Designing Vibrotactile Feedback for rendering Material and Force Experiences

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Abstract

When exploring the world using our sense of touch, there are various perceptual mechanisms which shape our material and textural experiences. Previous research replicated material experiences using sophisticated systems rendering vibrotactile feedback. However, there is a missing link between the material and force experiences created using vibrotactile rendering and the perceptual mechanisms which shape these experiences. To address this link, my research focuses on three main areas: investigating the perceptual mechanisms underlying the rendered material experiences; using embodied vibrotactile feedback to design tactile symbols and creating wearables for tactile augmented reality; leveraging perceptual mechanisms as a design tool for rendering vibrations. In this paper, I share my co-evolving insights from research on tactile perception and vibrotactile material rendering, while reflecting on my PhD journey and speculating about the quest ahead.

CCS Concepts

• **Human-centered computing → Haptic devices**; *HCI theory, concepts and models.*

Keywords

haptic devices, perception, vibrotactile rendering, haptic illusions

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1 Introduction

During my PhD, along with writing papers and doing research, I have engaged in haptics outreach by conducting workshops [32, 50], [1] with our prototypes. One striking observation is that with the same system, the designed embodied vibrotactile feedback is based on the users' tacit knowledge, lived experiences and contextual upbringing. For instance, children in rural India designed *"vibrations they feel while riding a bus"* or *"at a flour mill"*, while haptic experts from Germany assign similar vibration designs to *"rumble strips on roads"* and *"vibrations on their smartwatch"* [34]. This broad range of vibrotactile feedback can be designed based on multiple experiential factors, however, the perceptual mechanisms underlying those tactile experiences are the same across humans. **This symbiotic relationship between tactile perception and the design of vibrotactile feedback to render material and force experiences is the focus of my research.** My research investigates the following aspects:

- Understanding the perceptual mechanisms which shape material experiences, and using them as a design tool to render thoughtful vibrations.
- Developing systems capable of rendering material experiences with vibrotactile feedback and real-time, remote, collaborative design of tactons.
- Using embodied vibrotactile feedback (material experiences) to design tactile symbols and develop wearables for tactile augmented reality.

To investigate these aspects, I investigate the sense of touch, which we use to experience many of the material properties in the world. These material properties are primarily mediated through vibration [4]. For example, when we break a stick, move our hand over sandpaper or press into a sponge, the information about the consistency of the stick, textural properties of the sandpaper and compliance of the sponge is mediated through vibration. These vibrations are not consciously perceived as vibration, but rather as material properties of the objects we are interacting with. Research has shown that material experiences of virtual compliance [22, 40], stretching, twisting and bending [16] on rigid objects and virtual textures on smooth surfaces [28, 41] or in midair [38] can be induced by rendering vibration corresponding to user action. Thus, virtual material experiences can be created or modified by carefully measuring user action (such as user motion or user pressing a finger into an object) and then designing vibrotactile signals that are dynamically coupled to the user motion [33]. This method of rendering vibration proportional to user action is referred to as **motion-coupled vibration**. I developed a system called **Haptic Servos** [33] which can render embodied material experiences using motion-coupled vibration. The user studies conducted with haptic servos highlighted the close coupling between user action and vibrotactile feedback, thus helping to understand the perceptual mechanisms better.

I then explored the application of embodied vibrotactile feedback in two distinct areas: designing tactile symbols and wearables

[1] https://tactilevision.github.io/WHC23-CollabJam/

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for tactile augmented reality. Previously, tactile symbols used vibration [7], and modification of vibration parameters [6, 8, 14] to mediate information. For example, a phone might vibrate to acknowledge user input, or indicate that new information is available. Here, vibration is used abstractly to represent information which the user must consciously interpret [11], which is referred to as hermeneutic mediation by Don Ihde [17]. Another way of using vibration to mediate information is by creating natural experiences familiar to the user from their daily life. For example, vibration can be used to simulate the experience of friction, compliance, or other material properties [33]. The user need not attend the stimulus to interpret it; rather, there is a pre-reflective understanding based on lived experience, and is referred to as embodied mediation by Don Ihde [17]. Hence, I investigated, *"How can these embodied material experiences rendered using motion-coupled vibration be used as a design element to create a more intuitive tactile symbols?"*. Moreover, to explore the possibilities and opportunities presented by embodied vibrotactile feedback for tactile augmented reality, I designed wearables devices like shoes to modify gait patterns by creating augmented surfaces [49], finger-worn devices to change the experienced material properties of physical objects [19, 45] and creating a sensation of movement for the user while being stationary [13].

