigid) and isotonic (compliant) pedal configurations, with and without embodied vibrotactile feedback.

2.2 Haptic Feedback on Pedals

Feedback for pedal input has been provided using audio cues such as modulating the signal in guitar pedals [42] and audio-visual cues such as increasing the speed of a sewing machine pedal as we press into the pedal. However, for situations where the audio and visual modalities are overloaded, haptic feedback can serve as an additional non-intrusive feedback channel. One feature of haptic feedback systems is that the part of the body that receives the information can be the same one that manipulates the interface, thus opening possibilities to couple the user's action with haptic feedback. The most common type of haptic feedback is force feedback, where the pedal provides forces to the user's foot [54]. Force feedback has been used in the development of modern haptic pedals, which exert variable counter-forces depending on the vehicle dynamics, surrounding traffic or controlling speed [3, 11, 74]. Force feedback methods are also presented for simulating or enhancing classical pedal feeling in regenerative breaking [14] or break by wire systems [2]. While force feedback on the gas pedal is effective for car-following, it can be insufficient when quick corrective control actions need to be taken to prevent collision [53].

Another way of providing feedback is using vibrotactile feedback. For instance, warning signals in the form of vibrotactile pulses have been used in pedals to compel braking events and in speed or collision warnings [45, 72]. It is crucial to have a high stimulus-response compatibility with the action to be performed [72]. Therefore, the stimulus must be felt on the body part that needs to react [18, 69]. Vibration as a feedback strategy on gas pedals has also been shown to support economical driving [9, 46, 47] and elicit a positive eco-friendly driving experience [19]. Rosario et al. also found vibrotactile stimuli to improve the efficacy of the feedback and elicit differences in user perception [18].

However, if haptic feedback is abstract, it needs to be interpreted by the user, which can increase their cognitive load [17]. In the context of driving, this leads to a delay in the user's response and compromises driver safety [25]. We are interested in coupling vibrotactile feedback with user actions to elicit embodied and, hence, less cognitively demanding feedback for the user [61]. We focus on the use of pedals in the context of driving, as this is a commonly understood setting.

2.3 Embodied Vibrotactile Feedback

Vibrotactile feedback, when coupled with user action, can create embodied material experiences [61, 62]. Research has demonstrated that vibration coupled with the force applied by the user can simulate virtual compliance [35, 36]. Subsequent studies explored virtual compliance further, including creating the illusion of compliance through vibrations coupled with tangential forces [27, 28]. This method of coupling vibrations with user actions has been shown to alter the perceived interaction with objects. For example, Strohmeier et al. [66] induced the sensation of bending a smartphone, and Heo et al. [29] expanded this to include experiences like stretching, bending, and twisting of a rigid object. Additionally, Vega et al. [76] demonstrated that virtual compliance could be felt by providing vibrations at a different location than the body part exploring the object. Motion-coupled vibrations have also been used to make hard surfaces feel softer by providing vibrotactile feedback to the user's feet [67, 80].

Vibration coupled with the movement of a user-held object can create the sensation of moving over a textured surface with virtual friction. Romano and Kuchenbecker replicated the experience of moving over textures by recording probe movements and playing back these signals as vibrations on a smooth surface [16, 60]. Moreover, texture experiences can be generated on a smooth slider by coupling vibrations with user movement on the slider [61, 68]. Furthermore, Ding et al. [22] showed that vibration pulses coupled to user force can create an illusion of movement for the user, even when there is none. This shows that the same coupling of vibrotactile feedback with user action can generate virtual compliance and virtual textures based on the user action of pressing a surface and moving over a surface, respectively. However, to our knowledge, using vibrotactile augmentation on the same input device (pedal) for creating virtual compliance and virtual friction has not been studied. In this research, we implement these two established methods of vibrotactile augmentation and evaluate user controllability.

2.4 Sense of Agency: Overview and Evaluation

The sense of agency (SoA) describes the experience of controlling one's own actions, and through them, the events in the external world [1]. It is crucial to note that the SoA is a measure of the user's perceived control [71] and is different from the factual control of a task measured using Fitts' Law, Following Tasks, etc. In HCI, the user's SoA is an important consideration when designing new interfaces [48]. It has been described in Shneiderman's Eight Golden Rules of Interface Design, which states that designers should create interfaces that "support an internal locus of control" [65]. This is based on the idea that users "strongly desire the sense that they are in charge of the system and that the system responds to their actions" [65]. Experiencing a sense of agency during human-computer interaction is important, as it can benefit the overall user experience [43] and the feeling of responsibility [50].

Building on theories and methods from psychology, early studies on the sense of agency in HCI focused on details of interactions such as input modalities [15, 44], latencies [7], level of automation/computer assistance [8, 15], and how they affect the user's SoA. More recent work also looked at augmentation of the action or feedback. Feedback influences the sense of control we receive for our actions and is important to avoid sensory-motor conflicts that may disrupt the experience of the user [23, 39]. Kasahara et al. used electrical muscle stimulation to actuate the human body to improve the reaction speed during different tasks while maintaining the SoA [31, 32]. Further, vibrotactile feedback indicated that the sense of agency in quite minimal interactions could be manipulated with haptic feedback [66, 68]. Recent work on haptic feedback and agency for virtual avatar co-embodiment showed that the SoA decreased with haptic feedback compared to without haptic feedback for VR reaching tasks [77].

In the literature, there is a distinction between an implicit sense and an explicit judgement of agency [70]. The unconscious sense of agency happens pre-reflectively, while we feel in control over the action currently being performed and the outcome(s) it causes. Previous research has shown that the two ways to look at the sense of agency do not always show the same results [20, 21], but the implicit feeling seems to have an influence on the explicit judgement [55]. While the evaluation of the judgement of agency is quite straight forward, measuring the implicit feeling is more difficult because as soon as we ask participants about it, it becomes a conscious judgement. The literature currently describes two ways of implicitly measuring this feeling of agency: intentional binding [49] and sensory attenuation [12, 59]. The intentional binding measure is designed for a setting where the action and the outcome happen within a few milliseconds and at discrete points in time [49]. The sensory attenuation measure requires an outcome stimulus with a measurable intensity, such as the volume of a sound or the amount of pressure applied [34, 56]. In our study, we focus on explicit judgements of control, as the action and the outcome are continuous, and we do not measure changes in perceived stimulus. Hence, we evaluate the post-reflective judgement of agency by conducting a semi-structured interview with the participants about their subjective performance and control. Our work adds a dimension to this line of exploration by highlighting that the subjectively measured and the objective judgement of control can differ.

3 Design Rationale

In the year 2022, we had a discussion with an automotive manufacturer who mentioned that the mechanical pedals, although robust, are very expensive due to the multiple moving parts in the system. With the existing research on virtual textures and virtual compliance, we are curious to investigate how vibrotactile material rendering affects user experience and performance with rigid and compliant pedal configurations.