Finally, I delve into the perceptual mechanisms that underlie users' experience of exploring virtual materials and leverage these principles for designing more thoughtful vibrotactile feedback. Along with motion-coupled vibration, another way of providing embodied experiences is through thoughtful design of vibrations. Asymmetric vibrations have shown to elicit a sensation of force [1, 9, 12, 29, 42, 43]. However, the induced force, known as pseudo force, is inherently tied to unwanted vibrations. Therefore, with current approaches, it is not possible to induce a pseudo force experience or increase its intensity without the user also experiencing an increased vibration. Using two mechanisms established in sensory attenuation literature: (a) self-generated stimuli are perceived to be less intense compared to externally generated stimuli [2, 21, 47] and (b) the reduced perception of vibration during movement [3, 5, 25], to design vibrotactile feedback, I showed that it is possible to render the desired force sensation while significantly reducing the perceived vibration. This attenuation of vibration also contributes to users' experience of being in control, also known as sense of agency (SoA) [15]. However, *"does embodied vibrotactile feedback improves user's objective performance?"*, and *"whether it aligns with their subjective sense of agency?"* are the questions which I further investigated [31].

2 Context and Motivation

This section describes the research on vibrotactile material rendering for creating material experiences and the underlying perceptual mechanisms which shape these material experiences.

2.1 Vibrotactile Rendering for Creating Material Experiences

The primary method of creating material experiences with vibrotactile feedback is by coupling vibration with user action. When vibration pulses are provided based on measured user action within a certain time interval [22, 38, 46], the user neither perceives the action nor the vibration individually, but a cohesive material experience [33]. Motion-coupled vibration have been previously shown to elicit experiences of textures on a smooth rod [41] or surfaces [10, 28] as well as in midair [38]. Further, they have also been used to render experiences of bending [39] as well as of twisting and stretching [16]. Moreover, vibration coupled with user pressure has been shown to elicit virtual compliance in hand [22, 23] and foot based interaction [40].

Most of the systems mentioned above elicit different material experiences, yet share many implementation details. They involve high resolution sampling of human action and then use this information to modulate parameters of a vibrotactile signal. This implies that these known vibrotactile effects are merely specific instances of a broader range of vibrotactile material experiences. Hence, it is reasonable to assume that they are in fact different manifestations from the same underlying perceptual mechanism. I developed haptic servos as a platform to render material experiences based on this perceptual mechanism [33].

Beyond simulating material experiences, carefully designed vibrations have also been shown to convey force sensations [9, 12, 42, 43]. These forces, known as "pseudo forces" can be elicited using asymmetric vibrations, generated by unequally accelerating a mass in two mutually opposite directions [1, 12], which have been used to simulate weight, force, and inertia [9, 27, 43]. However, the current approaches of rendering pseudo forces are limited by their co-existence with vibration. Thus to induce a stronger sensation of force, a stronger vibration needs to be provided which is perceived to be distracting [44], annoying and aggressive [26, 33, 34, 36–38]. However, perceptual literature shows that self-generated stimuli are perceived to be weaker than the same intensity stimuli generated externally [24]. Thus, we rendered asymmetric vibrations coupled to user-motion which are perceived to be self-generated and induce similar level of perceived pseudo forces as shown in literature but were able to minimize the perceived intensity of vibration significantly.

2.2 Understanding Perceptual Mechanisms that Shape Material Experiences

There is a qualitative difference between the vibration of a phone, which feels more abstract and a material's texture, which feels natural, despite the fact that both of them are primarily mediated by vibration [4]. Katz [20] suggests that tactile information can be experienced in multiple ways: *proximal* stimuli, such as scanning a texture, requires direct contact with the skin of the user, while *distal* stimuli, like a mobile phone vibrating on a table, can be perceived anywhere on the table. Another distinction that differentiates the two experiences is that the mobile phone vibration feels as an external stimulus to the user, whereas experiencing the texture feels self-generated. This can be attributed to sensory attenuation, which is a perceptual mechanism describing the experience that self-generated sensory signals are perceived less intensely compared to externally generated signals of similar intensity [2, 21, 47]. Hence, motion-coupled vibration can be thought of as self-generated, attenuating the vibration while maintaining the induced material property. There is also a difference based on how the user explores the two experiences. The experience of mobile phone vibration is felt annoyingly stronger [34] as it is imposed on the passive user, whereas texture exploration is more active. Hence, this difference in the perceived intensity of similar stimuli between the vibration coupled to user motion and vibration independent of user motion can be attributed to the phenomena of Sense of Agency (SoA). The SoA describes the experience of controlling one's own actions, and through them, the events in the external world [15]. Thus, we have no agency over the mobile phone vibration, whereas a stronger SoA is felt when exploring a texture. Understanding these mechanisms and leveraging them as design principles for vibrotactile rendering is the other fundamental aspect my research focuses on.

3 Methodology

Here, I describe my research approach and evaluation methods used to investigate the questions posed above.

3.1 Research Approach

My research focuses on the simultaneous exploration of creating material and force experiences using vibrotactile feedback and understanding the underlying perceptual mechanisms. Hence, the starting point of my research is through hands-on exploration of system development while simultaneously reading literature on perception and mediation. I developed Haptic Servos to investigate the different material experiences, which share the same underlying principles. Using haptic servos [33] as the platform, I investigated if we can provide sensation of moving in the absence of movement [13], changing gait patterns by augmenting shoes [49] and back of the finger augmentation as a first step towards tactile augmented reality [45] I was also curious to understand the applicability of the algorithm developed in Haptic Servos. Hence, I tested the same algorithm to induce a compliance illusion with electrotactile stimulation [19].

Further, I explored how embodied experiences can be used as design elements for hermeneutic tactile symbols [34], since the current tactile symbol design is limited to symbols which need to be interpreted to understand the meaning they convey. To understand if embodied vibrotactile feedback had any perceptual advantages in increasing the user's sense of agency or performance, I designed an experiment with and without vibrotactile augmentation on gas pedals and evaluated the perceived control and objective performance [31]. Moreover, current approaches of designing vibrations or tactons are limited to in-person settings. In one of the projects, we developed *CollabJam* [2], a modified version of *TactJam* [48], to enable haptic designers to design tactons in real-time co-located as well as remote settings. Finally, in most of the projects, the vibration which was independent of user action was perceived to be stronger than the vibration which was coupled to user action. This finding led me to investigate whether we can use the phenomenon of sensory attenuation to design vibrotactile feedback so that vibration is attenuated while the elicited material quality is preserved.

3.2 Evaluation Methods

During my PhD, I have used both, qualitative and quantitative evaluation methods, since, understanding the perceptual mechanisms as well as unfolding the experience of inducing material properties using vibrotactile feedback is of utmost importance. Speaking about qualitative methods, I have used microphenomenology inspired techniques to investigate users'experience of exploring a material or a texture in [33]. Further, I have used semi-structured interviews to understand the qualitative preferences, design process, and experiential aspects of symbol design [34], movement modulation [13] and perceived control [31]. Analysis methods I have used so far include thematic analysis [33, 34, 45] and qualitative content analysis [30, 31].

Another dimension of my research uses psychophysics methods like magnitude estimation to understand quantitative differences in different qualities of the rendered material experiences based on the intensity of user action, vibration or electrotactile grain parameter or type of mapping [13, 19, 45]. Further, I have used two-alternative forced choice to compare and contrast between different designed symbols [34] as well between asymmetric and symmetric vibration to understand whether directionality can be induced [29]. Moreover, I have leveraged analysis methods including parametric and non-parametric methods like, 2, 3-way repeated-measures ANOVA, t-tests and Aligned Rank Transform ANOVA followed by appropriate post-hoc tests.