3.1 Rendering materials and virtual affordances

Vibration feedback is a common method for eliciting touch sensations by rendering high frequency tactile effects. Typically, vibrations are used to convey abstract information that needs to be interpreted by the user [10, 13, 17]. For example, a phone might vibrate to indicate that new information is available. Another way of conveying information using vibrotactile feedback is by designing vibrations that are embodied and feel natural to the user [62]. For example, vibration can be coupled to voluntary actions such as a limb movement or by applying pressure on a surface, similar to how the home button (iPhone) or virtual keyboard touches on some smartphones are coupled to vibration feedback. Hence, vibrations that are coupled to user actions can simulate physical control entities like buttons and sliders, offering alternative design approaches for such control hardware. These design approaches can include augmenting the existing control hardware with additional material sensations. For example, a slider that is controlling a speaker can be programmed to feel like it is resisting the user's command towards increasing the volume too much. Or a scroll wheel can have textured clicks for precise control, while switching to a smooth glide allows for larger adjustments.

Adding vibrotactile feedback can have a variety of benefits such as simplifying the design, fabrication, or maintenance of the interface or providing more available space for additional interactive hardware. Moreover, the simulation of control entities can enable completely replacing the conventional control hardware. For example, the iPhone home button is not necessarily more effective in terms of button control, but it creates additional advantages such as more screen space, water resistance, and ease of manufacturing. As for pedals, like we discussed with the automotive manufacturer, research shows that pedals, although robust, are very expensive due to the multiple moving parts in the system [30]. Further, the manufacturing of pedals is very complex, and they also need regular servicing. This affords the investigation of whether the current pedal limitations can be overcome by integrating embodied vibrotactile feedback, which has been robustly shown to render virtual textures and virtual compliance.

However, such crucial design decisions must be preceded by a careful assessment of the gained interaction opportunities and performance metrics. To evaluate the novel ways of interaction, we need to measure both objective performance and subjective experience of control (Sense of Agency). In this work, we investigate the effect of motion- and pressure-coupled vibration feedback on the users' pedal control. We compare four pedal configurations, with and without vibrotactile feedback, in rigid and compliant configurations.

3.2 Pedal Configurations

Most users are familiar with pedals in the context of the car driving experience. These automobile pedals have been studied extensively as input devices but are now being studied as I/O interfaces. The shortcomings of current pedals, based on the discussion with the automotive manufacturer, and the opportunities of creating material experiences with embodied vibrotactile feedback, raise an interesting question: Can we incorporate embodied vibrotactile augmentation into gas pedals to improve the user's perceived control of the interaction without affecting performance? We can relate getting rid of the movable pedal to getting rid of the button on iPhones. Our research seeks to answer the question of whether we need to rethink feedback strategies for foot pedals.

Embodied vibrotactile feedback can be elicited by providing pulses of vibration coupled with user movements. In the context of pedals, by providing vibrations based on the pressure applied by the user for rigid pedals, we expect the user to feel that they are pressing into a (slightly) compliant/ soft pedal. On the other hand, when the vibration pulses are provided with the physical travel of the pedal, we expect that the user experiences the movement of the pedal over virtual textures. Such pedals with embodied vibrotactile feedback would be mechanically simpler, cheaper to manufacture, easier to maintain, and would last longer; however, it is unclear if users would want to use such a pedal, and if it can provide a similar level of control as compliant pedals.

To test the aforementioned unconventional approaches, we evaluate the effect of having compliant vs. rigid and augmented vs. non-augmented pedals. This comparison gives us four pedal configurations, as shown in Figure 3 (Left):

- **Compliant and non-augmented (CN):** This refers to the conventional pedal approach. The pedal movement is not constrained, and there is no vibrotactile augmentation.
- **Compliant and augmented (CA):** The pedal movement is not constrained, and there is vibration feedback. This configuration can induce friction illusion.
- **Rigid and non-augmented (RN):** The pedal movement is constrained, and there is no vibration feedback. This configuration provides no proprioception or vibration feedback. The user can only feel the reaction force from the pedal and receive visual feedback from the GUI.
- **Rigid and augmented (RA):** The pedal movement is constrained, and there is vibration feedback. This configuration can induce compliance illusion.

Using these pedal configurations as the independent variables for our research, we investigate the performance of users and their perceived control. Our research questions are: (1) "How does vibrotactile augmentation affect the performance and perceived control of the users?" and (2) "How are subjective and objective performance correlated for the four pedal configurations?"

4 Implementation

In this section, we describe the hardware and firmware implementation of augmenting a single pedal to have multiple configurations. We also describe the algorithm used to provide motion-coupled vibration.

4.1 Hardware

Our hardware design consists of an augmented, commercially available gaming throttle pedal[1] with a force sensor (strain gauge) and a vibration actuator, as shown in the Figure 2. High-end commercial gaming pedals use an additional spring and load cell coupling for measuring the movement of the pedal. Since our rigid pedal scenario requires us to block the movement of the pedal, we moved the load cell directly behind the pedal plate. We connected the lower screw terminals of the load cell to the pedal plate and the upper screw terminals to the pedal are through a mounting unit. Thereby, the foot pressure on the pedal can be sensed by the load cell in both compliant and stiff cases. The mounting unit is also used for connecting the vibration actuator, Dayton Audio TT25-16 Tactile Transducer[2], on the pedal arm. The vibration actuator was controlled with a 40 W amplifier. The whole structure was connected to a large sigma profile base that rested on rubber dampeners, such that the propagation of the vibration to the surroundings was limited. To switch between the rigid and compliant pedal scenarios quickly during the experiments, we designed a blocking mechanism that can slide along the aluminum profile to constrain or release the pedal movement. The travel length of the pedal was 25mm, which was shown to be suitable [86].

We used haptic servos [61] to couple the vibration with user-applied forces. Haptic servos helped to keep the delay between the sensor value and vibration onset below *5ms*, which is important, as delay diminishes the SoA by inducing a temporal discrepancy between an action and its effect [78]. The signal chain consists of the user input of force sensed by the force sensor (20 kilogram strain gauge), which is converted to an analog signal using an HX711 breakout board that functions like a 24-bit Analog to Digital signal Converter. This signal is read by Teensy 4.1 microcontroller, which maps the input signal to the output vibration based on the binning algorithm (Figure 3, Right). The output signal is then converted to an analog signal using a PT2811 shield before finally amplifying

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[1] KRE Win Pv3 sim racing pedals: https://www.kre-sim.eu/kre-win-pv3-sim-racing-pedals/; accessed October 26, 2024

[2] Dayton Audio TT25-16 Tactile Transducer: https://www.daytonaudio.com/product/1037/tt25-16-puck-tactile-transducer-mini-bass-shaker-4-pk; accessed October 26, 2024

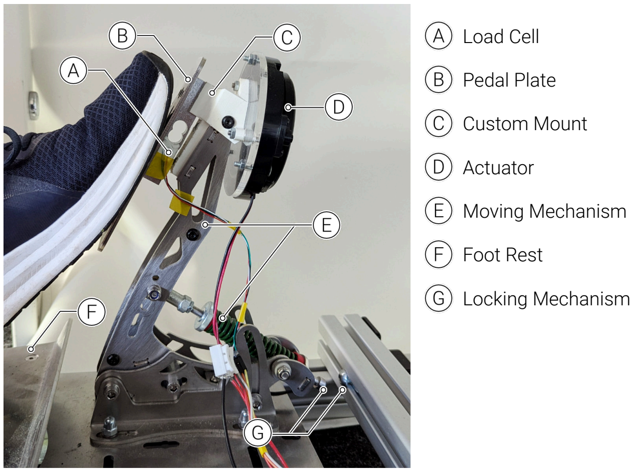

Figure 2: Modified off-the-shelf gaming pedal. We designed a custom part (C) to mount the load cell (A) and an vibrotactile actuator (D) on the top of the pedal. We mounted the pedal on a custom rack including a foot rest (F). A locking mechanism (G) was used to fixate the pedal's moving mechanism (E).

and feeding it to the actuator. The load cell values are sent to the computer via real-time serial communication.

4.2 Firmware

To render vibrotactile feedback based on the applied force by the user, we divided the sensor range between the resting value of force (global minimum) and maximum force applied on rigid and compliant pedals into a number of discrete bins. When a sampled sensor value enters a new bin, an AC pulse (i.e., audio signal) is generated, as shown in Figure 3-Right. Based on the changes in the measured signal, pulses are generated, i.e., if the signal changes fast, pulses are generated rapidly, whereas if the signal changes slowly, the pulses are generated proportionally slowly. The relevant variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range), a.k.a. granularity. The vibration specification of each pulse is determined by the type of waveform used as well as by the duration, amplitude, and frequency of that waveform. The duration was derived from frequency to minimize clipping artifacts. We found that both a full period and a half period of the waveform work well. The amplitude, frequency, and number of bins/grains were set based on the pilot studies within authors (Section 5.1). This leaves the frequency and number of bins as the primary parameters to consider when designing a vibrotactile material experience. The algorithm with the calibration code, the trajectories used, and processing UI used in the experiment are open source[3].

5 Evaluation

We evaluate the interaction between the objective performance of the user and their perceived control on an abstract task as well as an ecological driving task.

5.1 Pilot: Psychophysics study for parameter selection

We conducted a psychophysics study within 4 of the authors to ensure the use of correct parameters of the motion-coupled vibration, namely frequency and grains, for augmenting the pedals. The objective of this pilot study was to understand the effect of parameters of the vibrotactile augmentation that elicit an experience of softness and controllability.

5.1.1 Experiment Design. Frequency was selected as one of the independent variables since the used actuator's preferred operating range of frequency is between 20 and 80Hz for rendering haptics, whereas a frequency of 220Hz is best perceived by the meissner corpuscles. Moreover, the number of grains (pulses of vibration based on user input) has been shown to affect the user's sense of control [29]. Hence, the independent variables were the frequency of the vibration (20, 40, 60, 80, 220 Hz) and the number of grains (12, 24, 36). The amplitude and waveform of the vibration was kept constant throughout the study. The number of grains were mapped linearly throughout the sensor range, which was calibrated per participant (author). Only the rigid pedal with vibrotactile augmentation was used for the psychophysics study, as we were interested in the distribution of vibrotactile augmentation that would elicit an experience of softness (ability to push the pedal and not push into the pedal) and controllability. Each participant rated (on a free scale) the softness and controllability for the 15 possible combinations of the frequency and number of grains as well as for a rigid pedal with no augmentation, which was considered the ground truth. During the study, the participants wore noise-cancelling headphones playing white noise in order to mask the audio cues.

5.1.2 Pilot: Results. The results of the psychophysics study show that granularity relates to perceived control. Participants associated higher granularity (higher number of grains) with an increase in the sense of agency and vice versa. Two participants unknowingly tested a number of grains over 36 as well, but they reported that the vibrotactile feedback felt very noisy. Anecdotally, it appeared that frequency and grain count interacted, but we did not find a clear pattern. The results showed that frequency was related to the perceived softness. The 220Hz condition was rated to be least perceivable. We decided to choose the number of grains to be 36 as it seemed to provide good control and a frequency of 80Hz, which, in combination, seemed to elicit an experience of virtual compliance. The participants described the feeling of pushing the pedal as squeaky, crunchy, and crispy.

5.2 Study Design

We evaluated the objective performance of the participants using all four pedal configurations with an abstract line-following task and a driving task for testing the ecological validity. For the subjective performance evaluation, we conducted qualitative interviews with all participants.

5.2.1 Study Rationale. The first task was focused on evaluating the control with the different pedal configurations on a simplified one-dimension following task. The second experiment evaluated the controllability of driving a car in a Virtual Environment. Before

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[3] GitHub repository: https://github.com/sensint/HapticGasPedal

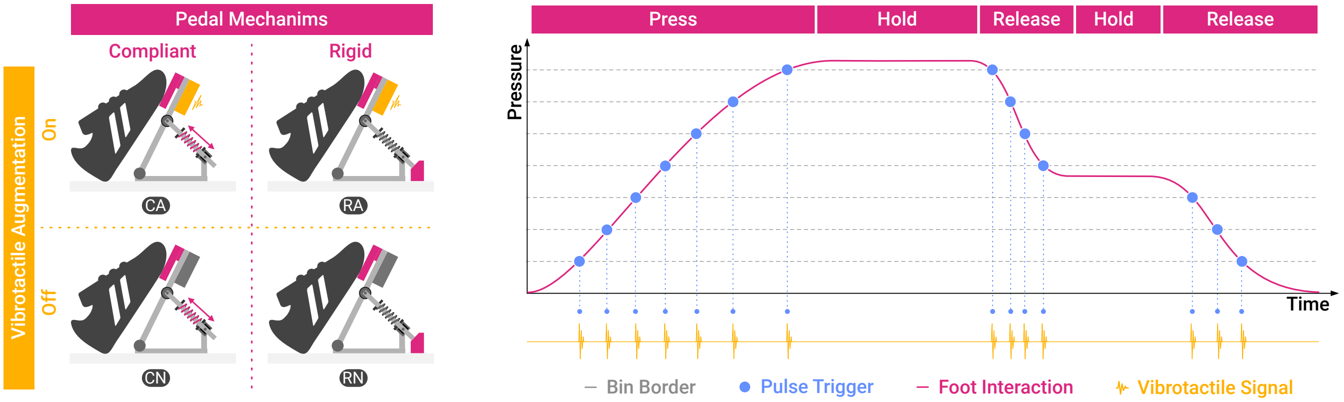

Figure 3: We designed four conditions based on two factors, i.e. pedal mechanism and vibrotactile augmentation, with two levels each (left). In the two conditions with activated vibrotactile feedback, we utilized a grain-based augmentation algorithm [61], which renders vibration pulses (grains) at certain levels of applied pressure, i.e. motion-coupled augmentation (right).

both experiments, training was conducted to familiarize the participants with the tasks and different pedal configurations. Finally, we concluded the study by interviewing the participants to understand their perceived control and customized design of vibrotactile augmentation with pedals.