Along with understanding the user and their experience, I have also conducted workshops to understand the feasibility of designing with the systems I have developed [33, 50]. Finally, I have evaluated *CollabJam* and *Haptic Servos* [33] for overall system latency.

4 Results and Research Contribution

To enable ourselves and other hapticians, designers and practitioners to easily create virtual material experiences, I developed Haptic Servos. Haptic Servos is an open-source, time-sensitive, self-contained vibrotactile rendering system offering high temporal resolution, which can enable the rendering of highly articulated high fidelity material experiences [33]. Through empirical studies, we showed that the experiences rendered using Haptic Servos are perceived to be natural. Investigating the building blocks of the virtual texture and compliance experience, we found that both of them are perceptually similar, with the user action being the key difference. By providing vibration coupled to user pressure, virtual compliance emerges; whereas by providing vibration coupled to movement, virtual textures emerge. A workshop showed that users with no or little prior experience in hardware design can use Haptic Servos to quickly and easily prototype material experiences.

Using haptic servos as a development platform, we showed that it is possible to render an illusion of softness on the palmar side of the finger by providing vibration on the dorsal side coupled to the change in oxygen levels with respect to applied pressure [45]. Further, we showed that it is also possible to generate an embodied illusion of softness in the shoe using motion-coupled vibration, while walking [49]. Coupling vibrotactile feedback with the force applied by the user, it is possible to provide an experience of movement to a stationary user [13]. When designing tactile symbols with continuous and motion-coupled vibration, our results showed that embodied experiences can be used for hermeneutic design, which extends symbol design opportunities in useful ways [34]. Thematic

[2]https://tactilevision.github.io/WHC23-CollabJam/

analysis of the interviews with haptic experts showed that the symbols they designed can be associated with lived experiences and have affective qualities.

Further, I looked at how embodied vibrotactile feedback affects the users' objective performance and their perceived control in an abstract and an ecological driving task using foot pedals [31]. Interestingly, the results show that presence vibrotactile augmentation does not affect the performance of the user for abstract as well as ecological tasks. However, the users' perceived control is increased, and they feel a higher sense of agency with vibrotactile feedback. Therefore, in principle, it is possible to integrate vibrotactile feedback to give the user a feeling of being in control and better performance. Further, using the perceptual mechanism of sensory attenuation as a design principle to render motion-coupled asymmetric vibration, we reduced the perceived vibration (equivalent to 30% reduction in amplitude) while preserving the amount of pseudo force.

So far, my PhD research contributions include three first author [30, 33, 34], two second author [13, 19] and one co-authored publication [45] at the two years of CHI I submitted to, since the start of my PhD. Two of my papers have received **Best Paper Honorable Mention** award at CHI 2023 and 2024. I have a first author paper at TEI 2025 [31] and co-authored publication at the Augmented Humans conference 2023 [49], and two papers under review in CHI 2025. I have also co-organized multiple workshops in TEI'24 [50], World Haptics Conference 2023 and CHI [18, 32].

5 Research Timeline

I am currently in my third year of doctoral studies at the University of Saarland and the Max Planck Institute for Informatics. Additionally, I am grateful to start as a visiting researcher at the Industrial Design department at the Korean Advanced Institute of Science and Technology (KAIST).