Trajectory Design: The easy level was designed using three types of segments in terms of the position-time graph: (1) Holding the position constant (corresponds to pushing the pedal with a constant force), (2) a sine connector (for slow approach and release), and (3) a line connector (for constant approach and release). Using these as the ground rules, trajectories were randomly designed with 3 second holds at 20, 40, 60, and 80% of the trajectory amplitude. The easy difficulty level had one hold each at every amplitude level , while medium and hard levels ran the same trajectories at 1.5 times and 2 times the frequency, respectively. Figure 3-Right shows a sample trajectory along with the algorithm used for rendering vibrotactile pulses coupled to user action.

5.2.2 *Procedure.*

The study consisted of the calibration phase followed by training, a line-following task, a driving task, and finally, qualitative interviews. The total time of the study was 1.5 hours.

Calibration: Calibration was done for the maximum force applied by every participant for the rigid and the compliant pedal configurations. Moreover, the global minimum force (for both pedals), when the participant rests their foot on the pedal, was calibrated to reduce fatigue and accidental activation, similar to [41]. These ranges of the applied force on the pedals enabled us to have an individualized task and vibrotactile augmentation for every participant. The grains were played with respect to the calibrated sensor range. We also calibrated the amplitude of vibration where the participant was able to feel the vibration without hearing it.

Training: Post calibration, there was a training phase before each task. The pedal order was generated for every participant using a balanced Latin square approach to mitigate any ordering effects, and was fixed throughout the study for each individual participant. Training was done to familiarize participants with the tasks, the pedal configurations, and the mappings between the force applied and the visual feedback they received. Training for the driving task made sure the participants were comfortable with the headset and the virtual reality environment and would not experience motion-sickness. The training phase was 30 seconds per pedal configuration for both the tasks and was done at the beginning of each task. Participants were allowed to repeat the training as many times as they wanted, provided they did it for all the pedal configurations.

Visualization: **Processing** version 3.5.4 was used to create a one degree of freedom following task. We used a multiscreen layout to enter the participant ID, followed by the code of the pedal selected for the trial, and a countdown timer to indicate the start of the task. The task screen, which can be seen in Figure 4-B, consisted of two rectangles on a white background. The movement of the target rectangle (red) was based on the predefined generated trajectory, while the movement of the other rectangle (blue) was mapped based on the pedal position, which was controlled by the user. There was no explicit information provided to the user in terms of the distance between the target and the user-controlled rectangle, besides the visual information on how far the two rectangles were, in order to avoid any distractions. Next steps, which included the next trials before going to the next pedal configuration, were displayed sequentially as the trials were completed.

Unity was used to create the ecological driving task showed in Figure 4-C. The cars were restricted to moving along a straight road. Natural artifacts such as trees, ponds, and rocks were placed around the road to augment optic flow in the peripheral vision of the participant to improve their sense of motion. As an indicator of performance, we considered adding a slider for informing the participant about their current distance in seconds from the leading car. Time-headway (THW) is generally used to indicate safe following distance at any speed. However, we omitted using an additional indicator for this, since it would introduce a higher cognitive load and would not be natural.

5.2.3 *Participants.*

We recruited 12 participants (7 identified as male, 5 as female), aged 23 to 33, with normal or corrected-to-normal hearing and vision. 9 out of the 12 participants had a full driving license and a median driving experience of 7 years. All the

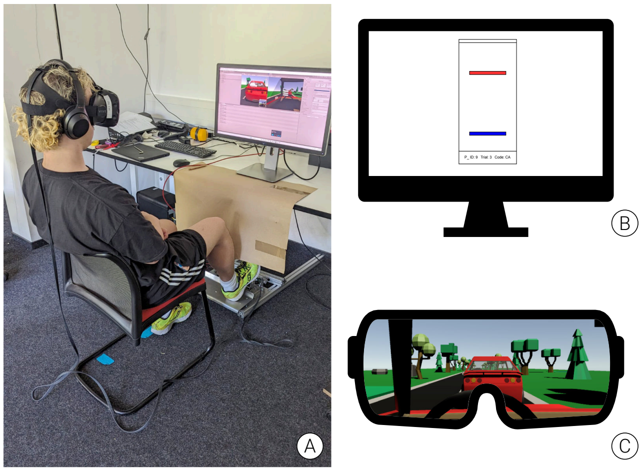

Figure 4: Participants sat at a table with the pedal rack underneath and a visual barrier attached to the table (A). In the *line-following* task, we presented them a simple GUI on a monitor, which showed two colored blocks representing the target (moves automatically) in red, and the follower (controlled by participants) in blue (B). In the *Driving* task, participants wore a VR headset (C).

participants wore shoes during the study, which, despite leading to changes in the perception of the vibrotactile cues, was our conscious decision to match the usual way of interacting with gas pedals. Participants were seated during the entire duration of the study. They were first briefed about the study, and their demographic information was recorded. To avoid any influence from fatigue, we instructed the participants to take breaks as needed before starting the subsequent trial. Participants wore noise-cancelling earphones playing white noise during the trials. The participants received a financial compensation of 18 Euros for their participation.

5.3 Task 1 - Line-Following

In this task, the participants were instructed to control the movement of a horizontal line (rectangle) for a one dimensional vertical movement to follow a target line, with the goal of maintaining the minimum distance between them (Figure 4-B). The position of the follower line was linearly mapped (positional mapping) based on the applied force on the pedal by the user for all the pedal configurations. Pushing the pedal with maximum calibrated force would position the line at the top of the area, while resting or removing the foot would cause the line to fall back down to the bottom. The task consisted of 3 difficulty levels for each pedal-easy, medium, and hard. Each pedal configuration had three trials of 30 seconds, each corresponding to the three difficulty levels. The order of the within pedal trial was always from the easiest to the hardest level of the designed trajectories. There was a 3-second countdown before the start of each trial. We analyzed the performance of all the participants using a three-way repeated measures ANOVA with the rigid/compliant; augmented/non-augmented and trial difficulty as the three within-subject factors. Normality of the data was assumed. Outliers within the data were retained to ensure that the analysis accounted for the full range of variability in the participants' performance. We evaluated the following metrics:

- *Root mean square error (RMSE):* The participants' mapped pedal positions were compared with the positions of the targets for the entire trial.
- *Pedal Adjustment Speed (PAS):* The differences between the participants' mapped pedal positions and the target positions, computed through cross correlation.
- *Overshoot Behavior (OB):* ratio of the differences between the maximum overshoot and the minimum overshoot during the hold phases of the trajectory. (Lower is better)

5.4 Task 2 - Driving task

To explore the pedals in a setting with higher ecological validity, we designed a second task. In this task, participants controlled a car in Virtual Reality (VR) to follow another car on a straight road (Figure 4-C). The participants could only control the car using the accelerator (gas) pedal. The driving task was in a straight line, and, hence, a steering wheel was not necessary. Applying force on the pedal accelerated the car forward, and wind drag and road friction forces worked in the backward direction, decelerating the car, meaning it would slow down until coming to a halt if not enough force was provided by the pedal input. The task consisted of two difficulty levels - easy and hard. In the hard level, the leading car ran the same trajectory as in the easy level, but at twice the frequency. The trial duration for each trajectory was 100 seconds. This duration was deliberately chosen to be longer than for the first task, as we were interested in how participants adapt to a car driving simulation and their control with different pedal conditions over a longer time period. The same trajectories were used for all the four pedal configurations in this experiment. This was intentional, as it allowed a direct comparison between the different pedal configurations. We analyzed the objective user performance in terms of the following parameters:

- *Root mean square error (RMSE) of vehicle velocity:* The following vehicle's velocity compared to the velocity of the leading vehicle for the entire trajectory.
- *Pedal Adjustment Speed (PAS):* The time difference between the velocities of the leading vehicle and following vehicle, computed through cross correlation for the entire trajectory.
- *Time headway (THW):* Safe following distance metric calculated by dividing the distance between two consecutive vehicles by the velocity of the following vehicle. Time headway is consistent for individual drivers for a large variety of speeds but could differ between drivers [79]. Insufficient THW is usually the cause of rear-end collisions.

We did not consider the overshoot behavior for the VR study as a metric due to lesser hold situations to imitate real-world driving. The analysis was done similarly to the first task. We used CSV files to save the data during both the tasks. MATLAB and R were used for data analysis.

5.5 Qualitative Evaluation

A semi-structured qualitative interview was conducted to understand primarily three aspects of the participants' experience with the four pedal configurations:

- Subjective performance and control
- Overall and task-based pedal preferences
- Designing pedals with vibrotactile augmentation

Moreover, we were interested to know how participants experienced the differences between virtual compliance elicited using RA and the physical compliance using CN pedals. We also wanted to understand whether they could associate vibrotactile feedback with any experiences, emotions, or objects from their daily life. The questions in the interview were as follows: 'How do the different pedal configurations affect your performance?'; 'How well are you able to control using the different pedal configurations, and why?'; 'What pedal configuration is preferred and why?'; 'How can vibrotactile augmentation be used for pedal interaction?' and 'What are the associations from real-life to the experience of vibrotactile augmentation?'. Depending on the participants' responses and interest, we were able to delve deeper into their experiences of control and designing of vibrotactile augmentation.

All the interviews were audio and video recorded with the consent of the participants. We transcribed the interviews and performed a qualitative content analysis following flexible coding approaches [51]. These approaches build on Grounded Theory to code data, but allow more flexible analysis. We analyzed the data using the questions asked to the participants. OtterAI was used for transcribing the data and taguette was used for coding. Coding of the interviews was done by one author, who approached the transcripts based on their dialogues with the participants during the study. The themes were constructed around the perceived performance, subjective experience of control, and designing with vibrotactile augmentation.

6 Results

We investigated the objective performance and subjective perception of control for two tasks using four different pedal configurations: compliant, rigid; with and without vibrotactile augmentation (Figure 3-Left).

6.1 Objective Performance Results

We provide a summary of the main results at the beginning of each subsection, followed by detailed statistics. To test for sphericity, Mauchly's test was used and then Greenhouse-Geisser correction was applied when the assumption of sphericity was violated, and, hence, no correction was applied to the reported p-values.

6.1.1 *Following Task.*

We conducted a 3-Way Repeated Measures ANOVA (augmentation, pedal, difficulty) to analyze the effects of augmentation (augmented or non-augmented), pedal type (rigid or compliant), and trajectory difficulty (easy, medium, hard) on performance metrics (RMSE, PAS, OB) for the following task. Figure 5 shows the mean and confidence interval along with the box-plots to represent the effects of the independent variables on each of the performance metrics.

***Root Mean Square Error (RMSE):*.** We found no significant main effects of augmentation or pedal type on RMSE, see Figure 5-Left. Specifically, the effects of augmentation: $F(1, 144) = 1.464$, $p = 0.2283$ and pedal type: $F(1,144) = 1.955$, $p = 0.1642$ were not significant, suggesting that performance on a targetting task is not affected by the pedal configuration. However, the trajectory difficulty had a statistically significant effect on RMSE: $F(2,144) = 3.454$, $p < 0.05$, $\eta^2 = 0.021$. The RMSE increase, with an increase in the difficulty level, serves as a validation of the setup and analysis. It further implies that as the task became more challenging, users tended to deviate more from the target trajectory. Finally, no significant interaction effects were observed between augmentation, pedal type, and difficulty on RMSE.

***Pedal Adjustment Speed (PAS):*.** Similar to RMSE, for PAS, neither augmentation: $F(1,11) = 3.208$, $p = 0.101$ nor pedal type: $F(1,11) = 2.279$, $p = 0.159$ had significant effects on performance, see Figure 5-Right. Hence, pedal configuration did not play a role in objectively improving the pedal adjustment speed or the latency between the target and their mapped pedal position. However, the main effect of difficulty was statistically significant, $F(2,22) = 22.199$, $p < 0.05$, $\eta^2 = 0.152$, indicating that an increase in trajectory difficulty resulted in slower pedal adjustment speed. None of the interaction effects were significant. This result supports the idea that task difficulty naturally modulates user response times, independent of augmentation or pedal compliance.

***Overshoot Behavior (OB):*.** In contrast to RMSE and PAS, vibrotactile augmentation played a significant role in reducing the overshoot behavior, $F(1,11) = 76.291$, $p < 0.05$, $\eta^2 = 0.468$, see Figure 5-Bottom. The significant effect of augmentation on OB suggests that vibrotactile feedback helped users limit their tendency to overshoot, giving them a stronger sense of control over the task. Pedal type and trajectory difficulty did not have significant effects on OB, $F(1,11) = 0.057$, $p = 0.815$ and $F(1.36,14.94) = 1.088$, $p = 0.337$, respectively. There was a significant interaction between augmentation and pedal type, $F(1,11) = 21.153$, $p < 0.05$, $\eta^2 = 0.074$, indicating that the vibration feedback's effectiveness in minimizing overshoot might have varied, depending on whether the pedal was rigid or compliant. This provides a potential area for further exploration on optimizing haptic feedback. No significant interaction effects were found between other combinations of the independent variables.

6.1.2 *VR driving task.*

The participants' performance in the VR study was measured by their performance in tracking the leading virtual vehicle. Similar to the following task, we performed a 3-Way Repeated Measures ANOVA on performance metrics of velocity tracking performance computed (RMSE), pedal adjustment speed (PAS), and time-headway (THW), see Figure 6.