5.1 Reflecting on my Previous Research

The first year of my PhD was focused on establishing a strong research foundation as well as developing a platform – Haptic Servos, which can render motion-coupled vibrotactile feedback [33]. Moreover, using Haptic Servos, I tried to understand how expert hapticians design tactile symbols with motion-coupled (embodied) and continuous (hermeneutic) vibration [34] and also used haptic servos to augment the inside of shoe-sole to see how it affects walking patterns [49] This was the time, I was really new to the field and was trying to find my niche and needed a considerable amount of support from my supervisor and colleagues. During my second year, I also had the opportunity to collaborate on three CHI projects which utilized aspects of Haptic Servos to render an illusion of movement [13], back-of-the-finger wearable capable of generating an illusion of compliance on the fingertip [45] as well as rendering an illusion of compliance using electrotactile stimulation where electrotactile pulses are provided based on the applied pressure by the user [19]. Although the second year project I led was not in-time for CHI'24, it is accepted at TEI'25 in my third year [31]. This project made me understand scientific rigor and I could see myself on a journey to become an independent HCI researcher. During my third year, I submitted a paper I led to CHI, which uses an established perceptual mechanism as a design principle to render vibrotactile feedback. Overall, it has been a quest from finding my niche, to becoming an expert in it, while collaborating with researchers from different institutes and fields of expertise.

5.2 Speculating the Next Steps

The plan for the next 1.5 years is to have a final capstone project and finish my PhD by the first half of 2026. Some initial ideas to explore include bi-manual haptics as most of the current research is focused on single hand interactions; exploring the design space of embodied vibrotactile feedback; leveraging the perceptual mechanism of sensory masking to design vibrations. Till April 2025, I hope to be working on one of these ideas, however it would be in the initial stage. Further, the research I have conducted so far seems to have multiple dimensions, but with loose ends. My supervisor and I are convinced that the doctoral consortium at CHI'25 in April would be an excellent opportunity to tie those loose ends of my PhD and have crucial feedback in the initial stages of the capstone project.

5.3 Open Questions and Challenges

Several open questions and challenges have emerged during my research that I believe are crucial to address. First, while I have successfully rendered material experiences using linear input-output mappings to generate vibrotactile feedback, the broader design space for creating realistic material sensations through vibration coupled with user actions remains largely unexplored. *How can we systematically explore and refine this design space to develop more robust material rendering techniques?* Moreover, the design of symbols using continuous and motion-coupled vibration at present is dichotomous. One of the questions which came from the interviews in [34] is: *What are other methods of combining continuous and motion-coupled vibration to create more realistic material experiences and tactile symbols?.* This opens up possibilities for creating more realistic, immersive effects by superimposing multiple vibrotactile illusions. My research sheds light on a few perceptual mechanisms in the process of designing vibrotactile feedback, yet questions remain about how these mechanisms interrelate. *Is perception a purely low-level, sensory process, or do higher-level cognitive functions intervene?* Additionally, thinking beyond human-centered perception, examples such as the Venus flytrap–an organism without a brain yet capable of distinguishing between stimuli like a fly or a human finger–challenge our understanding of how touch is processed. *What are the underlying sensory, neurological, and psychological systems that differentiate between natural and artificial textures, and how can we leverage this knowledge to create high-fidelity tactile experiences?*

Furthermore, in the design of vibrotactile feedback, one of the challenges is the lack of a common platform for designing vibration, which leads to everyone designing their own hardware from scratch [35]. Another challenge is that of collaboration with colleagues from different parts of the world. During the development phase of the research projects, all of us need to re-create the system to experience the haptic feedback and discuss the next steps. Moreover, it is very difficult to express and communicate haptic experiences and there is a need for a tactile vocabulary to describe embodied vibrotactile experiences. Regarding the process of doing research, there is a constant trade-off between exploitation and exploration in the different stages of the research as well as constant struggle of keeping up with advancements in the field, particularly after the availability of large language models.

Overall, one of the primary challenges I face is the focus on novelty for paper acceptance in top tier HCI conferences, which often pushes researchers to jump between projects instead of deeply investigating a single idea over several years. Another pressing challenge is that I feel that the research I am doing is driven primarily by curiosity and not by necessity, where in fact I would like to do both.

5.4 Long term goals

Whenever I think about the next 2 years, I am not sure where I would be but when I think about the next 5 years, I can confidently say that I will be in India, having my own HCI research lab with world-wide collaborations. I want to focus on two aspects: further investigating the perceptual mechanisms in the tactile exploration and design of intelligent vibrotactile feedback; applying my knowledge of haptics in the field of rehabilitation, sports, and education. Some goals for the next two years include: finishing my PhD, apply for grants and start as a post-doc/ independent researcher in a good institute.

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