***Root Mean Square Error (RMSE):*.** The participants performed significantly better in velocity tracking computed through RMS error during the easy trajectory compared to the hard trajectory, $F(1,10) = 35.8$, $p < 0.05$, $\eta^2 = 0.174$, see Figure 6-Left. In the easy scenario, in two trials, we observed instances of crashing into the leading car. In the hard scenario, more than half of the cases had at least one instance of crashing into the leading car, and most of these instances slightly touched the leading car. We did not find

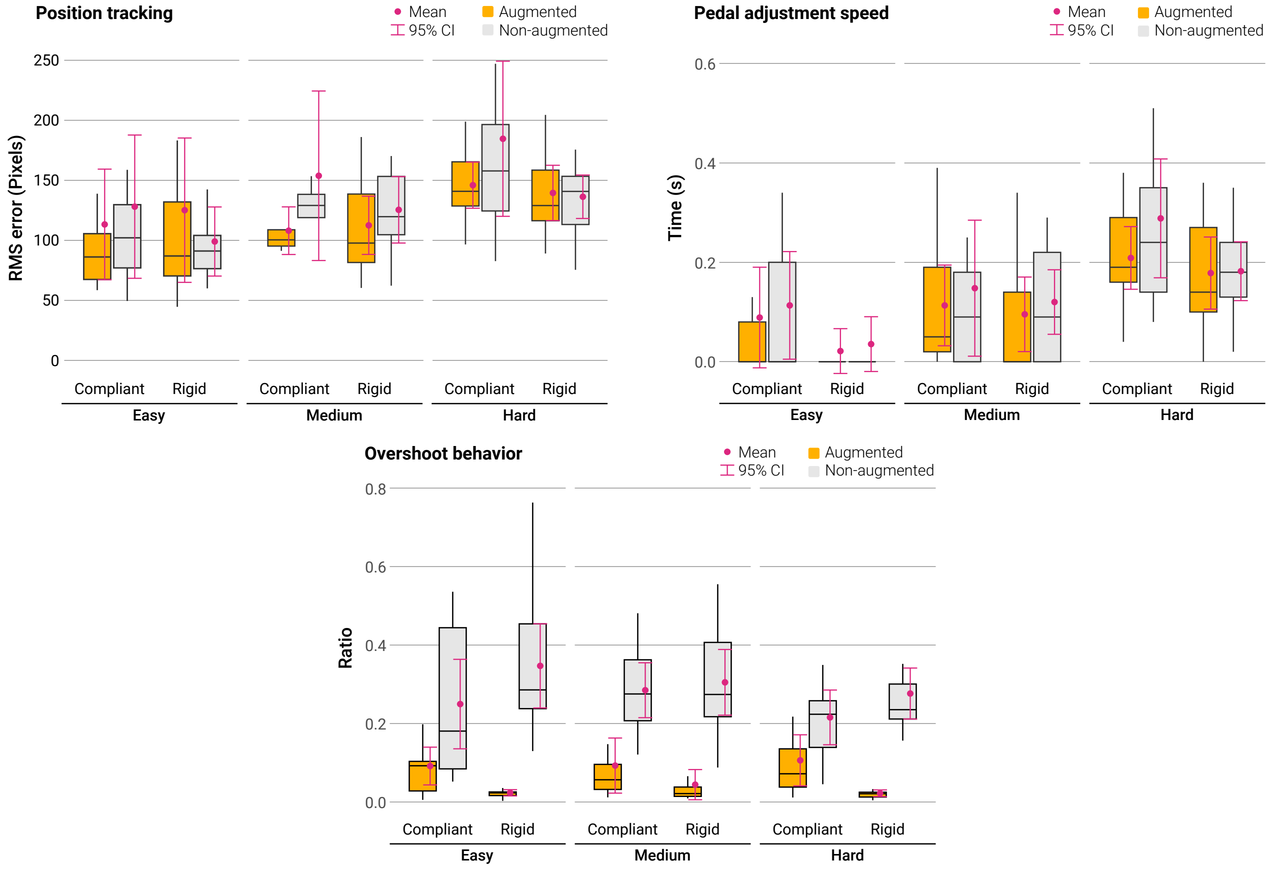

Figure 5: Line-following task results: The left plot describes the RMSE for the three levels of difficulty. The right plot shows the pedal adjustment speed. The bottom plot shows the overshoot behavior with respect to the independent variables of pedal type, augmentation, and trajectory difficulty. Each plot shows the box plots for each pedal configuration and the mean and confidence intervals.

any significant difference between the participant performances with respect to augmentation: F(1,10) = 1.72, p = 0.219 or pedal type: F(1,10) = 4.05e-5, p = 0.995. None of the interaction effects were significant.

Pedal Adjustment Speed (PAS):. The pedal adjustment speed between the pedal input and the tracking, calculated using cross correlation, showed no significant difference in terms of pedal type: F(1,10) = 2.93, p = 0.117; augmentation: F(1,10) = 3.17, p = 0.105; or difficulty: F(1,10) = 4.80, p ≈ 0.05, η^2 = 0.10. The interaction effects were not significant.

It is interesting to note that the trends of RMSE and PAS were similar for both tasks.

Time headway (THW):. The mean values of THW throughout did not show a significant difference in terms of pedal type: F(1,10) = 0.234, p = 0.639; augmentation: F(1,10) = 4.52, p=0.060; or difficulty: F(1,10) = 0.828, p = 0.384; see Figure 6-Right. None of the interaction effects were significant. This means that participants similarly consistently controlled their speed and distance to the leading car for all pedal configurations.

6.2 Subjective Control: Qualitative Content Analysis

Participants in the study expressed their preferences for specific pedal configurations and provided insights into their reasons for these choices. The favored pedal configuration across various tasks, such as line-following and car driving simulations, was the "soft pedal with vibration feedback." Participants found this configuration to be the most intuitive and controllable. Participant 2 highlighted this preference, stating, "Soft, with the vibration feedback for the following task" emphasizing the value of the compliant pedal combined with vibrotactile feedback.

Vibrotactile Augmentation increases the perceived Sense of Agency: The primary reason behind the preference for the "soft pedal with vibration feedback" was its perceived intuitiveness and the enhanced sense of control it offered. Participants found that this configuration allowed them to finely modulate their actions, particularly in tasks requiring precise control, such as line-following. P5 noted, "Soft [compliant] with vibration makes it easier to control the movements; it's intuitive." And P8 mentioned that the vibration feedback was perceived to be corrective, thus helping to make

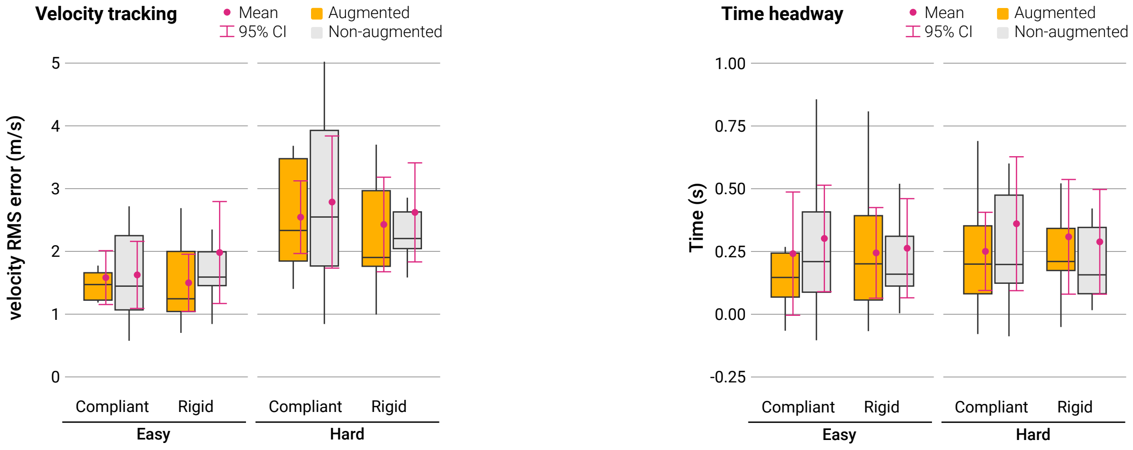

Figure 6: Left: root-mean-square (RMS) velocity tracking error for easy and hard cases; Right: Time headway (THW) over all pedal configurations. Each plot shows the boxplots for each pedal configuration and the mean and confidence intervals.

more precise movements. They said, "The vibrotactile feedback is a game-changer. It's like my feet know where to go without me having to think about it." Further, P1 said that the vibrotactile augmentation makes the pedal "more responsive", and P7 mentioned, "It enhances the overall performance". Moreover, P6 mentioned, "I like knowing exactly where each pedal is. It gives me confidence and reduces my mistakes." The tactile feedback provided an extra layer of information that complemented their actions, leading to a sense of mastery and comfort.

With respect to the kinesthetic cues, the compliant pedal was perceived to be easier to control. P1 mentioned, "The [compliant] pedal setup felt natural to me, which made it easier to control the vehicle. When the pedals were arranged differently [rigid], I felt less confident and in control." And P9 added, "Using pedals that I was already used to make a big difference. I didn't have to think about how to use them, which kept my focus on the task."

Vibrotactile Augmentation improves the perceived Performance The perceived performance varied significantly depending on the pedal configuration and the nature of the task, whether it was VR-based or a line-following task. Participants generally felt that their performance improved when the pedal setup provided clear vibrotactile feedback. P2 stated, "In VR, when the pedals are intuitive, I can focus more on the virtual task rather than worrying about my foot placement." The line-following task, on the other hand, required precise movements, and participants noted that compliant pedal configurations made it easier to follow the line accurately. P5 commented, "With the right [compliant] pedal setup, I can follow the line much more precisely. It feels more natural, and my performance definitely improves." Participants also pointed out that motion-coupled vibrotactile feedback played a critical role in enhancing their performance by providing immediate and intuitive cues about their actions. Participant 9 elaborated, "The vibration feedback tells me instantly if I'm doing something right or wrong. It's like having an extra sense that boosts my performance."

Balancing information and non-intrusiveness with vibrotactile feedback: Participants also mentioned that while compliant pedals were preferred, the addition of vibration feedback struck a balance between comfort and control. It enhanced the pedal's usability without causing discomfort or fatigue. This finding highlights the importance of providing users with tactile cues that amplify their sense of control without overwhelming them. P3 mentioned, "I like soft pedals, and the vibration makes it just right; not too hard, not too soft." On the other hand, P6 and P8 mentioned, "The vibration could be more subtle." and "the timing of the feedback needs adjustment." Participants identified the potential of vibrotactile feedback to enhance the overall user experience when interacting with pedals. They emphasized the importance of providing feedback on factors such as speed, pressure, and precision. P7 noted, "Vibration could help me understand how fast I'm pressing or if I'm applying too much pressure," highlighting the role of vibrotactile feedback in aiding a user's understanding of their actions.

Customizable and Context-Aware Design: Participants also emphasized the need for customizable vibrotactile feedback settings to cater to individual preferences and task-specific requirements. They suggested that users should have the flexibility to adjust the vibration intensity and patterns. Additionally, participants discussed the importance of context-aware feedback, where vibration cues adapt to different situations. P4 mentioned, "Customizable settings would be great, and it should change based on the task. In some situations, I may want more feedback than others." They stressed the need to prioritize safety and non-distracting feedback in real-world applications.

Associations Between Real-Life Experiences and Vibrotactile Augmentation: Participants in the study frequently drew connections between their real-life experiences and the sensations they encountered through vibrotactile augmentation. For instance, participants compared these tactile sensations to a sewing machine. P2 remarked, "It feels a little bit like the sewing machine. I can gauge the speed and force based on the vibration frequency." Moreover, some participants associated it with everyday safety alerts, such as phone vibrations for a call or notification. They emphasized that vibrotactile feedback should not be distracting or overwhelming, particularly in scenarios like car driving. P9 remarked, "In a car, the feedback should be subtle enough not to divert attention but still provide information about pedal usage." This connection emphasized the potential of vibrotactile feedback as a safety or warning mechanism in pedal-based interactions. Additionally, participants related the experience to the learning process in real-life scenarios, analogous to acquiring new skills or adapting to unfamiliar tasks, where feedback helps to learn. P7 described it like this, "It's like learning to ride a bike. You get the hang of it by feeling the subtle changes in vibration." These associations highlight the role of vibrotactile feedback, encompassing safety and control, and how motion-coupled vibration provided the participants with a tangible reference point for understanding the vibrations and how they related to their actions. Participants used these tactile cues to interpret their interactions with pedals. For instance, rapid vibrations were equated with high-speed movements, as illustrated by P8: "The vibration pattern tells me how fast I'm going. It's like revving an engine." This correlation between real-world actions and vibrotactile feedback highlights the potential for intuitive pedal interactions.

7 Discussion

"The horseman's stirrup, the farmer's hay fork and shovel, the pipe organist's bellows and foot keys, and the potter's kick wheel, are all pre-Industrial-Revolution examples of foot against tool, transmitting both power and control. As mankind captured in turn the power of falling water, burning hydrocarbons, and splitting atoms, rotary motion and electricity became commonplace, and human muscle was first multiplied and then significantly supplanted by machinery. Consequently, the function of newer foot-tools is no longer to apply both power and control, but chiefly control alone" [57]. But control in its essence has a subjective and an objective aspect to it, and, as shown by our results, at least in the case of foot pedals, they do not necessarily go hand-in-hand. Next, we discuss our findings and reflect on this consistency between objective (performance) control and subjective (perceived) control.

Our results show that the objective performance of subjects for the line following as well as the ecological driving task in VR did not vary significantly over the four pedal configurations, except for the overshoot behavior, where augmentation had a significant effect. This result differs from the studies done by Zhai et al., who found rate control to be better with isometric devices and position control to be better with isotonic devices [83, 85]. This difference might be due to the difference in interaction devices, type of interaction, or due to the task. One reason for the overshoot behavior being less for the augmented pedal configurations can be due to the vibrotactile feedback that notifies the user as soon as they apply different pressure or move. One of the participants also hinted at this in the qualitative interview, mentioning that the vibrotactile feedback helped them to understand how fast and how much pressure they were applying. For position as well as velocity *RMSE* and *PAS*, however, we believe that the participants relied on how they modulated their foot pressure and position according to the visual feedback from the line or the car they controlled rather than the vibration feedback. The findings of the objective performance metrics suggest that while vibrotactile feedback does not improve raw performance metrics such as tracking error and pedal adjustment speed, it positively impacts the user's behavioral control by reducing overshoot. Having no measurable differences in the performance of the different pedal configurations provides opportunities for the designer to fully focus on practical considerations and user experience, without worrying about performance. *THW* showed differences between subjects based on their driving style, but was constant over different pedal configurations. The THW metric evaluates the safe tracking distance, which is generally consistent at different speed levels but can differ from one driver to another [79]. The finding of significant differences between users in terms of average THW values over all pedal types implies that users were able to impose their unique driving styles despite the changes in pedal type.

In contrast, the qualitative content analysis of the interviews indicated that vibrotactile feedback increased the participants' perceived control as well as perceived task performance. Most participants preferred the compliant pedal configuration with vibrotactile feedback, which creates a virtual texture. The compliant configuration was preferred since the participants appreciated configurations that mirrored real-life experiences or provided a familiar interface; it helped them feel more in command, which is similar to the principles from past research [65]. Based on participant quotes, the embodied vibrotactile feedback assists in intuitively understanding the position of the pedal, providing an additional mode of feedback without increasing the cognitive load, as already observed by Sabnis et al. [62] in the context of symbol design. Furthermore, the embodied vibrotactile feedback provides additional sensory information that aligns with the user's actions, thereby enhancing user experience. The associations the participants were able to make due to motion-coupled vibrations emphasize the importance of designing systems that align with the user's existing sensory references and real-life experiences. Designers can use these associations to enhance the usability and intuitiveness of such systems, making them more effective tools for pedal-based interactions. Additionally, the design space of embodied vibrotactile feedback offers opportunities for the designers to create customized and real-life inspired experiences with vibrotactile augmentation on the gas pedal, prioritizing user needs and usability, without compromising performance.

Finally, the most interesting finding from our study is that the objective performance and the perceived control do not necessarily correlate. This mismatch between performance and perceived control highlights an interesting research opportunity. It appears that not only the successful completion of a task influences the user's experience of control, but also other factors, such as the feedback they receive while performing the task. In the present study, while the visual feedback remained the same, providing more levels of vibrotactile feedback increased participants' *judgment of control* during the tasks. One key factor might be that the vibrotactile feedback provides immediate sensory cues that make users feel more actively engaged with the task. Moreover, the pedal augmentation allowed our participants to get a clearer picture of their movement's impact on the pedal, which increased the pedal's perceived intuitiveness and ease of use of the pedal, increasing the overall confidence participants had when using the pedal. This can create an increased sense of control over the pedal's movement and position, which then transfers onto the visual outcomes of the pedal's movements, the position of the line, and the car. The increased intuitiveness and confidence using the pedal is likely to have caused the increase in perceived performance as well as the participants' feeling that they were able to communicate their intentions to the system more easily. Additionally, vibrotactile feedback provided using motion-coupled vibrations simulates a responsive interaction which might help users feel more attuned to the system's state. This might make the task feel more manageable and give an impression of improved control that does not correspond to actual performance metrics. However, this is only speculation, and further research is needed to provide a detailed explanation for this phenomenon. The results show a connection between people's perceived control and performance, highlighting that, especially in the design of haptics, one must consider subjective and objective controls separately, as some optimization might improve subjective experience without producing measurable improvement in performance. This does not mean that these optimizations are useless – on the contrary, they profoundly shape the user experience.

7.1 Application Scenarios

Among the many potential application scenarios, here we discuss three scenarios from different fields.

Fuel Efficient Driving: For fuel-efficient driving, the pedal should encourage smooth and gradual acceleration to promote economical driving habits. A compliant pedal with integrated vibrotactile feedback can serve this purpose by providing immediate feedback to the driver when excessive pressure is applied, thereby discouraging rapid acceleration. The feedback should mimic a resistance or a gentle pulse that intensifies with pressure, reminding the driver to ease off the pedal. This configuration might enhance the driver's sense of control while fostering a driving style that maximizes fuel efficiency. A version of this has already been prototyped[4].

Sewing Machine: In the context of a sewing machine, the pedal must enable fine control over the speed of the needle, allowing for both rapid stitching and precise, slow movements. A rigid pedal with augmented vibrotactile feedback would work well here. The vibrotactile feedback should be designed to provide a clear tactile response that increases with pedal pressure, giving the user immediate and intuitive feedback about the speed of the needle. This would help the user maintain a steady pace and make precise adjustments as needed, improving both control and confidence.

Pottery: For pottery, the foot pedal should provide smooth and precise control over the wheel's speed to accommodate the nuanced and gradual adjustments the potter needs to shape their work. A compliant pedal with vibrotactile feedback would be ideal, as it can simulate the feeling of the wheel's resistance, enhancing the potter's sense of connection with the material. The vibrotactile feedback should be subtle and proportional to the wheel's speed, providing an intuitive sense of how much pressure is being applied, thereby allowing for delicate adjustments without visual distraction.

7.2 Limitations and Future Work

The users relied on visual feedback for the tasks, and hence the differences in the task performance between the different pedal configurations was not significant. This can be investigated in future research about how the user performs on the given task with different kinds of haptic feedback only. Although we simplified the gas pedals in our study compared to their real-world application, it needs to be pointed out that controlling an automobile with a gas pedal is a safety-critical application, and augmenting such pedals should take into account the phenomenon of 'riding the pedal' [41]. Our results should not be taken as a proposal to replace existing gas pedals, but as a recommendation to think about embodied vibrotactile feedback as a control mechanism, which can increase perceived control and provide customizable designs and real-world associations on pedal interfaces. This study was driven by curiosity about pedals as an interesting I/O device to investigate the subtle intricacies of perceived and factual control, but our future work will explore whether the results hold for joysticks, sliders, knobs, and other interactive devices.

For future work on pedals, an interesting area to explore is the design space of the parameters of motion-coupled vibrotactile feedback on pedals, which could add realism to the different modes in an automobile (sports, eco, city, cruise, etc.). Moreover, future work could also investigate other modalities, such as auditory or visual cues, to determine whether the enhancement in perceived control is unique to vibrotactile feedback or generalizable across sensory modalities. Additionally, studying the long-term effects of embodied vibrotactile feedback on user learning and adaptation may reveal that extended exposure leads to improvements in actual performance, potentially bridging the gap between perceived and objective control. Lastly, these findings potentially inform the design of other simulated control systems, where enhanced perceived control through feedback could improve user experience and satisfaction in applications such as surgical training, movement guidance, virtual interfaces or remote-controlled systems, without requiring hardware modifications.

8 Conclusion

This study explored the relationship between objective performance and perceived control in the use of foot pedals with varying configurations. Despite the lack of significant differences in objective performance metrics across the four pedal configurations—rigid and compliant pedals, with and without motion-coupled vibrotactile feedback—the qualitative data gathered from participant interviews revealed a notable increase in perceived control when vibrotactile feedback was present. This finding underscores the importance of considering both objective and subjective measures when evaluating user interfaces for dynamic control systems. The enhanced perceived control with vibrotactile feedback suggests potential benefits in user experience and satisfaction without detriment to performance. Consequently, this research paves the way for designing customized pedal feedback mechanisms that enhance user perception and interaction, thereby contributing to the development of more intuitive and effective control interfaces. Future work should balance objective and subjective evaluations to fully capture the nuances of user interaction with emerging technologies.

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